Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency and raw materials

# MAGIC

## Moving Towards Adaptive Governance in Complexity: Informing Nexus Security

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## 1. Changes with respect to the DoA

Substantively, the deliverable is in accordance with the DoA; its finalization was delayed by 2 months, due to unforeseen data processing requirements, as communicated to the Project Officer.

## 2. Dissemination and uptake

This deliverable presents the potential of a tool-kit to perform quantitative analysis of the metabolic pattern of social-ecological systems (SES) in relation to their sustainability and the Nexus. This deliverable is intended to be used within the consortium and beyond. For the consortium, this tool-kit becomes the backbone of the upcoming case studies to be developed in WP5 and WP6. Moreover, this deliverable and tool-kit will be the basis for a series of policy brief/fact sheets and will serve to engage with stakeholders. Hence, we expect this deliverable to be of interest beyond the consortium (especially, policy-makers and researcher, but also civil society), by illustrating the potential of an alternative and innovative analytical toolkit able to check the robustness of narratives in sustainable development. The report is publicly available on the project website: http://magic-nexus.eu/documents-repository.

## 3. Short Summary of results (<250 words)

The sustainability agenda builds on key components (i.e. food, water, energy, land use, climate and environment) that are inherently interconnected in a Nexus. MAGIC uses an innovative approach to test the robustness of narratives about the Nexus in Europe and focuses on the EU' sustainable strategy. The aim of this deliverable is to operationalize and test a tool-kit to structure the quantitative analysis of the metabolic pattern of social-ecological systems in relation to their sustainability and the Nexus, at different levels of aggregation and spatial scales (EU, country or regional level). We use "quantitative story telling" as an alternative approach to use scientific information generated and better inform policy-makers. This deliverable build on the methodological approach and the basic features of the theoretical framework of accounting called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). The application of the tool-kit in this deliverable has the only goal of illustrating the potentiality of the approach. In a series of chapters we i) present the theoretical background and features of the tool-kit used to characterize the state-of-the-play (diagnostic analysis) with regard to the sustainability of SES; ii) provide an overview of the results obtained in the analysis of 8 EU countries (i.e. France, Germany, Italy, Netherlands, Romania, Spain, Sweden and United Kingdom); iii) demosntrate the capability of the toolkit to perform the anlysis at diffrent scales (in this case, at a lower aggregated level -NUTS2-); and iv) highlight the methodological breakthrough provided by relational analysis and its relevance for policy making with regard to the water-energy-food-environment Nexus.

## 4. Evidence of accomplishment

This report**.**

## 5. **Document History**

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|---|---|---|
| Version | Publication Date | Change |
| 1.0 | March 2018 | Initial version |
| 2.0 | June 2019 | Revision in response to Project Review (Reporting Period 2):<br><br>- A synthesis oriented toward policymakers has been added that summarizes the key outcomes and messages and the policy relevance of the results has been highlighted (See: EXECUTIVE SUMMARY FOR POLICY MAKERS)<br><br>- To better ground the synthesis for policy makers, the Executive Technical Summary has been modified (See: EXECUTIVE TECHNICAL SUMMARY)<br><br>- Clarification about access to the databases in the data repository in Annex 5 has been provided<br><br>- An earlier omission in authorship (Z. Kovacic) has been corrected. |

Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency and raw materials

Deliverable D4.2

# Report on EU socio-ecological systems

**(First revision)**


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# List of acronyms and abbreviations

AG Agricultural sector
BEP Bio-economic pressure
DPSIR Driving forces ('Drivers'), Pressures, States, Impacts, Responses framework
ECj Energy Carriers – the index j (1à 3) refers to: electricity, heat and fuels.
EEA European Environment Agency
EJPi Economic Job Productivity – Quantity of GVA per hour of Human Activity in i
Elec Electricity
EM Energy and mining sector
EMR Exosomatic metabolic rates
EMRij Energy Metabolic Rate – Quantity of Energy Carrier j per hour of Human Activity in i
EPM Environmental pressure matrix
$EPM_{EXT}$ Externalised environmental pressure matrix
$EPM_{LOC}$ Localised (internal) environmental pressure matrix
ES Energy Sector
ETij Energy Throughput – Quantity of Energy Carrier j metabolized per year in i
EU European Union
EU-8 EU countries selected for analysis in this report (Germany, France, United Kingdom, Italy, Spain, Netherlands, Romania, Sweden)
EUM End-use matrix
$EUM_{EXT}$ Externalised end-use matrix
$EUM_{LOC}$ Localised (internal) end-use matrix
FAO Food and Agriculture Organization of the United Nations
FAOSTAT Food and Agriculture Organization Corporate Statistical Database
GDP Gross domestic product
GER Gross Energy Requirement
GHG Greenhouse Gases
GVAi Gross Value Added (average year) in the compartment i
HA Human activity
Hai Human Activity (average year) in the compartment i
LU Land Use
MC Manufacturing and Construction sector
MuSIASEM Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
NPK Nitrogen (N), phosphorus-oxide (P2O5) and potassium-oxide (K2O) based fertilisers
PES Primary Energy Sources
PW Paid Work

SES Social-ecological system
SG Service and government sector
STEEP Social, Technological, Economics, Ecology, Politics
TOE Tonnes of Oil Equivalent
VW Virtual water
WEF Nexus Water-energy-food resource security Nexus
WW Withdrawal

## EXECUTIVE SUMMARY FOR POLICY MAKERS

Author: *Mario Giampietro and Raimon Ripoll Bosch*

Within MAGIC, Work Package 4 'Nexus Structuring Space' has the goal to provide a conceptual framework and a practical tool-kit for structuring the perception (qualitative choices) and representation (quantitative choices) of the nexus. The conceptual framework and the analytical tool-kit are needed to help a process of co-production of knowledge claims in participatory processes to be used for decision-making. In relation to this task, the approach proposed in MAGIC, called *Quantitative Story-Telling*, represents a novel philosophy in the use of scientific evidence for the governance of sustainability. The first deliverable of WP4—D4.1 (first submitted 29 July 2017, revised 28 November 2017)—illustrated the conceptual pillars of the approach, based on the concept of the metabolic pattern of social-ecological systems. This second deliverable—D4.2 (first submitted 31/03/2018)- builds up on the first one and provides practical examples of how to structure the perceptions and representations of the Nexus according to the philosophy of Quantitative Story-Telling. It has the goal of illustrating in concrete terms how to implement the theoretical framework through practical applications of the tool-kit.

### 1. Challenges in the field of science for governance addressed in this deliverable

* *Identifying a procedure for carrying out a quality check on the process of co-production and use of scientific evidence in the governance of sustainability*

The disappointing results achieved so far in relation to sustainability issues (e.g., reduction of greenhouse gas emissions, protection of biodiversity, or circularization of the economy) flag the necessity to improve the effectiveness of the process used to discuss and select sustainability policies. To this purpose, it is necessary to learn how to improve both: (i) the quality of proposed sustainability policies; and (ii) the quality of the process used for generating them. In order to tackle this challenge, we have to identify the expected characteristics (in terms of salience, fairness, robustness) of the information required to generate effective policy. In relation to this objective, quantitative story-telling draws philosophically on post-normal science applied to governance, where the quality of analytical outcomes depends on clarifying the choices the evidence base and the modes of analysis considered as salient and credible. Quantitative story-telling is not, therefore, concerned with refinement of the minutiae of existing evidence but rather questioning whether existing science-policy consensuses—i.e. the story-telling(s) endorsed in the form of policy packages authored

by the European Union—are ignoring crucial problems because of a too narrow view of the challenges to be tackled.

When dealing with a quality check of the scientific evidence informing policy, it is essential to identify the integrated set of expected characteristics of the information used in decision-making. These characteristics should include relevance, robustness and fairness. Within this logic, the use of individual pieces of quantitative information proposed as "scientific evidence" (e.g., ecological footprint, economic energy intensity, GDP, the monetary cost of carbon emissions) taken out of a holistic contextualization and without a proper understanding of their role and their meaning in the policy discussion, should be considered as an irresponsible use of quantitative analysis that can lead to the implementation of ungovernable policies.

* *Exploring an alternative way of generating scientific evidence for use in policy-making*.

The philosophy of quantitative story-telling is based on the consideration of the following questions: (i) "what if it is not possible to identify the optimal solution to *the problem*?" (whose problem?); (ii) "what if it is not possible to identify an uncontested intervention that will provide an optimal *improvement*?" (for whom? for how long? at which costs?); (iii) what if it is not possible to eliminate large doses of uncertainty both from our analysis of the existing situation and from our predictions of future events?

If, when dealing with complex sustainability issues, these questions are taken seriously, then the conventional approach to purposeful modelling (the Cartesian dream of prediction and control) might not be the most suited approach. But if we admit that it is impossible to make predictions and to provide control about desired futures, what is then the possible role of quantitative analysis? In quantitative story-telling, scientific analysis is applied to answer questions such as: "what could go wrong if we try to implement this policy?" or "can we define the consequences of proposed policies in terms of winners and losers?"

According to this philosophy, when dealing with complex "wicked" issues, MAGIC avoids the use of complicated models. MAGIC's strategy is to develop and test an analytical framework based on complexity to test the plausibility of proposed policies. This is done by checking the quality of:

- the chosen story-telling, that is the chosen framing of the problem based on the identification of a given set of concerns;
- the chosen narratives used as explanations and associated with the identification of relevant agents, processes and relations of causality over events; and
- the chosen models, data and indicators (targets) used to discuss and implement policies in terms of quantitative targets and indicators.

** Learning how to admit uncomfortable knowledge in sustainability discussions*

As stated by Rayner (2010) the systemic refusing of handling uncomfortable knowledge is the main mechanism of the social construction of ignorance in science and environmental policy discourses. In relation to this point Quantitative Story-Telling could represent a solution to this problem, helping to learn how to handle instances of "uncomfortable knowledge" by contrasting different knowledge claims, visions and aspirations about the future. In relation to this task, Quantitative Story-Telling does not declare to provide uncontested 'facts' to the process of deliberation over sustainability policies but to help a more informed discussion of the problems and the potential implications of proposed solutions. The Quantitative Story-Telling proposed by MAGIC is generated using a quite sophisticated analytical framework (based on insights derived from complexity), but still it does not entail that the knowledge claims it proposes are "truer" than the other knowledge claims found in ongoing discussions. The existence of disagreements about what should be considered a "fact" is perfectly legitimate (besides being unavoidable) when dealing with the analysis of the possible evolution of complex adaptive systems. Therefore, disputing over the truth of proposed facts should not be used to avoid the discussion of the concerns identified by using alternative framings of the issue to be discussed. That is, the philosophy of Quantitative Story-Telling suggests moving away from a discussion based on "matters of fact" (i.e. whether a fact is "truer" than another) to a discussion about "matters of concerns" (i.e. assessing the plausibility of the concerns arisen from different framings, formalizations and analyses of the issue).

In this new philosophy, policies should not be checked in relation to "what will happen if" but rather by reaching an agreement on "what cannot happen if" and "what may happen if" - i.e. the anticipation of the potential consequences of the policies in terms of side effects. That is, an analysis relevant for decision-makers should be based on a series of checks addressing different aspects of the sustainability predicament: (i) feasibility check - in relation to constraints imposed on the society by processes outside human control, invisible to economic analysis; (ii) viability check - in relation to constraints determined by processes under human control that can be observed through both economic or technological analysis; (iii) desirability check – in relation to normative values, existing institutions and aspirations of the social actors, outside the reach of technocratic analysis. The quality of the information used for policy depends on the ability of critically appraise scientific evidence using more than one lens at the time.

The systemic attempt of falsifying existing narratives or story-telling proposed by Quantitative Story-Telling should not be intended as aimed at taking sides favoring or damaging one or the other side in the discussion of specific policies. On the contrary, we are convinced that a more informed discussion trying to: (i) eliminate from the discussion impossible options; (ii) clarify the potential consequences of policies in view of the unavoidable existence of power asymmetries among social actors; and (iii) acknowledge the implications of uncertainty - will beneficiate all social actors by

allowing a more robust framing and a more informed discussion over discording, but legitimate, endorsements of sustainability policies.

In conclusion, Quantitative Story-Telling is about integrating the diversity of available knowledge claims that are considered as credible and relevant to better understand the nature of wicked problems. For achieving this result, it is essential to avoid the hegemonization of specific standard narratives and story-telling in the chosen framing of the problems to be solved. A diversity of framings of a given issue is the only strategy making it possible to reduce the unavoidable generation of "hypocognition" (the missing of relevant aspects, Lakoff, 2010) associated with any quantitative representation of a problem/solution.

Within the goals of MAGIC, the contribution of WP4 is to find a method capable of combining different types of quantitative analysis in an integrated information space, that should be co-produced with the final users (social actors) in order to allow more informed and fairer policy choices. This is what is developed in the activities of WP4 and what is presented in this deliverable.

## 2. The policy relevance of the results

In this deliverable we present an analytical framework, based on a complex representation of the metabolic pattern of social-ecological systems that is capable of combining different types of quantitative information into an integrated characterization of sustainability issues. This analytical framework can be used (and should be used: (i) to carry out a quality check on the process of co-production and use of scientific evidence in the governance of sustainability; and (ii) to co-generate an integrated information space produced together with the final users (social actors) to deliberate about more informed and fairer policy choices

The material presented in this deliverable does not represent an application of Quantitative Story-Telling to concrete policies (examples of this application are given in WP5, namely D5.5 and D5.7), but it illustrates the potentiality of a tool-kit that can be used to generate scientific evidence for use in policy making within the paradigm of Post-Normal Science. Important features of the proposed analytical framework are:

1. It allows to preserve coherence across quantitative analyses based on different metrics carried out across different levels and dimensions across indicators. This is extremely important because of the existence of unavoidable side effects (negative consequences of an improvement according to an indicator over other indicators) to be expected when considering the different dimension of the nexus. The "silo-governance syndrome" is exactly generated by an excessive importance given to the achievement of a specific target when side effects in relation to other targets are not considered. For instance when solving a problem in relation to food, we may be generating a problem in relation to water, and so on. The existing entanglement over the flows associated with

the NEXUS implies that it is impossible to define sound policies and useful targets, without considering the side effects associated with proposed changes. For this reason, in societal multicriteria evaluation, the organization of information should consider simultaneously the effects of policy in relation to different criteria of performance (i.e. *impact matrix*). The tool-kit developed in MAGIC makes it possible to anticipate some of the side effects (improvement and worsening) in relation to the chosen integrated set of indicators of sustainability within the impact matrix. This awareness of the unavoidable existence of side-effects is essential to prevent the syndrome of silo-governance when dealing with the NEXUS.

2. It facilitates the consideration of different story-tellings and different narratives about the definition of "concerns", "problem" and "solutions". This is extremely important because of the complexity of social relations. As discussed earlier, solving a problem identified by a group of social actors – e.g. suggesting a move to a massive production of electric cars – may imply generating a huge problem to other social actors – e.g. the workers in the traditional automotive industry that can lose their jobs if the production of electric cars moves to another economy. In societal multicriteria evaluation, it is essential to organize the information in order to be able of considering simultaneously the discording perceptions of "concerns" and "improvements" found among the social actors. Quantitative Story-Telling allows a discussion of the generation of winners and losers associated with the implementation of a given policy. If a policy is justified as the solution to a given problem, we should answer the question "whose problem?" Who are the winners and who the losers after the implementation of a policy regarded as a solution? This feature is required to guarantee fairness in the governance of the NEXUS.

3. It helps to boost the legitimacy and trust in the process of decision making by providing an alternative way of generating scientific evidence. By moving to an analysis of "concerns" rather than an analysis of "facts" it helps the acceptance of uncomfortable knowledge in the deliberations over sustainability. In a world that is no longer "black" or "white" defined on the basis of uncontested facts, in which uncertainty can no longer be ignored, considering a diversity of contrasting opinions and story-telling should be considered as a strength of the process of assessment. Moreover, Quantitative Story-Telling is totally transparent in relation to the definition of assumptions, source of data, and the mechanisms used to generate results. This approach can be used to replace the "mysterious models", that sometimes seem to be used today the same way oracles were used in the past. A co-produced living information space can be used to continuously evaluate the available knowledge claims at the moment of informing polity;

4. In scientific terms, the proposed analytical framework represents a radical departure from the traditional paradigm of quantitative analysis used in conventional models. The information space generated in this way is capable of handling: (i) impredicativity (chicken-egg causality dilemmas); (ii) contingent assessments (entangled what-if scenarios); (iii) the epistemological challenge of how to integrate non-equivalent metrics

across scales, if needed, with the use of Geographic Information Systems to carry out the analysis of impact in spatial terms.

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**EXECUTIVE TECHNICAL SUMMARY**

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## 1. What has been achieved in the research done

The application of the procedure of Quantitative Story-Telling proposed in MAGIC includes four steps:
(1) STEP #1 - identification of the narratives used to inform policy;
(2) STEP #2 - identification of the relevant factors determining the feasibility, viability and desirability of expected results;
(3) STEP #3 - run a quantitative analysis checking whether all these three factors can be met or whether at least one of these three factors is not met (one of the assumptions of sustanaibility is falsified), which would indicate an implausibility of the expected results; and
(4) STEP #4 - identification of knowledge gaps in the existing discussions over the issue.

To apply this procedure it is essential to have a conceptual map establishing a link between the various pieces of information required to carry out the quality check in relation to feasibility, viability and desirability.
In MAGIC the initial identification of the narratives to be checked for falsification has been done in Step #1 (in different WPs coordinated by WP2), without using Quantitative Story-Telling. However, after having identified a specific set of narratives used to justify the choice of specific policies, it becomes essential to have a theoretical framework that makes it possible to apply QST to the analysis of the quality of the chosen narratives.

The operationalization of the theoretical framework into an accounting scheme allowing quantitative analysis - what is called in the MAGIC jargon as “the Marauder Map” – is required in STEP #2. For this task we used the conceptual framework of the metabolic pattern of social-ecological systems for identifying the key factors determining the conditions of sustainability (feasibility, viability, desirability). The accounting framework built on this rationale allows the integration of different types of quantitative analysis (demographic, technical, ecological, level of openness due to trade, economic, evolutionary) based on the integrated adoption of non-equivalent metrics in order to be able of describing relevant events across different scales and dimensions of analysis. This is the main result presented in this deliverable.

To generate specific applications of Quantitative Story-Telling we have to populate the accounting scheme with data by producing information in both:

(i) diagnostic mode – addressing current situation to identify the relative importance of the various processes considered, the quantitative and qualitative characteristics of the elements of the metabolic pattern, bottlenecks, critical situations of the system, troubles and potential collapse in relation to changes in boundary conditions;

(ii) anticipatory mode – to explore using contingent analysis over "what if" scenarios (based on desired futures associated with policy interventions) the internal or external limits of the option space to identify aspects of the metabolic pattern that can result not feasible, viable and desirable.

In relation to this point, this deliverable D4.2 presents quantitative examples of applications in diagnostic mode. An application in anticipatory mode is given in Deliverable 4.3 (D4.3).

This organization of the scientific information makes it possible to identify knowledge gaps in the existing framing of the issues, potential weakness in the assumptions supporting the choice of policies and targets, and the selection of indicators. Examples of discussions of this type can be found in deliverables of WP5, especially in Deliverable 5.5 (analyzing narratives associated with the policy domain of the CAP) and in Deliverable 5.7 (analyzing narratives associated with the energy policy domain).

## 2. The three phases of the development of the tool-kit described in this deliverable

The deliverable describes the phases used to operationalize the theoretical framework into an accounting scheme that has been implemented in practical applications.

### *2.1 PHASE 1 – Explanation of how the rationale of DPSIR (Driver, Pressure, State, Impact and Response) can be applied to the analysis of the metabolic pattern of social-ecological systems*

In Section 2 the text presents the various theoretical concepts derived from complexity studies that have been used in combination to develop the analytical framework:

1. the basic concept of *dissipative systems in non-equilibrium thermodynamics* in relation to the formalization of the STATE-PRESSURE relation;

2. the principles of *relational analysis of metabolic systems* explaining the concept of emergence in autopoiesis as the establishment of a functional impredicative relation (chicken-egg relation) between constituent components and the whole in metabolic systems;

3. the basic concept of *holons in hierarchy theory* allowing to define in quantitative terms notional elements (non-material element, that can be represented in relation to their expected characteristics resulting by their relation with other elements of the system to which they belong – i.e. network niche, mutual information);

4. the *flow-fund model of Georgescu-Roegen* allowing the characterization of metabolic flows on the basis of the characteristics of the fund elements that either generating or using them.

By combining these theoretical concepts, we can explore and characterize:

*(i) the STATE-PRESSURE relation* as a family of impredicative definition of: (i) *Primary Sources* and *Primary Sinks* (-dSe: negative entropy provided by favorable boundary conditions in the narrative of non-equilibrium thermodynamics); and (ii) definition of *carriers* – secondary inputs required for the metabolism of the system (+ dSi: the internal production of entropy in the narrative of non-equilibrium thermodynamics associated with the existence of favorable initiating conditions). This analysis can seem esoteric but it is essential to address one of the most important epistemological challenge of biophysical analysis: how to measure quantities of energy belonging to different energy forms in complex metabolic systems. In fact, concepts such as energy, food and water, are semantically open and in order to be measured have to be contextualized. The STATE-PRESSURE relation, based on non-equilibrium thermodynamic principles can be used to define, according to the situations, how to quantify non-equivalent definitions of energy, food and water. For example: (i) when dealing with energy – *when considering a refrigerator* "-$dS_e$" is a power plant generating the electricity, whereas "+$dS_i$" is the flow of electricity coming from the power point; BUT *when considering an airplane* "-$dS_e$" is a refinery producing jet fuels whereas "+$dS_i$" is the quantity of jet fuels required for the next trip. What is a quantity of "energy" for an airplane is not energy for a refrigerator; (ii) when dealing with water – *when considering a person* "+$dS_i$" is the flow of water coming out of the faucet, whereas "-$dS_e$" is the maximum amount of water that can be abstracted from the aquifer supplying the water distribution system; BUT *when considering a crop-field* "-$dS_e$" is the combination of green and blue water supplying water to the soil, whereas "+$dS_i$" is the water that is available to the roots from the soil; (iii) when dealing with food; *when considering a cow* "-$dS_e$" is the pasture whereas "+$dS_i$" is the grass; BUT *when considering a person* the "-$dS_e$" may be represented by a cow (when used for preparing a steak) and the "+$dS_i$" is the steak. To make thinks more difficult, when considering food available for people, we may face a situation in which a given "+$dS_i$" – e.g. ham for a Spaniard - would not be considered as a possible food end use by another class of people - a Muslim. These examples show the importance to check the quality of the model used to describe the metabolic pattern of social-ecological systems. Contrary to what believed by many simplistic approaches to energy, water, food and material accounting, the definition of what has to be accounted as a given quantity of energy, water and food is complex – there are primary vs secondary flows, and different forms of energy (thermal and mechanic) and water (solid, liquid and vapor). A proper biophysical accounting does requires a pre-analytical definition of the set of logical criteria that have to be used to define lexicons and taxonomy of energy, water and food forms.

*(ii) the PRESSURE-IMPACT relation* as a family of contingent relations between the specific characteristics of the flows *coming from* and *getting to* the environment and the specific characteristics of the ecological funds expected to either produce or to absorb these flows.

The identification of possible impacts requires always a contextualization, because the use of indicators out of context can be missing important aspects and result misleading. In fact, we can measure a given environmental pressure – e.g. the pressure on the environment determined by the dumping a quantity of a given substance in a body of water. However, this pressure can have different impacts depending on the characteristics of the receiving body. For instance, the difference of environmental pressure between dumping 50 kg or 100 kg of salt into a water body could be: (i) totally irrelevant if we are dumping them into the sea (different pressures – 50 and 100 kg will give the same negligible impact; or (ii) very relevant if the system has a limited tolerance in terms of the required quality of water (salt sink capacity of water tanker). When operating close to a critical threshold even small differences in pressure can become extremely relevant in terms of impact. Also in this case, there are no "one size fits all" indicators (like in the case of GHG emissions). The environmental impact has always to be assessed by comparing the effect of the pressure (determined by the metabolic characteristics of the socio-economic activity) and the impact (determined by the lack of compatibility with the metabolic characteristics of the ecological funds required to provide Primary Supply or Primary Sink capacity).

(iii) DRIVERS are those systematic changes, taking place in the elements of the metabolic patterns, altering the relations between pressures and states. They can do that either by changing the relative size of fund elements – e.g. increase in population – or by changing the metabolic rate of fund elements – e.g. an increase in consumption per capita.

(iv) RESPONSE can be described as a purposeful adjustment in the factors determining the expression of the metabolic pattern, aimed at eliminating or reducing specific attributes of the STATE that are generating a negative PRESSURE (either inside the socio-economic system or in the ecological systems) within the Social-Ecological System.

According to this conceptual framework it is possible to represent the metabolic pattern of social-ecological systems in terms of a set of relations organized in a complex organization space: (i) lexicons of energy, water and food forms that have to cover the quantitative representation of primary sources and primary sinks (the characterization of "$-dS_e$") and energy, water and food carriers (the characterization of "$+dS_i$"); (ii) taxonomy of relations over the various accounting categories reflecting the relations between functional and structural elements (representations of notional/functional and observable/structural components); (iii) grammars – expected relations over fund/flows, primary/secondary flows making it possible to define the boundary of the system. When defining the boundaries of the metabolic pattern we face a logical bifurcation at the moment of deciding what is "inside" and "outside" what. A logic is to make a distinction between the activities taking place inside the technosphere (processes under human control) versus activities taking place in the biosphere (processes outside human control). Another logic is to make a distinction between the activities taking place inside the administrative border of the societal ecological system

under study (including both processes taking place in the biosphere and in the technosphere) and the activities taking place outside the administrative. These external activities are relevant because of trade (imports and exports): they are needed to stabilize the current metabolic pattern of the system under analysis. This point is better explained below.

### *2.2 PHASE 2 – Combining these theoretical concepts into a tool-kit capable of identifying and characterizing in quantitative terms, the various factors determining the sustainability of the metabolic pattern of social-ecological systems*

The visualization of the concept of STATE of socio-ecological systems (SES) is illustrated in Fig. 1 (this scheme is based on the narrative proposed by the European Environmental Agency). Fig. 1 represents how a given society, represented by the different economic sectors (i.e. households, services, mobility, industry and agriculture), metabolizes a series of inputs (i.e. water, energy, food) using labour (human activity) to function in its current state. This information is represented in the so called "end-use matrix" characterizing how inputs are used inside the socio-economic system to express the metabolic pattern associated with the expression of the identity of the society. This snapshot of the socioeconomic picture of the society should be embedded in an environmental context, in which the primary sources and stocks and primary sinks required by the society are determined. The information regarding "demands" from the biosphere can be summarized in an "Environmental pressure matrix". This matrix describes the size of the sources, stocks and sinks required by the activities carried out in the technosphere (represented by the End-use matrix) from its environmental context.

However, this simplified visualization of the set of relations would be useful to study the STATE-PRESSURE relation in the metabolic pattern of a Social-Ecological System, only if the system were closed or isolated. In a globalized economy this is no longer the case because primary sources, stocks and primary sinks available elsewhere can be used in an indirect way embodied in the traded products and services. The complications of the analysis determined by the consideration of the effects of trade is illustrated in Fig. 2 in which the information provided by the END USE MATRIX (a tool describing how secondary inputs are used inside the society – what is generating "$+dS_i$" ) and the ENVIRONMENTAL PRESSURE MATRIX (the consequence requirement of primary sources and flows – what is needed to generate "$-dS_e$") is now distributed across two different coupled matrices.

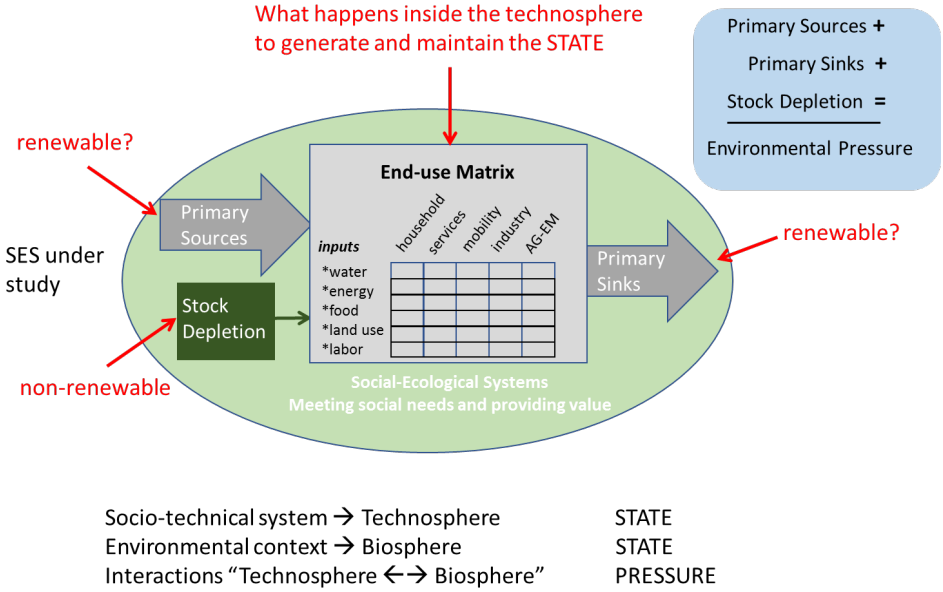


*Fig. 1 The relation between the End Use Matrix (expected "+$dS_i$") and the Environmental Pressure Matrix (required "-$dS_e$") in the narrative of the EEA (no trade)*

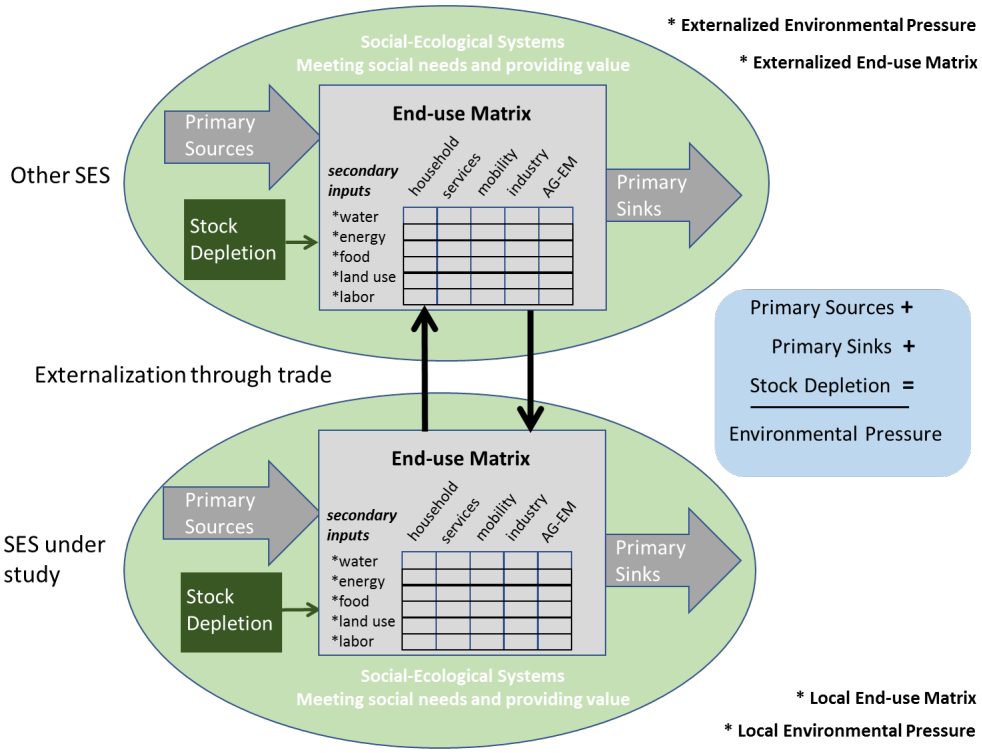


*Fig. 2 The LOCAL End Use Matrix ("+$dS_i$"); Environmental Pressure Matrix ("-$dS_e$"); the EXTERNALIZED End Use Matrix ("+$dS_i$"); and Environmental Pressure Matrix ("-$dS_e$")*

In summary, and in practical terms, it means that there are two main types of MuSIASEM matrices: (1) the end-use matrix (EUM → "+$dS_i$") that can be LOCAL and EXTERNALIZED; and (2) the environmental pressure matrix (EPM → "-$dS_e$") that can be LOCAL and EXTERNALIZED. As a reminder, the former relates to those processes inside the technosphere using secondary inputs (e.g. electricity as a carrier, or form of, energy) that are distributed among structural and functional components of society. The latter relates to processes in the technosphere which directly interface with the biosphere, requiring the existence of Primary Sources/Stocks and Primary Sinks. These processes include the extraction of fossil energy, mining, agriculture or the emission of wastes into the environment. Each of these matrices is multilevel, meaning that they can be split between sectors, sub-sectors and sub-sub-sectors. The characteristics of the local matrices ($EUM_{LOC}$, $EPM_{LOC}$) and externalised matrices ($EUM_{EXT}$, $EPM_{EXT}$) illustrated in Fig. 2 are specified in Table 1.

*Table 1 – The four types of matrices used to describe the STATE-PRESSURE relation*

| Acronym | Matrix | Meaning | Question answered |
|---|---|---|---|
| $EUM_{LOC}$ | Local end use matrix | Local investment of labour and resource carriers (multiscale) | What inputs are required from the local technosphere to sustain the local metabolic profile (viability and desirability) |
| $EUM_{EXT}$ | Externalised end use matrix | Externalised investment of labour and resource carriers (multiscale) | What inputs, direct and indirect ('virtual'), are required from the external (non-local) technosphere in order to sustain the local metabolic pattern |
| $EPM_{LOC}$ | Local environmental pressure matrix | Local inputs and outputs to and from the biosphere (multiscale) | What environmental pressures are placed on the local biosphere's sources and sinks (feasibility: water use, emissions, etc.) |
| $EPM_{EXT}$ | Externalised environmental pressure matrix | Externalised inputs and outputs to and from the biosphere (multiscale) | What environmental pressures are externalized, directly and indirectly ('virtual') |

In order to link variables across different levels (process level, economic sector, whole society) the MuSIASEM accounting method characterize the various elements and vectors inside the matrices (local and externalised). The different categories of accounting across different levels of organization must be chosen with the goal of guaranteeing the congruence across levels of analysis. The quantitative assessments must remain coherent across non-equivalent accounting metrics (more details in the text of the deliverable).

When using this multi-level and multi-dimensional approach it becomes possible to generate and integrate quantitative information in relation to: (i) the analysis of

processes taking place inside the technosphere, at different hierarchical levels; and (ii) the analysis of processes taking place in the biosphere, at different hierarchical levels.

### *2.3 PHASE 3 – Populating the tool-kit with available data*

In this phase the various datasheets required to calculate the values inside the matrix have been populated with data gathered from statistical sources. This operation is illustrated in the deliverable using a large number of tables and figures. Technical guides explaining how data on energy, water and food has been produced and handled, plus an analysis of limitations and recommendations about working with such data, can be found in the appendix. With regards to the deliverable, two examples of applications of the "state of the play" (applications in diagnostic mode) can be distinguished:

1. *Applications at the national level* – The MAGIC approach was applied in a diagnostic mode to calculate the local end-use matrix, local environmental pressure matrix, externalized end-use matrix and externalized environmental pressure matrix for a sample of eight EU countries. Visualization of the results of the comparison of nexus performance was illustrated for three countries: the Netherlands, Germany and Romania. This visualization exemplifies how the data of the end-use matrix and the environmental pressure matrix (reflecting the metabolic pattern *inside* national borders) can be contextualized against the information from the externalized end-use matrix and the externalized environmental pressure matrix. Another application of the approach in "diagnostic mode" concerned an assessment of the bio-economic pressure, an indicator of economic development based only on relations over biophysical characteristics of society.

2. *Applications at hierarchical levels lower than the national one* – which imply the reproduction of the analysis at a level. The tool-kit was applied in a diagnostic mode to generate (i) a multi-level analysis of the energetic metabolic pattern of Catalonia (with its interface with Spain); (ii) a metabolic analysis of livestock systems in Scotland.

## 3. Lessons learned from this application

When applying the analytical framework to the analysis of the 8 EU states of the selected sample, we realized the overwhelming importance the implications associated with trade. The extreme openness of modern economies operating in a globalized market allows the externalization to other social-ecological systems of both the environmental pressure – i.e. land, water, destruction of habitat, pollutions – and socio-economic pressure – i.e. the requirement of labor and technical capital that is allocated to exports, rather than to satisfy the internal demand for goods and services. For this reason, we had to introduce a second semantic bridge over metrics and move to a mechanism of accounting based on the simultaneous use of three non-equivalent definitions of "energy", "food" and "water": (i) to describe the state of the system at the macroscopic

level – a pattern of internal consumption of carriers; (ii) to describe the level of externalization – the meso level – a pattern of domestic and externalized supply of commodities; (iii) to describe the environmental pressures that can be localized in space to assess impact – a pattern of productions processes identifying the local primary sources and sinks used locally.

Another important lesson from these applications has been about the challenges found in the communication of the result. The density and the diversity of the information generated by this analysis makes the visualization of the results very difficult. The task of communication poses a continuous series of dilemma about what to include and what to leave out when presenting the results. In fact, both the analyst and the reader can be easily overwhelmed by the sheer quantity of information provided by the simultaneous consideration of the effects of many relations characterized across different dimensions of analysis and across different scales. At the moment, this (too much of a good thing) represents one of the main challenges for the last phase of the project: how to organize the results in the form of dashboards to better visualize the rich information space they span across.

# 1. Introduction

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The sustainability agenda builds on key components (i.e. food, water, energy, land use, climate and environment) that are inherently interconnected in a Nexus. The word Nexus is becoming popular in the sustainability discussion and used in several contexts and by serval stakeholders (e.g. researchers, policy-makers, civil society, and spreading on the Internet). This means that there have been many definitions and interpretations of the NEXUS concept and the way to tackle the NEXUS problem. This broad concern indicates acknowledging the existence of a problem and the difficulty to articulate it. Especially because it is a complex problem that occur at different aggregated scales (e.g. from farm, region, country and up to global scale), and because it is currently analyzed and tackled from different disciplines. For instance, from ecology perspective, the problem may be seen as the use and depletion of ecosystems and natural resources, leading to degradation of the natural environment (especial focus on the "biosphere" side); from economy perspective, the problem may be perceived as a problem of allocation of resources to generate "goods and services" and maintain economic development (especial focus on the "technosphere" side); while from social sciences perspective, the problem can be framed as the social processes that affect and are affected by the issue, as well as the generation and interpretation of knowledge about the problem in society (especially in the interface science-policy).

The different perspectives make it particularly difficult to engage in a constructive discussion and identify solutions. The MAGIC project has the particular aim to explore the various ways in which the NEXUS concept is framed and operationalized in different policies and stakeholder narratives. The already multidisciplinary consortia and the intervention of all partners in all work packages of the project (also in this WP4) makes a great contribution to bring together the different perspectives on the topic.

On the other hand, MAGIC explores an innovative approach to address complex issues, aimed at understanding the origin and testing the narratives about the Nexus in Europe. MAGIC, therefore, focuses on the EU' sustainable strategy, considering the main components (i.e. food, energy, water and land use) and the relationships among them. For instance, food security, energy security and water security compete for the usage of the same resources and there are inherent trade-offs when aiming for individual targets. MAGIC uses the metabolic pattern of socio-ecological systems as underlying theoretical concept at different levels of aggregation and spatial scales (EU, country or regional level). MAGIC, therefore, challenges the ongoing established practice of developing

quantitative analyses of the dynamic balance between demand and supply of food, energy and water that consider these resources flows individually.

The role of WP4 is to develop a procedure helping a more robust structuring of the perception and representation of the Nexus in quantitative terms using the approach called Quantitative Story-Telling (QST). This proposed approach blends together different types of expertise in order to generate a more rigorous scientific understanding of the Nexus using an operational definition of 'Nexus Security' based on the integrated check of feasibility (external constraints), viability (internal constraints) and desirability (normative values) that goes beyond connecting the definitions of food, water and energy security considered in isolation. This common understanding of the implications of the Nexus and the possibility use of QST to check the quality of narratives will be used by the different topical teams (policy teams and innovation teams) in WP5 and in WP6.

The aim of this deliverable is a first attempt to operationalize a tool-kit to structure the quantitative analysis of the metabolic pattern of social-ecological systems in relation to their sustainability and the Nexus. First, we defined a general framework for the quantitative analysis of the Nexus based on "grammars" (semantic characterization of the factors determining the option space, e.g. consumption level of energy and food, degree of self-sufficiency by domestic production, dependence on non-renewable resources or efficiency in the use of resources). Second, and specifically in this report, we tested the framework by carrying out a first state-of-the-play analysis. This is a diagnostic of the metabolic pattern of Socio-Ecological Systems at different countries of the EU (i.e. France, Germany, Italy, United Kingdom -UK-, Spain, the Netherlands, Sweden and Romania). Working in different teams, this deliverable generated a series of processors and brought them together to operationalize the tool-kit. The concept of processor refers to elements of a system that metabolize a mix of inputs to carry out a process and generate a certain amount of outputs (see section 5.2 for further information on the concept "processor"). The different working teams generated processors related to energy (i.e. fuel supply, heat supply and electricity supply), to crop production (i.e. grain, roots and tubers, representing crops with high nutritional content on carbohydrates and proteins; oilseeds, representing fats and oils, second in nutritional importance in the diets; and vegetables, pulses and fruits, which provide essential nutrients, but not so important in calorific terms) and livestock production (i.e. dairy and beef cattle, swine and poultry –broiler and egg-). Finally, an effort to bring together the different pieces (i.e. processors) enables the construction and reproduction of the metabolic pattern of the different countries.

This deliverable build upon the discussions and material generated in the previous deliverable 4.1. The discussions grounded on the existing narratives to frame the issue of sustainability and the emergence of the term "Nexus". In this context, the idea of

“quantitative story telling” as an alternative to “evidence-based policy” raised, to better use scientific information generated. Is in Deliverable 4.1 where the methodological approach and the basic features of the theoretical framework of accounting called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) was presented. That deliverable presented some applications of MuSIASEM in heterogeneous case studies.

Deliverable 4.2 takes the steps of integrating lessons learnt in deliverable 4.1. and generates a first tool-kit concept developed for MAGIC project to generate a quantitative analysis of the Nexus in European context. Hence, the tool-kit generated in this deliverable should be interpreted as a first attempt to bring the concepts in practice. A first step to generate a tool-kit to be further developed, refined and validated with the coming steps. The bases on which MAGIC will operate and build the upcoming analyses. This tool-kit, therefore, becomes essential for deliverable 4.3, in which MAGIC studies the implications of global drivers, planetary boundaries and the effect of externalization of pressure and impacts of EU imports to other (external) socio-ecological systems; and becomes key for the development of WP5 and WP6. The tool-kit here presented will assist the topical teams in the use of QST for checking the narratives behind EU directives and policies in WP5 and to check the quality of the process of assessment of Nexus related innovations in WP6.

# 2. The tool-kit

*Author: M. Giampietro*

This chapter describes the toolkit used to characterize the state-of-the-play (diagnostic analysis) with regard to the sustainability of social-ecological systems. The toolkit is described in general terms. Detailed practical guides on how to perform the analysis are provided in Appendix

## 2.1 The theoretical background: the rationale of DPSIR (Driver, Pressure, State, Impact and Response) applied to the analysis of the metabolic pattern of social-ecological systems

### 2.1.1 Bioeconomics and metabolic studies applied to the issue of sustainability

In the 60s and 70s, when looking at the scaring trends of population growth (in that period the population doubled from 2 billion to 4 billion in 44 years) many scientists were concerned by the fact that extraordinary economic growth experienced by developed countries in those decades could become "too much of a good thing". ). The publication of the Limits to Growth by Meadows et al, in 1972, primed an intense discussion over the sustainability of a model of economic development based on the plundering of non-renewable resources. However, the orthodox economists of the neo-classical school did not see any problem in accepting as possible the idea of a perpetual economic growth (which is basically the idea of continuous growth based on circular economy!) in a finite planet. The debate between "cornucopians" (those saying that an economic perpetual growth was possible according to the narratives of neo-classical economics) and "prophets of doom" (those saying that perpetual economic growth is not possible when considering the biophysical roots of the economy) became quite intense also among economists. The famous quote of Kenneth Boulding - one of the heterodox economist involved on the "prophets of doom" side - indicates the level of confrontation: "Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist" (1966). In the context of this confrontation the discipline of bio-economics was suggested by Nicholas Georgescu-Roegen (Mayumi, 2001) as a necessary complement to neo-classical economics in order to avoid the dangerous hypocognition determined by the neo-classical economic framing of the issue of sustainability. However, the discussion over the feasibility of perpetual growth ended abruptly in the 90s with a clear victory of the "cornucopians" in the society. This sweeping victory was not determined by convincing scientific

arguments, but rather by ideological arguments associated with the ongoing cold war. In those years, the narrative of "cornucopians" was instrumental for the victory of the western civilization endorsing capitalism over communism. During the ideological war between capitalism and communism it was not admissible to put in doubt the feasibility and viability of perpetual growth. In fact the cold war was won, not because of a stronger military power, but rather by convincing the world (and in particular the people living in communist regimes) that by embracing capitalism and rejecting communism all the economies of the world would have soon enjoyed the American dream.

After the ideological victory the field of the "prophets of doom" was totally dismantled, heterodox economists addressing the issue of sustainability from a biophysical perspective were marginalized and no departments of energetics (flourishing in the 80s) were still operating at the end of the 90s: energetics (a discipline aimed at generating a systemic analysis of the biophysical roots of the economy) was eradicated from academia! Mainstream economists ruled unchallenged and the concerns raised by the limits to growth were ridiculed.

### 2.1.2 Scientific fields providing the conceptual basis of bio-economic analysis

In his seminal book "What is life?" Schrödinger (1967) proposed a revolutionary explanation for the extraordinary capacity of living systems to self-organize. To this purpose, he introduced the concept of negative entropy and thereby paved to way to the development of non-equilibrium thermodynamics. The school of non-equilibrium thermodynamics (Glansdorff and Prigogine, 1971; Prigogine, 1978, 1961; Nicolis and Prigogine, 1977; Prigogine and Stengers, 1984) then postulated that the property of self-organization is unique to open systems — they have to gather inputs from their environment and dispose wastes into it. This property carries with it an existential predicament for all self-organizing systems: in order to survive they must "stress" the admissible environment they operate in. This predicament can become fatal for complex metabolic systems, such as human societies, that can grow both in size and in pace of activity per unit of size (e.g., economic growth). For these complex metabolic systems to survive they must be able to learn and adapt to changes in their boundary conditions, and specifically to anticipate (Poli, 2017) potential future troubles. To stress this peculiar characteristic of this class of systems Rosen (1985) aptly introduced the term "anticipatory systems" and Prigogine (1978) "becoming systems". The revolutionary findings in non-equilibrium thermodynamics has shaped several scientific fields studying the process of self-organization applicable to the analysis of the functioning of human societies, namely:

1. The field of complexity theory (an evolution of the field of general systems theory) dealing with self-organizing open systems in general terms. This includes complex adaptive systems (Holland, 2006; Gell-Mann 1994), autopoietic systems (Maturana and Varela, 1980, 1998), self-modifying systems (Kampis, 1991) and metabolic-repair (M-R) systems that can operate as anticipatory systems (Rosen, 1958; 1991);

2. The field of theoretical ecology specifically dealing with ecosystems providing general principles applicable (and applied) also to the analysis of socio-economic systems (Lotka, 1956; H.T. Odum, 1971, 1996; E.P. Odum, 1971; Ulanowicz 1986; Holling, 1973).

3. A variety of fields dealing with the biophysical analysis of social systems, including "energetics" (Ostwald, 1907, 1911; Lotka, 1956; Soddy, 1926; Vernadsky 1926, Cottrell, 1955; Debeir et al. 1991; Gever et al. 1991; Giampietro et al., 2012; 2013; Hall et al, 1986; Hall and Klingaarden, 2012; Leach, 1976; Pimentel and Pimentel, 1979; Slesser, 1978; Smil, 1991; 2003; 2008; 2017), the work of White (1943) and (Zipf, 1941) in the disciplines of anthropology and sociology, respectively, and the recently-developed field of societal metabolism (e.g., Broto et al., 2012; Daniels, 2002; Fischer-Kowalski and Hüttler, 1998; Martinez-Alier, 1987; Swyngedouw, 2006; Tainter, 1988; Wolman, 1965).

All these disciplines show the existence of a clear analogy between the process of self-organization of ecological systems and social systems. Both metabolic processes require the existence of favorable boundary conditions and the capacity to exploit these (Odum, H.T., 1971; 1983; Ulanowicz, 1986; Margalef, 1968; Gunderson and Holling, 2002). Note that we define a social-ecological system as a set of functional and structural components operating simultaneously both in the technosphere (societal processes) and in the biosphere (ecological processes) within a prescribed boundary. This implies that the metabolic identities of the two sub-components – the technosphere and the biosphere embedding the technosphere – can only be observed and described in non-equivalent ways – i.e. money is irrelevant for describing ecological processes. However, when coming to the processes determining the reproduction and the maintenance of their identities, the processes must remain compatible with each other. That is the process of maintenance and reproduction of the components of the technosphere should not interfere too much with the process of maintenance and reproduction of the components of the biosphere. All these scientific fields agree on the fact that: (i) social-ecological systems must be open systems (they must exchange flows – inputs and wastes - with their context), so they depend on their context; (ii) the level of activity of social-ecological systems depends on the throughputs of energy and material they process – the higher the level of their activity (the pace of production and consumption of goods and services) the higher the pace and density of the energy flows they metabolize; (iii) social-ecological systems must be adaptive and anticipatory because processes outside their control do affect the definition of their option space.

### 2.1.3 Non-equilibrium thermodynamics and the relational analysis of the metabolic pattern of social-ecological systems: the theoretical basis of the "state-pressure" relation

Since then, the basic rationale of non-equilibrium thermodynamic has been used to explain and study the metabolic pattern of society (Allen, 1997; Dyke, 1988a, 1988b; Von Schilling and Straussfogel, 2008). In particular, the openness of cities and their dependence on the activities of processes taking place outside their border has been described using the jargon of non-equilibrium thermodynamics using the concept of "entropy debt" (Dyke, 1988a; Pelorosso et al., 2017; Von Schilling and Straussfogel, 2008). For example, in relation to the analysis of the metabolic pattern of cities Dyke (1988) says: "They maintain their internal order by utilizing an ambient energy flux and dissipating degrade forms of that energy into the environment. Internally, their order is maintained (or even increased), which occasions an "entropy debt" that is paid by the increased disorder of the environment". Pag. 144.

With the expression "entropy debt" Dykes described the forced relation between: (i) the activities carried out by humans in their process of self-organization/autopoiesis inside the "technosphere" – i.e. the set of transformation under human control; and (ii) the activities carried out by ecological and natural processes in the "biosphere" – i.e. the set of transformations determining the boundary conditions of the society outside human control. To better understand the concept of "entropy debt" we can get back to the basis conceptualization of the stability of dissipative systems in non-equilibrium thermodynamics.

The concept of dissipative systems represents a radical departure from the type of systems studied within the mechanistic epistemology of reductionism (Giampietro et al, 2013). In fact, dissipative systems have three peculiar characteristics that provide the conceptual framework of the sustainability predicament: (i) thermodynamically open systems – so it is very difficult to define an uncontested border for them – they are made of what they metabolize (inputs), but they are different from their inputs…; (ii) they are operating far from thermodynamic equilibrium but still they can express a predictable identity in time because they can express a dynamic pattern associated with a quasi-steady state regime; (iii) they are fully dependent on the favorable gradients provided by their boundary conditions, but their own existence implies destroying these favorable gradients. For these reasons they have to learn how to become something else in the long run (how to adapt), and for doing this they have to develop effective anticipation.

To make things more challenging, it is not possible to observe a dissipative system as such. In fact, a dissipative system is composed by two sets of processes operating at different scales (they cannot be observed in the same descriptive domain). Yet the two

sets of processes have to be compatible with each other. We have:
1. a dissipative structure which provides the observable aspects of a dissipative system, associated with the establishment of a dynamical régime that can be considered as a "reproducible steady state" – e.g. a tornado, a functioning city or a functioning economy;

2. a system of support capable of stabilizing the metabolic process. The reproduction of dissipative structures – e.g. what we see when we watch a city or an economy - depends on their ability of obtain a stable supply of inputs to be metabolized and the ability of disposing into their environment the resulting wastes and emissions.

Therefore, a dissipative system is different from a dissipative structure. A dissipative system is determined by the ability of establishing a set of expected relations between: (i) a network of processes taking place inside the dissipative structure (e.g. the city or the economy) – required to express its expected identity; and (ii) a network of processes taking place outside the dissipative structure required to guarantee the appropriate favorable conditions to reproduce the interaction that the system (the city or the economy) has with its context. This implies that the sustainability of a dissipative structure (internal processes) has to map onto processes taking place outside its border (external processes), capable of keeping stable the favorable boundary conditions (the supply of inputs and the sink capacity for wastes and emissions). We can use the original conceptualization given in non-equilibrium thermodynamics, based technical jargon, to illustrate this forced relation.

"Let dSi be the entropy production in the system due to irreversible processes and dSe be the entropy flux due to exchanges between the system and the environment. The total entropy change of the system is given by:

$$dS = dSi - dSe \quad [1]$$

The second law states that $dSi > 0$. However, if sufficient low entropy flux enters the system – when $dSe \leq 0$ it becomes possible that $|dSe| > |dSi|$ which implies that can be $dS < 0$. If this is the case, then the system will be driven away from equilibrium. It is also possible for the system to eventually reach a steady state ($dS = 0$). It is the process which leads to this steady state and the accompanying coherent behavior which Prigogine, for special cases, has developed a theory for."

(James Kay personal home page [https://www.jameskay.ca/musings/mep.pdf])

Relation [1] can be used to describe the standard situation in which metabolic systems

– such a living system, a city or an economy – operate. When expressing a set of expected functions needed to reproduce their sets of structural elements they are operating at a value of dS ≤ 0. Within this framework of analysis, the dissipative pattern expressed by the city or an economy (dSi) represents an "entropy debt" that the dissipative structure has with its context. This means that the dissipative structure must be capable of: (i) importing continuous fluxes of both energy and material inputs coming from the environment; and (ii) exporting continuous flows of wastes and emission into the environment. The combination of these two flows represents the low entropy flux – dSe.

An example of the relation between the dissipative structure and its support system is given in Figure 1.

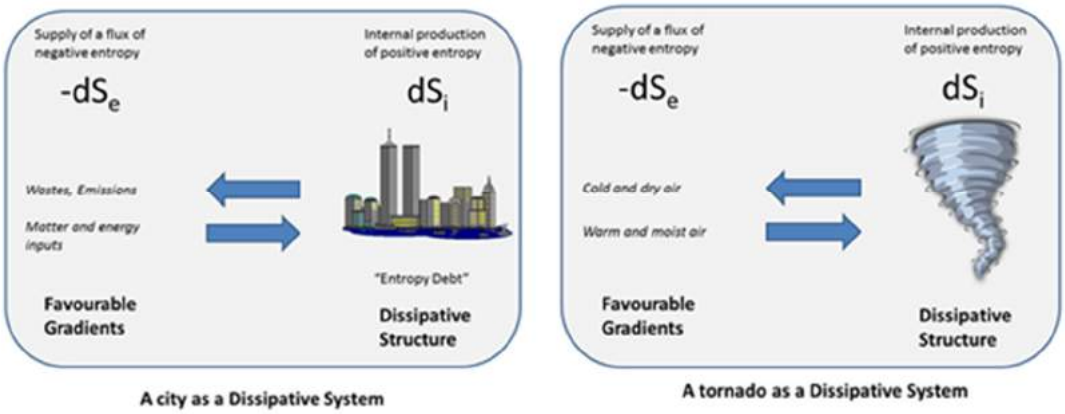


*Figure 1. The relation between a dissipative structure and its system of support*

### 2.1.4 The hypocognition determined by the adoption of standard economic narratives

Classical economics portrays the economic process as a self-sustaining merry-go-round between production and consumption, in which the crucial role of the environment in providing primary inputs and recycling wastes is simply not considered. We could also call it 'the business point of viewpoint' as it reduces the economic process to the circulation of monetary flows in the reverse direction of products and factors of production inside the technosphere. The example in Figure 2 has been selected from among the innumerable schemes of this type available on the internet.

*Figure 2. The double circularity of flows (goods and services vs monetary flows) in the economy (https://justdan93.wordpress.com/tag/circular-flow-of-economic-activity/) .*

This simplistic representation of 'circular flows' within the economy neatly reflects Pigou's (1935) statement on the stationary state: "In a stationary state factors of production are stocks, unchanging in amount, out of which emerges a continuous flow, also unchanging in amount, of real income." Exactly the same message is given to the students by modern economic textbooks: "We can picture the circular flow of economic life. The diagram provides an overview of how consumers and producers interact to determine prices and quantities for both inputs and outputs" (Samuelson and Nordhaus, 2010, p. 28).

Note that in his "Principles of Economics", Marshall (1920 pag. x) himself acknowledged the limitations of this view and apologized to the reader for this simplistic view of the economy: "The Mecca of the economist lies in economic biology rather than in economic dynamics. But biological conceptions are more complex than those of mechanics; a volume on Foundations must therefore give a relatively large place to mechanical analogies; and frequent use is made of the term" equilibrium," which suggests something of statical analogy".

In conclusion, in the classic representation of the economic process there is no place for the role of the environment or the activity of ecological fund elements. As a consequence, neo-classical economic analysis simply cannot compare the size of the funds and flows operating inside the economic process with the size of the ecological

funds and flows in the embedding environment on which the economic process depends. The economic narrative does not have any power of discrimination or anticipation with regard to the sustainability of the interaction with the environment. Unfortunately, the role of the environment in the stabilization of the economic process is essential, and this is exactly the missing piece of information that the adoption of bio-economics can provide.

The bio-economy represents the interface between the technosphere and biosphere within a social-ecological system. The interface of a metabolic system with its context can be observed from two distinct perspectives: (i) from the inside – the view from the components of the societal systems – what gets into and out the parts inside the black-box – inside the technosphere; (ii) from the outside – the view of the context interacting with the black box – what gets into and out the various components of the environment when observing the interaction of the technosphere with the biosphere. This is shown in Figure 3.

On the bottom part of the Figure we can see the processes taking place in the primary sectors of the economy (Agriculture, Energy and Mining) – what we call the catabolic part of the metabolic process. In the catabolic part primary sources (favorable gradients provided by natural process) are degraded to produce secondary inputs (commodities, goods and services) that are used inside the technosphere. These secondary inputs are used to generate other secondary inputs (either flow or fund elements) used to build the functional and structural elements. Therefore, in the anabolic part the secondary inputs are both produced and consumed in the economic process. This means that the secondary outputs of a given sector – e.g. the supply of electricity or food – becomes secondary inputs to another sector. Therefore, all the secondary outputs, generated in the internal production of goods and services, become either secondary inputs to another process or wastes. In fact, if they were not used as “input” by other metabolic elements secondary outputs would not be produced in the first place! This fact may explain the “feeling” of circularity of the economy expressed by the standard economic narrative (Figure 3).

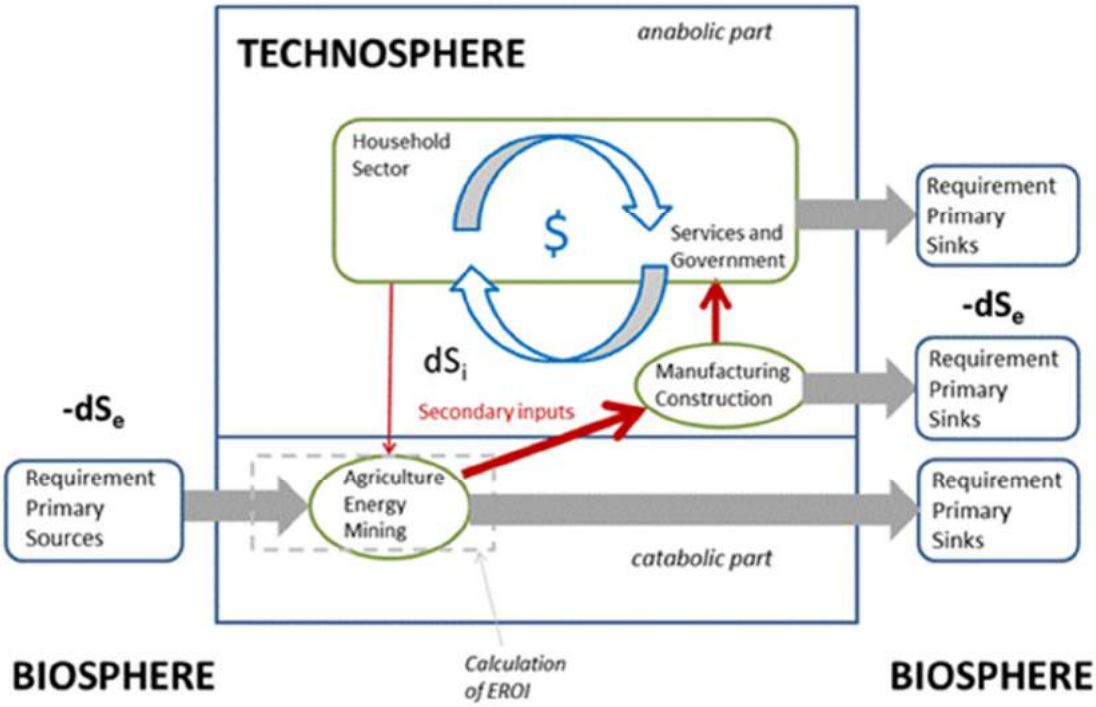


*Figure 3. The metabolic pattern requires the definition and use of two categories of labels (primary and secondary inputs/outputs) to describe water, energy, food and mineral flows.*

Acknowledging the existence of this dual view of the metabolic pattern associated with the economic process is essential if we want to carry out a robust quantitative analysis of social-metabolic systems. Quantitative assessments of internal consumption of water, energy and food carriers (inside the dissipative structure "technosphere") are non-equivalent to quantitative assessments of the required primary supply capacity and primary sink capacity from the support system "biosphere". This implies that when dealing with the metabolic analysis of social-ecological systems generic terms such as "water", "energy" and "food" are just semantic labels that cannot be formalized, measured and quantified as such – Giampietro et al. 2012; 2014. The concepts of water, energy and food can only be formalized after defining in a pre-analytical phase a taxonomy of energy, food and water forms (categories of accounting) in relation to both the external (primary) and internal (secondary) views – Figure 4. This means that we have to look at these flows considering the existence of two interfaces:

1. primary flows are getting from the biosphere into the technosphere – in the example given in Figure 3 the inputs are "primary sources" – e.g. aquifer, coal, arable land – and

the secondary inputs used inside the system are described as a supply of "carriers" - e.g. irrigation water, electricity, potatoes - used inside the metabolic system;

2. secondary inputs are used in the technosphere and consumed in end uses that entail both the expression of a wanted task (production of secondary inputs) and the unwanted generation of wastes and emission dumped into the biosphere. In this case the inputs are "carriers" of water, energy and food - e.g. irrigation water, electricity, potatoes. There are two types of outputs: (i) the expression of functions associated with useful task for the society – "end uses" - e.g. evapotranspiration of water for biomass production, consumption of electricity for expressing a task, eating of the potatoes; and (ii) generation of "wastes" to be discharged outside – e.g. water vapor, heat and emissions for electricity, faeces from food.

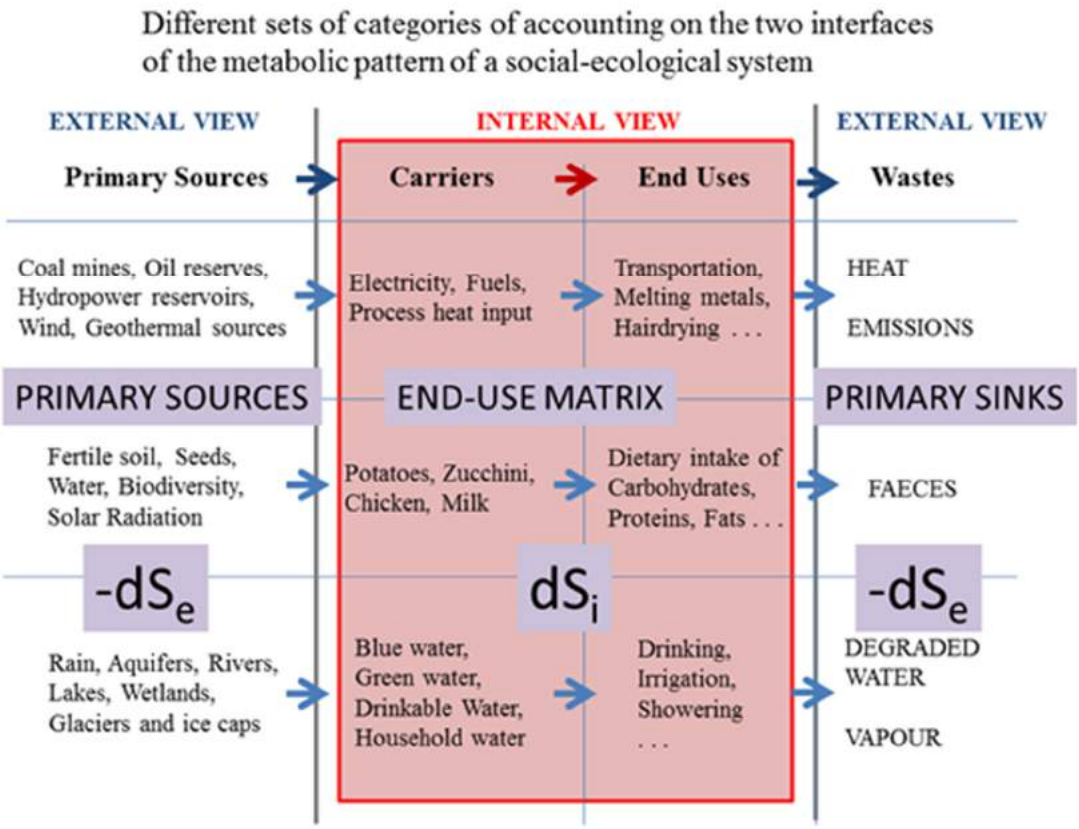


*Figure 4. The pattern of conversions over the two interfaces for energy, food and water.*

When analyzing the metabolism in this way we can realize that inside the technosphere there is no recycling of primary flows of water, energy and food inputs nor primary sinks are provided. Energy carriers, nutrient carriers and water carriers are simply consumed and transformed into end uses and wastes. Gasoline becomes a mix of gas emissions,

food becomes a quantity of faeces, water loses its original attributes of usefulness after the use.

## 2.2 The quantitative characterization of the state-of-the play: presenting the tool-kit

### 1.2.1 The DPSIR framework

DPSIR (Driving forces 'Drivers', Pressures, States, Impacts and Responses) is a causal framework proposed by the EEA in 1999 and adhered to since. The introduction of DPSIR extended the preceding PSR (Pressure, State, Response) model developed by the OECD. For these reasons, literature on the approach is well known, and the framework's provision of a 'typology of indicators' proves substantially useful in structuring the reporting of environmental issues (Smeets and Weterings, 1999).

Using the MuSIASEM approach the State-Pressure of a social-ecological system can be defined using a combination of three pieces of information:

1. The observable characteristics of the internal metabolic pattern – that we represent using a data array called the end use matrix (EUM). EUM characterizes in qualitative and quantitative terms: (i) the set of constituent components of a society expressing metabolic activities; (ii) their relative size; (iii) the different forms of inputs of water, energy and food metabolized in the pattern, (iv) the quantity of each type of metabolized input; (v) the quantity of human activity (and other fund elements) required in the end-uses; (vi) benchmarks describing how the inputs are used (metabolic rate per unit of fund element); (vii) why these inputs are used by the various component of the society; (ix) the quantitative set of relations between the metabolic characteristics of the whole and the metabolic characteristics of each one of the constituent components. The forced congruence across hierarchical levels over the metabolic characteristics of metabolic elements described using a mix of intensive and extensive variables (what is called the "Sudoku effect") is a standard feature of the data array adopted in MuSIASEM.

2. The environmental pressure that is associated with the metabolism of society. According to non-equilibrium thermodynamics the metabolism of secondary inputs (e.g. energy carriers such as electricity and fuels, or food product) inside the technosphere requires the availability of primary sources (e.g. physical gradients such as oil stocks or fertile soils and aquifer) and the availability of primary sink (e.g. the wastes, pollutants and emissions associated with the metabolism) in the biosphere. These primary sources and primary sinks are not determined by processes under human control (otherwise they will be part of the technosphere).

So an End Use Matrix describing the metabolism inside the system entails the existence of an Environmental Pressure Matrix affecting the stability of boundary conditions. Because of the openness of modern countries – made much more important by the phenomenon of globalization - the environmental pressure cannot be assessed only observing the processes taking place inside the borders of the considered society. The use of local resources and environmental services for the stabilization of flows, both on the supply and the sink side (the observed pressure at the local scale), refers to only a part of the total amount of flows metabolized by the society. Imported resources used as inputs of the metabolic pattern inside the society imply the existence of another amount of environmental pressure that is externalized to other Social-Ecological Systems - where the production of the imported inputs took place. For this reason, the environmental pressure associated with the metabolism of a society requires the use of two different types of data arrays: (i) the domestic environmental pressure matrix – based on observable data - referring to the assessment of required flows of inputs taken from the local environment and the resulting flows of wastes and emissions discarded into the local environment; (ii) the externalized environmental pressure matrix – reflecting the effect of externalization of the environmental pressure due to imports (used as an alternative to local production) of the inputs required by the metabolic pattern;

3. the level of openness of the societal metabolism determined by the level of imports of food, energy and other material inputs (an assessment based on observable data). The quantities of imported inputs can be translated into a set of “virtual requirement” of internal end-uses and environmental pressures associated with processes that took place in other Social-Ecological Systems (an assessment based on notional data).

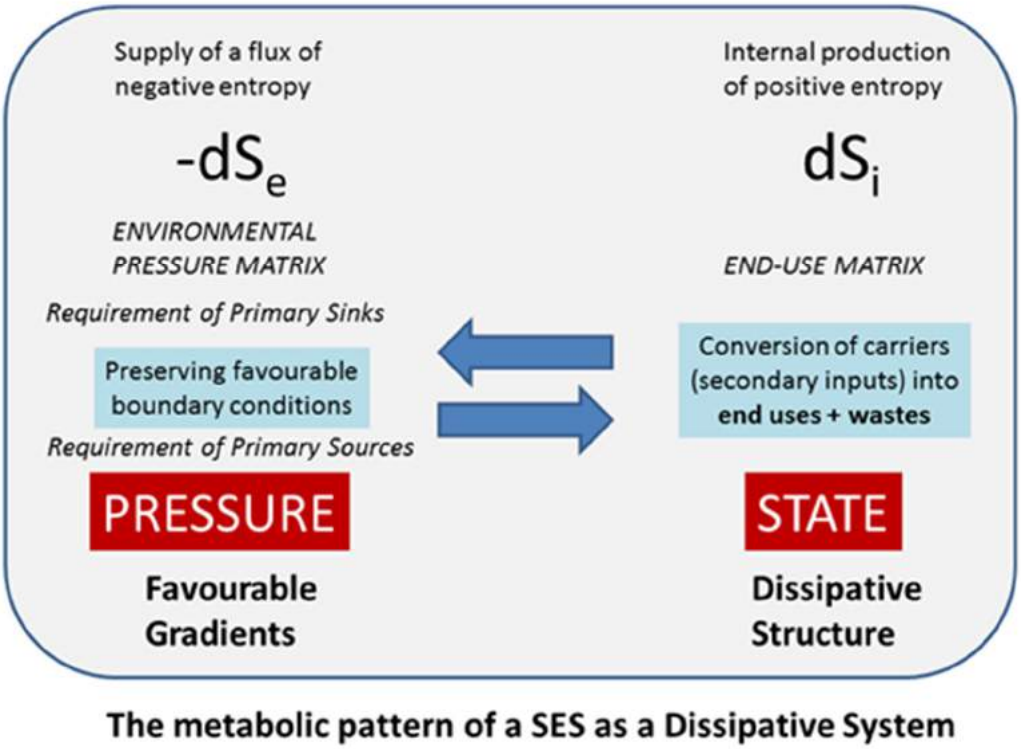


*Figure 5. The State-Pressure relation in the metabolic pattern of Social-Ecological Systems.*

An overview of the relation between the information given by the end-use matrix (conversions taking place inside the technosphere) and the environmental pressure matrix (the required primary supply capacity and primary sink capacity in the biosphere) is shown in Figure 5.

At this point we are able to conceptualise the remaining three components of the DPSIR framework.

Impacts are determined by excessive Pressures on the environment that either damage or stress environmental processes required to stabilise the boundary conditions of a society. Said processes are outside of human control. Within our narrative, they are said to take place in the biosphere. In order to assess an impact, one must contextualise a specific type of pressure (e.g. water abstraction from the environment or nitrogen leakage into the water table) with the supply (or the sink) capacity of the ecological fund elements used to stabilise that specific flow – i.e. the specific aquifer from where the water is abstracted. This contextualisation requires a spatial analysis and the

identification of an appropriate scale – decisions which depend on the type of pressure (on the soil, on terrestrial ecosystems, on aquifers, on the global atmosphere).

Drivers are the factors determining changes in the metabolic pattern. In this report relevant Drivers are related to the mechanisms explaining the identified megatrends. Drivers refer to, for example, changes in the composition and relative size of the constituent components making up a society, changes in the size of population, mix of activities (levels of consumption) and the benchmarks (technical coefficients for used technologies) used in the EUM and EPM, as well as changes in the level of openness. Within the narrative of relational analysis of the metabolic pattern of SES, drivers are changes in either the size of the fund elements – e.g. increase in population, increase in the amount of technology – or changes in the identity of the processors – e.g. increase in the pace of metabolism per unit of fund size (see the flow-fund model in the next section) or change in the mix of end uses. Therefore, drivers entail an expected change in the profile of pressures on the environment.

Responses are purposeful actions aimed at re-adjusting the metabolic characteristics of an SES in order to solve problems. Because of complexity's implication of impredicativity, and therefore trade-offs and uncertainties associated with anticipations of the future, the selection of Responses is often contested.

## 2.3 The implementation of the MuSIASEM tool-kit

The purpose of this section is to provide an overview of the MuSIASEM structure of accounting. The quantitative analysis is structured into six data arrays – namely six typologies of matrices split between two semantic groupings: $EUM_{LOC}$ $EUM_{EXT}$, EUM and $EPM_{LOC}$, $EPM_{EXT}$, EPM. Each data array provides different types of information, where their combined use permits the implementation of the DPSIR rationale. Figure y provides an overview of these arrays and their relations where textual description follows.

### 2.3.1 How to combine the different types of data arrays into the tool kit

**Internal description of the state-pressure of an SES**

To begin with, we consider the portion of an analysis concerned with the local level (internal to the SES's geographic boundaries). In this regard and in this analysis, we describe how the local end-use matrix is related to the local environmental pressure matrix. That is, how energy carriers, food products and water quantities used inside the various constituent compartments of an SES are related to the quantity of primary sources required to generate the inputs, and the quantity of primary sinks required to absorb the resulting wastes and emissions. This relation can only be established after having defined the set of 'production systems' adopted in the primary industrial sectors

(i.e. above all the agricultural sector and the energy and mining sector) for the domestic generation of metabolised inputs.

(i) Local end-use matrix (EUMLOC)

The $EUM_{LOC}$ describes how the various flows of water, energy and food are metabolised inside an SES's geographic boundaries. The $EUM_{LOC}$ is split between a set of functional sectors of society (constituent components), e.g. the household sector and the energy sector. The $EUM_{LOC}$ therefore specifies: (i) the constituent component; (ii) the type of metabolised flows considered; (iii) which constituent component is using which type of flows; (iv) for doing what; (v) the quantities of flows consumed; and (vi) how they are used (described by benchmarks). The multi-level and multi-scale nature of the $EUM_{LOC}$ allows analysts to discern a metabolic pattern at different hierarchical levels – i.e. an entire country, a local administrative unit, individual sectors of the economy, individual sub-sectors – and then study and compare their relevant attributes across different levels for different SESs.

(ii) Local environmental pressure matrix ($EPM_{LOC}$)

The $EPM_{LOC}$ is determined by the requirement of primary sources (for the supply of inputs) and primary sinks (for the absorption of wastes and emissions) of the adopted production and consumption systems described by the EUMLOC. The $EPM_{LOC}$ allows the identification of: (i) on the supply side, the amount of primary production factors (primary energy sources, primary agricultural factors, primary water sources) required for the domestic production of the material and energy inputs consumed by society; and (ii) on the sink side, the flow of wastes and pollutants dumped into the environment, which can be mapped against typologies of ecological funds – i.a. terrestrial ecosystems, soil, aquatic ecosystems, aquifers (underground and surface), global atmosphere, local atmosphere.

**External description of the state-pressure of an SES**

The local definition of an SES is, however, incomplete without information about the level of openness of the system: how much of the inputs consumed by the society come from other SES as imports. After detailing information about the imports we can apply one of the three logics (Note 1) to calculate both: (i) the externalised end-use matrix (the quantity of internal inputs and production factors that are required for the production of the imported inputs); and (ii) the externalised environmental pressure matrix (the quantity of primary sources required to generated the metabolised inputs and the quantity of primary sinks required to absorb the resulting wastes and emissions and depending on the chosen logic of estimation).

(iii) Externalised end-use matrix ($EUM_{EXT}$)

The level of openness of the metabolic pattern of an SES is determined by the dependence on imports of the flows used by the EUMLOC. That is, the total amount of flows consumed in the EUM is divided by the quantity of these flows produced inside the society by its hypercyclic part (sectors of agriculture, energy and mining, and manufacturing and construction). In this way, we can identify the mix of imports required by a society to achieve the dynamic equilibrium between the hypercyclic and the dissipative parts. Using this information, we can calculate the amount of secondary inputs (human made inputs internal to the technosphere) required to generate the imported inputs. Using one of the three logics of internalisation (Note 1) we can then define a 'virtual end-use matrix' – the $EUM_{EXT}$ – that complements the information given by the $EUM_{LOC}$ in the definition of the requirement of secondary inputs needed to stabilise a respective metabolic pattern.

(iv) Externalised environmental pressure matrix ($EPM_{EXT}$)

The $EPM_{EXT}$ is determined by the requirement of primary sources (for the supply of inputs) and primary sinks (for the absorption of wastes and emissions) of the production systems associated with the $EPM_{EXT}$. The $EPM_{EXT}$ allows us to assess: (i) on the supply side, the amount of primary production factors (primary energy sources, primary agricultural factors, primary water sources) required for a specified production of material and energy inputs consumed by society; and (ii) on the sink side, the flow of wastes and pollutants dumped into the environment. These outflows are further mapped against typologies of ecological funds – i.a. terrestrial ecosystems, soil, aquatic ecosystems, aquifers (underground and surface), global atmosphere, local atmosphere – in order to grasp an idea of their potential impacts.

**Comprehensive description of the state-pressure of an SES**

Finally, we may look at the $EUM_{LOC}$ and $EUM_{EXT}$ together, and at the $EPM_{LOC}$ and $EPM_{EXT}$ together. By looking at how the various constituent components (sectors of the society) are metabolising flows for their specific end-uses one can identify the existence of an internal dynamic equilibrium between: (i) the fraction of the total amount of flow and fund elements allocated to produce goods and services, i.e. what is consumed by the primary industrial sectors; and (ii) the fraction of the total amount of flow and fund elements allocated to consume goods and services in the purely dissipative part of the society, which provides control. The analysis of this dynamic equilibrium can be used to study the existence of internal biophysical pressure in the society. This pressure, referred to in MuSIASEM and bio-economic pressure (BEP), imposes a minimum level of biophysical productivity of labour inside the economic process. With that, we arrive at a well-rounded picture of two final data arrays:

(v) End-use matrix (EUM): the sum of secondary inputs ($EUM_{LOC} + EUM_{EXT}$)

The EUM is an assessment of the overall internal requirement of secondary inputs (carriers of water, energy, food and labour) obtained by summing together the information contained in the $EUM_{LOC}$ and the $EUM_{EXT}$. Depending on the assumptions and the definitions chosen for assessing the values in the $EUM_{EXT}$ (among the three possible rationales - Note 1), the EUM indicates the quantity and quality of secondary resources needed by a SES in order to stabilise its metabolic pattern.

(vi) Environmental pressure matrix (EPM): the sum of primary sources and sinks ($EPM_{LOC}$ + $EPM_{EXT}$)

The EPM is an assessment of the overall external requirement of primary sources (referring to the supply of water, energy, food) and primary sinks (for wastes, pollutants and emissions) obtained by summing together the information contained in the $EPM_{LOC}$ and the $EPM_{EXT}$. This information is useful in structuring an impact pre-analysis. Whereas local environmental pressures can be contextualised in relation to local primary sources and primary sinks in order to assess their potential impact, externalised environmental pressures are more difficult to contextualise. Except in the case of pressures with generous spatial smoothing (e.g. GHGs), in order to contextualise externalised environmental pressures in relation to their potential impact ad hoc analytical strategies must be developed depending on the purpose of the analysis.

**Additional information about desirability**

One final data object exists in addition to the above six data arrays: the bio-economic pressure indicator (based of the EUM or one of its subarrays – the $EUM_{LOC}$ and $EUM_{EXT}$). The bio-economic pressure indicator is useful in characterising the desirability of the state and pressure in relation to the aspirations and normative values of the people living in the analysed SES.

(vii) Bio-economic pressure (BEP)

The bio-economic pressure (BEP) describes the internal pressure of the expected productivity of production factors in the primary and secondary sectors of the economy that must grow with the level of economic development (Pastore et al. 2001, Giampietro et al, 2012). It is definable when studying the dynamic equilibrium inside the metabolic pattern of a society. The level of BEP is directly proportional to the level of economic development of a society (it correlates well with GDP and all other indicators of economic development ). The level of BEP is measured by the fraction of the flows of energy carriers and the fraction of human activity allocated on activities carried out in the service and government sector and household sectors in relation to the total amount of energy carriers and human activity in society. The larger the pressure, the smaller the amount of secondary inputs (labour, technology, energy and material inputs) that can

be used in the primary and secondary sectors. The information used to generate the BEP is provisioned by either the EUM, the $EUM_{LOC}$ or the $EUM_{EXT}$, depending on the goal of the analysis. For example, a BEP indicator based off the $EUM_{LOC}$ illustrates the bio-economic 'boost' that may be obtained by a SES when externalising the requirement of secondary inputs (labour and carriers) required for the production of imports from external SESs.

### 2.3.2 An overview of the different pieces inside the tool kit

Only then can we obtain the specification of the mix of primary sources and the techniques of production used to generate the required mix of inputs. From there we can characterize the state-pressure relation combining 7 different data arrays as illustrated in Figure 6.

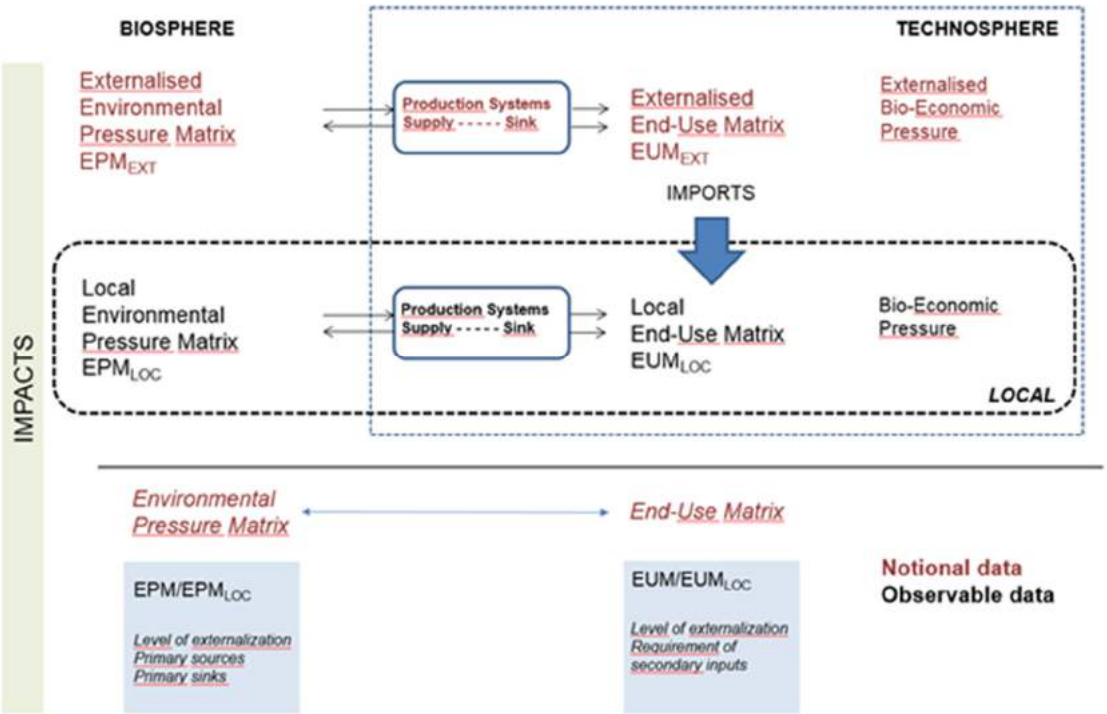


*Figure 6. Overview of the relations between the six matrices and the Bio-Economic Pressure data array*

# 3. State of the play at the national level

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This chapter provides an overview of the results obtained for the state of the play for the 8 EU countries considered: France, Germany, Italy, Netherlands, Romania, Spain, Sweden and United Kingdom.

## 3.1 Illustrating the tools used in the tool-kit to generate a relational analysis

### 3.1.1 Characterization of the "state-of-the-play"

The state-of-the-play analysis provided in this deliverable refers to a "diagnostic analysis of the metabolic pattern" of 8 countries (NUTS1 definition) – presented in this section - and examples of application of the method in 2 regions (NUTS2 definition) – presented in Section 4. Diagnostic analysis describes the metabolic profile of a country in terms of an integrated set of data arrays providing key quantitative information relevant for a deeper understanding of the relation over factor determining the desirability, the viability and feasibility of the metabolic pattern.

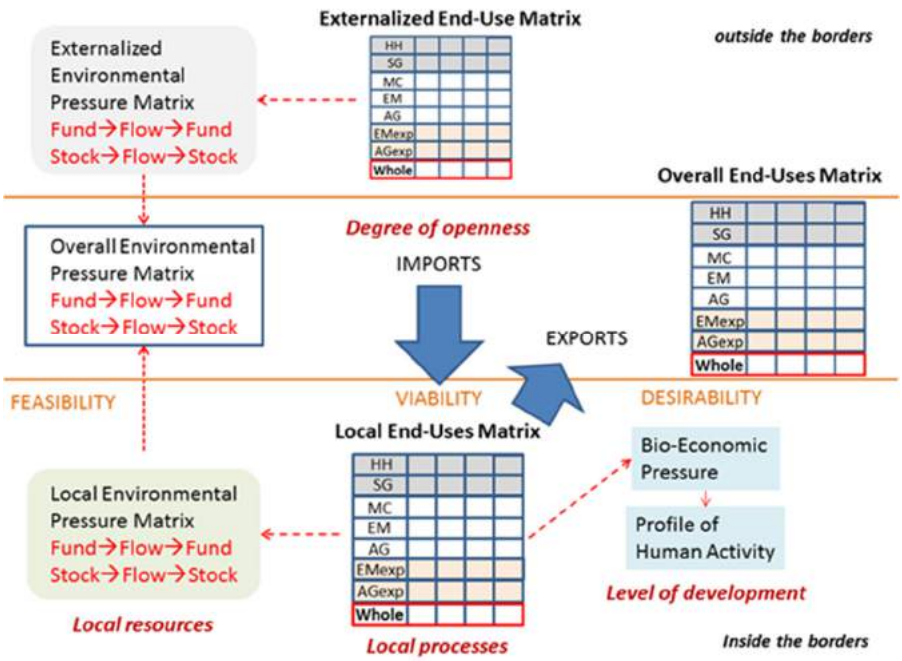



*Figure 7. An overview of the elements of the tool-kit used to characterize the state-of-the-play of a Social-ecological System*

As illustrated in Figure 7, our tool-kit combine the information given by the following 8 data-arrays: (i) the local end-use matrix; (ii) the local environmental pressure matrix; (iii) the externalization end-use matrix; (iv) the externalized environmental pressure matrix; (v) the overall end-use matrix; (vi) the overall environmental pressure matrix; (vii) the bio-economic pressure matrix; which reflects (viii) the profile of human activity in the society.

In the rest of this section we illustrate: (i) the different elements of the analytical tool-kit; (ii) how to organize available quantitative information into an integrated analysis of the state of the play based on this tool-kit. This requires the ability of establishing semantic bridges across non-equivalent descriptive domains [the need of using several non-equivalent definitions of what should be considered as "the coastline of Britain" when observing it at different scales, an issue discussed in Section 5.1] used to measure the quantities of interest.

Before presenting the quantitative results, it is important to clarify and remind again the meaning of the quantitative information provided in this study. As already explained in the introduction, the analysis carried out in this deliverable had the following goals:

(i) exploring the possibility of developing a tool-kit based on the application of relational analysis (implemented within the MuSIASEM approach)

to be used to study the metabolic pattern of social-ecological systems making it possible to study the Nexus between water, energy, food and land use in relation to three criteria of sustainability – desirability, viability and feasibility;

(ii) populating the various data arrays included in the tool-kit with data to verify the possibility of carrying out such an analysis using a sample of 8 EU countries analyzed at the level NUTS1 (two additional exploratory applications at the level NUTS2 are presented in Section 4);

(iii) visualizing the results obtained in this application to check the usefulness of this innovative type of analysis in relation to the analysis of sustainability when addressing the issue of the Nexus;

(iv) identifying potentialities for specific applications of the tool-kit in the cases study to be developed in WP5 and WP6 and problems to be addressed in the rest of the activities of WP4.

As a matter of fact, due to the innovative features of the proposed method of accounting the implementation of the quantitative analysis has implied facing a series of new and unexpected epistemological challenges. To the best of our knowledge this is the first study that handles a statistical data set, which is defined across three different descriptive domains implying the selection of different accounting categories referring the "the same" quantities measured at three different scales (a more detailed discussion of this point in Section 5). For this reason, it is extremely important to keep in mind that the quantitative results presented below should be considered as preliminary. A special feature of this tool-kit is that the more it is used the more it generates robust results. In fact, when building a multi-level set of relations across scale the tool-kit generate mutual information (the so-called Sudoku effect) because of the innate redundancy of its information space. This means that the discussion of the quantitative results provided below, reflecting just a single run of the tool-kit, has the only goal to illustrate the type of discussions that are possible when using it. We did not run all the possible checks of congruence of information across different levels that would be required to increase the level of robustness of the set of data generated in this first application.

### 3.1.2 The analysis of the profile of human activity in a society (the internal view)

The analysis of the profile of human activity in the society is a special feature of the MuSIASEM approach that focuses on a key aspect often neglected by conventional biophysical analysis of the economic process focusing only on the flows of matter and

energy. In fact, the demographic structure of a country (defining the dependency ratio) and the definition of the quantity and the quality of the flows metabolized by society are essential in determining the existence of a biophysical economic pressure on the primary and secondary sector of the society (Giampietro et al. 2012; 2014). An ageing society may have a 60% dependency ratio – meaning that only 40% of the population can be included in the work force. If we add to this fact that the work load of modern western societies – around 1,800 hours/year per worker – is only 20% of the human activity of the work force, we can conclude that the fraction of human activity in the paid work sector is less than 10% of the total. To make things more challenging, in developed countries the ageing of population and the high level of material standard of life imply that the fraction of the work force absorbed by the service sector can be well above 65%. This situation – that in our tool-kit is characterized and measured as a very high level of bio-economic pressure on the primary and secondary sector - reduces dramatically the hours of human activity available for the primary and secondary sectors. For this reason, it is essential to study the profile of human activity associated with: (i) demographic changes (ageing); (ii) the post-industrialization of the economy (knowledge economies); (iii) the growing level of urbanization, because all these factors contribute to the build-up of the bio-economic pressure. This analysis uses only quantitative information referring to the internal view – i.e. it observes only processes taking place inside the technosphere and inside the borders of the social-economic system considered. When considering the internal view we should focus first of all on one of the most important limiting factors of human affairs: "not having ***enough time*** to do both what has to be done and what one would like to do" (this point is made by the popular say – in modern times time is money!).

Our analysis is based on the budget of human activity in relation to the set of activities that have to be done. This description is given by the end use matrix. In this way, we can visualize that the requirement of hours of human activities for a given task can be associated with an "opportunity costs". That is, when a certain quantity of human activity is invested in a given end use – e.g. sleeping - then it is no longer available for another end use – e.g. working. Starting from the demographic structure of a country we can study the factors determining the availability of human activity for the various end uses required by the functioning of a society. This is illustrated in Figure 8. This overview shows that different factors determine this split: (i) the population structure (affecting the dependency ratio: people outside the working age and people in the working age); (ii) the level of employment and the work load of the people working in the paid work sector; (iii) the level of leisure, education and personal care (outside the paid work sector); and (iv) the distribution of the work force over the different economic sectors (inside the paid work sector). To understand better these relations, let's go

through the data provided in Figure 8 (referring to Spain, in 2012) following the numbered red points.

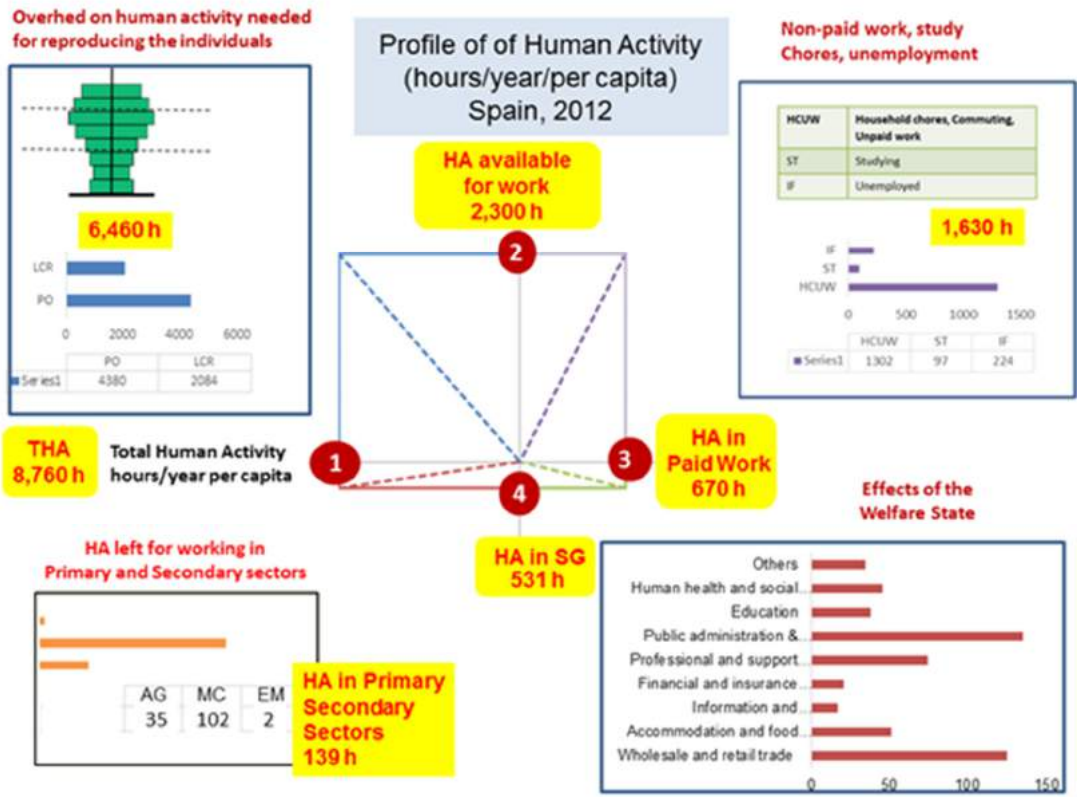



*Figure 8. The splitting of human activity in different categories of end uses*

**Red Point #1** - we start from the value of 8,760 hours per capita per year (24 x 365) that is the total amount of human activity available in the society. Depending on the structure of the population (only a fraction of the population can work) and on other factors only a fraction of this human activity can be used in the Paid Work sector (upper left corner). A first reduction is due to a natural physiological overhead on the activity of people – i.e. sleeping and personal care - and by the level of leisure, cultural and recreational activities (LCR). These end uses eliminate hours of human activity from the pool that can be used for working.

**Red Point #2 -** the amount left – 2,300 hours per capita per year – has to be further reduced because of additional factors preventing these hours to go entirely into the paid work sector (upper right corner). There are other end uses of human activity to be considered: unpaid work (e.g. household chores, taking care of relatives, shopping), hours of study by students and the idle activity of unemployed people;

**Red Point #3 –** the amount of working hours available for Paid work after the first two reductions is equal to 670 per capita per year. These are the available hours to express all the types of end uses required to provide the goods and services consumed per capita per year by a person living in this society.

**Red Point #4 –** probably the most important piece of information in Figure 8 is represented by the relation between the value given in the red point #3 – 670 hours p.c. per year of supply of Paid Work and the value of hours given in the red point #4 – 531 hours p.c. per year of requirement of Paid Work in the Services and Government sector. This value can be calculated from labour statistics by dividing the amount of hours of paid work in the service and government sector by the population of the country. The requirement of Paid Work in Services and Government is a sort of bio-economic overhead that socio-economic development implies on the functioning of the economy. In developed society the economy is no longer responsible only for the supply of food, energy, water plus a few other basic products as it was in pre-industrial times. Developed economies have to guarantee not only the supply expected by the primary and secondary sectors but also a wide set of services associated with the welfare state. That is when we combine the effect of the dependency ratio and the physiological overhead (the reduction from the amount of human activity assessed at point #1 to point #2) with the effect of the reduction of human activity not invested in Paid Work (the reduction from the amount of human activity assessed at point #2 to point #3) then we find out that less than 8% of the total hours of human activity in are available for activities carried out in the Paid Work sector. To make things more challenging almost 80% of these hours in developed societies must be allocated to the service sector.

### 3.1.3 The information space associated with an end use matrix

The implications of a given profile of human time allocation in the different end-uses can be appreciated by using an end use matrix – an example of the end use matrix of EU27 + Norway is given in Figure 9.

10% of PW

1 hours of PW/16 hours Non-PW → hour of PW < 7%

| 2012 EU27+N | HA ($10^6$ h/year) | | HA per Capita (h) | EMR_elec (MJ/h) | EMR_heat (MJ/h) | EMR_fuel (MJ/h) | EJP (€/h) | | ET_elec (PJ/year) | ET_heat (PJ/year) | ET_fuel (PJ/year) | GVA ($10^3$ €) | EEI (MJ/€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Society | 4.422 | x | 3760 | 2,6 | 4,3 | 3,9 | 2,6 | = | 11.415 | 19.110 | 17.243 | 11.631 | 6,4 |
| Household | 4.167 | x | 8.256 | 0,74 | 1,7 | 1,9 | 0 | = | 3.098 | 7.078 | 7.889 | 0 | - |
| Paid Work | 255 | | 505 | 33 | 47 | 37 | 46 | | 8.317 | 12.033 | 9.354 | 11.631 | 4,1 |
| Agriculture, Forestry & Fishing | 21,4 | x | 42 | 8,0 | 15 | 26 | 9,2 | = | 171 | 326 | 556 | 198 | 7,9 |
| Energy & Mining | 3,9 | | 8 | 280 | 612 | 17 | 122 | | 1.092 | 2.386 | 68 | 475 | 12 |
| Manufacturing & Construction | 65 | | 128 | 57 | 103 | 7,1 | 36 | | 3.706 | 6.664 | 459 | 2.347 | 7,5 |
| Service & Government | 172 | | 341 | 19 | 15 | 48 | 50 | | 3.348 | 2.657 | 8.271 | 8.611 | 2,7 |
| Agriculture & Forestry | 20 | x | 40 | 8,4 | 16 | 25 | 9,3 | = | 169 | 322 | 495 | 187 | 7,9 |
| Fishing | 0,23 | | 0,5 | 8,5 | 16 | 260 | 36 | | 2,0 | 3,6 | 61 | 8,4 | 11 |
| Service & Government (wt Transport) | 166 | x | 328 | 19 | 14 | 3,7 | 41 | = | 3.116 | 2.255 | 607 | 6.827 | 1,7 |
| Transport Services | 6,3 | | 12 | 37 | 64 | 1.224 | 17 | | 232 | 401 | 7.663 | 109 | 107 |

*Figure 9. An example of end-use matrix showing the profile of allocation of human activity and energy carriers in the different constituent components of the society*

The data given in Figure 9 referring to the average of EU28 countries (plus Norway) confirm the data given for Spain in Figure 10. EU economies have a fraction of hours of human activity in Paid Work lower than 7%! In the example given in Figure 9 the end use matrix shows the profile of allocation of human activity and also of energy carriers (electricity, process heat and fuels) in the society at different levels of analysis:

(i) level n – average of society – defining the society as a whole;

(ii) level n-1 – the average of society is split into two constituent components: Household and Paid work;

(iii) level n-2 – the Paid Work is split into four constituent components: Agriculture and Forestry, Energy and Mining, Manufacturing and Construction, Service and Government;

(iv) at level n-3 – each of the previous constituent components can be split into lower level constituent components – e.g. Service and Government can be split in Transportation and Other SG without transportation.

The end use matrix makes it possible to identify and characterize inside the society: (i) who is using energy carriers, (ii) which type of energy carriers is used; (iii) how much of each type of energy carrier is used; (iv) how energy carriers are used in the end use (e.g. the power level per hour of labor); (v) why energy carriers are used, in relation to which task. The end use matrix is defined across multiple-levels so the analysis can be carried out to lower and lower levels in order to observe energy uses at the level of sub-sub-sectors of the economy – a simplified example is given in Figure 10.

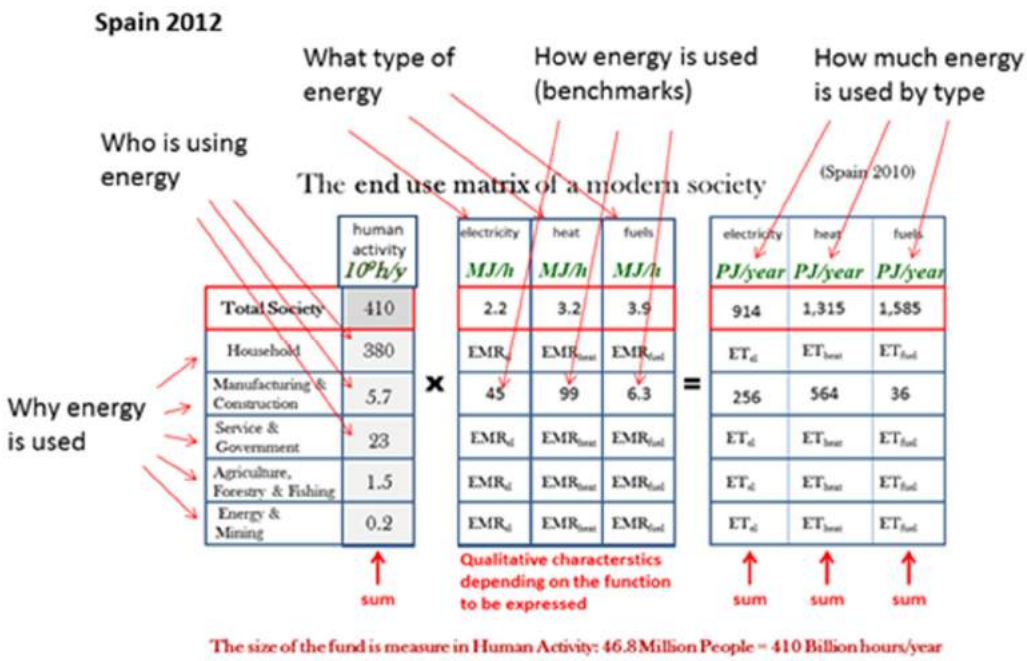



*Figure 10. The organization of information in the end use matrix*

Organizing our quantitative representation in this way we can track the various biophysical functions expressed by the end uses at the local scale (Velasco-Fernandez and Giampietro, 2018). If we do this exercise, then we can see that an increase in bio-economic pressure - the progressive movement of labour and energy carriers toward both the service-government sector and the household sector, away from the primary sectors (agriculture and energy and mining) imposes a formidable constraint on the viability of this metabolic pattern. In fact, in the example given in Figure 9, the supply of the mix of secondary inputs required to guarantee energy and food security has to be obtained using only: (i) 2 hours per capita per year, in the energy sector for the supply of all the energy carriers consumed per capita per year in the society (for all possible activities of production and consumption) and (ii) 35 hours per capita per year for the

supply of all the food products consumed per capita in a year in the society (directly and indirectly through processed food products and animal products).

### 3.1.4 The Bio-Economic Pressure (BEP)

The Bio-Economic Pressure (BEP) is another conceptual tool proposed by MuSIASEM (see the discussion in Deliverable 4.1). There are two methods to calculate the Bioeconomic pressure:

Method #1. Based on the distinction between endosomatic and exosomatic metabolism – this assessment makes a distinction between: (i) the consumption of the constituent components generating a net surplus of biophysical outputs used by the humans - Agriculture, Energy and Mining, Manufacturing and Construction; and (ii) the consumption of the purely dissipative part - households and services and government. The higher is the fraction of allocation of human activity and energy carriers to the dissipative part, the higher is the bio-economic pressure. This pressure requires that the primary sectors (AG, EM) and secondary sector (MC) must have a very high labor productivity. The productivity of the primary and secondary sectors is called in MuSIASEM jargon the Strength of the Exosomatic Hypercycle.

Method #2. Based on the distinction between catabolic and anabolic metabolic compartments – this assessment makes a distinction between those constituent components (the primary sectors – AG and EM) that exploit favorable gradients provided by nature (primary agricultural sources, primary mineral sources, primary energy sources, primary water sources and associated sink capacities associated with environmental services). In this second assessment the values of the pressure are much stronger, because as illustrated earlier the amount of hours of work in EM and AG are almost negligible compared with the total of 8,760.

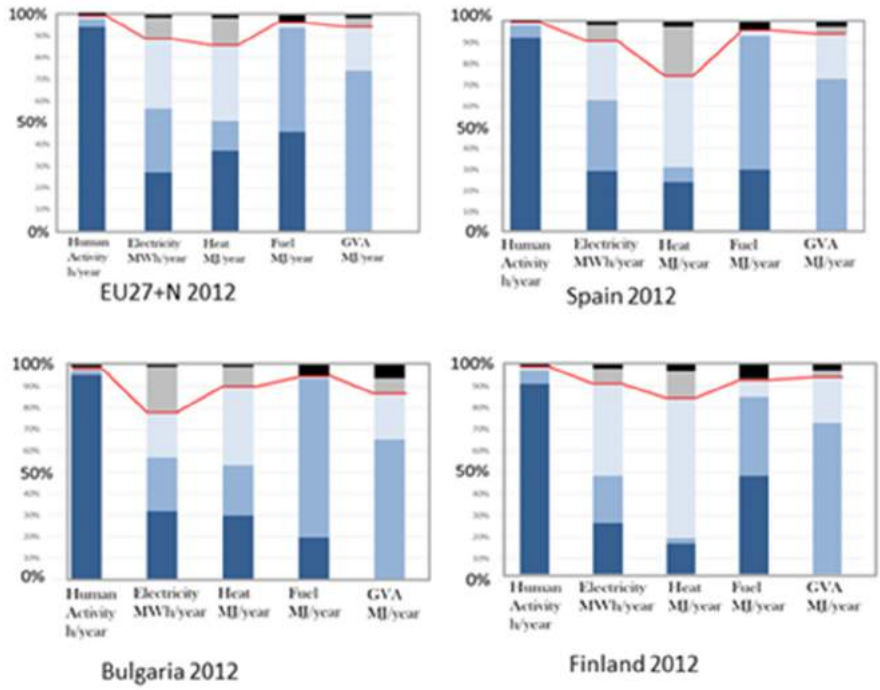



*Figure 11. A visualization of BEP in Spain (using the method #1)*

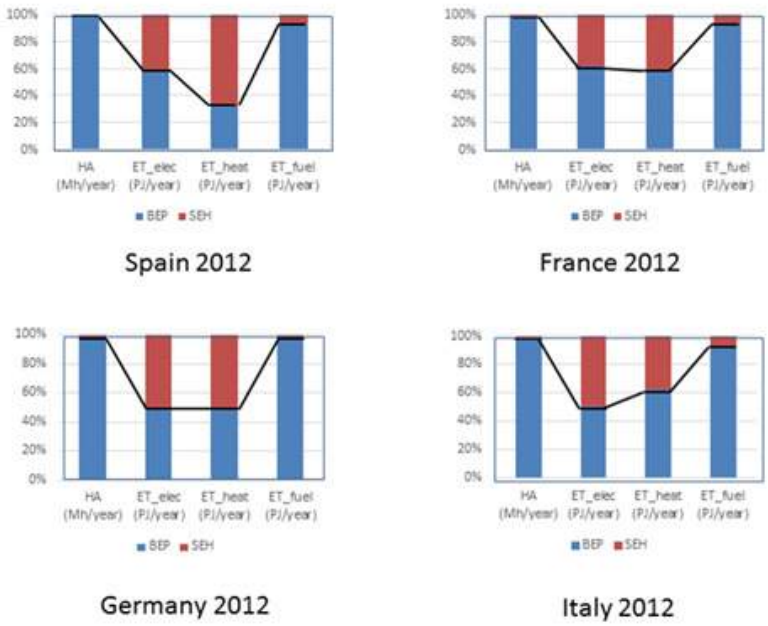



*Figure 12. A visualization of BEP in different countries (including Spain) using method #2*

The examples illustrated in Figure 11 describing the effects of BEP in relation to the average of EU27+ Norway and for a sample of other 3 EU countries (Spain, Bulgaria and Finland) indicate a very high level of BEP in all EU countries. The examples illustrated in Figure 12 confirm the homogeneity of the pattern: the inclusion of the energy consumption of Manufacturing and Construction simply moves down the line dividing investments in production vs investments in consumption in relation to the consumption of energy carriers. This means that the huge overhead of the welfare state (the need of employing a large fraction of the work force in the service sector) forces a very high productivity of labour in the primary sectors. The net surplus consumed by the dissipative sectors (HH and SG) has to be produced with a very small fraction of the work force. In the post-industrial world, the expected high level of material standard of living of urban elites is more and more perceived as a sort of “human right”. This means that a high level of Bio-Economic Pressure is no longer negotiable with the voters!

### 3.1.5 The factors determining the viability of the Bio-Economic Pressure

The stability of our institutions and social fabric heavily depends on the ability to preserve the high level of bio-economic pressure (Giampietro et al. 2012). In turn this means that the food supply and the energy supply of modern societies has to be guaranteed by a fraction of the work forced that combined is around 3%. This translates into a severe biophysical constraint on the biophysical labor productivity of farmers. They have to produce 800 kg of grain per hour of labour (the value we obtain when looking at the technical coefficients describing the production of grains in monocultures). These values are forced by a situation in which a very small number of farmers still producing grains have to produce a very large amount of grain. In the same way, the workers in the energy sector of EU countries are supplying energy carriers at a level of 20 GJ of per hour of labour. This assessment can be easily obtained by dividing the amount of energy consumed in one year by a country by the hours of labour in the energy sector.When combining all this information we can visualize a set of expected relations affecting the various numerical values found in the various analytical tools.

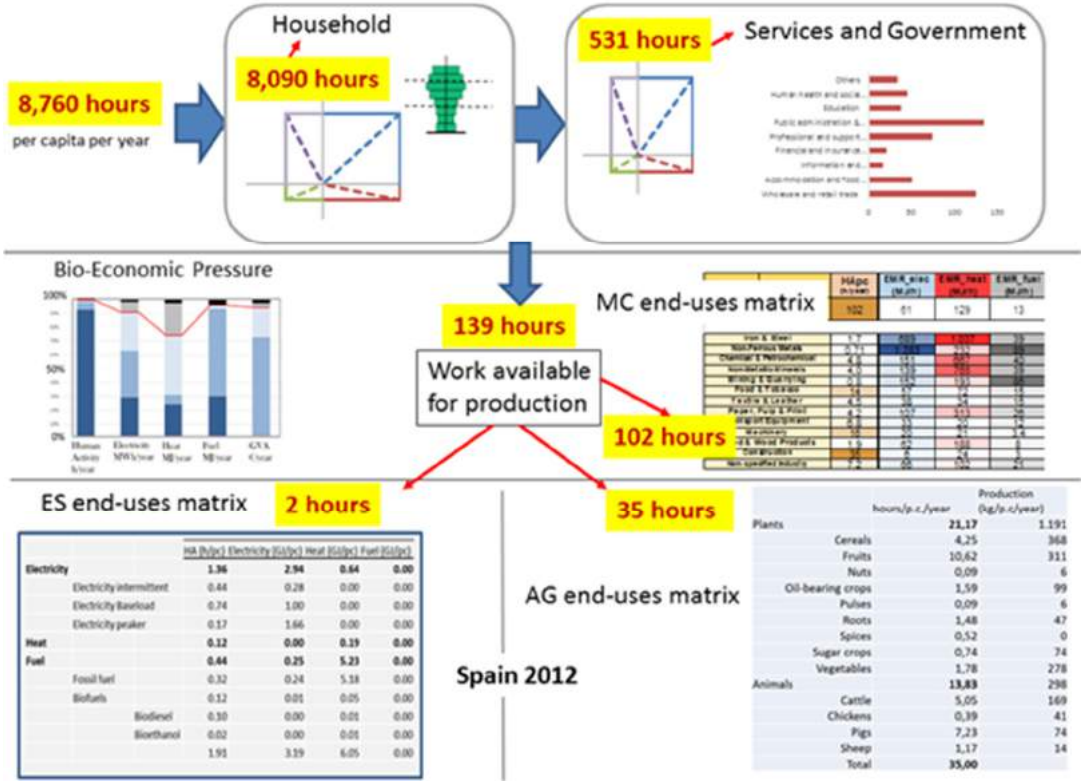



*Figure 13. Establishing a relation between: (i) profile of allocation of human activity in society; (ii) a multiscale analysis of end uses; (iii) the resulting value of BEP*

The information over the forced relation over metabolic characteristics of the different constituent components of the society provided in Figure 13 flags the existence of two types of constraints (reflecting the impredicative nature of the characteristics of the metabolic pattern). These constraints determine the possible characteristics of the metabolic pattern. We can start the analysis of the forced relation from the top (left corner) with the total human activity per capita – following the same logic of analysis described in Figure 8.

Using again the example of Spain, after taking out the amount of hours of human activity outside Paid Work and after taking out the amount of hours of human activity required for Service and Government we arrive to a quantity of 139 hours of work per capita per year used in Paid Work. This quantity has to be capable of producing the required set of goods consumed by society when used in the three remaining sectors – Manufacturing and Construction, Agricultural sector and Energy and Mining.

This limited quantity of working time is the result of the Bio-Economic Pressure associated with the material standard of living and represents the first type of constraint, associated with the desirability of the metabolic pattern. That is, this is a

constraint coming from the upper part of the graph (a downward causation determined by the aspirations of the people living in the society.

The analysis of the relation over different quantities of human activity to be distributed across different constituent components has to be complemented using a different type of analysis based on the information associated with the end-use matrix. End use matrices characterize how much human activity is required to produce in the various economic sectors the various types of products consumed by society. This second type of analysis flags the existence of another type of constraint affecting the viability and feasibility of this metabolic pattern. This second type of constraint is determined by the characteristics of the technical coefficients determining how much labor is required to produce the goods consumed by society. This upward causation – determining what can be done in biophysical terms, *independently of the aspirations of the people*, is called in the MuSIASEM jargon – the Strength of the Exosomatic Hypercycle (Giampietro et al. 2012). This label refers to the fact that exosomatic devices (machines, infrastructures and computers) are essential to the welfare of humans. However, they require an internal consumption of production factors (flow and fund elements) for their operation. Exosomatic devices can generate a hypercycle (they generate a supply larger than the input they require) by converting energy outside the human body: machines à fossil energy à more machines à more fossil energy. The stronger is the strength of this autocatalytic loop (the return on the investment) in the primary sectors the larger is the productivity of human activity used in the primary and secondary sector, the larger is the net surplus of labor and other production factors for the household and the service sector.

This type of analysis of constraints is important because it clearly shows another key feature of modern economies. Looking at the benchmarks reported in the end-use matrices one can understand the crucial role played by imports (externalization) in supporting the wealth of European economies. For example, the data in Figure 13 show that for the supply of fossil fuels in Spain the energy sector consumes 0.32 hours per capita per year (19 minutes!). In 19 minutes of their work the workers of the energy sector in Spain can guarantee the total amount of fuels consumed per capita in Spain in a year (including private mobility, commercial transportation, public transports, residential and manufacturing). It should be noted that this assessment underestimates the working time in the administrative offices of the energy companies (accounted in the service sector). Still the order of magnitude of this value clearly indicates the overwhelming effect of two factors: (i) EU liquid fuels come from fossil energy (oil), and therefore they are quite easy to produce in large refineries; (ii) EU liquid fuels are massively imported. If Spain would have the oil reserve of Saudi Arabia, when considering the end use matrix of oil extraction and of refinery, when extracting its own

oil, it would have to invest much more than 19 minutes to extract, transport, and refine oil into final liquid fuels.

The overview provided in Figure 13 illustrates another crucial point. The solution to avoid the limitations imposed by technical constraints by importing is easy very and effective in relation to the end use matrices of Agriculture, Energy and Mining and Manufacturing and Construction. If you import goods, you save the requirement of investment of labor and other inputs to produce them. However, when dealing with the activities of the service sector and the household the externalization is more difficult. End uses have to be expressed inside the borders of the country. The alternative solution – importing labor from the outside to increase the available input (immigration) – is more problematic for social reasons. Moreover, top down constraints (the characteristics of BEP) reflect the demographic structure of a population (determined by the living inside the country), the expected material standard of living (associated with a high level of services), the need of taking care of the local population.

Looking at all these factors we have to conclude that there is a limited ability to externalize the requirement of jobs in the service sector. On the contrary the production of biophysical goods is much easier to externalize both in relation to the production of raw materials (e.g. the huge import in EU of primary energy sources such as oil, minerals or feeds for animal) and in relation to finished products (the important flow of imported goods from China).

In conclusion, Figure 13 shows the existence of a set of relations between: (i) the profile of allocation of human time; (ii) the level of Bio-Economic Pressure (associated with the level of economic development and material standard of living); and (iii) the technical coefficients determining the characteristics of the end-use matrices in the various compartments of the economy. Because of this set of relations, a heavy reliance on fossil energy and a massive externalization may represent, at the moment, “the” solution to achieve a very high level of economic development. But what would happen to the “knowledge society” if farmers would produce only 10 kg of grain per hour (and therefore we would require a fraction of farmers in the work force similar to the one used right now in the service sector) or if the energy sector would be based on biomass as primary energy source? What if, without fossil energy, the society would require a quantity of land and labor per capita orders of magnitudes larger than the ones available today?

The tool-kit illustrated here makes it possible to answer this type of questions when discussing of the future sustainability of EU: Would it be possible to maintain the existing level of bio-economic pressure if we de-carbonize? Do we have alternative technologies

that can guarantee the same productivity of labour both in agriculture and in the energy sectors without using fossil energy?

It is important to have a quantitative idea of how technological coefficients of specific processes can affect the viability of metabolic pattern. For example, in Brazil the production of biofuels from sugarcane has a productivity of labour (net supply per hour of labour) in the order of 0.4 GJ of energy per hour of labour (vs 20 GJ experienced in EU energy sectors powered by fossil energy) – Giampietro and Mayumi, 2008. If we want to check whether the second generation of biofuel will be capable of changing dramatically the picture, this is the benchmark to study. We need an analytical tool-kit capable of checking the feasibility, viability and desirability of proposed scenarios.

### 3.1.6 How to assess the implications of externalization of feasibility constraints

As explained in Section 5.3 (where the logic and the protocols of the quantitative assessment are explained more in detail) there are three different logics that can be used to assess both "virtual requirement of end-uses" and "externalized environmental pressures" in notional terms:

(i) We can use the information gathered about the production of the imported flows to generate "virtual processors" that would be required by the importing country to produce these flows on its own. In this way we can assess both the end-uses and the environmental pressures that would be required by the importing society if it had to produce the imported input on its own – i.e. using the technical coefficients of the production systems needed to supply these inputs and the primary sources and primary sinks used in domestic production. This logic is important to study the issue of "food and energy security" – what if the society had to produce what it needs on its own?;

(ii) We can use the information gathered about the production of the imported flows to generate "virtual processors" that reflects the characteristics of the processes taking place in the exporting country to produce these flows. In this way we can assess both the end-uses and environmental pressures that have been required by the exporting countries when producing the imported inputs – i.e. using the technical coefficients of the production systems used to produce them and the primary sources and sinks used by the exporting countries. This logic is important to study the ethical implications of the strategy of externalisation to other countries;

(iii) We can imagine that the imported flows were generated by "virtual processors" defined using benchmarks of end-uses and environmental pressures associated with the expected characteristics of known typologies of processes of

production – i.e. assuming a mix of typologies of production systems and a mix of typologies of primary sources and primary sinks. This logic is important to study the biophysical limits that we can expect at the level of the whole planet – i.e. when making scenarios in global stoke taking.

The detailed explanation of how to calculate externalization using the concept of processors within the rationale of relational analysis is provided in Section 5. Here we just provide an example of environmental pressure matrix of Spain which has been calculated using **the first of the three methods** – i.e. the virtual externalization of production factors associated with imports has been assessed by using the technical coefficients of production of Spain, using the data referring to both the end use matrix and the environmental pressure. Therefore, the assessment is about the extra requirement of production factors for Spain if the imports were produced in Spain.

## 3.2 The results of the tool-kit in relation to the End-Use Matrix (combining Local End Use Matrix and Externalized End Use Matrix)

### 3.2.1 The visualization of results

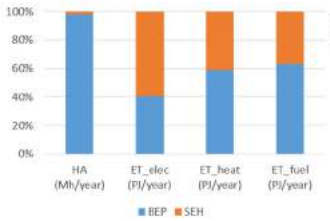
The information about the EUM of a country obtained by combining together data from the Local EUM and the Externalized EUM can be described using a visualization that integrates several metrics at the same time, as shown in Figure 14.

**STATE**

NETHERLANDS (2012)
POPULATION 16.7 Million

| | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | Relative to EU 8 countries | 2.49 | 2.41 | 1.42 | 5.05 | 3.47 | 1.41 | 0.60 | 0.81 | 1.44 | 1.18 | 1.25 |
| HOW (1) | TOTAL CONSUMPTION | 5740 | 1451 | 39 | 306 | 182 | 363 | 851 | 769 | 82 | 0.799 | 40400 |
| HOW (2) | EXTERNALIZATION | 3970 | 475 | 17 | 138 | 86 | 26 | 513 | 580 | 56 | 0.622 | - |
| | Total consumption/ domestic production | 3.24 | 1.49 | 1.78 | 1.82 | 1.89 | 1.08 | 2.52 | 4.07 | 3.17 | 4.52 | - |
| WHY (3) | FOR SECURITY | 2187 | 548 | 35 | 74 | 39 | 351 | 760 | 252 | 82 | 0.799 | - |
| WHY (4) | FOR EXPORT | 3553 | 903 | 4 | 232 | 143 | 12 | 91 | 517 | 0 | 0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1970 | 530 | 26 | 67 | 39 | 326 | 302 | 62 | 8760 | 1767 | 40400 |
| AF | 26% | 11% | 7% | 8% | 3% | 6% | 0% | 91% | 0.25% | 62% | 2% |
| MC | 32% | 0% | 29% | 26% | 3% | 76% | 0% | 0% | 1.00% | 1.33% | 18% |
| ES | 0% | 0% | 12% | 16% | 0% | 2% | 100% | 9% | 0.04% | 0.21% | 3% |
| SG | 12% | 2% | 32% | 20% | 52% | 2% | 0% | 0% | 6.79% | 26% | 77% |
| HH | 29% | 87% | 21% | 29% | 42% | 14% | 0% | 0% | 91% | 10% | - |

*Figure 14. state of the play for the Netherlands.*

The different items of the Figure are explained below.

**First row:** Indicator showing the relation between: the values of the various indicators and the average values of the same indicators calculated for the EU-8 countries

X = Value of the country/Average value for EU8

**Red point #1:** Total Consumption – the values in the top row of the EUM

$$EUM = EUM_{LOC} + EUM_{EXT}$$

The elements of the top row of the EUM (summing the consumption in the various constituent components) includes:

A. 8 data over flows: (i) two categories of nutrient carriers (animal and plant food products); (ii) three categories of energy carriers (electricity, heat and fuels); and (iii) three categories for water end uses (blue water consumptive, blue water non-consumptive, and green water); and

B. B. 2 data over funds: (i) human activity; and (ii) land uses.

The values in EUM are obtained by combining the values of $EUM_{LOC}$ and $EUM_{EXT}$.

**Red point #2**: the values in the top row of the Externalization End Use Matrix ($EUM_{EXT}$)

It should be noted that in this study we are calculating the effect of externalization only in relation to the imports associated with Food and Energy. This implies an underestimation of the effect of externalization of imported products referring to Manufacturing. In fact, in the calculation of EUM we do not consider the externalization referring to the economic activities taking place in the Manufacturing sector (e.g. the massive imports from China). Data in the vector reflecting the top row of the Externalization End Use Matrix are calculated as:

$$EUM_{EXT} = EUM_{imp} + EUM_{virtualimport}$$

Where $EUM_{EXT}$ accounts the quantities of flow elements (nutrient carriers, energy carriers and water end uses) and fund elements (labour and land uses) that would be required by the country (if using its own technical coefficients) to produce the flow of imported inputs. $EUM_{EXT}$ combines together the profile of inputs (flow elements) directly imported ($EUM_{imp}$) and the flow and fund elements that would be required by the country to produce, on its own, the imported flows ($EUM_{virtualimports}$).

The row below indicates the boost given to the domestic production by externalization (imports). It is calculated for the various elements of the vector as:

Boosting index = "total consumption *i*" / "domestic supply *i*"

**Red points #3-4**: Trade-off in end uses: "Security" and "Economic Export"

The profile of values describing the overall use of flow and fund elements in EUM can be split into two sub-matrices: (i) a first fraction of these production factors is used to generate the flows consumed by the society – this fraction can be labeled: Security; (ii) the remaining fraction of these production factors is used to generated exported commodities - that contribute to the economic performance, but that are not metabolized as such in form of consumption – this fraction can be labeled: Economic Export.

As explained in Section 5 the tracking of the imported flows that may be re-exported makes it very difficult if not impossible to account the split across categories of imports and production systems. So, we solved the problem by adding a new constituent component to the end-use matrix (splitting both AG and ES into: (i) $AG_{security}$ and $AG_{export}$; and (ii) $ES_{security}$ and $ES_{export}$; and then we used the ratios between two quantities:

(1) EXPORT/(DOMESTIC SUPPLY + IMPORT) = x; and

(2) DOMESTIC CONSUMPTION/(DOMESTIC SUPPLY + IMPORT) = 1-x

At this point the split of the EUM over the two sectors AG and ES can be obtained as follows:

* the row $EUM\text{-}AG_{security} = AG \cdot (1-x)$; and the row $EUM\text{-}AG_{export} = AG \cdot x$

* the row $EUM\text{-}ES_{security} = ES \cdot (1-x)$; and the row $EUM\text{-}ES_{export} = ES \cdot x$

**Red point #5:** BEP matrix

BEP quantifies the fraction of the total quantity of human activity and the profile of flows of energy carriers used by the purely dissipative sectors over the total:

$$\text{vector } EUM_{BEP} = \text{vector } (EUM_{HH} + EUM_{SG}) \text{ / top vector EUM}$$

Bio-economic pressure is the ratio between the quantities describing the size of flows and funds allocated to the consumption (dissipative) part of society in relation to the total flows and funds available. BEP is a a good proxy of the material standard of living in relation to all the conventional indicators of development (Giampietro et al. 2012). The higher the fraction of internal resources allocated to the HH and SG sectors, the higher the living standards, so this can be used as a welfare indicator for the country.

**Red point #6**: Profile of allocation of end uses over the constituent components in relation to the metabolism of FOOD, ENERGY and WATER

The end use matrix –Figure 9 and Figure 10- is a series of vectors describing the profile of allocation of production factors (divided in the two categories of flow and fund elements) across the constituent components (economic sectors) of a society. In relation to the data described in the previous points we have been using in the information reflecting only the values of the top vector of the matrices (at a single level of analysis). However, the end use matrix has the form of a series of vectors capable of describing the metabolic characteristics not only at the level of the whole, but also at lower levels where we can observe the metabolic characteristics of constituent components. That is the vector describing the metabolic characteristics of the whole society (the top vector) can obtained by summing the values of the metabolic characteristics of the constituent

components: $EUM_{whole} = EUM_{AF} + EUM_{ES} + EUM_{MC} + EUM_{SG} + EUM_{HH}$. Where $EUM_{AF}$ is the profile of consumption of the different carriers and funds in the AF sector, $EUM_{ES}$ is the profile of consumption of the different carriers and funds in the ES sector, etc. In conclusion on the bottom of Figure 14 we provide the breakdown of end uses in relation to the consumption of nutrient carriers, energy carriers and water end uses that are relevant for studying the implications of the Nexus.

The visualization for each one of the eight countries following the template given in Figure 14 is provided in Appendix 4.

### 3.2.1 Overview of the data of the End-Uses Matrix (local and externalized) for the sample of 8 EU countries

In this section we provide an overview of the values found for the 8 EU countries of the sample – Table 1. The solution of keeping data disaggregated is essential to preserve valuable information (e.g. the distinction between different typologies of nutrient carriers, energy carriers and water uses). However, it makes difficult to understand the quantitative characterization because it tends to generate an overload of information. To reduce this problem, we use the Flag model (red = bad, green = good, yellow in the middle). This solution helps pattern recognition and the identification of outliers in the data set.

| | Food | | Energy | | | Water | | | Funds | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Plant | Animal | Electricity | Heat | Fuel | Blue Water Consumption | Blue Water Non Consumptive Use | Green Water Consumption | Human Activity | Land Use | GDP |
| | **End uses in relation to EU8 average** | | | | | | | | | | |
| **FR** | 1.29 | 1.04 | 1.25 | 0.70 | 0.86 | 1.28 | 1.26 | 1.25 | 0.68 | 1.04 | 1.02 |
| **DE** | 1.00 | 1.22 | 1.12 | 0.91 | 0.93 | 0.63 | 1.08 | 0.87 | 0.55 | 0.67 | 1.16 |
| **IT** | 0.79 | 0.80 | 0.78 | 0.84 | 0.84 | 1.05 | 1.25 | 0.95 | 1.19 | 0.86 | 0.84 |
| **NL** | 2.49 | 2.41 | 1.42 | 5.05 | 3.47 | 1.41 | 0.60 | 0.81 | 1.44 | 1.18 | 1.25 |
| **RO** | 0.74 | 0.62 | 0.41 | 0.52 | 0.34 | 0.48 | 0.46 | 1.64 | 4.38 | 1.28 | 0.25 |
| **SP** | 1.06 | 0.80 | 0.86 | 0.61 | 0.82 | 1.95 | 0.55 | 1.46 | 1.11 | 1.41 | 0.72 |
| **SE** | 0.83 | 1.01 | 2.43 | 1.08 | 1.45 | 2.25 | 5.31 | 0.77 | 0.74 | 1.93 | 1.43 |
| **UK** | 0.57 | 0.77 | 0.77 | 0.93 | 1.00 | 0.31 | 0.36 | 0.49 | 0.49 | 0.93 | 1.24 |
| | **Boost to the domestic supply because of externalization** | | | | | | | | | | |
| **FR** | 1.35 | 1.16 | 1.14 | 1.26 | 1.72 | 1.18 | 1.30 | 1.57 | 1.34 | 1.33 | |
| **DE** | 2.02 | 1.27 | 1.11 | 1.12 | 1.30 | 1.09 | 1.32 | 1.72 | 1.75 | 1.66 | |
| **IT** | 1.84 | 1.55 | 1.25 | 1.37 | 1.09 | 1.21 | 1.37 | 1.74 | 1.62 | 2.10 | |
| **NL** | 3.24 | 1.49 | 1.78 | 1.82 | 1.89 | 1.08 | 2.52 | 4.07 | 3.17 | 4.52 | |
| **RO** | 1.25 | 1.13 | 1.10 | 1.09 | 1.28 | 1.09 | 1.07 | 1.21 | 1.18 | 1.20 | |
| **SP** | 1.74 | 1.31 | 1.11 | 1.40 | 1.31 | 1.35 | 1.03 | 1.56 | 1.92 | 1.52 | |
| **SE** | 1.83 | 1.40 | 1.09 | 1.43 | 1.34 | 1.06 | 1.07 | 1.68 | 1.46 | 1.27 | |
| **UK** | 2.79 | 1.39 | 1.06 | 1.24 | 1.47 | 1.05 | 1.04 | 1.89 | 1.85 | 1.98 | |

*Table 1. Normalized end-use values for EU8 sample and the boost due to externalization*

The ranges of values used for the flag model characterization are:

| | | |
|---|---|---|
| <0.75 | Green | Values under the first quartile of EU8 |
| 0.75-1.25 | Yellow | Values in between first and third quartile of EU |
| >1.25 | Red | Values over the third quartile o EU8 |

The data shows that the end use matrices show significant differences when considering the selected 8 countries. Netherlands is clearly the outlier on the top with the largest number of values above the average end use per capita of all EU8, followed by France and Sweden. On the other side, Romania and UK with low values of end-uses. However, the low values of end uses for these two countries hide substantially difference in the metabolic patterns that can only be observed moving at lower analytical levels (looking at the values of individual profiles for the constituent components). Even though these differences between Romania and UK can also be detected, remaining in an analysis carried out at the level of the whole, by looking at their different performance in terms of GDP (UK above the average and Romani below) and labor requirement (Romania is a clear outlier, above the average, and UK on the opposite side).

When coming to the boost to domestic supply because of externalization. The ranges of values used for the flag model characterization are:

| | | |
|---|---|---|
| <1.2 | Green | Low dependency on externalized resources |
| 1.2-1.6 | Yellow | Medium dependency on externalized resources |
| >1.6 | Red | High dependency on externalized resources |

It should be noted that the method used for assessing the effect of externalization presented in this assessment is method #1 - based on the technical coefficients of importing countries. This method only shows the production factors that are 'saved' by the importing country in relation to a set of products that are not produced. A different assessment of the quantity of production factors – i.e. nutrient carriers, energy carriers, water uses, labor and land - embodied in the imports can be obtained by using method #2. In this case the method requires tracking the flows of imported commodities and then using the technical coefficients of the production systems producing them in the countries of origin. In this way we can have a better idea of the actual quantities of

nutrients, energy, water, labor and land that have been used to produce the imported commodities. This is an important observation because due to the very high productivity of production factors in EU countries, the assessments obtained with Method #1 tend to be much lower than the ones obtained with Method #2.

Netherlands 2012 - Plants - Method 2

| | Food EPM$_{local}$ | | | | | | | Food EPM$_{import}$ | | | | | | | Food EPM | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | Crop (10^6 t) | Land (10^6 ha) | N (10^3 t) | P2O5 (10^3 t) | K2O (10^3 t) | Green water (10^9 m³) | Blue water (10^9 m³) | Crop (10^6 t) | Land (10^6 ha) | N (10^3 t) | P2O5 (10^3 t) | K2O (10^3 t) | Green water (10^9 m³) | Blue water (10^9 m³) | Crop (10^6 t) | Land (10^6 ha) | N (10^3 t) | P2O5 (10^3 t) | K2O (10^3 t) | Green water (10^9 m³) | Blue water (10^9 m³) |
| Plants | 21 | 0.6 | 78 | 24 | 50 | 2.0 | 0.1 | 57 | 11 | 797 | 346 | 449 | 77 | 5.3 | 78 | 11.6 | 875 | 370 | 499 | 79 | 5.4 |
| Cereals | 2 | 0.2 | 32 | 2 | 2 | 0.8 | 0 | 12 | 3 | 263 | 81 | 95 | 9.5 | 0.5 | | | | 83 | 97 | 10.3 | 0.5 |
| Fruits | 1 | 0 | 1 | 1 | 2 | 0.1 | 0 | 9 | 1 | 62 | 29 | 53 | 6.7 | 1.7 | | | | 30 | 55 | 6.8 | 1.7 |
| Oil-bearing crops | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 12 | 6 | 369 | 181 | 232 | 35.4 | 2.6 | 12 | 6 | 370 | 181 | 232 | 35.4 | 2.6 |
| Pulses | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 0.2 | 0 | 0 | 0 | 2 | 2 | 2 | 0.2 | 0 |
| Roots and tubers | 7 | 0.2 | 25 | 10 | 26 | 0.5 | 0.1 | 3 | 0 | 16 | 8 | 17 | 0.1 | 0 | 10 | 0.2 | 41 | 18 | 43 | 0.6 | 0.1 |
| Others | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 47 | 28 | 21 | 23.8 | 0.3 | 1 | 1 | 47 | 28 | 21 | 23.8 | 0.3 |
| Sugar crops | 6 | 0.1 | 8 | 4 | 5 | 0.3 | 0 | 17 | 0 | 32 | 14 | 24 | 0.8 | 0 | 23 | 0.1 | 40 | 18 | 29 | 1.1 | 0 |
| Vegetables | 5 | 0.1 | 11 | 7 | 15 | 0.3 | 0 | 3 | 0 | 6 | 4 | 5 | 0.5 | 0.2 | 8 | 0.1 | 17 | 11 | 20 | 0.8 | 0.2 |

$$\frac{\text{total land use}}{\text{land use inside NL}} = 19/1$$

0 - negligible (generally less than half the smallest unit or decimal of the heading)

*Figure 15. Assessment of land embodied in the imports of crops of NL using Method #2*

Just to give an idea of the difference that the change of the of method of assessment can have, we are showing in Figure 15 an analysis of the effect of externalization of the imports of crops - for human consumption, for feed and for re-export - of the Netherlands based on the adoption of Method #2. This different assessment method has the goal of calculating the amount of actual land used to produce the quantity and mix of crop consumed by the Dutch economy. As indicated by the Figure the total land use calculated in this way (the sum of hectares directly used inside the Netherlands and indirectly used outside the Netherlands through imports) is 19 times larger than the land used inside NL.

Coming to the values shown in Table 1 most EU8 countries heavily rely on externalization in terms of plants a strategy associated with the eternalization of green water, human activity and land uses. This has important consequence for the nature of the agricultural sector of EU. The majority of imported crops are used as feed for animal production. This makes it possible to concentrate the activity of the residual fraction of the work force employed in agriculture on the production of animal products. A supply system of animal products in EU is easier to sustain in economic terms, due to its high biophysical concentration of flows in space and time.

The two outliers confirm the importance of the role of externalization in determining the profile of end uses: Netherlands is the country with the highest externalization rates in most production factors, Romania is the country with the lowest level of openness. In this example we can see how the analysis of the effect of externalization provides a different insight on how the economic performance of a social-ecological system is affected by biophysical processes. Netherlands is a clear example of an economy based on trading of commodities for economic profit whereas Romania is an example of an economy whose performance is much more determined by the characteristics of the biophysical processes taking place in its own borders. Looking at the other countries in the sample, UK, Germany and Italy have a higher level of openness than France, Spain and Sweden.

### 3.2.1 Comparing Netherlands, Germany and Romania in relation to EUM

Again, we want to remind the reader that what is presented here are preliminary results and that therefore our analysis of data has more the goal to illustrate the type of comparison that can be done using this information space, rather than provide the "ultimate truth" about the various assessments presented.

**Netherlands**

The data of the state of the play of the Netherlands obtained by combining the information of the End-Use Matrix (localized and externalized) are shown in Figure 14.

Netherlands stands out in the sample by being the country with the largest level of openness. Most of the values of its end uses are above the EU8 average and its economy relies to a great extent on externalization. In particular, the use of heat and fuel per capita and of food products, both plants and animals, are the largest of the EU-8.

Because of this level of openness, the Netherlands show a peculiar behaviour: it is the largest importer of energy carriers (in particular electricity and heat) per capita but also the largest exporter. The externalization includes both direct and virtual imports. In Netherlands the direct import of ECs is prominent, especially heat and fuel. The high dependence from imported fossil fuels is partially responsible for boosting the virtual heat demand (required to refine the crude oil). Conversely, virtual electricity accounts for almost the double the of the electricity directly imported (breakdown not shown in the Figure).

The same pattern of extreme openness is found when considering food metabolism. The Netherlands again use much more plants and animal products per capita than the rest of the analyzed countries. However, these crops are used for the local production of animal products, especially dairy in the form of feed from plant products. As a result, we

can observe a boost of domestic production of 3.24 times for plant, whereas for animal is “only” 1.49 times.

The share of food destined to final consumption in the Household sector looks smaller than in other countries. However, when looking at the absolute value of consumption per capita the value is similar to the other of countries (the kilograms of food per capita consumed in households cannot be much bigger since humans cannot eat much more than other humans). This difference can be explained by the larger level of consumption of food in the rest of sectors (AG, MC and SG) for feed, production of food products and export.

The overall input of hours of labour per capita is high (second in the EU8). The hours of labor “saved” by the Dutch economy because of imports are 3.2 times more than the actual hours of labor in the country. To make things more complicated it should be noted that this assessment is a strong underestimation because: (i) the adoption of Method #1 for this assessment implies a major underestimation of the hours of work that went in the production of the imported commodities. The production of 1 tonne of imported soya produced in Brazil or Argentina for sure requires much more labor than the one accounted in Method #1; (ii) in this study we are accounting of hours of labor externalized only in relation to labour invested in the food and energy supply. The accounting of labour in manufacturing embodied into the imported goods is not included in this study. Finally, although in general the labour invested into the energy sector is relatively small compared to the labour invested into agriculture (due to the high mechanization of the energy sector), the externalized hours of labor related to the energy supply in the Netherlands is higher than the average per capita (only Spain results to be slightly higher than Netherlands). In Netherlands the labour saved in the energy sector is more than the double (around 8.4 h/p.c.) than the domestic investment (around 4 h/p.c.). The largest share (around 60%) of the domestic labour in energy is allocated to electricity production and distribution. On the contrary the largest share (around 65%) of externalized labour (embodied in imports) is allocated to the extraction of Primary Energy Sources (breakdown not shown in the Figure).

An exception to this rule are the use of blue water non-consumptive uses per capita which is significantly below EU8 average because the country imports nearly half of its electricity from other countries. Moreover, even though land uses and green water per capita use do not pass EU8 average the imports of these resources boost local production capacity by 5 and 4 times, respectively. This high level of externalized resources is determined by the very large rate of vegetable imports.

The contribution of externalized blue water to the overall blue water consumption is rather low as compared to other countries. It is worth noting that the imports of blue

water are mostly related to food products and that they double what is locally consumed. However, the country counts with a large MC sector responsible for most of its blue water consumption. In the case the effect of imports related to manufactured products were considered in the accounting, the value of this contribution would be probably increase dramatically.

In relation to the split between resource use of national security vs for exporting commodities, the Netherlands is the only country of the EU8 with larger food investment in the latter. When considering food Dutch exports are to a great extent re-exports of imported commodities. In particular, the country exports two times more animals than locally consumes, and 1.65 times more crops.

When looking at end uses of energy carriers, compared to the average, Netherlands is the country consuming more process heat[1] in internal uses (Sweden stands out for electricity and Germany for fuel). It consumes near two times the heat consumed by the majority of EU-8 countries (producing the oil products it re-exports). Looking at the pattern of consumption within the sectors, the services sector (SG) results to be particularly relevant, consuming a fifth (20%) of the heat consumed by society.

Looking at the distribution of domestic use among sectors, an outstanding pattern is observed for blue water consumption with 76% of resources allocated to the MC sector. This is due to the fact that the utilization of blue water in agriculture is marginal. It is the country with the largest share of water in this sector of the EU8, and the second in total volume consumed after Germany. This is a very different pattern than for instance Spain, which has 66% of its blue water consumptive uses in agriculture, a sector with a much lower GDP than the others.

In conclusion, in Netherlands we can observe a large use of resources in the economy that also translates in a higher GDP per capita, with the particularity that the majority of resources used are not produced within the country, but rather imported directly and indirectly, and re-exported in many cases. It is a country specialized in using resources as commodities for trading rather than as inputs used for stabilizing the internal metabolic pattern.

**Romania**

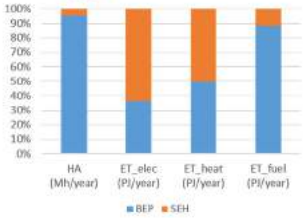
[1] Heat includes 'Derived Heat' and Heat products (e.g. natural gas, refinery outputs, etc) as specified in the Annex

**STATE**

ROMANIA (2012)
POPULATION 20.1 Million

| | | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | Relative to EU 8 countries | 0.74 | 0.62 | 0.41 | 0.52 | 0.34 | 0.48 | 0.46 | 1.64 | 4.38 | 1.28 | 0.25 |
| HOW | 1 TOTAL CONSUMPTION | 1703 | 374 | 11 | 32 | 18 | 123 | 660 | 1552 | 250 | 0.864 | 8100 |
| | 2 EXTERNALIZATION | 337 | 43 | 1 | 3 | 4 | 10 | 41 | 271 | 39 | 0.143 | - |
| | Boost of domestic production | 1.25 | 1.13 | 1.10 | 1.09 | 1.28 | 1.09 | 1.07 | 1.21 | 1.18 | 1.20 | - |
| WHY | 3 FOR SECURITY | 1318 | 357 | 10 | 30 | 13 | 114 | 622 | 1289 | 250 | 0.864 | - |
| | 4 FOR EXPORT | 385 | 17 | 1 | 2 | 5 | 9 | 38 | 263 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1274 | 356 | 10 | 29 | 13 | 105 | 583 | 1064 | 8760 | 7213 | 8100 |
| AF | 26% | 3% | 1% | 1% | 5% | 37% | 0% | 97% | 2.33% | 95% | 4% |
| MC | 13% | 1% | 35% | 32% | 5% | 8% | 0% | 0% | 2.00% | 0.34% | 30% |
| ES | 0% | 0% | 27% | 18% | 1% | 25% | 100% | 3% | 0.08% | 0.26% | 4% |
| SG | 3% | 1% | 16% | 6% | 60% | 3% | 0% | 0% | 4.09% | 2.13% | 62% |
| HH | 57% | 95% | 21% | 43% | 29% | 27% | 0% | 0% | 91% | 2.53% | - |

*Figure 16. Data referring to EUM describing the state of the play of Romania*

Romania falls on the opposite side than Netherlands in our analysis. It is the country with the lowest GDP per capita of the EU8 (one fourth of the average) and with a lowest input of most flows of production factors (around half of the average). Although both values are lower than the average, the proportion of the quantity of inputs per unit of GDP is the double when compared to other countries. This indicates that the biophysical economic productivity (meaning the amount of added value generated by the resources used to produce GDP) is very low. In the Table we can also observe very clearly that on the other hand, the country shows the highest domestic use of fund elements (4.38 times more labour and 1.28 more land per capita). This indicates both a low technical capitalization of the economy using its own fund of labour rather than machinery and that the economic process is not boosted neither by depletion of energy (stocks) nor by imports. Labour per capita appears four times larger than the average of the sample and the level of externalization much lower.

Looking at the information given by end use matrix about the allocation of flows and fund elements in the different constituent components. Romania has the largest labour investment in AF and ES, 204 and 7 h per capita compared with the rest of the sample. Conversely the externalized labour accounts for a minor contribution: 15% and 20% of the total labour required, respectively. As a result of this situation, the country's fraction of investment of end-uses in guaranteeing internal consumption is the largest of the EU8. Food exports are associated to vegetables and green water (i.e. rainfed crops), whereas energy exports are minors.

The use of green water per capita is also large with the lowest rate of externalization of this resource. This analysis reveals a typology of crop production specialised in low input

rainfed agriculture. The consumption of Energy Carriers is lower than the EU-8 average and the same also for the energy externalization except for fuels: one third of the domestically consumed fuel is directly imported.

In relation to viability, the domestic consumption of ECs is half the average domestic consumption in EU-8. The country shows a low electricity and heat share in the services sector as compared to other countries and high share of electricity and fuel in MC & ES. On the hand, fuel use in SG has large share (small share in HH). It also counts with the largest share of land uses of agriculture in AG of EU8 (95%), supporting the finding of low productive farming systems in monetary terms.

The pattern of blue water consumptive uses shows large shares of both agricultural uses and the energy sector, these latter driven by the important activities of mining for PES (lignite and uranium).

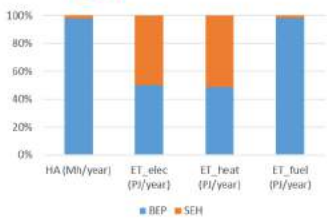
**Germany**

**STATE**

GERMANY (2012)
POPULATION 80.3 Million

| | | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | Relative to EU 8 countries | 1.00 | 1.22 | 1.12 | 0.91 | 0.93 | 0.63 | 1.08 | 0.87 | 0.55 | 0.67 | 1.16 |
| HOW | 1 TOTAL CONSUMPTION | 2300 | 734 | 31 | 55 | 49 | 161 | 1541 | 825 | 32 | 0.453 | 37500 |
| | 2 EXTERNALIZATION | 1160 | 157 | 3 | 6 | 11 | 13 | 370 | 345 | 14 | 0.180 | - |
| | Boost of domestic production | 2.02 | 1.27 | 1.11 | 1.12 | 1.30 | 1.09 | 1.32 | 1.72 | 1.75 | 1.66 | - |
| WHY | 3 FOR SECURITY | 1509 | 494 | 28 | 46 | 42 | 153 | 1262 | 572 | 32 | 0.453 | - |
| | 4 FOR EXPORT | 791 | 240 | 3 | 9 | 7 | 8 | 279 | 253 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1430 | 488 | 27 | 44 | 42 | 141 | 959 | 333 | 8760 | 2728 | 37500 |
| AF | 21% | 6% | 2% | 1% | 5% | 10% | 0% | 96% | 0.16% | 76% | 1% |
| MC | 37% | 1% | 37% | 41% | 1% | 43% | 0% | 0% | 2.00% | 0.72% | 27% |
| ES | 0% | 0% | 12% | 10% | 0% | 16% | 100% | 4% | 0.05% | 1.13% | 2% |
| SG | 5% | 2% | 27% | 14% | 41% | 1% | 0% | 0% | 5.86% | 14.5% | 70% |
| HH | 37% | 91% | 23% | 34% | 57% | 30% | 0% | 0% | 92% | 7.58% | - |

*Figure 17. Data referring to EUM describing the state of the play of Germany*

Germany has an average consumption per capita in most of its end-uses. In a few end-uses it has a relatively low use of funds (labour and land) largely externalized. This is signs of a highly capitalised economy and productive agriculture. In relation to final consumption Germany stands out for a domestic animal consumption mostly locally produced. On the other hand, most of its crop consumption is based on externalization (on imported commodities), with ensuing relevant imports of green water flows.

The country is also highly self-sufficient in electricity supply and this is reflected in the great attention given to the "Energiewende" having the goal of substituting the reliance

on nuclear and coal with alternative sources. Moreover, it imports rough 30% of its domestic consumption of fuels, therefore the virtual demand for heat is prominent (as already mentioned above, the refinery processing is particularly heat-demanding). Blue water consumptive uses are rather low as compared to other countries with large shares allocated to both MC and ES sector while irrigation is rather minor.

Whereas energy and blue water resources are mostly used for covering internal consumption, exports are mostly associated to vegetables, with a large contribution of re-exports and rainfed crops. Approximately 50% of animal production is exported. The export of ECs is also not negligible, but it does not cross the 20% on average.

The pattern of resources use reveals the industrial character of Germany[2], with the MC sector contributing to national GDP more than in the other EU8 countries. The MC sector appears also strong in the use of most energy and water resources and labour. Indeed, the investment of labour and ECs is higher than the average in MC and on the average for the other sectors, except fuels consumption in household that results to be the second standing out after Italy.

## 3.3 The results of the tool-kit in relation to the Environmental Pressure Matrix (combining Local EPM and Externalized EPM)

### 3.3.1 The visualization of results

The visualization of EPM splits the pressures between related to the energy and food supply sectors, and between the direct pressure on the local environment and the externalized pressure on other foreign environments. This analysis becomes especially useful when we can identify a list of indicators of pressure that can be used to check possible environmental impacts at regional or local levels. These indicators of pressure have to be related to both: (i) stocks - the impact is then represented by the depletion of the stock; and (ii) primary sources and primary sinks requiring the activity of ecological funds – the impact is then represented by an excessive stress that can imply damages to the health of ecosystems. As explained in Section 5 an assessment of environmental impact requires a proper contextualization both in relation to the chosen dimension of analysis (the variables to be considered to assess the pressure) and in terms of scale (the space-time domain at which the impact has to be assessed). Therefore, an assessment of environmental impact cannot be carried out at this level of analysis (only the GHG emissions can be assessed at the national level) and beyond the scope of this first appraisal. What we provide here is an assessment of different examples of

[2] The red values for energy use in agriculture mean they are mean values extrapolated from other countries due to missing data.

environmental pressures indicators that can be associated with a characterization of metabolic pattern of Social-Ecological Systems. This information is useful to understand the volume of direct extractions and discharges (requirement of primary sources and sink capacity) inside the borders of national economies and requirement of primary sources and primary sinks that are externalized to other social-ecological systems. A visualization of the result is given in Figure 18.

**PRESSURE**
UNITED KINGDOM (2012)
POPULATION 63.5 Million

| | | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity p.c./year | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0.25 | 0 | 0.66 | 0.65 | 0 | 0.08 | 0.01 | 337 | 2 | 0 | 0.2 | 0 | 5.44 | 328 |
| | Food | | | | | | | | 11 | 241 | 0.29 | 26 | 19.3 | | |
| EXTERNALIZED | Energy | 0.74 | 0 | 1.19 | 0.81 | 0.0032 | 0.03 | 0.05 | 2 | 1 | 0 | 0.75 | 0 | 0.33 | 2 |
| | Food | | | | | | | | 5 | 209 | 0.3 | 34 | 10.3 | | |
| | Total consumption/ domestic production | 3.96 | - | 2.80 | 2.25 | >1000* | 1.38 | 6.00 | 1.02 | 1.86 | 2.03 | 2.33 | 1.5 | 1.06 | 1.01 |
| TOTAL | Energy | 0.99 | 0 | 1.85 | 1.46 | 0.0032 | 0.11 | 0.06 | 339 | 3 | 0 | 0.95 | 0 | 5.77 | 330 |
| | Food | | | | | | | | 16 | 450 | 0.59 | 60 | 29.6 | | |

To be assessed using lower level analysis

STOCKS

Reduction of the size and quality of reserves

FUNDS

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure 18. The information space generated by the combination of data from EPM*

**Local:** Environmental matrix for local pressures ($EPM_{LOC}$)

**Externalized**: Environmental matrix for externalized pressures ($EPM_{EXT}$) due both to direct imports ($EPM_{IMPORT}$) and virtually associated with imports ($EPM_{VIRTIMP}$)

$$EPM_{EXT} = EPM_{IMPORT} + EPM_{VIRTIMP}$$

Therefore, the overall EMP will be: $EMP = EPM_{LOC} + EPM_{EXT}$

The level of externalization of the environmental pressure is assessed using the ratio total environmental pressures (EPM) / local environmental pressure ($EPM_{LOC}$).

The visualization of the information space based on data organized in EPM illustrated in Figure 18 for the eight countries is provided in Appendix 4.

### 3.3.2 Overview of the data of the Environmental Pressure Matrix (local and externalized) for the sample of 8 EU countries

As done with the analysis based on data provided by the various types of EUM, we are now looking at the information space associated with the data provided by the various types of EPM. As already explained earlier the information space associated with EPM makes it possible to estimate the requirement of primary sources and primary sinks. Obviously, the indications of a requirement of primary sources and primary sinks reflect the pre-analytical choices of a given representation of the metabolic pattern of the social-ecological system. In fact, the environmental pressures are assessed by looking at the chosen identities of the processors - the inputs coming from biosphere such as wind, fossil energy, aquifers indicate the requirement of primary sources and the outputs going into the biosphere, such as GHG emissions, nitrogen into the water table, solid wastes indicate the requirement of primary sinks. These primary sources and primary sinks are outside human control. Therefore, in order to guarantee a situation of quasi-steady state to the metabolic pattern these primary sources and primary sinks must be made available by the biosphere.

Two important warnings about the results that we are presenting below are needed:

(1) In our analysis we assess only a few indicators of pressures (many more indicators would be possible) used as example;

(2) we are only considering examples of indicators of pressure associated with the activities of the agriculture and energy sectors (we are focusing on the Nexus and therefore, the relation between water, energy, food and land use is more evident in the analysis of these two sectors.

In this study focusing on the implications of the Nexus we are not considering the implications of the metabolic characteristics of MC sector, neither transportation of food and energy items, nor the final consumption of the HH sector. Therefore, CO2 emissions are only referring to the energy supply sector.

Again, we remind the reader that the application of the tool-kit in this deliverable has the only goal of illustrating the potentiality of the approach. In order to have this tool-kit properly applied one should have first of all a concrete problem of environmental impact to be tackled. In fact, it is only after having defined a concrete case study that it

becomes possible to involve the potential users of the analysis in the key decisions about the selection of pressures and impacts to be considered. In a specific situation it becomes possible to select the relevant criteria of performance to be reflected in an integrated set of indicators of environmental pressures relevant for the problem to be analyzed. Later on, this integrated set of indicators of pressure can be used to assess the level of environmental impact by contrasting their information against the information about the available primary source capacity and primary sink capacity. This analysis requires an appropriate contextualization at a pertinent scale. In fact, it is not possible to assess the environmental impact of water withdrawal (something associated with the consumption of blue water) in "France". The scale at which we are defining the entire country does not make it possible to check whether the quantity of abstracted water surpass the pace of recharge of the aquifer or the supply capacity of the rivers. This type of environmental pressure has to be contextualized at an appropriate scale at which this comparison is possible.

Therefore, the information provided in the following Tables is not an assessment of actual levels of impact on the environment. Yet in general terms we can at least compare the level of environmental pressures, in terms of amount of primary sources and primary sinks capacity used per capita, and how this requirement different along the 8 EU countries. The differences can be due to a different endowment of resources or to different levels of externalization. An overview of the values found is given in Table 2.

| | STOCK DEPLETION | | | | | FUND STRESSED SUPPLY CAPACITY | | | | | FUND STRESSED SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hard Coal | Lignite | Oil | Gas | Uranium | Wood Biomass | Crop biomass for biofuel | Withdrawal | Soil moisture | Land use | NPK | Manure | CO2 | Water Discharge |
| | **Primary Sources and Primary Sinks capacity requirement in relation to EU8 average** | | | | | | | | | | | | | |
| **FR** | 0.39 | 0 | 0.67 | 0.46 | 2.29 | 0.60 | 1.14 | 1.33 | 1.38 | 0.98 | 1.14 | 1.07 | 0.29 | 1.58 |
| **DE** | 1.21 | 4.92 | 0.75 | 0.78 | 0.48 | 0.56 | 1.22 | 0.85 | 0.83 | 0.64 | 0.89 | 0.77 | 1.82 | 1.07 |
| **IT** | 0.70 | 0 | 0.68 | 0.83 | 0 | 0.60 | 0.46 | 0.64 | 0.91 | 0.87 | 0.62 | 0.76 | 0.88 | 0.51 |
| **NL** | 2.86 | 0 | 2.53 | 4.07 | 0.10 | 0.46 | 1.45 | 0.74 | 0.64 | 1.19 | 1.99 | 1.64 | 1.56 | 0.90 |
| **RO** | 0.11 | 3.08 | 0.27 | 0.42 | 1.66 | 0.83 | 0.38 | 0.43 | 1.62 | 1.18 | 0.60 | 0.84 | 0.71 | 0.37 |
| **SP** | 0.88 | 0 | 0.76 | 0.47 | 0.46 | 0.46 | 1.14 | 1.87 | 1.44 | 1.40 | 1.25 | 1.08 | 0.85 | 0.80 |
| **SE** | 0.36 | 0 | 1.36 | 0.07 | 2.55 | 4.25 | 1.75 | 1.42 | 0.71 | 0.80 | 0.71 | 0.80 | 0.46 | 1.84 |
| **UK** | 1.50 | 0 | 0.97 | 0.90 | 0.46 | 0.22 | 0.46 | 0.72 | 0.47 | 0.93 | 0.79 | 1.04 | 1.44 | 0.92 |
| | **Reduction of environmental pressure due to externalization** | | | | | | | | | | | | | |
| **FR** | >1000* | - | 128 | 74 | >1000* | 1 | 3 | 1.09 | 1.42 | 1.42 | 1.44 | 1.23 | 1.13 | 1.09 |
| **DE** | 5.33 | 1.07 | 47.67 | 9 | >1000* | 1 | 4 | 1.11 | 1.67 | 1.87 | 2.02 | 1.36 | 1.08 | 1.10 |
| **IT** | >1000* | - | 14.44 | 9.64 | >1000* | 1.15 | 6 | 1.18 | 1.70 | 2.32 | 1.96 | 1.66 | 1.15 | 1.01 |
| **NL** | >1000* | - | 69 | 1.38 | >1000* | 1.53 | 19 | 1.18 | 3.28 | 6.35 | 8.12 | 1.59 | 1.37 | 1.13 |
| **RO** | >1000* | 1.06 | 2.74 | 1.28 | 1.15 | 1.03 | 5 | 1.10 | 1.21 | 1.26 | 1.21 | 1.17 | 1.04 | 1.06 |
| **SP** | 6.44 | - | >1000* | >1000* | >1000 | 1 | 15 | 1.34 | 1.56 | 1.63 | 1.89 | 1.45 | 1.05 | 1.06 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | * | | | | | | | | | |
| **SE** | >1000* | - | >1000* | >1000* | >1000* | 1 | 4.6 | 1.16 | 1.57 | 2.27 | 2.35 | 1.69 | 1.09 | 1.16 |
| **UK** | 3.96 | - | 2.80 | 2.25 | >1000* | 1.38 | 6 | 1.02 | 1.86 | 2.03 | 2.33 | 1.54 | 1.06 | 1.01 |

*Table 2. Overview of the values found in the EPM of the sample of 8 countries.*

Looking at the data in Table 2 we can see that the requirement of primary sources and primary sinks, when assessed per capita, present a wider diversity than in the analysis of end uses per capita. The differences are more determined by the type of pressures (columns of variables) than on the difference of type of economic system (rows of countries). There are several cells presenting the value "<1,000*" indicating a total reliance on imports – i.e. the domestic production is so small to be considered negligible and this would imply a value of infinite in the cell.

The massive dependence on externalization is found in the energy sector, where there is a high level of externalization of PES resources (between 90-100% of coal, oil, gas and uranium for most countries). With the exception of the Netherlands, Romania and UK (for natural gas) all the European economies rely on fossil energy (and uranium) from abroad. Looking in the categories of domestic extraction the Netherlands stands by its high rates of use of PES (stock depletion pressures). As noticed when discussing of the EUM this high requirement of PES is due to the large metabolic flow of energy that the Netherlands use for exports. Also Romania is high in some indicators of stock-depletion because of its large production of lignite and uranium. The difference between the two countries can be understood by looking at their externalization levels: while the Netherlands imports almost all its primary energy sources but gas, Romania produces internally the resources it consumes with the exception of oil. Germany shows average values of PES use, except for lignite that is nationally produced. An analysis based on EPM shows that in general, for energy the EU countries use first those resources that are available within their territory, although that does not necessary prevent them from importing a lot of other PES.

Sweden shows a high level of use of oil and uranium, 100% of which is imported and also stands out by its use of biofuel crops - imported in the case of crops and locally produced in the case of wood. In the Table we can see that in general most biofuel crops refined within EU8 countries are in reality grown and imported from outside the EU. In regard to other 'fund stressed supply capacity' pressures, Spain appears as the one with largest stress on water and land resources (mostly driven by irrigated agriculture) followed by Romania on green water (mostly driven by low-input rainfed crop production). Sweden is the country with largest ratio of water withdrawal for electricity production due to the higher share of hydroelectric power, while France uses it both for agriculture and cooling of thermal plants. Similarly, to the EUM, the level of openness is high for land uses and soil moisture. However, the level of externalization is in general quite low for water withdrawals, because the water considered serves greatly to cool the electric thermal plants producing the domestic electricity.

Finally, coming to the pressures related to sink capacity, i.e. emissions and wastes to the environment – we are considering as example indicators of environmental pressure: (i) the load of fertilizers and manure (that can be translated into impact on the soil and

water pollution when properly contextualized); (ii) CO2 emissions; and (iii) water discharges (mostly from cooling and mining activities). The key observation here is the large level of externalization of fertilizers use is linked to the vegetables production in most of countries. On the contrary, the manure is mainly produced locally since Europe is more specialized in animal production. Similarly, energy-related emissions are mostly internal to countries since we are accounting for the combustion processes for electricity generation in the domestic energy supply sector. Again, we remind the reader that in this study we are not accounting for the embedded energy and related emissions (e.g. energy and emissions in China) of any of the products imported by the MC sector.

### 3.3.3 Comparing Netherlands, Romania and Germany in terms of EPM

**Netherlands**

Netherlands has important gas fields, but it also shows the largest requirement of PES in terms of coal, oil and gas per capita (around three times larger than EU-8 average). While the majority of the gas is directly imported as PES (only 4% of the natural gas is virtually imported as electricity), the country stands out on virtual import of oil (i.e. oil embedded to produce the imported fuels): around 40% of total imported crude oil required is virtual, whilst the EU-8 imports around 20% as virtual (on average) (values not shown in the Figure). This also justifies the high virtual heat consumption observed in EUM (see section 3.2.1).

**PRESSURE**
NETHERLANDS (2012)
POPULATION 16.7 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | FUND STRESS SUPPLY CAPACITY | | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0 | 0.07 | 4.79 | 0 | 0.15 | 0.01 | 288 | 17 | 0 | 0.9 | 0 | 4.57 | 285 |
| | Food | | | | | | | | 20 | 172 | 0.12 | 18 | 29.6 | | |
| EXTERNALIZED | Energy | 1.89 | 0 | 4.76 | 1.82 | 0.0007 | 0.08 | 0.18 | 37 | 7 | 0.02 | 4.61 | 0 | 1.69 | 37 |
| | Food | | | | | | | | 18 | 424 | 0.62 | 130 | 17.3 | | |
| | Total consumption/ domestic production | >1000* | - | 69.00 | 1.38 | >1000* | 1.53 | 19.00 | 1.18 | 3.28 | 6.35 | 8.12 | 1.6 | 1.37 | 1.13 |
| TOTAL | Energy | 1.89 | 0 | 4.83 | 6.61 | 0.0007 | 0.23 | 0.19 | 325 | 24 | 0.02 | 5.51 | 0 | 6.26 | 322 |
| | Food | | | | | | | | 38 | 596 | 0.74 | 148 | 47 | | |

To be assessed using lower level analysis

STOCKS

Reduction of the size and quality of reserves

FUNDS

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure 19. The combination of data from EPM referring to the Netherlands*

On the other hand, it refines biofuels mainly from imported crops. Indeed, the Netherlands is one of Europe's largest bio-methanol producers but it imports most of the crops used to produce biofuel (in particular sugarcane from Brazil). This determines a boost in the external requirement of biomass (around 14 kg of biomass are required to produce 1 kg of bioethanol) and land. Water withdrawals are mostly driven by cooling activities in the energy sector, responsible also for most of water discharges.

The country has the largest use of fertilizers per capita of all EU-8 countries (two orders of magnitude), 88% of which is in virtual forms (use of fertilizer externalized in the production of imported crops), that is correlated with the highly externalized land use and soil moisture use.

In terms of manure, Netherlands in well known for having an enormous problem of eutrophication of soils and water bodies due to the high levels of manure produced in their farming systems. Although the value of manure in the EPM of Netherlands is the highest in Europe, note that it is expressed in unit per capita and not in unit per hectare, which would be much higher given the high population density of the country (Netherlands triples the average population density of the rest of countries), and it would better reflect the dimension of the problem in the country.

Netherlands also shows the highest GHG emissions[3] per capita, and only one third of them are “virtual emissions” (externalized) since they are mainly coming from fossil energy combustion taking place in the country. An important part of these emissions is due to the production of oil products that are exported (not consumed in the country).

**Romania**

Romania shows by far the lowest pressures on the biosphere: both in terms of source and sink capacity; in fact it is well below the EU-8 average in all the selected indicators. Even though it shows a pressure associated with consumption in line with average value, like in case of lignite depletion, the level of externalization is very low. Only 6% of the lignite actually used in Romania is imported. This means that Romania tends to use its own local resources to produce its own Energy Carriers. This is also the case of uranium, being Romania the only country in EU mining it. Anyway, in general terms, Romania comes second for total uranium depletion after Sweden (that currently gets about 40% of its electricity from nine nuclear reactors). But the uranium depletion of Sweden is in virtual form (due to imports). The Netherlands shows the lowest externalization of oil

[3] The GHG emissions, as well as all the pressured considered in the EPM, are only referred to the energy and food supply. In this specific case, the GHG emissions only include those coming from the energy sector (Indirect land use change - ILUC - emissions are not taken into consideration).

(around 60% of the total consumption, same as UK, a net oil exporter). The majority of it (40%) is imported directly as crude oil and refined within the country; only 20% of oil is imported as virtually embedded into the imported fuels (values not shown in the Figure). The high level of openness is confirmed also in relation to the import of crops for biofuels: virtual imports contribute the most (around 53% of total imports)[4].

**PRESSURE**
ROMANIA (2012)
POPULATION 20.1 Million

| | | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity p.c./year | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0.77 | 0.19 | 0.54 | 0.01 | 0.4 | 0.01 | 152 | 40 | 0 | 0.3 | 0 | 2.73 | 125 |
| | Food | | | | | | | | 56 | 1241 | 0.6 | 38 | 20.6 | | |
| EXTERNALIZED | Energy | 0.07 | 0.05 | 0.33 | 0.15 | 0.0015 | 0.01 | 0.04 | 8 | 4 | 0.01 | 0.73 | 0 | 0.12 | 7 |
| | Food | | | | | | | | 11 | 271 | 0.143 | 7.3 | 3.43 | | |
| | Total consumption/ domestic production | >1000* | 1.06 | 2.74 | 1.28 | 1.15 | 1.03 | 5.00 | 1.09 | 1.21 | 1.26 | 1.21 | 1.2 | 1.04 | 1.06 |
| TOTAL | Energy | 0.07 | 0.82 | 0.52 | 0.69 | 0.0115 | 0.41 | 0.05 | 160 | 44 | 0.01 | 1.03 | 0 | 2.85 | 132 |
| | Food | | | | | | | | 67 | 1512 | 0.74 | 45.3 | 24 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure 20. The combination of data from EPM referring to Romania*

Romania water withdrawals are also driven by the energy sector but in this case mining activities are responsible for more than half of them. Therefore, the type of water discharges associated to these water uses are different than in the case of Netherlands. Romania shows one of the lowest value of GHG emissions together with Sweden.

[4] This result is affected by the assumptions presented in the Appendix (see for further details)

## Germany

**PRESSURE**
GERMANY (2012)
POPULATION 80.3 Million

| | | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity p.c./year | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0.15 | 1.23 | 0.03 | 0.14 | 0.00 | 0.28 | 0.04 | 370 | 21 | 0.01 | 1.9 | 0 | 6.73 | 347 |
| | Food | | | | | | | | 16 | 16 | 0.208 | 32 | 16.6 | | |
| EXTERNALIZED | Energy | 0.65 | 0.08 | 1.4 | 1.12 | 0.0033 | 0 | 0.12 | 35 | 4 | 0.01 | 2.72 | 0 | 0.56 | 34 |
| | Food | | | | | | | | 6 | 318 | 0.18 | 32 | 5.79 | | |
| | Total consumption/ domestic production | 5.33 | 1.07 | 47.67 | 9.00 | >1000* | 1.00 | 4.00 | 1.11 | 1.67 | 1.9 | 2.02 | 1.4 | 1.08 | 1.10 |
| TOTAL | Energy | 0.8 | 1.31 | 1.43 | 1.26 | 0.0033 | 0.28 | 0.16 | 405 | 25 | 0.02 | 4.62 | 0 | 7.29 | 381 |
| | Food | | | | | | | | 22 | 776 | 0.388 | 64 | 22.1 | | |

To be assessed using lower level analysis

STOCKS

Reduction of the size and quality of reserves

FUNDS

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure 21. The combination of data from EPM referring to Germany*

As the majority of the EU-8 countries, Germany heavily relies on externalization (imports of fossil resources) generating high environmental pressures abroad. The only exception is lignite, being a prominent producer of it. It imports almost all the oil used (98%) and the majority (around 80%) is directly imported as crude oil and then refined within the country, thus only a minor part (20%) is embodied as "virtual" in the imported fuels (data not shown in the Figure). Although it results to be on the EU-8 average regarding the pressure on the crop production for biofuel, it externalizes (four times the domestic production) most of the crops used for biofuels (this is common also to the other EU countries).

Germany has a high ratio of local water withdrawal per capita in the energy sector, largely driven by the important mining for coal, gas and lignite activities, followed by cooling. Its withdrawal for agriculture is rather low as compared to soil moisture uses, both local and externalized. As shown in the EUM, most agricultural production is rainfed in this country and water resources are mostly allocated to ES and MC sectors.

## 3.4 Comparing the information in the Bio-Economic Pressure matrix (the level of material standard of living)

It should be noted that a high value of BEP is observed consistently across all the European member states. A high BEP value requires a very strong exosomatic hypercycle in the primary sectors – i.e. a very high biophysical productivity of labor and the generation of a large surplus by the technology used - that is, a very high productivity of the secondary inputs used to supply the flows consumed by the secondary, tertiary, and household sectors.

In societal terms, the strength of the hypercycle (a high productivity of the production factors) can be obtained in two ways: (i) by exploiting resources of a very high quality (providing a very high return on investment in biophysical terms); and/or (ii) by focusing on the production of high value products and services (e.g. financial economy). This allows the externalization of those processes of production of goods and commodities having a low productivity of the production factors required. For this reason, in developed countries we find a continuous reduction of the relevance of primary sectors (both in terms of employment of the labour force and in terms of the contribution of the sectors to the GDP) in the economy. In relation to this point, we already visualized the relative unimportance of primary production in EU countries – energy and mining and agriculture are relatively insignificant in terms of both energy consumption (electricity, heat usage, and petroleum fuel) and human activity – Figure 11 and Figure 12. Moreover, they are also becoming negligible in terms of their fraction of the sectoral GDP. This clear trend is reflected by the service-sector dominating the European 'knowledge society'. It should be noted that even when considering the country of our sample – Romania – that is less "post-industrialized" in terms of externalization and levels of consumption per capita, still when looking at the dynamic equilibrium associated with the activities of the sectors producing (orange) and consuming (blue) food and energy – Figure 22- we can still observe the expected pattern of high value of bio-economic pressure for the EU-8 (shown in Figure 11 and Figure 12.

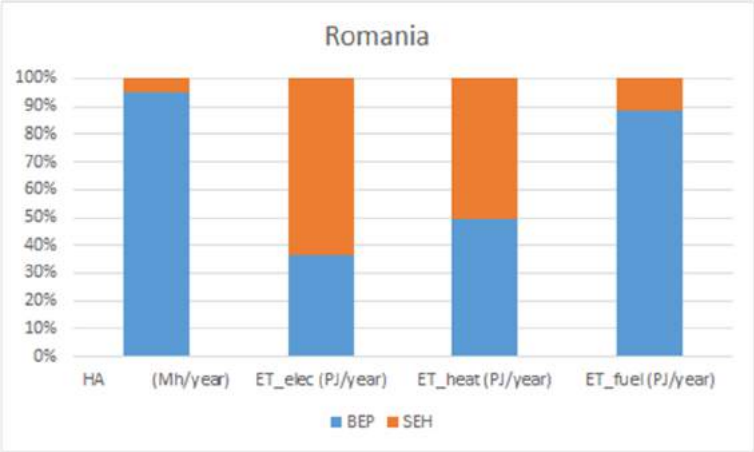



*Figure 22. The combination of data from EPM referring to Romania*

Showing the factors determining the viability and feasibility of the dynamic budget between the Strength of the Exosomatic Hypercycle and the Bio-Economic Pressure is essential in order to gain anticipation in relation to future scenarios in impredicative way. We can start setting the expected characteristics (performance) of the energy sector and the food sector characterizing the option space associated with SEH – i.e. the upward causation imposed by what is viable - and then discuss how the society should adapt inside this option space. In alternatively, we can start designing a (desirable) pattern for the society in terms of an expected value of BEP – i.e. a downward causation determined by what is desirable - and then look at the technical characteristics of the energy sector and the agricultural that would be required to achieve the stabilization of this pattern. The set of forced relations illustrated in Figure 14 can be used to illustrate this type of impredicative analysis.

By applying this analysis it becomes possible to identify situations in which:

(1) the standard of living of the population is dictated by external constraints (the upward causation is too strong and the value of BEP has to adapt to the option space provided by SEH;

(2) the strive for better standards of living pushes the society to find new ways of expressing a more desirable metabolic pattern at a higher value of BEP. This can be obtained by exploiting resources of higher quality, getting better technology or by externalizing the constraints to other Social-Ecological Systems and by increasing the level of credit leverage (making debts on permanent basis).

The tool-kit presented here makes it possible to gain a better understanding of the strategies used in modern economies for stabilizing (for how long?) the dynamic equilibrium between BEP and SEH.

Of particular importance is the pattern of requirement of human labor in the Service sector (a major driver together with the aging of the society of the increase in BEP) which is observable in all modern economies. This large requirement of labor (expressed in hours per capita per year) is evident in our sample of 8 countries and is illustrated in Figure 23. It goes from 600 hours p.c./year for the richer countries to around 500 hours p.c./year for the other (with the exception of Romania).

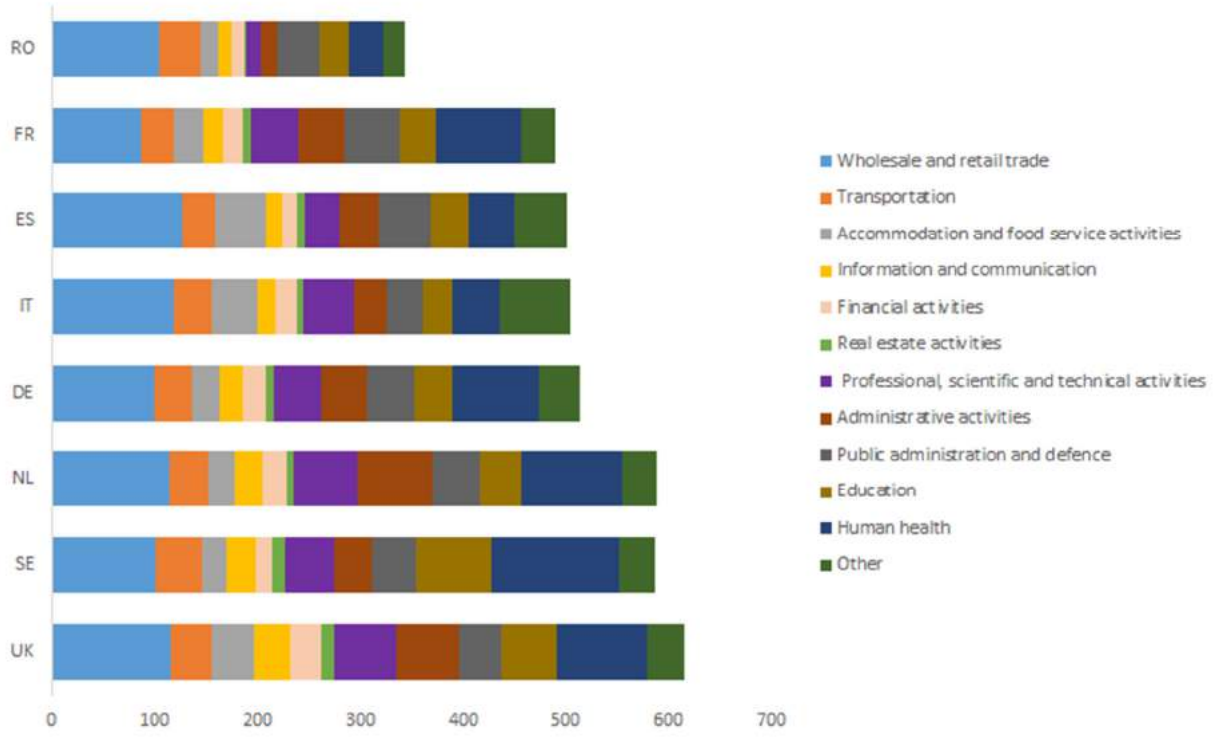



*Figure 23. The profile of allocation of labor in the service sector in the sample of 8 EU countries*

## 3.5 Problems experienced in the use of the tool-kit for the analysis of the Nexus

It is obvious, that the development of an innovative tool-kit which is quite "different" from conventional quantitative analysis and its applications to a quantitative characterization of the desirability, viability and desirability of the metabolic pattern of EU countries in relation to the Nexus between water, energy, food and land uses has implied facing a lot of theoretical and practical problems. How to establish bridges among quantitative representations referring to different scales and dimensions (on the theoretical side) and how to gather the required data from a heterogeneous set of sources, which are not always consistent with each other in relation to the definition of the categories of accounting (let alone being affected by missing data) have been problems that we had to solve in WP4. A discussion of these points is given in Section 5, but it is framed using a positive spin – how the innovative features of this approach make it possible to handle these epistemological problems and how the approach can be used to check and improve the robustness of statistics.

We want to discuss here another completely different type of problem that we experienced after generating the information space associated with the use of the proposed tool-kit. The problem we faced was that of "*too much of a good thing*". The tool-kit generates too many pieces of relevant information at a density that makes it difficult to use them. At the beginning, when preparing the first tables, we immediately realized that if we wanted to keep the record of all the information produced in relation to: (i) the different elements of the Nexus – food, energy, water, plus labor and land; (ii) the different categories of accounting PES; energy carriers and end uses; (iii) the different possible levels of analysis – the whole society versus the constituent components (AF, ES, MC, SG and HH); (iv) the internal view of the EUM and the external view EPM; (v) the level of openness of the system (local versus externalized); (vi) the distinction between what is used by a society for its internal consumption and what is used for export – we would produce a table so densely populated of cells that the numbers to be written in it will be invisible to the human eye. For this reason we tried to split this information in different tables. But the more we were splitting the more we realized that the major difficulty in the use of this tool-kit is the excessive density of the information flow it generates.

The quantitative relational analysis across levels and dimensions has similarities with fractal objects, you can move across levels and across dimensions of the Nexus, and then the description of "what you see" in the multi-level multi-dimensional representation is based on a quantity of data that exceeds the human capacity of handling them in the brain. In this exploratory exercise our focus has been that of developing the set of

quantitative relations, populating the set of relations with data and then generating the required results. However, we are now aware that the next key step for the successful use of this tool-kit is the development of a dedicated software helping the user of this information space to handle the density of the information: the overwhelming cascade of quantitative information has to be tamed. An interactive software is needed to extract only the information that is defined as relevant by the users, making it possible to define "à la carte" the type visualization the better suits the discussion of a given problem, the assumptions that have to be used to generate results. For sure in the rest of the MAGIC project this will represent "*the*" challenge to be faced, when applying the tool-kit to different specific set of questions in different types of case studies. Pertinent representations have to focus on the relevant aspects of the policy to be discussed.

# 4. State of the play at the regional level

This chapter provides an overview of results that exemplify the applications of the toolkit to NUTSx level of analysis

## 4.1 The Nexus in the energy metabolism of Catalunya

*Authors: Di Felice L., Giampietro M., Renner A., Ripa M.*

### 4.1.2. Overview of case study

The case under study is the energy sector of the Autonomous Community of Catalonia, located on the north-eastern extremity of the Iberian Peninsula, for the year 2012. To describe Catalonia's energy sector across hierarchical levels, both top-down and bottom-up data are needed, as different data describe different levels. We refer to top-down data as data collected through statistical bodies, and to bottom-up data as data collected for instances of power plants, refineries and other structures, mostly through reports. Top-down energy statistics were collected from the Catalan Institute of Energy (ICAEN). Different sources of bottom-up data were used to characterize processors. When possible, data specific to individual power plants, and of the correct year (2012) were used. For the chosen case study, we do not consider every step of the energy system's sequential pathways, but focus on describing the steps that happen within the geographical boundaries of Catalonia, i.e. production of electricity, heat and fuels. To further simplify our example, we do not describe transport, transmission and distribution of energy carriers.

In order to give a general overview of Catalonia's energy system before describing it hierarchically through processors, Table 3 shows a summary of relevant top-down statistics characterizing Catalonia's energy sector in 2012. In the first part of the Table, extraction data of PES, as well as net imports, are provided. Following the MuSIASEM distinction between PES and EC, the second part shows refinery process outputs of fuels and heat products, and production of electricity, with their respective net imports. Catalonia produces most of its electricity, while importing almost the entirety of its crude oil and natural gas supply. For heating and transport fuels, there are differences among different elements, with a high production of gasolines and gas-oils and imports of naphtha, fuel-oils and biofuels. This characterization is similar to that of other EU countries which are poor in natural resources and have a large amount of power plants as well as complex refining capacity[1], therefore importing PES to produce EC.

*Table 3. Top-down characterisation of Catalonia's energy system. Source: ICAEN (2012). Focal level.*

| **Primary Energy Sources** | **Extraction (ktoe)** | **Imports-Exports (ktoe – tU for Uranium)** |
|---|---|---|
| Coal | 23 | 10 |
| Oil | 149 | 10113 |
| Natural Gas | 1 | 5961 |
| Non-renewable industrial waste | 112 | 0 |
| Uranium[a] | 0 | 63 |

**Energy Carriers**

| **Heat & Fuels** | **Refinery process output (ktoe)** | **Imports-Exports (ktoe)** |
|---|---|---|
| Refinery gases | 0 | 0 |
| GLP | 364 | 260 |
| Naphtha[b] | -27 | 2157 |
| Gasolines | 1362 | -495 |
| Kerosene | 871 | 244 |
| Gas-oil | 2991 | 840 |
| Fuel-oil | 1588 | -1193 |
| Biogas | 64 | 0 |
| Biofuels | 28 | 303 |

| **Electricity** | **Production (TWh)** | **Imports-Exports (TWh)** |
|---|---|---|
| | 45 | 4 |

a Imports of uranium are not provided in statistical tables and have been derived by assuming that 0.73 kg of Uranium are needed for each TJ produced in a nuclear pressurised water reactor (PWR) (Dones et al., 2007)

[b] Negative values in the refinery process output refer to fuels and heat products that are consumed in the intermediate refinery process, where the total consumption is higher than the refinery output (since only net outputs are available through ICAEN, similarly to how only net imports are available, leading to negative imports-exports balances)

To have on overview of the process of electricity production within the boundaries of Catalonia, Table 4 is introduced. Each type of power plant is associated with its installed capacity, gross electricity generation and capacity utilization factor (CUF)[2]. It can be seen that nuclear power produces over 50% of Catalonia's electricity, and CUFs of different types of power plants vary between 18% for hydropower and 19% for Solar PV (lowest) to 87% for nuclear and 92% for Pig Manure (highest). In the analysis presented hereon, only the power plants accounting for a minimum of 5% of the total installed capacity are considered. The CUFs are an important proxy to determine the function of different types of technologies: a low CUF, paired with a non-renewable resource, usually means that the plant has been used to cover peak demand (such as natural gas combined cycle plants, in this case). Similarly, high CUFs from non-renewable resources imply that the power plant is producing electricity used to cover baseload demand. For renewable resources, the CUF alone does not provide a satisfactory indicator of the role played by the electricity production system: the low CUF of solar panels, for example, does not mean they are used to cover peak demand, but is a reflection of the intermittency of the PES.

*Table 4. Characterisation of Catalonia's electricity sector. Source: ICAEN (2012). Level -1.*

| | **# of plants** | **Installed Capacity (MW)** | **Electricity (GWh)** | **CUF[a] (%)** |
|---|---|---|---|---|
| Natural gas combined cycle (CC) | 9 | 4112 | 8342 | 23 |
| Nuclear | 3 | 3147 | 23996 | 87 |
| Hydropower | 335 | 2361 | 3653 | 18 |
| Wind | 44 | 1258 | 2691 | 24 |
| Combined Heat & Power (CHP) | 135 | 1021 | 5896 | 66 |

| | | | | |
|---|---|---|---|---|
| Solar PV | N/A | 249 | 406 | 19 |
| Pig Manure | 6 | 92 | 738 | 92 |
| WWTR | 16 | 66 | 413 | 72 |
| Urban Solid Waste | 4 | 46 | 139 | 34 |
| Concentrated solar thermal | 1 | 24 | 0,6 | 0 |
| Landfill | 6 | 19 | 80 | 48 |
| Industrial Waste | 4 | 18 | N/A | N/A |
| Eco parks | 6 | 17 | 56 | 37 |
| Forest Biomass | 2 | 4 | 24 | 69 |
| Waste treatments on farms | 9 | 3 | 18 | 65 |
| Total | 580 | 12440 | 46456 | |

[a] CUF calculated as: (Electricity kWh/Installed Capacity kW) * (100/8760)

### 4.1.3. Production side: structural and functional processors

A hierarchical map of processors can be built both starting from top-down statistics and disaggregating them into their parts, or aggregating structural processors from bottom-up data. Here, the bottom-up approach is taken; therefore, the first step in the analysis is to build structural processors for different energy technologies fulfilling the role of electricity, fuel and heat generation, and then to move up the hierarchy by aggregating elements.

Structural processors can be defined either for specific instances of a technology, e.g. a specific oil extraction platform, or for a type, e.g. for off-shore oil extraction platforms in Europe. “Type pertains to an observation protocol that sets a class of entity that one might use as a search image, for instance the type of ecological thing that we agree to

call organism" (Zellmer et al., 2006, p. 176). The choice of the types to be included in the taxonomy depends on the purpose of the analysis. Since our purpose here is to give an overall description of the energy system, a generic structural description of the system is maintained, by representing the main typologies of power plants, i.e. those that account for at least 5% of the total installed capacity. These are: Combined Heat and Power (CHP) plants, Nuclear Pressurised Water Reactors (PWR), Natural Gas Combined Cycle (CC) plants, Small Hydropower Plants (< 1 MW), Regular Hydropower Plants (> 1 MW), Pumped Hydropower Storage (PHS), On-Shore Wind Turbines and Solar Photovoltaics (PV) for electricity production. For fuels, there is an overlap between the type and the instance, as there is only one refining complex in Catalonia, so there is no need to build a typology (data is collected directly for the specific instance).

In MuSIASEM, heat refers to either process heat or heating fuels. Examples of heating fuels include refinery gases and petroleum coke[3]. In Catalonia, there are no processes producing singularly either of these, therefore the functional element "heat generation", which can be further broken down into "process heat generation" and "heating fuels generation", is fulfilled by CHP plants and refineries. Data can be collected either for specific instances and then averaged out to form a type, or at the typology level. Here, a mix of both techniques is used depending on available data. Figure 3 shows a map of the relevant structural and functional elements considered in this case study, maintaining the hierarchical organization introduced in Figure 24, which in this simplified case does not include sequential pathways. Throughout the analytical steps of the case study, we will zoom into different sections of the Figure, always making the hierarchical level at which we are operating explicit.

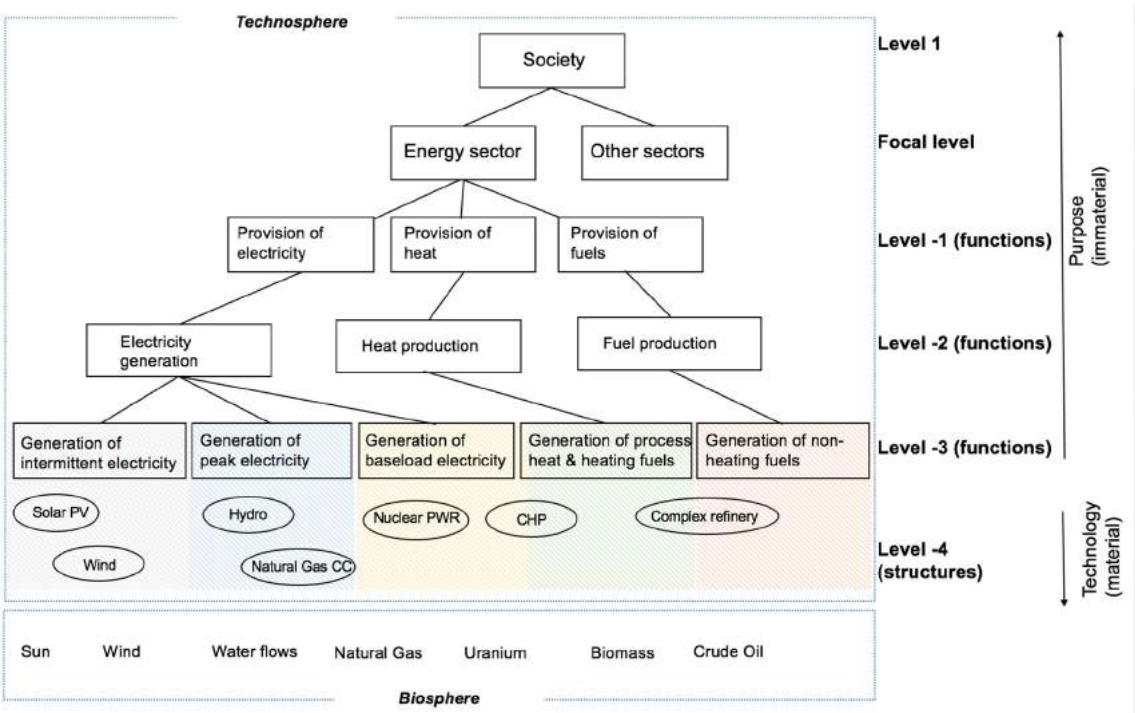


*Figure 24. Hierarchy of structures and functions for the case study of Catalonia*

Once the structural typologies are chosen, processors are built by defining a pattern of inputs and outputs associated with each technology. The following set of inputs and outputs is considered for each type:

1. Flows coming from the technosphere: electricity and fuels;

2. Flows coming from the biosphere: water;

3. Technosphere funds: land use, human activity (intended as labour) and power capacity;

4. Flows to the biosphere: GHG emissions.

Therefore, each processor represents a pattern of the water-energy-land-labour-climate Nexus. The water considered is that which is consumed during the process, therefore does not include water withdrawn and then released. This means, for example, that the water flow input for hydropower plants represents the water evaporated during the process, and not that which passes through the dam. Labour, labelled as Human Activity, includes the working hours spent to produce the output (thus plant manufacturing is not included) and does not include indirect jobs – therefore, it describes the labour of operation & maintenance (O&M), and management overhead, accounted for in hours (h). Climate is addressed by accounting for the GHG emissions which contribute to global warming according to the IPCC Fifth Assessment Report (AR5), and by converting them into $CO_2$ equivalent (by using the characterization factors provided by the report). Land Use is intended as the area of land occupied by the power plant or installation. For hydropower, this doesn't include the occupation of water bodies. Since land use is not discounted over the life of the processes, as the analysis has a yearly timescale, it is negligible for production of fuels and electricity (apart from renewables), as the majority of land used in the energy sector is during mining and extraction operations, and for the production of crops for biofuels. It should be noted again that the choice of what to include in the processor and how to define its inputs and outputs is not fixed and therefore can be contested. Moreover, definitions can be adjusted depending on the goal of the analysis and on who the information is being produced for (or with).

In order to be able to compare and aggregate processors, all inputs are intensive, scaled by the main output – in this case, GWh of electricity for power plants and TJ of fuels for refineries. In this way, each process is described in relative terms (unitary operations). This kind of abstraction is useful to be able to compare processes, for example to see which type of power plant consumes more water per GWh produced. However,

representations referring to unitary operations have to always be scaled in terms of absolute values, in order to contextualize their representations. This is where the functionality of different elements comes into play: a certain process may take up less land than others, but also produce a different type of energy carrier which is, in turn, used differently by a societal compartment to perform a specific task. This duality between the need for both intensive values referring to typologies and the need for extensive values contextualised to specific instances of energy systems is central to our approach. By considering simultaneously the two non-equivalent descriptions of the system, a better understanding of its behaviour can be reached.

The production of intensive descriptions of inputs and outputs becomes problematic for co-generation processes, where the same profile of inputs refer to a profile of outputs. In our case this occurs in CHP and refinement. To avoid allocation, a pattern of fixed output ratios is associated with the typology. There are limits to this kind of simplification, but by avoiding allocation methods, the inherent entanglement of patterns is explicitly addressed, therefore fitting within our approach from complexity and within the MuSIASEM rationale. Table 5 shows an example of intensive data for the processor “On shore wind power”, where only four inputs are relevant. Similar tables are collected for each structural processor and are included in the *Appendix*. Then, a functional grouping of structural processors is performed, aggregating them based on the functionality of their outputs, thus moving up the hierarchy (Figure 4). For electricity, three functions are identified: production of baseload electricity, production of peak electricity, and production of intermittent electricity. These three types of electricity generation are well-known in engineering, where they are often split into further sub-categories such as middle-load or load-following. However, in broader energy studies the distinction is rarely made – see, for example, some of the 100% renewable energy studies published over the past decade, where all electricity is referred to as being the same (Jacobson et al., 2015), (Williams and Meisen, 2011) (Mason et al., 2010)(Lund and Mathiesen, 2009). While physically (i.e. structurally) all electricity is indeed the same, being a flow of electric charge, it serves different functions depending on how, when and where it is generated and how, when and where it is used.

*Table 5. Structural processor (intensive) for "On shore wind power". Level -4*

| Type: On-shore wind power | | | | |
|---|---|---|---|---|
| **Details** | **Label** | | **Unit** | **Source** |
| Internal flow input | Electricity | 22 | MWh/GWh | ICAEN, (2012) |

| | | | | |
|---|---|---|---|---|
| Internal flow input | Fuels | 0 | GJ/GWh | -- |
| External flow input | Water | 0 | $m^3$/GWh | -- |
| Internal fund input | Human Activity | 120 | h/GWh | Budia et al., (2013) |
| Internal fund input | Power Capacity | 470 | kW/GWh | ICAEN, (2012) |
| External fund input | Land Use | 12 | ha/GWh | Budia et al., (2013) |
| External flow output | GHG emissions | 0 | t CO2 eq./GWh | -- |

The aggregation of structural elements of electricity generation into distinct functional roles can be used to highlight the importance of including functionality as an emergent property stemming from complexity. Part of the functionality of different types of electricity generation can be traced back directly to the structures themselves: nuclear power, for example, is an inflexible type of power plant which means that its electricity is always used to cover baseload demand. For other types of power plants, however, the functionality can be both context-dependent, and not traceable to structural qualities: hydropower, for example, can be used either to cover base or peak demand depending on the country, water availability and on the behaviour of the other elements of the energy system, as well as the technology itself. In the EU, for example, the CUF of hydropower can vary between 15% for Romania to over 50% for Sweden (Eurostat, 2012a) (Eurostat, 2012b).

Breaking down the electricity production curve into baseload and peak production also allows us to comment on the role of renewables: since the electricity generated from renewable sources is outside human control, it cannot be channelled into a desired function of baseload or peak production. This is why a third processor of “intermittent generation” is included in the analysis, since technologies relying on intermittent sources have different metabolic characteristics than others, as well as different functionalities. Intermittent generation can become functionally equivalent to either baseload or peak when paired with storage technologies or back-up infrastructure, or both (Steinke et al., 2013).

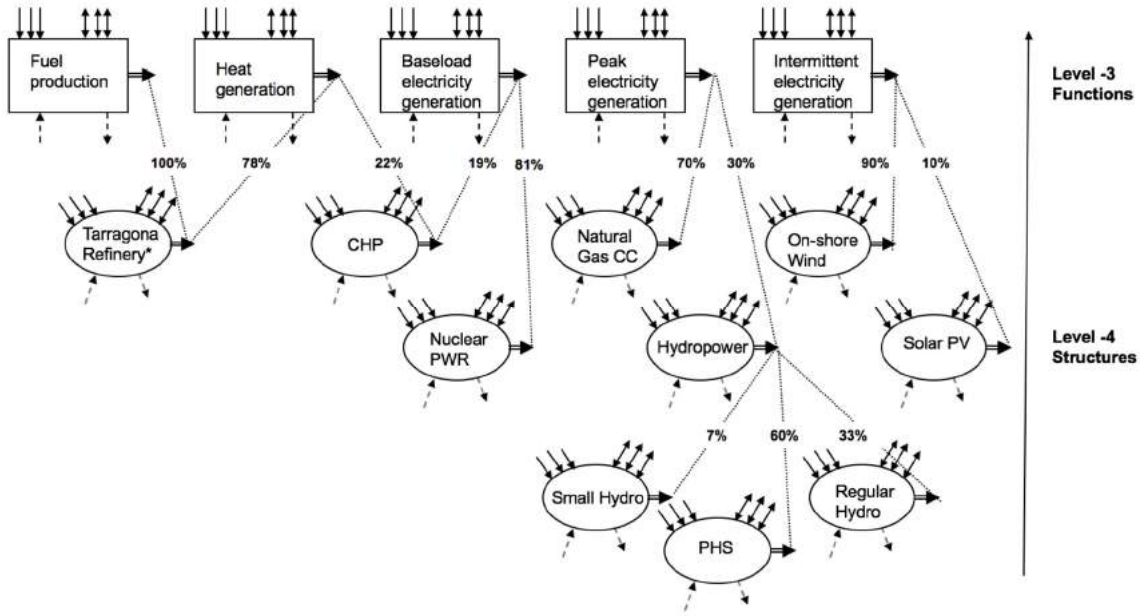



*Figure 25. Functional aggregation of structural processors*

Storage technologies and back up infrastructure are one way to deal with changes in the energy system, by fixing a required pattern of functions performed by society (demand side) and shifting from a mode of production (with non-intermittent sources) to another one (with intermittent sources). This can be done by adding auxiliary technologies to create a different structural group which can mimic the functionalities of the one it is replacing, albeit with different metabolic requirements. An alternative is demand side management, where the functions performed by society are changed in order to respond to a desired change in the structures, and therefore functional outputs, of electricity generation. Aggregating electricity generation into baseload, peak and intermittent, finally, allows comparing the differences in types of electricity generation, by generating intensive functional processor – a quantitative description of the functional group. Table 6 shows how, for the same GWh of baseload, peak and intermittent power produced in Catalonia, a different pattern of flows and funds are needed[4].

*Table 6. Comparison of intensive processors for baseload, peak and intermittent electricity. Level -3*

| Details | Label | Unit | Baseload | Peak | Intermittent |
|---|---|---|---|---|---|
| Internal flow input | Electricity | MWh/GWh | 42 | 23 | 20 |
| Internal flow input | Fuels[a] | GJ/GWh | 216 | 0 | 0 |
| External flow input | Water | $m^3$/GWh | 161 | 474 | 0 |
| Internal fund input | Human Activity (HA) | h/GWh | 111 | 57 | 151 |
| Internal fund input | Power Capacity (PC) | kW/GWh | 140 | 544 | 504 |
| External fund input | Land Use (LU) | ha/GWh | 0 | 0 | 11 |
| External flow output | GHG emissions | t $CO_2$ eq./GWh | 69 | 321 | 0 |

[a] Fuels do not include the primary energy source, e.g. Uranium for PWR or natural gas for CHP

Some descriptive comments can be made: the production of a GWh of baseload electricity in Catalonia requires double the amount of electricity than for peak and intermittent outputs; baseload electricity also requires a higher labour input than peak electricity, however not higher than intermittent at 151 hours per GWh produced. Water consumption is highest for peak electricity (more than double what is needed for baseload), as well as GHG emissions, while the only type of electricity generation with a substantial land use requirement is intermittent, at 11 hectares per GWh.

As mentioned previously, a combination of intensive (abstracted) and extensive (contextualised) representations of the entangled pattern of Nexus elements is useful to have a sound overview of the energy system. Therefore, Table 7 includes inputs and outputs for functional electricity generation groups, this time in an extensive format. This shows how, for example, intermittents consume more human activity per GWh produced than the other two types, but in extensive terms they are the sector which employs less human activity. The analysis for heat and fuels is simpler for this case study,

as the functional groups are not split into further sub-functions. Table 8 shows the set of inputs and outputs associated to the refinery process[5].

*Table 7. Comparison of extensive inputs and outputs for functional electricity generation groups, and their relative share of the total. Level -3*

| Label | Unit | Baseload (66%[a]) | % | Peak (27%[b]) | % | Intermittent (7%[c]) | % | Total |
|---|---|---|---|---|---|---|---|---|
| Electricity | GWh | 1.26E+03 | 79 | 2.71E+02 | 17 | 6.00E+01 | 4 | 1.59E+03 |
| Fuels | TJ | 6.41E+03 | 100 | 0.00E+00 | 0 | 0.00E+00 | 0 | 6.41E+03 |
| Water | $10^3m^3$ | 4.79E+03 | 46 | 5.69E+03 | 54 | 0.00E+00 | 0 | 1.05E+04 |
| Human Activity (HA) | $10^3h$ | 3.29E+03 | 74 | 6.86E+02 | 15 | 4.51E+02 | 10 | 4.43E+03 |
| Power Capacity (PC) | MW | 4.15E+03 | 34 | 6.53E+03 | 54 | 1.50E+03 | 12 | 1.22E+04 |
| Land Use (LU) | ha | 1.81E+02 | 1 | 2.37E+02 | 1 | 3.31E+04 | 99 | 3.35E+04 |
| GHG emissions | $tCO_2eq.$ | 2.06E+03 | 35 | 3.85E+03 | 65 | 0.00E+00 | 0 | 5.91E+03 |

[a,b,c] The percentage given in brackets is in relation to the contribution of each functional group to Catalonia's total electricity production

Table 8. Extensive and intensive inputs and outputs of the refinery process. Source: PRTR. Level -4

| Details | Label | Unit intensive | Value intensive | Unit extensive | Value extensive |
|---|---|---|---|---|---|
| Internal flow input | Electricity | GWh/TJ | 8.27E-01 | GWh | 4.36E+02 |
| Internal flow input | Fuels | GJ/TJ | 4.00E+00 | TJ | 1.86E+03 |

| | | | | | |
|---|---|---|---|---|---|
| External flow input | Water | m3/TJ | 1.40E+01 | m3 | 7.40E+06 |
| Internal fund input | Human Activity | h/TJ | 4.00E+00 | h | 1.95E+06 |
| External fund input | Land Use | ha/TJ | 8.00E-04 | ha | 4.43E+02 |
| External flow output | GHG emissions | t CO2 eq./TJ | 4.00E+00 | t CO2 eq. | 2.32E+06 |
| Internal flow output | Total refinery output | | | TJ | 5.27E+05 |

Having described the patterns of inputs and outputs required for the production of electricity, heat and fuels, these can be aggregated into a final pattern required for the whole energy sector, in what is represented as an *energy sector processor* (Figure 5 and Table 9). This processor reflects data which can be, in some cases, available top-down (although often not to this grain of detail), but obtaining the set of data from bottom-up aggregation is key in understanding the sets of different mechanisms and functionalities that generate the final pattern. A sound understanding of the underlying metabolism leading to the final behaviour of the energy sector is useful if one wants to modify such pattern, for example with the aim of reducing emissions or water use. Table 10 represents the various inputs and outputs of the energy sector. The data in this case is extensive rather than intensive, therefore is obtained by summing the extensive data of the three functional processors below it. The first column of the Table represents the labels shown in the energy sector processor of Figure 26.

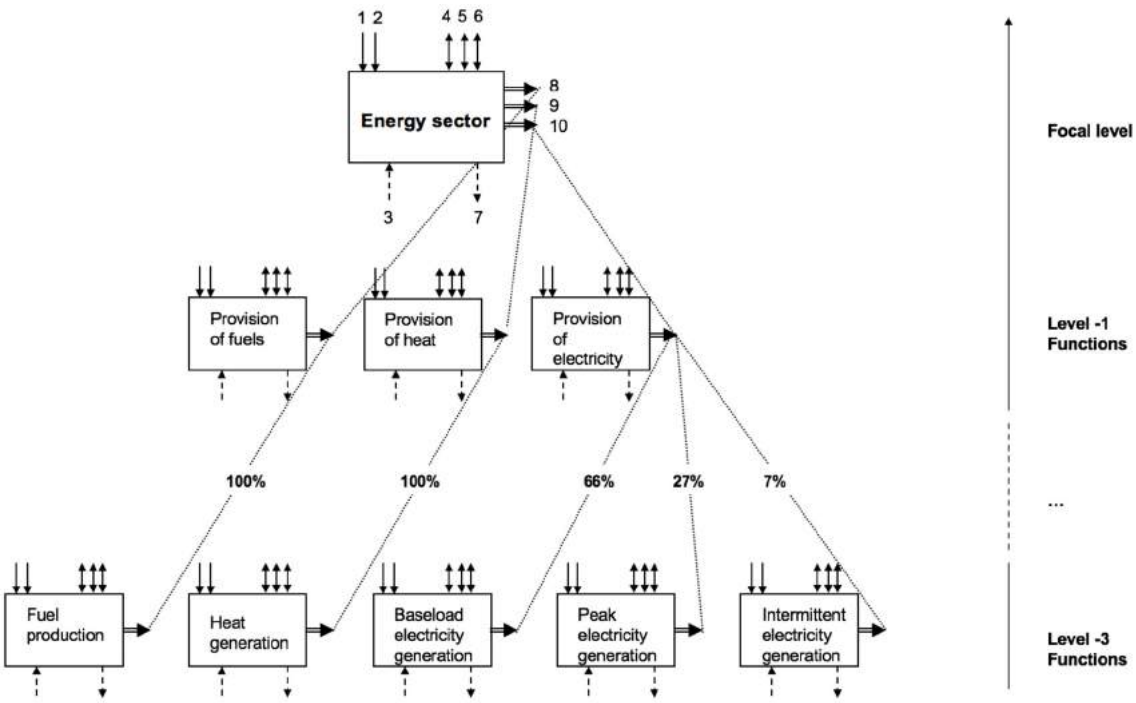



*Figure 26. Energy-Nexus map - Energy processor*

*Table 9. Data for energy sector processor (including only generation of heat, fuels and electricity) Focal level*

| # on Figure 5 | Details | Label | Unit | Value |
|---|---|---|---|---|
| 1 | Internal flow input | Electricity | GWh | 2.03E+03 |
| 2 | Internal flow input | Fuels | TJ | 8.27E+03 |
| 3 | External flow input | Water | $10^3$ $m^3$ | 1.79E+04 |
| 4 | Internal fund input | Human Activity (HA) | $10^3$ h | 6.38E+03 |
| 5 | Internal fund input | Power Capacity (PC) | MW | 1.22E+04 |
| 6 | External fund input | Land Use (LU) | ha | 3.39E+04 |
| 7 | External flow output | GHG emissions | t $CO_2$ eq. | 2.33E+06 |

| | | | | |
|---|---|---|---|---|
| 8 | Internal flow output | Electricity | GWh | 4.67E+04 |
| 9 | Internal flow output | Fuels | TJ | 3.06E+05 |
| 10 | Internal flow output | Heat | TJ | 1.37E+05 |

### 4.1.4. End Uses: linking production to consumption

The internal flow outputs, finally, can be allocated to different sectors of society. Since part of what the energy sector produces is also consumed within the sector itself, the representation linking the energy sector processor to End Uses (Figure 27) also shows this hyperclic loop.

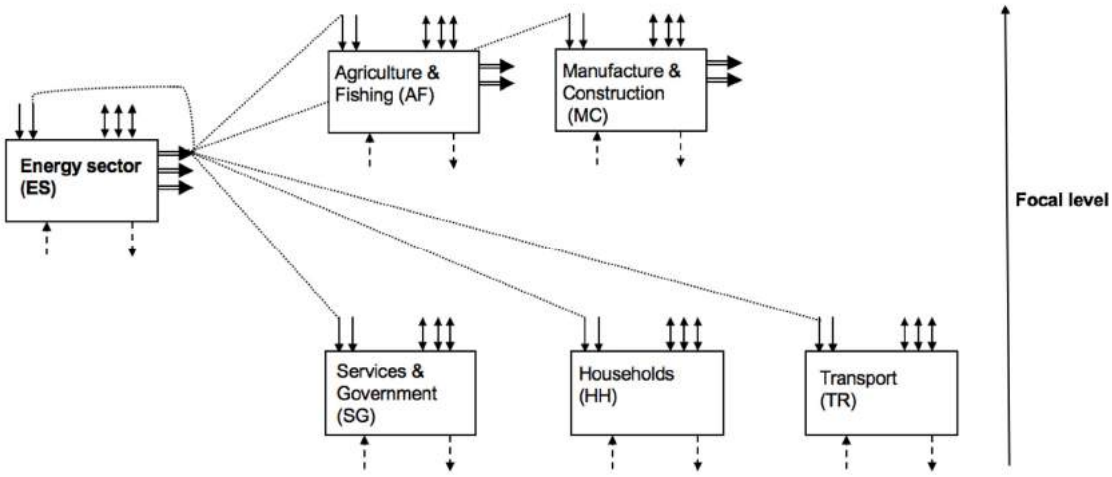



Figure 27. Energy-Nexus map (end uses)

*Table 10. End Uses (EUs). Level 1*

| | Baseload electricity (GWh) | Peak electricity (GWh) | Intermittent electricity (GWh) | Fuels (TJ) | Heat (TJ) |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Energy sector (ES) | 1760 | 100 | 100 | 8010[a] | 57800 |
| Agriculture & Fishing (AF) | 370 | 20 | 10 | 12390 | 5320 |
| Manufacture & Construction (MC) | 14880 | 1160 | 500 | 9640 | 85080 |
| Services & Government (SG) | 7360 | 5880 | 1470 | 9300 | 13940 |
| Households (HH) | 5330 | 4260 | 1070 | 10430 | 41620 |
| Transport (TR)[b] | 900 | 70 | 30 | 2277720 | 0 |

[a] data on fuel consumption of the energy sector does not include PES
[b] includes consumption of passenger vehicles

For representational simplicity, only one hypercyclic flow is represented in Figure 27, while Table 10 shows how each energy carrier flow is consumed by different parts of society, including the energy sector. Opening up consumption across sectors into the different types of energy carriers allows us to build a direct link from primary energy sources, to the technologies harnessing them, to their function in society. This link is essential to be able to have an informed debate about possible changes in the energy system. Table 10 shows, for example, how the Manufacture & Construction sector is the one consuming the highest amount of baseload electricity – this is because industries tend to operate 24 hours a day, 365 days a year. Over 80% of baseload electricity is produced by nuclear power (see Figure 26). Therefore, when discussing a shift from nuclear power to renewable energy in Catalonia, it is important to consider the role that electricity from nuclear power plays in the industrial sector, and whether intermittent sources can be used to cover the same function, and if so at which social, capital and biophysical cost. On the other hand, the household sector has a high consumption of peak electricity, since demand in households varies throughout the day. In this case, flexible forms of demand-side management, integrated with intermittent generation, could be more successful.

Moreover, Table 11 shows how electricity and thermal energy (heat and fuels) are consumed differently by society. Structural changes can partially be used to interchange the two, for example by using electric vehicles to reduce fuel consumption in the

transport sector. However, not all functions covered by thermal energy can be replaced by electricity – a further disaggregation of end uses into specific processes could show, for example, how many of the fuels consumed in the transport sector are for road vehicles and how many are for navigation and aviation, where electricity may not be a suitable substitute. In the Manufacturing & Construction sector, similarly, some processes such as smelting furnaces used to make iron require a thermal input which renewable sources struggle to provide. A further disaggregation of heat and fuels on the consumption side can provide stronger links with the production side, and is one of the areas which requires further development, especially for the discussion of transitions and transformations.

### 4.1.4. Highlighting the multi-scalar approach: link between the analysis of Catalonia and the analysis of Spain

The intensive benchmarks obtained to describe the metabolic pattern of Catalonia's energy sector can be compared with the same intensive variables obtained for the description of Spain - this allows checking homogeneities and differences across different scales of analysis. Table 12 shows a comparison of the different metabolic behaviour of Spain and of Catalonia, at the focal level (energy sector) and at the level -1 (functional compartments). From the Table, it can be seen that values fall within a similar order of magnitude. Catalonia's energy sector is characterised by the predominant role played by nuclear power, requiring very low inputs of human activity per electricity produced. This has implications mostly for GHG emissions, which are lower for Catalonia's energy sector, due to the lower amount of emissions for the production of baseload electricity. Compiling regional characterizations and then comparing them to the overall metabolic pattern of nations could also be used as a tool to check for inconsistencies between regional and national statistics.

*Table 11. Intensive characterization of Spain and Catalonia's energy sectors (Level 0)*

| | Spain | Catalonia |
|---|---|---|
| HA p.c. | 2 | 1.5 |
| EMR thermal (TJ/Mh) | 3163 | 1296 |
| EMR electricity (TJ/Mh) | 1668 | 1145 |

*Table 12. Intensive characterization of Spain and Catalonia's electricity production. Levels -1 and -2.* All values per capita.

| | | Production of electricity | Baseload | Peak | Intermittent |
|---|---|---|---|---|---|
| Spain | GHG emissions (kg CO2 eq.) | 2860 | 2411 | 449 | 0 |
| | HA (h) | 1.4 | 0.8 | 0.2 | 0.5 |
| | Electricity (MJ) | 2939 | 999 | 1675 | 265 |
| | Thermal energy (MJ) | 635 | 0 | 635 | 0 |
| Catalonia | GHG emissions (kg CO2 eq.) | 781 | 390 | 507 | 0 |
| | HA (h) | 0.8 | 0.6 | 0.1 | 0.1 |
| | Electricity (MJ) | 1512 | 1195 | 257 | 60 |
| | Thermal energy (MJ) | 847 | 847 | 0 | 0 |

## 4.2. The societal metabolism of livestock systems in Scotland

*Authors: K. Mattews (Hutton) , M. Giampietro (UAB) , J. Cadillo-Benalcazar (UAB) , D. Miller (Hutton) , D. Wardell-Johnson (Hutton)*

This chapter is different from the previous chapters presented in this deliverable. In fact, the document presented here is not focused on the illustration of technical aspects of quantitative analysis. Rather it is focused on how best to engage with stakeholders and communicate the ideas of the MAGIC tool-kit to policy makers. Therefore, this chapter is an example of an effort to generate synergies with ongoing activities of applied research and for this reason is a work in progress document. More specifically, The James Hutton Institute got funds from the Directorate of Environment and Forestry of the Scottish Government – Rural and Environmental Science and Analytical Division to develop analytical tools useful to study "the environmental sustainability and circularity of the rural economy". This topic was addressed in the pilot case study presented in Deliverable 4.1 – Case Study D. **Using MuSIASEM to check the level of openness of the animal production system of Scotland and to generate a decision support tool.** In that deliverable the MAGIC team developed an elaborated conceptualization of how to address this problem.

However, the document presented here does not use the approach developed in Deliverable 4.1. It refers to a different operationalization of the MuSIASEM approach made possible by the availability of a new dataset taken from UK Cattle Tracing Scheme run by the British Cattle Movement Service, a system tracking in space and time - one by one! – the cattle staying in (entering and leaving) Scotland (https://www.gov.uk/government/organisations/british-cattle-movement-service).
This provides a very detailed supply of top-down information (statistics) making it possible to use better the bottom-up information (based on the known physiological characteristics of the animals).

For this reason, we do not present the quantitative results of this study, because they are not in the public domain yet. What we present is the effort made by the team of MAGIC (a collaboration between the Hutton and UAB partners) to generate a text explaining the political relevance of the quantitative analysis produced using the method: how and why the quantitative analysis can be used to provide policy relevant input of information across different levels of analysis.

### 4.2.1. Introduction

**This document**

The intent of this document is to summarise the state of play of a research project that it is experimenting with applying to Scotland new sustainability assessment methods developed in EU Horizon 2020 research projects. The document is intended to serve as the basis for interactions with Scottish Government analysts and domain experts in other stakeholder organisations (e.g. Quality Meat Scotland). These interactions will make a judgement on whether the methods have potential value and specify meaningful applications to be developed in the Scottish Government's strategic research program. As such it is intended to be *a living document* – that it will be added to, modified and improved in the light of interactions. This approach to building science-policy and science-stakeholder interactions follows that used by the research team in previous SG and other EU projects.

This document is thus the first step in the translation of the research-based methods so that they can begin to inform policy or other decision-making processes.

**Project background**

The growing consumption of animal products in the diet of modern countries represents an important challenge for decision makers in relation to sustainability. Four aspects associated with sustainable development may be considered:

- *Feasibility,* to check the compatibility of the socio-economic system with the biosphere,
- *Viability*, to check how the demand and supply are balanced in the inside of the socio-economic system,
- *Desirability* to assess the acceptability across society of outcomes, an essential feature of any policy, and
- *The level of openness* of the system that makes it possible to alter the definition of feasibility, viability and desirability because of the *externalization* to other social-ecological systems of the requirements for production factors.

To obtain an integrated characterization of these aspects, new methodological tools and processes of analysis are needed that can coherently integrate information derived simultaneously from different perspectives and thereby obtain a holistic picture of the issue.

Scotland's livestock based agri-food system is a good case study for such analysis because: (i) in 2015 the livestock sector represented around 60% of the whole agricultural sector (Scottish Government, 2016a), (ii) the dependence of many

businesses on subsidies makes this sector sensitive to policy and institutional change; (iii) marginal profitability combines with biophysical constraints to limit the viable alternative land use options meaning it can be vulnerable to biophysical events (e.g. weather) and market fluctuations, and (iv) the new political situation determined by BREXIT may affect the level of trade (openness of material flows) between Scotland and the EU.

**Conceptual basis**

This project draws on a conceptual framework and tools for analysis being developed in the MAGIC Horizon 2020 EU funded project. The MAGIC project brings together, from multiple research centres across the EU, expertise in biophysical, computational, economic and social sciences underpinned by theories of transdisciplinary science-for-governance. The quantitative engine of MAGIC is MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) an innovative method of accounting having the goal of keeping coherence across scales and dimensions of quantitative assessments generated using different metrics. This has been applied in a variety of settings including Water, Energy, Food and Environment (WEFE) Nexus studies (see Giampietro et al. 2014). MuSIASEM analysis is framed using a societal metabolism metaphor. That is, it focuses on the funds used to create the flows of materials, energy and money that reproduce and maintain the identity of the system of interest (e.g. current patterns and trajectories of consumption). These funds are typically land area, human time and technology (expressed as power capacity), but for livestock systems the funds also include maintaining the breeding stock needed to generate offspring. The methods also consider the draw by human created systems (referred to here as the *technosphere*) on the natural capital within the bio/lithosphere where rates of usage may exceed rates of replacement. The MuSIASEM analysis is conducted simultaneously across scales (geographical or hierarchical/functional) to highlight contrasts and key externalisation effects and dependencies that may undermine long-term security. The Table below sets out in more detail some of the key MuSIASEM concepts.

| | |
|---|---|
| Feasibility | Assesses the compatibility of an aspect of the technosphere (e.g. a production system, sector or society) with the biosphere in which it is embedded. Compatibility is quantified relative to external limits. These limits can be either hard or soft (where limits can be exceeded but only temporarily or with negative consequences). The use of resources within the technosphere requires a supply capacity for *primary input flows.* The continuing availability of primary inputs flows depends on the availability of *biosphere funds* (natural capital) and *bio-geo-chemical processes* outside human control – e.g. rainfall as a provider of blue water. Technosphere systems can often also require a *sink capacity* for |

*wastes* or other losses (typically to air, water or soils). Exceeding the sink capacity can reduce the sink capacity, degrade its quality or reduce the availability of biosphere funds and compromise the bio-geo-chemical processes that underpin ecosystem functions and services.

Viability — Assesses the compatibility of one component of the technosphere with another (e.g. a production system with the demand from society or a regulatory regime). These are *internal limits* (within the technosphere) and are thus at least to a degree subject to decisions within and between governments and in wider society. Viability has several dimensions:

- *Technical* – assesses if it is feasible for the system concerned to deliver the desired outputs required using the quantities of inputs available to it. Typically, this is measured using *technical coefficients* (the ratios of inputs to outputs). The maximum value for such coefficients will depend on the nature of the system e.g. for transportation it will vary by mode (air, land or sea) and level of technology or capital investment assumed (horse and cart versus lorry). Increasing technical coefficient values can mean an increase in *efficiency* but can also lead to increased overall consumption if efficiency gains translate into reduced costs (the *rebound effect* or *Jevons paradox*). Needing to exceed maximum values means the available inputs and expected outputs are incompatible with the system as it is currently configured and there will need to be a change in either the supply of inputs, the demand for outputs, restructuring of the system or substituting with imports.
- *Economic* – assesses the capability of economic agents to add-value and to break-even in their economic activities. This is a conventional reading of the technosphere and is subject to all the caveats and definitional issues associated with such a representation of the system. For example, an economic viability reading needs to better account for the intergenerational equity issues of public and private sector debt and the apparent disconnect, since the late 1970's, between rising GDP and the standards of living experienced by the population. In the context of a MuSIASEM analysis these economic or financial analyses are contextualised by the other metrics. This can highlight where policies that only recognise economic drivers or are based on naively applied neoclassical economic theories may mean inappropriate policy decision are made.

- *Institutional* – assesses the implications for the system of interest of the governance arrangements at multiple scales (as such it is linked to the degree of exposure of a system in terms of its *Openness*). It is particularly concerned with identifying supra-national agreements that affect the flows of materials, foods and services (tariff and non-tariff barriers, standards and principles of policy making such as polluter pays). Dependencies here highlight security issues (food and energy most prominently) and the consequences of potential for disruption.

Desirability — Refers to the compatibility of the operation of the system of interest with the normative values, goals and expectations of the people living in a respective society. As such desirability can most readily be assessed in terms of existing (or changed) distributional outcomes (e.g. of disposable income, life expectancy, education or other quality of life measures). Desirability assessment requires the greatest degree of qualitative interpretation of MuSIASEM outputs and in policy terms this means the need for political processes of consultation and deliberation. The assessment of desirability across geographical scales or sectoral hierarchies does though highlight key dependencies relevant to policy making. Undesirable outcomes can be mitigated for an existing population by externalising activities (such as heavily polluting heavy industry) or relying on immigrants prepared to accept conditions otherwise unacceptable to enough of the indigenous population. Examples here would include the dependence of some parts of the agricultural, service and social care sectors on immigrant labour.

Openness — The degree of dependence of the system of interest on resources from beyond its borders.

**Objectives**

This pilot case study presents an application of MuSIASEM to the analysis of the production of food of animal origin in Scotland (in this report beef and milk but to also include lamb, pork chicken meat and eggs).

The main objective of this work is to demonstrate that the MuSIASEM approach can be used:

- to provide robust information about the level of openness (dependence on resources beyond Scotland's borders), and

- to generate an analytical framework with potential to be used for diagnostic analysis and simulations relevant to key policy questions.

### 4.2.2. Methods

#### Defining the scope of the analysis

In making an analysis of Scotland's livestock-based agri-food systems it is useful to distinguish five different (non-equivalent) perspectives that can be used together to define an analytical framework useful to considering policy questions. In doing so the shape of the analysis (what's included and excluded) is defined semantically. This is a key step as it has profound implications on which questions can be answered by the analysis and the nature of the answers that can be provided. In policy supporting analysis, this step can mean an analysis conforms to, reinforces or challenges existing narratives on a topic.

The perspectives used in the analysis of the Scottish livestock based agri-food system are illustrated in **Error! Reference source not found.**28 and explained below.

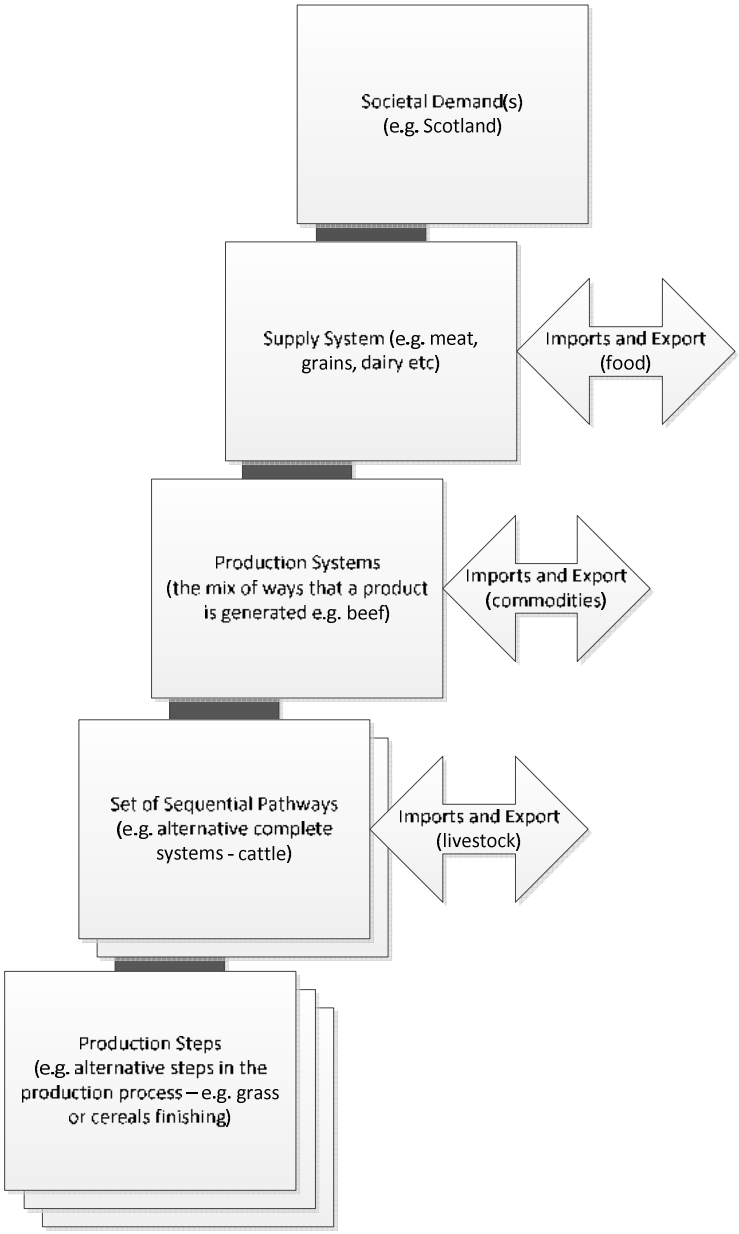



*Figure 28. The perspectives used in the analysis of the Scottish livestock based agri-food system.*

At the highest level is the view of the system as a desired mix of outcomes and outputs (**Societal Demand(s)** level). At this level policy decisions need to balance all aspects of societies interactions with the livestock systems. These are highly complex, and value laden decisions that balance issues such as food security, food prices, food quality, animal welfare, environmental impacts, local employment, and linkages with other agricultural or manufacturing sectors (e.g. whisky or tourism). In analytical terms the questions at this level are **contingent** – that is answers depend on the questions asked.

Below the Societal Demand(s) level, the next level at which crucial policy decisions are made is considering the livestock system as part of the **Supply System(s)** (in this case of food). It is at this level that in supplying the desired mix of outcomes and outputs the balance between local production the use of imports is made. Within the Supply System analysis, it is possible to identify the effects of governance arrangements for trade (tariff and non-tariff barriers), the relative balance of support and regulation for agriculture, manufacturing and services and the virtual (or embodied) resources on which food imports depend (land area, water, agrichemicals, labour etc). The latter highlights dependencies and potential security of supply issues but also where the overall efficiency of Scotland production systems is being enhanced or the environmental impact are being minimized using imports. These linkages can also highlight where Scotland's food supply systems may depend on the exploitation of low wages or poor animal welfare or environmental standards, particularly where there are linkages beyond the borders of the EU.

The next level considers **Production System(s)**. These provide the interface between the mainly commodities-based view of the Supply System and the specific agricultural management systems of production as defined by the Sequential Pathways (see below). It is thus the domain of within Scotland agri-food policies. A Production System in this context would contain all the ways in which a commodity is delivered to market (for example all the cattle systems that deliver beef). The number and specificity of Production Systems distinguished is a function of the policy questions being addressed but within it would fall decisions on the relative levels of support between commodity producing agricultural sectors and investment in the infrastructure of processing (and thus the value added captured within Scotland).

Instances of Production Systems are represented as a set **Sequential Pathways**, each of which defines a way of producing the livestock. For the beef Production System, a sequential pathway would for example be a spring, summer, autumn or continuous calving system. The Production System for Scotland then reflects the relative importance of each Sequential Pathway (e.g. spring calving accounts for the majority of all calves). These Sequential Pathways are still functional types since they are not fully parametrised with data for specific instances of production. It is, however, possible to discriminate between sequential pathways in terms of their individual characteristics e.g. their extents or intensities of resource use. It is also possible to contextualise Sequential Pathways in geographical space and therefore to link them with the regional impacts of policy or to be more specific about their environmental impacts (by linking environmental pressures generated by the SPs to the locales on which they occur).

The components of the Sequential Pathways are the **Production Steps**. These are building blocks of the analysis. This means the process being represented is not broken

down into further sequential pathways and there is also no differentiation in terms of the ways in which the process is being undertaken. The definition of Production Steps is again part of the process of semantically defining the analysis (though this may also be driven pragmatically by a lack of sufficiently specific data being available, either to define steps or know who carries them out in that way).

For policy level questions it is argued by the authors that Production Steps that distinguish between, Breeding, Rearing and Finishing are useful since these activities can be conducted by different businesses and/or regions and previous and current agricultural support payments have distinguished between these stages for some livestock types (particularly for beef cattle).

A livestock Sequential Pathway can also be linked to one or more Crops or Pasture Sequential Pathways for feed so that the interactions between livestock and feed systems within Scotland can be assessed. By so doing it is possible to look at how policy may influence potential for competition for resources between livestock and other agricultural, energy or manufacturing systems – e.g. the use of distillers' grains as a feed versus their use as an input to anaerobic digesters for energy production.

**Processors –formalising the semantic choices**

All the levels presented in the previous section are formalised in the analysis using Processors – this is a reusable way of organising data both conceptually and operationally (a formalism) to make sense of the system performance.

Conceptually the Processor is the expected (i.e. not just by chance) combination of inputs needed to get one or more outputs. It is thus like a Production Function in economics or the functioning of an Enzyme in bio-chemistry. It is represented in the computer systems (formalised) as a data array with profiles of inputs and outputs for both the Technosphere and the Biosphere. The Technosphere is that part of the system over which humans have influence. This contrasts with the Biosphere where (without disruptions) processes operate and materials are made exclusively by nature and usually on timescales incompatible with human systems (e.g. the creation and functioning of soils). In such cases these resources are effectively irreplaceable Stocks which when they are exhausted then require the substitution by other resources (potentially of lower quality). Analyses that neglect to include the biosphere can fail to recognise when the Technosphere parts are unsustainable in anything but the short term.

<u>Anatomy of the processor</u>

At its simplest the Processor shows how a variety of inputs are used to generate the required outputs (see Figure 2929 a Processor for a livestock Production Step). The rates of conversion from inputs to outputs are governed by Technical Coefficients (held in the

associated Dictionaries, see Section 0). When the data on the extents of inputs and outputs and the technical coefficients are added the analysis is now dealing with *structural types* (i.e. entities that exist in the real world) rather the *functional types* (i.e. the notional entities represented in the semantic analysis above). Analytically, the Processor integrates two fundamentally different analytical perspectives – that of the Technosphere (typically the domain of economics) and the Biosphere (the domain of natural sciences). This is the key contribution that MuSIASEM and the Processor formalism can make to policy-making for complex, coupled social-ecological systems. Providing a coherent framework in which a truly bio-economic analysis can be made, using empirical data rather than theories and not making assumptions on how a system operates now or how sustainable that it is in the longer term.

The Processor approach makes explicit four key elements of systems – Technosphere Input Flows, Technosphere Input Funds, Biosphere External Inputs and Biosphere External Outputs (or pressures) (see Figure 29).

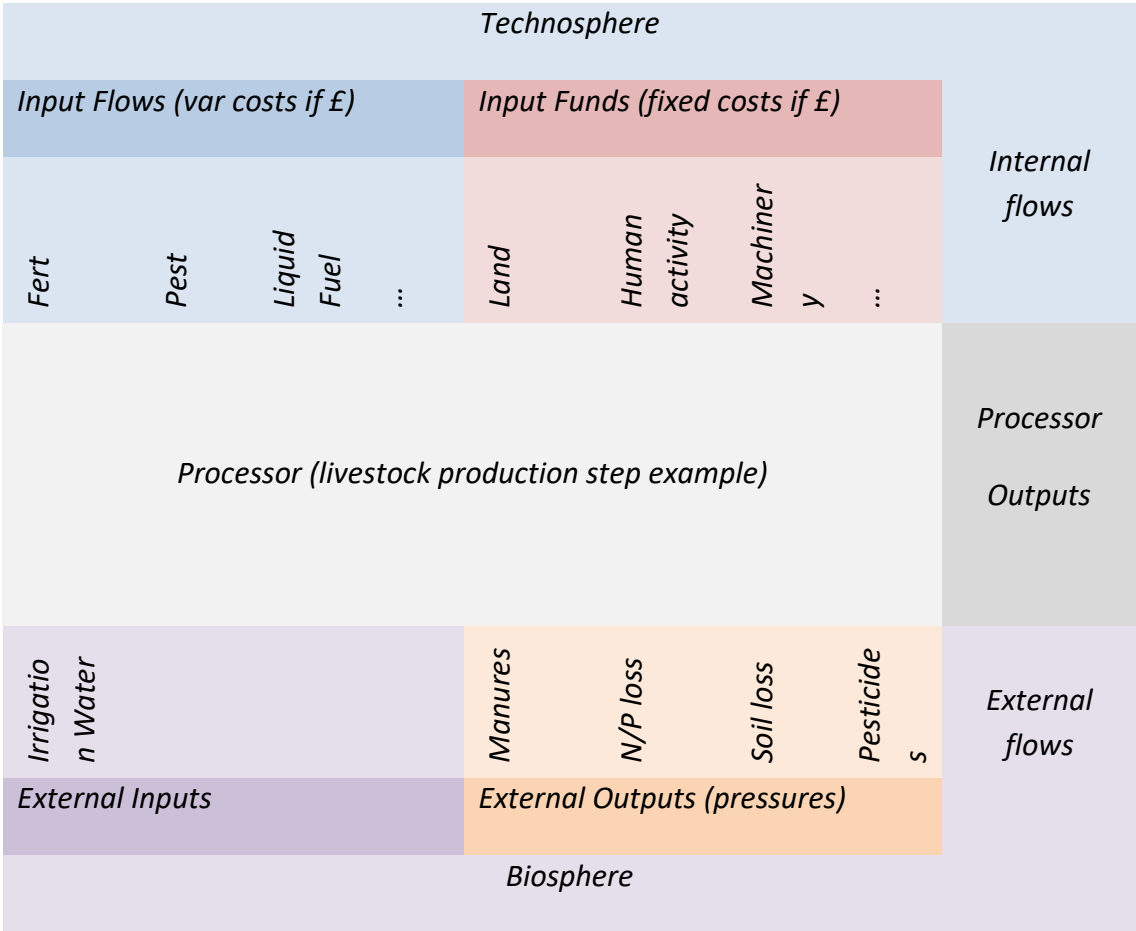


*Figure 29. The Processor approach and the four key elements of systems – Technosphere Input Flows, Technosphere Input Funds, Biosphere External Inputs and Biosphere External Outputs (or pressures).*

- **Technosphere input flows** – these are the materials, services, or money (for example agricultural support payments) delivered by systems under human control (primary industries; energy, mining and manufacturing and services and government). Example of technosphere inputs for an agricultural system, would include fertilisers, pesticides, fuel. These flows are best represented in physical terms if certainty on the nature of processes within the Processor is desired, but flows can also be represented in financial terms. Such a satellite accounting allows for the integration of public sector finances into the analysis where this can be a key aspect of policy making (for example agriculture).
- **Technosphere input funds** – these are the overhead of resources that need to be maintained to allow the conversion of input flows into the outputs from the processor. These include land (expressed as area to provide insights on spatial intensity), human activity (in time which provides insights on productivity but also on the work/non-work time for individuals and societies) and power capacity (a useful measure of the degree of mechanisation within a system which governs productivity but may also reveal inefficient use of resources when the use to non-use time is considered). While these have some similarities to land, labour and capital as in economics they differ by being represented in non-monetary terms as this provides a significantly more insightful perspective on the operation of systems, their vulnerabilities and nature of their wider outcomes for society beyond the financial/economic systems. Combined with the technosphere flow data they generate a series of flow/fund ratios that can articulate a comprehensive yet comprehensible understanding of the functioning of the system repented by the Processor. This is potentially a substantial improvement for supporting policy making by avoiding the hypocognition imposed using a single (financial) lens or indicator frameworks with their disparate bases and dependence in interpretation or decision making on weightings or orderings.
- **Biosphere – External Inputs** – these are the flows into a system from the natural world unmediated by human systems. The flows enter the Processor, but their sources are not conceptualised as being part of the Processor. Biosphere inputs would include green water (water in soil), abstracted water (e.g. from aquifers) which is then used inside the technosphere (e.g. for

irrigation or cleaning[5]) and plant nutrients generated by bio-geo-chemical processes. Depending on the timescales considered these inputs will be defined as somewhere on the spectrum from renewable or non-renewable. Flows that depend on non-renewable sources either locally or globally are in effect depleting a special instance of funds (that is ones that cannot be created by humans) – termed stocks. Once depleted such stocks would need to be substituted otherwise the system would have to be reorganised and/or would cease to exist in their present form. This raises policy questions of the intergenerational equity (especially now that the modernist assumptions of subsequent generations always having the wealth to solve any issues is being questioned). Even where this isn't an issue stock depletion may raise issues of security, efficiency or distributional fairness especially where market or governance failures means that exploitation of stocks with potential to continue to generate public good are instead drawn down by owners with requirements beyond the capacity of systems to replace.

- **Biosphere – External Outputs.** These are the material flows that leave the Processor and are returned to the biosphere – i.e. to the funds and stocks that make up the environment in which the Processor is situated (and for some Processors on which it depends heavily). In a conventional reading of the system these flows are often ignored as externalities (with costs assumed to be borne by the environment). In policy terms, the use of the Processor based analysis makes possible an improved quantification of the trade-off between socio-economic returns from a system and the damage to the environment in terms of point source or diffuse pollution, habitat loss, or loss of ecosystem functions or services (with tangible value within the Technosphere). Combining the Biosphere - External Outputs (flows) with the extents of the Technosphere – Inputs (funds), as flow/fund ratios, gives indications of the intensity of pressures per unit of area or per capita. Set instead against the extents of Outputs from the Processor it provides an assessment of the efficiency of production in terms of pressure on the biosphere per unit of output (or value added if the outputs are in financial terms). The Biosphere - External Output flows are not the impact, however, only the potential for impact. The severity of consequences will depend on the quality and quantity of the flows and the specific geographical and other contexts within which the External Outputs occur. The resilience of the biosphere in terms of its ability to cope with pressures and the size of the available sinks or dilution effects will vary widely. This means that a full interpretation of impact will in some cases need to link

[5] Water once within the technosphere is referred to as blue water and this then also embodies the overheads of energy and infrastruicture requred for its processing and distribution.

(for example within a GIS) the pressures to appropriate geographical entity: ecosystem, river basin, etc). In policy terms this means the need to have regulation and other policy and governance instruments vary in space (targeting) which involves the trade-offs between simplification and effectiveness or the potential to over prescribe limits in areas where the biosphere is more resilient. The multi-level nature of biosphere interactions can be a challenge for policy making with implications for governance responsibility, authority and resource allocations. It remains a domain where government may need to play an active part to guard against market failure and to ensure that policy principles such as the polluter pays are enforced, and free-riding is avoided.

Extensive and Unitary Processors

The processor outlined above is an Extensive Processor in that all the quantities within the Processor depend on the size of the system being represented by the Processor (i.e. a conventional beef finishing system using cereals which is practiced widely will have large flows, funds, outputs etc, whereas a more niche system such as organic beef finishing on grass will be associated with smaller flows).

For some analyses, however, it can be useful to generate a Unitary Processor that defines the resources needed to generate a unit of output for a defined geographical extent or sectoral hierarchical level[6]. This is particularly useful in assessing the potential savings in local resources (or conversely loss of local opportunities) within the Technosphere that result from the decisions to use imports (see Section 0 below).

Unitary processors can also be used to make some assessments of changes in Pressures and Impacts on the biosphere, but these are strongly context dependent (for example the loss of soil biodiversity occasioned by pesticide loads in the soils of some of the fields in a watershed)[7]. The quantification of Pressures or Impacts on the biosphere included in a Unitary Processor are valid only for:

- the specific mix of Technosphere funds and flows included in the Extensive Processor from which it is derived and

[6] The coefficients defined within unitary processors are dependent on the semantic definitions used in the analysis – particularly what is considered inside the system and what is considered the context within which it exists.

[7] This can of course be further complicated when considering the potential transport of pollutants, and the mixing and dillution effects occuring in water systems or can be simpler for example in consdiering GHG emissions as entering a single atmospheric sink.

- the specific geographical region and spatial patterns in which the Pressures are imposed.

If because of imports, a reduction in Pressure on the biosphere occurs other than in the region for which the Unitary Processor was derived then further analysis will be needed to derive appropriate reductions in pressures and impact relationships for the locale in which the reduction occurs.

A key distinction for the livestock systems processors

A key distinction in analysis is between livestock biomass that should be treated as a funds and as flows.

- **Fund Biomass (tonne days/year)** - this is the biomass reproduced and maintained within the livestock system (the breeding stock from which are derived new offspring or other products such as eggs or milk that enter the food or other supply chains) over a given time duration. These animals are not considered to be changed significantly within the time frame of the analysis.
- **Flow biomass (tonnes/year)** is biomass transformed into animal products within the time frame of the analysis. This amount corresponds to a supply of non-living biomass.

Utility of Processors

Using Processors, (albeit in a variety of ways), for all the individual levels represented within an analysis makes it possible to better maintain coherence while simultaneously taking very different perspectives on the functioning of a complex social-ecological system (e.g. as a supply system, production system or as a sequential pathway). It is also possible to integrate these individual perspectives on the system to see the ways in which each influences the other (cross scale analysis). To integrate between these perspectives the analysis takes the data from the processors and presents it as an End Use Matrix (see Section 0 below). By so doing it is possible to derive representative values that can be used in processors defined at successively higher levels of aggregation/simplification, but which can be explained and verified by reference to the scale of analysis from which they are derived.

Note that the interactions between analytical perspectives (e.g. between Supply and Production systems) tend to be non-deterministic in that each influences the other (e.g. choice of diet influences what is produced but the available foodstuffs also affect the diet choices that can be made). This means that the relationships are *impredicative* which in policy terms means that any scenario analysis should be conducted in both

directions (assessing both preferences and constraints) and resolved (or not) by taking account of what is learned from both analyses.

**End Use Matrix - formalising the outputs from the analysis**

The End-Use Matrix provides a way of summarising the performance of a system (taking a viewpoint that defines the whole system as an emergent property determined by the cooperation of different constituent components) and at the same time generating data that can be used in analyses being conducted at higher levels of aggregation.

Anatomy of an End Use Matrix (for a Sequential Pathway)

Following the same logic, the End Use Matrix (EUM) for a Sequential Pathway (SP) has a line for each of the defined Production Steps (PS). More colloquially each line in the EUM represents a way of doing part of a recognisable livestock management process taking stock from birth to death. Within this analysis the EUM of a SP of beef production thus has three lines – Breeding, Rearing, Finishing.

| |
|---|
| Breeding |
| Rearing |
| Finishing |

The numbers of animals and the time they spend in each category are defined using tonne days per annum. This is the Total Animal Activity (TotAA) for each Production Step (highlighted in orange in the Table below). The TotAA numbers per Production Step for Scotland are the net outcome of local production within Scotland, plus imports minus exports. Here imports and exports include both transfers to or from other parts of the UK and international transfers (highlighted in yellow). Tonne days per annum (td/yr) is used for TotAA since the analysis is interested in the funds of animals that must be maintained to generate the flows of materials though the Sequential Pathway and ultimately the outputs as required by society[8]. For a cattle Sequential Pathway, within this analysis, this is the output of meat (beef) but of course there are other cattle-based products that could also be analysed (highlighted in green). The sum of TAA for each of the Production Steps gives a total for the Sequential Pathway as a whole (highlighted in blue).

TotAA (td/yr)

[8] This "demand" is determined by interactions at both the Societal Demands (diet) level, the Supply Systems that balance local production versus imports of meat and the Production System that reflects the mix of Sequential Pathways used to deliver local production of cattle to enter the Production System (see earlier Figure **Error! Reference source not found.**).

| | | |
|---|---|---|
| Cattle (type) | X | Output Flow Beef (t/yr) |
| Breeding | $x_1$ | ↔IMP-EX calves (td/yr) |
| Rearing | $x_2$ | ↔IMP-EX stores (td/yr) |
| Finishing | $x_3$ | ↔IMP-EX finishers (td/yr) |

The next components of the End Use Matrix that needs to be considered are the Technical Coefficients. These permit the quantification of the resources needed to maintain the funds and flows of animals within the Sequential Pathway and to generate the required Outputs. In the example below two technical coefficients are used (highlighted in orange). These are both examples of Animal Metabolic Rates (AMR) defined in tonnes of feed consumed per tonne day of animals (t/td) in each Production Step. The AMR values each apply to a different feed type ($F_1$ and $F_2$). These technical coefficients are intensive variables for the Production Step and reflect the local conditions and management practices, the degree of investment in infrastructures and machinery. In this analysis these coefficients reflect expected practice and performance as defined by the SRUC farm management handbook. Clearly it would be possible to differentiate within the population of farmers by employing more than one Production Step and varying the technical coefficients. The challenge then is populating the end use matrices with reliable data on the distribution of technical coefficients and the associated numbers of practitioners. Presenting the technical coefficients in the EUM can support interpretations of existing levels of efficiency of local production and how far that could be changed. Both are topics with relevance to agricultural and related policy making. Note that at this stage there are no technical coefficients for the overall Sequential Pathway (highlighted in yellow) as these are derived from the mix of Production Steps in the later stages of the End Use Matrix construction.

| | TAA (td/yr) | $AMR_{F1}$ (t/td) | $AMR_{F2}$ (t/td) | |
|---|---|---|---|---|
| Cattle (type) | X | | | Output Flow Beef (t/yr) |
| Breeding | $x_1$ | $Y_{11}$ | $Y_{12}$ | ↔IMP-EX calves (td/yr) |
| Rearing | $x_2$ | $Y_{21}$ | $Y_{21}$ | ↔IMP-EX stores (td/yr) |
| Finishing | $x_3$ | $Y_{31}$ | $Y_{32}$ | ↔IMP-EX finishers (td/yr) |

Using the TAA and the AMR values it is then possible to quantify the funds and flows included within the processor defining each Production Step. In the example below the requirements are for two kinds of Feed (for example grass and concentrates) in tonnes per annum. This is an extensive variable defining the magnitude of the requirement. The overall requirement for the Sequential Pathway is the sum of requirements for each Production Step values, as extensive variables can be summed (highlighted in orange

and yellow). The other funds and flows from the processor for the Production Steps that are considered relevant to the policy or other question can be added as further columns of the End Use Matrix with the limitation that beyond a certain point the interpretation of such matrices becomes challenging. In this case there may be the need for core and satellite accounts to be presented as multiple end use matrices.

| | TAA (td/yr) | $AMR_{F1}$ (t/td) | $AMR_{F2}$ (t/td) | … | $Feed_1$ (t/yr) | $Feed_2$ (t/yr) | … | |
|---|---|---|---|---|---|---|---|---|
| Cattle (type) | X | $Y_{F1}$ | $Y_{F2}$ | … | $F_1$ | $F_2$ | … | Output Flow Beef (t/yr) |
| Breeding | $x_1$ | $y_{11}$ | $y_{12}$ | … | $f_{11}$ | $f_{12}$ | … | ↔IMP-EX calves (td/yr) |
| Rearing | $x_2$ | $y_{21}$ | $y_{21}$ | … | $f_{21}$ | $f_{22}$ | … | ↔IMP-EX stores (td/yr) |
| Finishing | $x_3$ | $y_{31}$ | $y_{32}$ | … | $f_{31}$ | $f_{32}$ | … | ↔IMP-EX finishers (td/yr) |

The technical coefficients for the Animal Metabolic Rates for the two feeds at the level of the Sequential Pathway (highlighted in green above) are derived by dividing the extents of the funds or flows ($Feed_1$ and $Feed_2$ in the example) by the value for Total Animal Activity. These are nominal intensive values, in that they are derived and which while potentially useful in other analyses at higher levels they cannot in themselves be linked back to specific instances of biophysical systems. If linked Sequential Pathways for fodder crops and grazing land are used, then it is also possible to link the livestock sequential pathway back to patterns of land use and assess the implications of the intensity of resource use and productivity.

**Interpreting the end use matrix - the role of imports and exports**

Imports and exports change the relative balance of livestock numbers within each of the Production Steps. The demands on feed and other resources in Scotland is reduced by imports at any stage but most significantly when this occurs later in the process. The balance of value added between the Production Steps and physical limitations on the operations that can be carried out will to a degree influence where in the Sequential Process imports or exports occur. Importing saves (within Scotland) the use of resources depending on the point with the Sequential Pathway that it occurs. Importing weaned calves saves the "overhead" of the breeding production step (both the creation of the mother and her maintenance during pregnancy and with calf at foot). Importing during either Raising or Finishing saves both the Breeding Step and the proportion of time in Raising or Finishing. Imports can be seen just before the last three months of life – the minimum period required for the cattle to count as Scottish. In interpreting the magnitude of the effects of imports it is possible to use the unitary processors for the

relevant Scottish sequential pathway (see Section 0 above) to quantify the resources that would have been required within Scotland if the production had been local (an Internal Reading). Alternatively, if the source of imports is known and benchmarks are available then an estimate of the actual resources embodied in the imported livestock can be made (an External Reading). The balance of imports, exports and local production defines the degree of openness of the system and the extent to which policy within Scotland has influence over the Sequential Pathway, Production or Supply System.

**Making sense of the analysis – feasibility, viability and desirability**

Making sense of the data that can be generated by MuSIASEM has some similarities to the challenges of dealing with and multi-metric analysis at some point the information has to be brought together into a format that can be used for decision making. This inevitably means a degree of simplification since decision makers will rarely have time or domain expertise to engage with the detail of analysis. The developers of the MuSIASEM approach acknowledge this need and provide a way of structuring the outputs in a way to make it decision focused (while being fully aware that research derived knowledge will be only one of several influences on any decision maker).

Figure 30, below, identifies three summary characteristics of the system being analysed – desirability, viability and feasibility. Each of these characteristics and its relationship with the MuSIASEM analysis process is set out below. The key point of using the all three characteristics is that they bring together perspectives from across the scales of analysis so that decisions are made that do not exclude relevant factors (however inconvenient these may be).

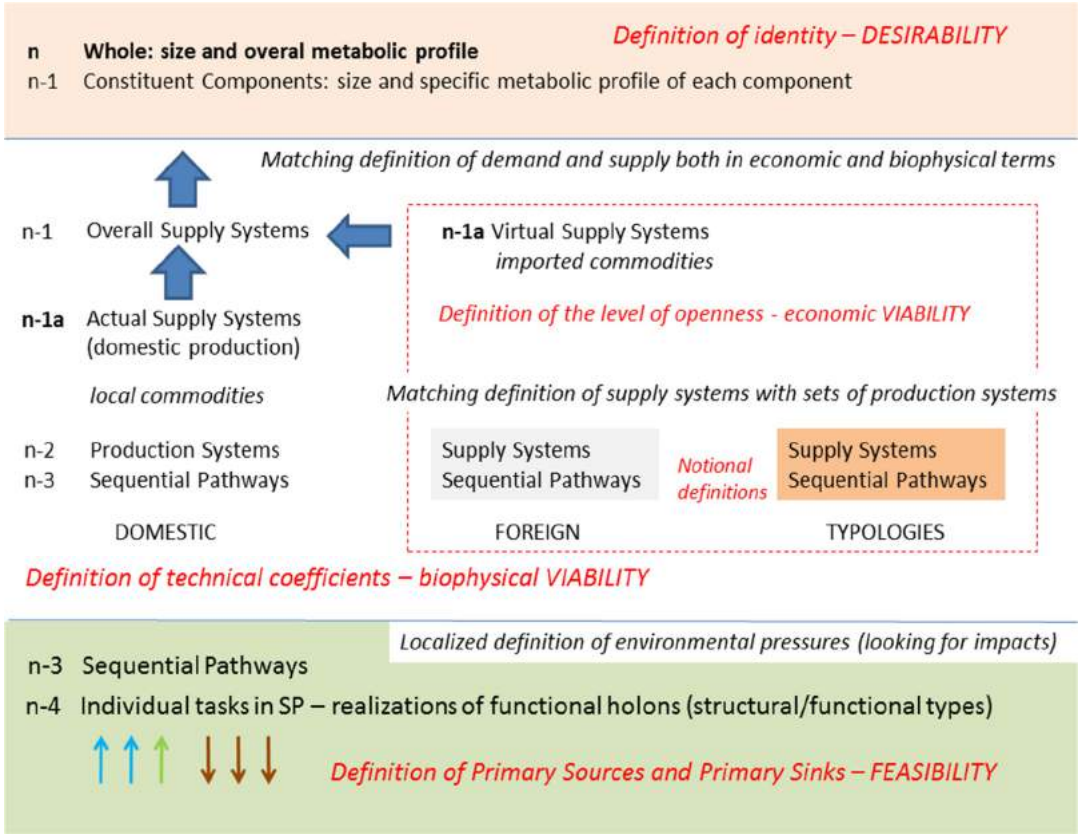



*Figure 30. Characteristics of the system being analysed – desirability, viability and feasibility.*

- **Desirability** in this example is about the balancing of demands from citizens with the local supply (inexpensive food balanced against the desirability of maintaining the country's ability to feed itself). In the analysis presented here this is the highest-level analysis and brings together all the lower levels aspects. Yet it is not a passive outcome since policy decisions made at this level (and the limitations on them) shape the space in which all the other aspects are played out. This is the most strongly normative characterisation and one that requires political judgements as it deals with the balance of distributional outcomes, equity within and between generations, citizens health and wellbeing and the rights of human and other entities. It is particularly politically sensitive since food is fundamental to citizens lives and there are many strong and conflicting narratives backed by substantial interest. It requires the interpretation of rights and responsivities and is guided by principles of policy making such as polluter pays or precaution.
- **Viability** deals with two key aspects – the economic viability of the Supply System and the biophysical viability determined by the technical coefficients of Production Systems and specific Sequential Pathways.

  - **Economic viability -** is characterised by the level of openness of the Supply System – that is the ability to obtain those imports desired and to have markets for exports. Viability for imports in this case is the availability of food at prices that consumers can pay. Changes in demand in the developing world and competition for these resources by states with stringer economies may mean that ease of availability and low prices may no longer be certain. Key aspects of food security policies play out in this domain.
  - **Biophysical viability** - is the limit on domestic production consistent with the patterns of land use and the intensity of land management (accounting for any land sparing). Increases in efficiency of production are still possible but either require ever increasing investments of capital, infrastructure and energy or the substitution of less productive parts of the Sequential Pathway with imports (changing the mix of production to achieve an apparent increasing efficiency). For modern production systems there are diminishing returns (in production terms if not in the environmental protection offered). Systems of production that depend on significant labour inputs also face scarcity of supply given the low wages that can be sustained.
- **Feasibility** – deals with for how long the natural environment can support the patterns of production. The interactions between specific sequential pathways of production and their interactions with their environments are the concern here. The analysis identifies where are there are issues of the pressure being exerted by production systems exceeding the capacity of the natural environment to absorb them or at least dissipate their effects. Environment policy as it relates to natural capital is a key aspect in assessing feasibility.

**Processes of using this analysis**

What can be seen hopefully clearly from the above exposition is that the MuSIASEM analytical approach is one that provides a coherent and integrated approach and one with the potential to be informative for a variety of policy questions. It cannot, however, be interpreted as simple. Indeed, the developers of MuSIASEM have deliberately included those aspects of systems (the biophysical) that are often ignored by approaches with narrower and more theoretically limited perspectives. The reason for this is to avoid hypocognition (finding only those answers predefined by the theories and aspects of the problem included within the analysis). The complexity should not be seen as overwhelming however, as the approach deliberately allows for building analyses from a combination of top-down and bottom-up to provide useful insights over the course of an analytical process. The expectation is that any analysis will be undertaken as a partnership between policy makers/advisers, exploring the sematic

choices and formalising these into a series of interlinked analyses. The detail of the analysis is progressively brought in to sharp focus by identifying the key aspects that really affect the outcomes of any decision. An example of such a process is the Quantitative Story Telling (QST) being conducted with the institutions of the EU in the MAGIC H2020 project where more detail of QST can be found[9].

### 4.2.3. Data used in the analysis

**Livestock Production – the Sequential Pathways**

The livestock systems being considered are those based on cattle (beef and dairy), sheep, pigs and chickens. The report presents examples only for cattle systems but the systems for pigs and chickens are relatively simple given the greater uniformity of their production methods. Sheep systems have some unique features that are being resolved (and will this be included in subsequent updates to this document.

<u>An animal-based perspective in using the Sequential Pathways</u>

In this analysis the Sequential Pathways for beef production are structured using the lifecycle of the animals. That is each pathway follows livestock through all three Production Steps from the Breeding into Raising and finally to Finishing or Production (for milk).

The Productions Steps included in this analysis are

| Breeding | Rearing | Finishing |
|---|---|---|
| Beef Service Bulls | | |
| Beef Suckler Cows | | |
| | Spring Born | |
| | Summer Born | |
| | Autumn Born | |
| | Winter Born | |
| | | Cereal Finished |
| | | Grass Finished |
| Dairy Service Bulls | | |
| Dairy Cows | | |
| | Dairy Beef | |

<u>A farm business perspective in using Sequential Pathways</u>

[9] http://www.magic-Nexus.eu/content/what-quantitative-story-telling

Policies that target subsector(s), business sizes or geographical areas (such as those with physical disadvantages) need to be able to diagnose the health of such systems and see how policies would play out against a sub-population of businesses as well as for the production system as a whole (for example the materials available to the processing sector). This means being able to take a farm business perspective.

From a farm business perspective, it can seem like there is a near infinite variety of constantly changing "systems" of production. The reason for this apparent complexity is that individual businesses may be specialising in one Production Step (e.g. calf raising) or Finishing using cereals. Businesses may also undertake a mix of activities such as Raising store cattle and Finishing cattle for slaughter, with the mix of activities changing dependent on environmental (weather) or market conditions. The systems of production are also complicated by the interactions of farm businesses with non-farm actors in the network of transactions such as livestock traders.

Yet if it is possible to classify individual animals into an animal-based Sequential Pathway, it is then possible to allocate their lifespan to Production Steps and disaggregate the time across all the farm businesses that take part in each Production Step. Typically, the number of businesses that take part in the later stages can be much larger than those in the earlier ones. The complexity in the patterns of farm business systems is actually an outcome of variations is the mix of animal focused Sequential Pathways peer business and their interactions with each other in the beef Production System as whole.

The classification of animals into compete Sequential Pathways is accomplished for cattle using an animal movements database and in UK this can be linked to data on agricultural holdings or other premises.

**Dictionaries – the processor content**

The dictionaries are the definitions associated with each processor holding the extents of flows and funds and the technical coefficients that convert inputs funds and flows into Processor outputs. An example of the flows and funds included for beef and dairy production (for all the alternative Sequential Pathways) is reproduced below.

*Table 13. Flows and funds included for beef production*

| | Flow/Fund | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Fund | Fund | Fund |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Type** | N | $P_2O_5$ | $K_2O$ | Seed | Diesel | Elec | Gas | Pest | Conc | Straw | Forage | Green water | Blue water | Dead biomass | Living biomass | Labour | Land |
| | **Units** | | | | | | | | | | | | | | | | | |
| **Production Step** | **Crop - Local production** | ■ | ■ | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | | | ■ | ■ |
| | **Crop-Processing** | | | | | ■ | ■ | ■ | | | | | | ■ | | | | |
| | **Crop - Import Production** | ■ | ■ | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | | | ■ | ■ |
| | **Import – Processing** | | | | | ■ | ■ | ■ | | | | | | ■ | | | | |
| | **Grazing** | ■ | ■ | ■ | | ■ | | | | | | | ■ | ■ | | | ■ | ■ |
| | **Silage** | ■ | ■ | ■ | | ■ | | | | | | | ■ | ■ | | | ■ | ■ |
| | **Breeding** | | | | | ■ | ■ | | | ■ | ■ | ■ | | ■ | | ■ | ■ | ■ |
| | **Raising** | | | | | ■ | ■ | | | ■ | ■ | ■ | | ■ | | ■ | ■ | ■ |
| | **Finishing** | | | | | ■ | ■ | | | ■ | ■ | ■ | | ■ | | ■ | ■ | ■ |
| | **Processing - Meat** | | | | | | ■ | | | | | | | ■ | ■ | | ■ | |

*Table 14. Flows and funds included for dairy production*

| | Elements | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Flow | Fund | Fund | Fund |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Type** | N | $P_2O_5$ | $K_2O$ | Seed | Diesel | Elec | Gas | Pest | Conc | Straw | Forage | Green water | Blue water | Dead biomass | Living biomass | Labour | Land |
| | **Units** | | | | | | | | | | | | | | | | | |
| **Production Step** | Crop-Local production | ■ | ■ | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | | | ■ | ■ |
| | Crop-Processing | | | | | ■ | ■ | ■ | | | | | | ■ | | | | |
| | Crop - Import production | ■ | ■ | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | | | ■ | ■ |
| | Import - Processing | | | | | ■ | ■ | ■ | | | | | | ■ | | | | |
| | Grazing | ■ | ■ | ■ | | ■ | | | | | | | ■ | ■ | | | ■ | ■ |
| | Silage | ■ | ■ | ■ | | ■ | | | | | | | ■ | ■ | | | ■ | ■ |
| | Breeding | | | | | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | | ■ | ■ | ■ |
| | Milk Production | | | | | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ |
| | Milk Processing | | | | | | ■ | ■ | | | | | | ■ | ■ | | | |

**Data Sources**

The data sources that underpin the analysis are set out in the sections below.

Livestock numbers

The period used to develop and test the methods was 2012. Data on beef and dairy cattle were obtained from the UK Cattle Tracing Scheme run by the British Cattle Movement Service[10] which record the movements between locations of individual animals. This data set is held by the Animal and Plant Health Agency and made available for research purposes through the Scottish Governments Centre of Expertise on Animal Disease Outbreaks[11]. This dataset provides detail of breed, gender, birth and death dates, spatial location (e.g. upland or lowland), dates of import or export (both between Scotland and the rest of the UK or internationally) and the nature of the premises on which the animal is residing. The dataset also records parent-child relationships which can be used to differentiate between livestock being used for breeding purposes. These data were used to assign each animal that was alive in Scotland in 2012 to one of the Sequential Pathways (from birth to death) and for 2012 the time in each Production Step was derived. The time in each production step was also disaggregated across the premises on which the animal was resident during the Production Step making the link to farm businesses. Making this last linkage allows for the integration of the animal focused analysis with information held by the research teams on agricultural support payments and other aspects of the farming system such as crops or other enterprises.

Beef production

Data for the modelling of production systems, such as the period, duration, entrance weight, exit weight, mortality, fertility, cow ratio, slaughter live weight, percentage of carcass obtained per animal, land use required for grazing and silage, human activity were obtained from (SAC Consulting, 2016), energy consumption of (Williams et al., 2006), water consumption for service was obtained from (Mekonnen & Hoekstra, 2010a) and drinking water of (SEPA, 2013). For meat processing, energy was obtained from (AHDB, 2011a), human activity from (Jacques & Blaxter, 1978) and water consumption from (AHDB, 2011b).

Milk production

Data for the modelling of production systems, such as average annual milk yield, lactation days, average cow weight, herd lifespan, amount of feed required for both the

[10] https://www.gov.uk/government/organisations/british-cattle-movement-service
[11] http://www.epicscotland.org/

animal in production (cow) and for their replacement (heifer) were obtained from (SAC Consulting, 2016). The energy consumption was obtained from (Williams et al., 2006), water consumption for service was obtained from (Mekonnen & Hoekstra, 2010a)and drinking water of (Thompson, King, Smith, & Tiffin, 2007). For milk processing, energy and water consumption were estimated from (Sheane et al., 2011).

**Other systems have also been parameterised but are not included in this version of the report.**

Animal Feed Production

The ingredients of animal feed are very varied between species and within the same species. In addition, producers are not always transparent about their formulation. In this study we adopted the formulation proposed by (Wilkinson, 2011), illustrated in Fig. 4. The agricultural crops selected for the analysis were winter wheat, winter barley, spring barley, spring field beans, soya beans, maize grain and winter rapeseed. In the case by-products were considered soya-bean meal, rapeseed meal, wheat-feed. However, we do not consider other by-products in the analysis due to lack of information to define their primary agricultural products. Similarly, minerals and vitamins were not considered. The treatment for the analysis of by-products is to transform them into their primary products, using the conversion factors estimated from (Bell, Morgan, Dick, & Reid, 2012).

Inputs used in the crop production, such as fertilizers (N, $P_2O_5$, $K_2O$), seeds, labour (human activity), yield (both main product and straw) were obtained from (SAC Consulting, 2016). Energy consumption was estimated from (Williams, Audsley, & Sandars, 2006), the water required for the crops was obtained from (Chatterton, Hess, & Williams, 2010, Mekonnen & Hoekstra, 2010b).

Inputs used in the processing of by products, such as water for the soya-bean meal and the rapeseed meal were obtained from (Schneider & Finkbeiner, 2013), in the case of by products from cereals no information was found. In addition, a water consumption corresponding to feed preparation was added, this data was obtained from (Chatterton et al., 2010). Energy required for by-products from cereals were estimated from (Bell, Morgan, Dick, & Reid, 2012), while for soyabean meal and rapeseed meal was obtained from (Schneider & Finkbeiner, 2013).

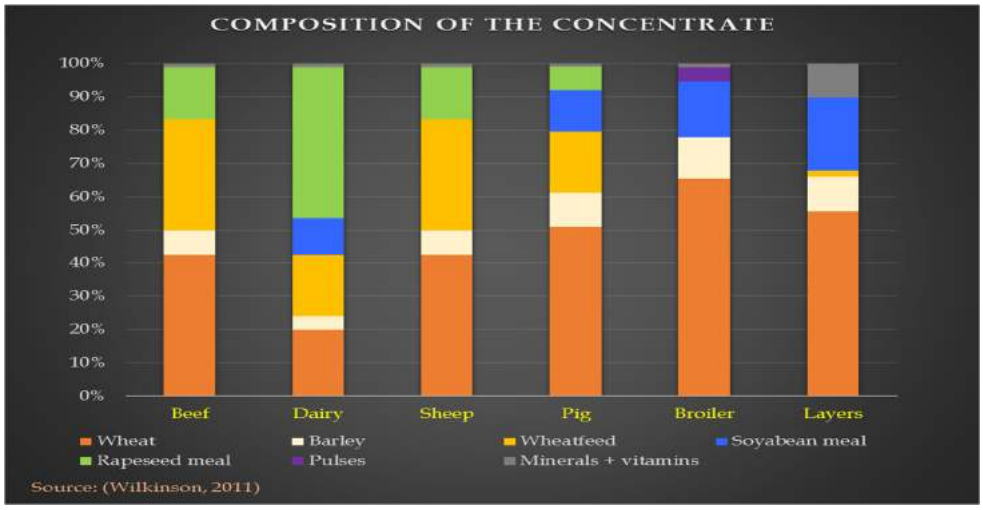



*Figure 31. Composition of the concentrate.*

Grass and silage production

Data on the planting period, fertilizers, labour (human activity), fuel and yield were obtained from (SAC Consulting, 2016), While, the water consumption was obtained from (Chatterton et al., 2010) and the energy required of (Williams et al., 2006)

Food Supply System (specifying demand)

In the absence of a Food Balance Sheet for Scotland is difficult to determine trade (import, export, stock variation). For this reason, we assumed that any surplus between production and local supply is destined for export. In contrast, any deficit between production and local supply comes from imports.

The amount of beef, pork, mutton/lamb and chicken meat corresponding to the local supply was estimated from the annual per capita consumption obtained (QMS, 2015) multiplied by the number of people estimated in Scotland for 2014 obtained from (National Records of Scotland, 2015). The amount of meat eaten (intake) corresponds to the quantity supplied minus the amount of food lost or wasted. The coefficients for losses and wastes in the household were obtained from (Quested & Murphy, 2014). The coefficients for losses and wastes in the animal production and meat processing were obtained from (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011). The nutritional composition of meat was obtained from (Finglas, Roe, Pinchen, & et. al., 2015).

Regarding milk consumption: the consumption per capita of dairy products semi-skimmed milk, skimmed milk, yogurt, cream, butter and cheese (obtained from [AHDB, 2015]), were converted to their primary product (raw milk). In the case of semi-skimmed

milk and skimmed milk a percentage of 85% was used, while for yogurt a percentage of 80% was used. For all the rest, we used the conversion factors for the United Kingdom obtained from (FAO, 2002). The sum of all these conversions gives a total of 215 kg of raw milk/person/year, although, this value is less than 232 kg of raw milk/person/year (not including butter) estimated for 2013 (FAO, 2017). Probably, this difference is due to the fact that FAO estimate corresponds to the consumption in UK. The consumption of Scotland is smaller than the one of the UK.

# 5. Novelty of relational analysis and its relevance for policymaking

This chapter highlights the methodological breakthrough provided by relational analysis and its relevance for policy making with regard to the water-energy-food-environment Nexus. Relational analysis is a powerful tool in that it allows the *simultaneous* use of different metrics in a multi-scale quantitative representation of the metabolic pattern of social-ecological systems.

## 5.1 Using relational analysis to generate an impredicative (contingent) quantitative representation of the metabolic pattern across different levels and scales of analysis

### 5.1.1 The distinction between Predicative Scientific Quantification and Impredicative Scientific Quantification

A predictive scientific representation is based on the assumption that it is possible to generate **uncontested/defensible quantitative results** determined by a combination of chosen pre-analytical insights/perceptions and chosen representations. Unfortunately, when dealing with the quantitative analysis of complex systems operating simultaneously across different levels of organization – requiring different descriptive domains for their representation – these choices cannot be assumed as uncontested. Let alone if we want to anticipate future states. When dealing with complex metabolic systems we must learn how to use non-equivalent and non-reducible representations of the same event that can be observed from different levels of observation and using different lenses (selection of different relevant attributes). In fact, after having defined the set of relevant insights that should be considered in the analysis of the sustainability of a complex system, we are forced to conclude that they can only be observed by adopting different descriptive domains referring to various scales and the dimensions. Moreover, because nobody can predict with certainty the future, it is important to deploy a method of quantitative analysis based on the “what if” hypothesis (contingent representations) keeping open the information space in order to be able to explore a set of possible futures.

This standard epistemological predicament implies that we have to learn how to generate a type of quantitative analysis that is **impredicative**. This analysis must be capable of generating **contingent results** that can be integrated across different scales and dimensions of analysis depending on the assumptions and definitions taken in the pre-analytical phase. The concept of contingent or impredicative can be explained using

an example taken from natural languages. In natural languages there are words called "deictic" whose meaning depends on the context in which there are used. The sentence "you have to come here, now" has a meaning only if we can contextualize who is speaking, when and where. The same applies to statement of the type "it is on your right" or "it is above you". In scientific terms "statements" about the external world that depends on a required contextualization can be associated with the term "impredicativity". The statement "John is the tallest person in the room" is a statement clearly identifying the subject of analysis – i.e. it can be operationalized and used to guide action. However, this statement is effective only if we are capable of establishing a relation between the observed relevant attribute of John (his height) and the analogous attribute of the other elements of the set to which John belongs. Therefore both the identification and the statement about the ranking of John in relation to height are contingent on the previous effective specifications of the members of the set used to define "who John is" and "how does he rank in terms of height in relation to the rest of the set". If the elements of the sets change (if a person taller than John enters in the room) then the definition loses its original validity. It has to be changed too. A famous example of a contingent quantitative assessment has been proposed by Mandelbrot in his seminal paper on the length of the coastline of Britain (an example that will be discussed below).

### 5.1.2 Relational analysis of metabolic patterns an introduction

Relational analysis is a term co-opted by numerous scientific disciplines. In this report, we engage the term as described and proposed for systems analysis by von Bertalanffy in General System Theory (1968). In this sense, the understanding of relational analysis derives from the work of Nicolas Rashevsky, and later his student Robert Rosen.

Key to the implementation of relational analysis are: (i) the concept of metabolic systems; and (ii) the concept of processors. In fact, metabolic processors can be used in the relational analysis of social-ecological systems to study in quantitative terms the relations between functional and structural elements across different hierarchical levels of organization and across different dimensions of analysis.

Relational analysis has been defined by Rosen as the study of "how any system is organised to the extent that it can be analyzed into or built out of constituent components. The characteristic relationships between such constituent components, and between the components and the system as a whole, comprise a new and different approach to science itself, which we may call the relational theory of systems" (Rosen, 1991). Relational analysis can be used to handle the unavoidable epistemological ambiguity determined by the phenomenon of "multi-realizability". That is after having identified the identity of a system in terms of its constituent components – the set of

functional compartments required for its reproduction – we are forced to admit that the same set of functional elements can be realized in different ways. A herbivore may be an insect or a mammals, the transportation of oil can be done by trucks, barges or pipelines, the production of milk can be obtained by giving to the cows hormones or organic feeds. The compatibility of inputs and outputs can be calculated in monetary terms (the break-even point of an economic enterprise) or in material terms (the mass balance of a process of production). In order to be able to integrate different views of the events taking place in a social-ecological systems across different levels and dimensions of analysis we have to be capable of performing a continuous quality check on the semantic of the numbers – what they mean and how they can be contextualized in relation to other numbers referring to a different dimension or a different scale of analysis. Before explaining how we use relational analysis to provide this integration we briefly address the two epistemological conundrums faced when studying in quantitative terms the characteristics of metabolic systems. As discussed in Section 1 (Figures 1, 3, 4, 5) metabolic systems must be open and becoming in time. We discuss two implications of this fact relevant for discussing the problems associated with their representation: (i) they can only be observed across different levels of observation (different scales imply non-equivalent descriptive domains); (ii) their identity is associated with the ability of stabilizing metabolic pattern, that is to maintain something predictable and recordable (about the pattern) because of a continuous process of destruction of gradients and metabolism of existing structures. These two points are briefly explained in the next two section in order to better explain the role that the concept of processor plays in relational analysis.

### 5.1.3 Hierarchy Theory and the challenge of multi-scale integrated analysis

Hierarchies are epistemological devices that humans use in order to make sense of the overwhelming flow of information coming from their observation of a complex external world. Hierarchy theory has positioned itself a central consideration in general systems theory, following the proliferation of the complex systems viewpoint. Hierarchy theory focuses on the implications of the choices of the observer in relation to the definition of what is observed (Allen and Starr, 1988). A discussion of hierarchy necessarily introduces the discussion of structure vs function. In epistemological terms, one cannot have function without structure and one cannot have structure without function. This fact is central to the relational analysis paradigm. A key concept developed in hierarchy theory in relation to the issue of “multi-realizability” is the concept of the “holon”.

In the field of hierarchy theory (Ahl and Allen, 1996; Allen and Starr, 1982; Pattee, 1973; Salthe, 1985; Simon, 1962; Whyte et al. 1969) the concept of holon is described as an epistemic devices capable of handling the fuzzy mapping across different hierarchical

levels of analysis: (i) a structural type (e.g. a person) is defined over three continuous hierarchical levels of analysis – i.e. level n-2 tissues and cells/level n-1 organs/level n the whole person; and (ii) a functional type (e.g. a professor) is defined over three continuous hierarchical levels – i.e. level n individual person/level n+1 educational system/level n+2 society in which education takes place). The two types do have a level of analysis in common – i.e. at the level n the holon is both a professor and a person. However, if we want to carry out a quantitative analysis of the characteristics of the structural type - i.e. what type of professors and her attributes at the level n+1 – we have to use data non relevant for describing the characteristics of her physical body at the level n-1 . Exploring the nature of the ambiguity of the concept of holon, Giampietro et al. (2006) observe that the epistemological problem associated with the concept of holon is even deeper, because holons entail another logical "bifurcation" when handling their perception and representation: we can only observe "instances" (material realizations) of either functional and structural types, but we cannot observe either "structural or functional types" as such. Types are just a set of expected relations over characteristics and therefore they are immaterial and out of scale – they are notional representation (the concept is discussed in Section 3.1.5).

Coming back to relational analysis a complex metabolic system must have an effective combination of functional elements (functional types), that must be realized (following the blue prints of structural types). However, the coupling of a structural type and a functional type - required by the operation of metabolic systems - implies a systemic degeneracy in the mapping of structural and functional elements. Different structural types (e.g. rabbits, cows, sheep) can map onto the same functional type (e.g. herbivores) and the same structural type (e.g. a rabbit) can map onto different functional types (e.g. a father, a herbivores, a course in a meal). This systemic degeneracy requires an organization of our perceptions and representations capable of increasing our discriminatory power. Indeed, higher level functions are realised by a multitude of lower level realization of structural types that must be able to express as "emergent property" the functions that are required by the whole. For this reason there are two major roles that information plays in the stabilization of the metabolic pattern of a complex autopoietic system: (i) reproducing realization of structural elements; (ii) describing in notional terms, in the system of control, the expected characteristics of the functional elements (e.g. cybernetics). The marrying of function and structure into a holistic logical device is what the term holon refer to (Koestler, 1967; Wiener, 1948). A group of causally related holons is in turn given the term holarchy.

Before leaving this section it is important to illustrate the concept of contingent quantitative representation when dealing with the representation of systems that can be observed simultaneously at multiple scales. In a seminal paper entitled "How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension" Benoit

Mandelbrot (1967) explained that geographic objects can only be measured in a contingent way. Coming to his example of the length of the coastline of Britain, the length can only be defined (and therefore measured) after having chosen – in a pre-analytical step – the scale of the map. In turn this choice will depend not on the characteristics of the observed system, but rather on the perception of what the observer mean with the "coastline". A self-explanatory example of this problem is given in Figure 32. The data found in official statistics depends on the chosen scale of the map. As illustrated in Figure 32, depending on the scale the measured length could be 3,876 miles or 11,023 miles (but it may get to millions of miles!). There is another important point to be made about this example illustrated on the right side of the Figure. Depending on the perception – i.e. the meaning assigned to the expression "coastline" – we may face a situation in which depending on the scale the relevant attribute can no longer be measured. Let's imagine that one wants to leave a reclining chair on a given beach in Britain and adopt the perception of the location of the coastline using this very local scale of analysis. Because of the phenomenon of tides it would not even be possible to define a clear location of the coastline!

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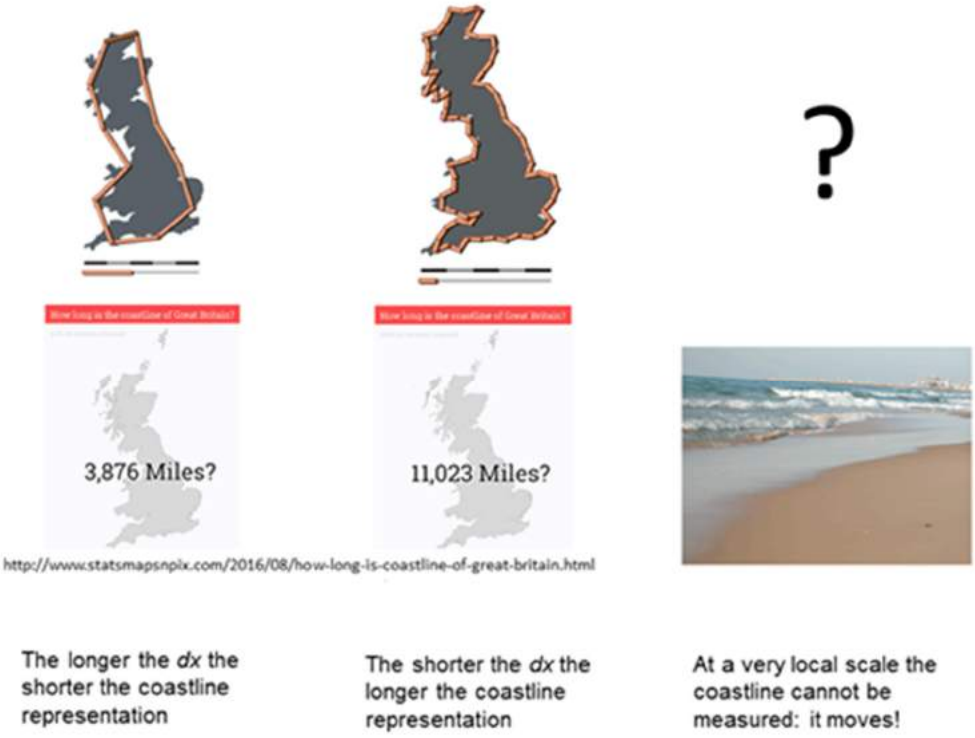


*Figure 32. The contingent assessment of the length of the coastline of Britain*

When dealing with the analysis of complex systems we have always to consider the implications of the issue of scale. We cannot see the nose of a person when observing her with a microscope, and the distances among the components of the cells of the nose are not directly usable to calculate the distance of the nose from the mouth.

### 5.1.4 The flow-fund model of Bioeconomics (Georgescu-Roegen)

The flow-fund model is a set of accounting criteria proposed by Georgescu-Roegen in order to avoid confusion in the quantitative representation of sustainability in an economic process (1971). The flow-fund model has been discussed at length in Deliverable 4.1. Georegescu-Roegen considered the economic process as an entropic process associated with the metabolism of matter and energy. His flow-fund model requires a pre-analytical identification of what should be considered as a 'flow', a 'stock', or a 'fund' in the metabolic process. In turn this classification depends on the pre-analytical choice of a scale of analysis. In fact, the classification is based on the following criteria:

(i) a flow element is associated with **a quantity of metabolised flows** – e.g. eaten food, consumed fuel, evapotranspirated water, a produced pizza – that either disappears or appears **within the duration of the analysis**;

(ii) a stock element is associated with **a quantity of accumulated flows** – e.g. a reservoir of oil, a mine, the accumulated wastes in a dumping site for waste disposal – that changes **over the duration of the analysis** because of the supply (or the sink) of the flow (or flows) to which it is related. Flows coming from stocks (and filling sinks) are typical of the exploitation of non-renewable sources;

(iii) a fund element is associated with **the size of a metabolic agent** that remains constant **during the duration of the analysis** – e.g. a cow providing milk, or a healthy crop field producing food. A fund element: (a) entails an identity relation between the identity of the fund and the identity of the flow (cows do not eat electricity); (b) requires an overhead for its reproduction (in order to produce milk cows must eat, reproduce and must be cared for); (c) imposes limits on the pace and density of the supply (the pace of milk supply of a cow is limited). Fund elements are damaged if they are forced to operate outside their 'physiological' limits (cows producing 75 litres of milk a day do not last).

Using this classification we can say that flows coming from (and absorbed by) fund elements are typical of the exploitation of renewable sources, whereas flows coming from (and absorbed by) stock elements are typical of the exploitation of non-renewable resources.

*Flows, stocks, and funds are critically important accounting categories in their own sense, but moreover their magnitudes relative to each other (e.g. flow-fund ratios) are invaluable indicators in assessing sustainability aspects of SESs. A working knowledge of Georgescu-Roegen's flow-fund model is critical to understanding the presentation and significance of the diagnostics of the state of the play found later in this deliverable Figure 37. The contingent assessment of the length of the coastline of Britain*

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## 5.2 Using the concept of processor to deal with the entanglement of water, energy, food, and land across levels and scales and across the internal and external view

*Author: Mario Giampietro*

### 5.2.1 Introducing the concept of processor

The concept of processor is essential for the implementation of relational analysis that will be illustrated in details in Section 5.2. In this section we want to illustrate the semantic richness of this concept that is essential to deal with the epistemological challenges associated with complexity. When dealing with impredicative and contingent definitions of characteristics structural and functional elements that are affecting each other across different scales and different dimensions of analysis one should abandon the strategy based on complicated models and more powerful computers. Models and computers are certainly essential to be able to handle a large information space, but they cannot provide the required semantic inputs for transferring the meaning of numbers across descriptive domains (scales and dimensions).

The concept of processor refers to a special characteristic of self-producing adaptive systems. Because they are capable of reproducing themselves through an informed auto-catalytic loop they must have the capability of: (i) reproducing structural elements; and (ii) regulating the action of these structural elements in order to obtain the expression of the required function in the right moment in the right place. This means that self-producing adaptive system produce their own structural element with a

purpose – a eye is needed to observer, a leg is needed to walk, and so on. The structural elements of a self-producing system are produced for a purpose – to express a given function required by the system. A more detailed discussion of this point can be found in Deliverable 4.1.

So we can say that the concept of "processor" refers to the ability of self-producing adaptive system to generate expected processes capable of performing expected tasks. In biochemistry this concept is expressed in terms of biochemical enzyme-substrate complex. These complexes are specific combination of particular enzymes and substrates combined to carry out specific biochemical reactions. In economics the same concept is expressed in terms of expected combination of production factors combined in order to obtain a given final product – then the processor is called extended production function. The semantic similarities across r the two concepts is illustrated in Figure 33.

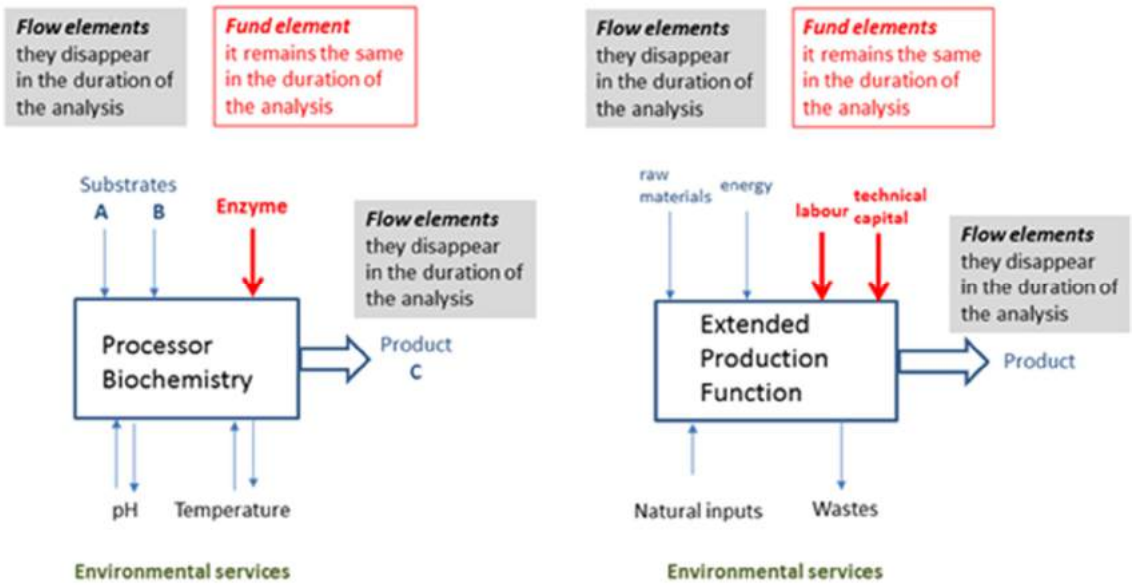


*Figure 33. Illustration of similarity in semantics of processors. Example from biochemical reaction and in economics to create a product.*

The concept of processor as the enzyme-substrate complex in biochemistry (on the left) and as the extended production functions in economics (on the right)

In both cases we find that an expected output (the final cause in the jargon of relational analysis) is achieved by a transformation (the efficient cause) determined by an

integrated use of flow and fund elements, which can be defined as structural types (the formal cause) at a given scale in an admissible environment (what is required to define the representation of the instances of the types – the material cause).

A formal representation of the key features of a processor is given in Figure 34. In formal terms a processor can be represented in the form of a data array.

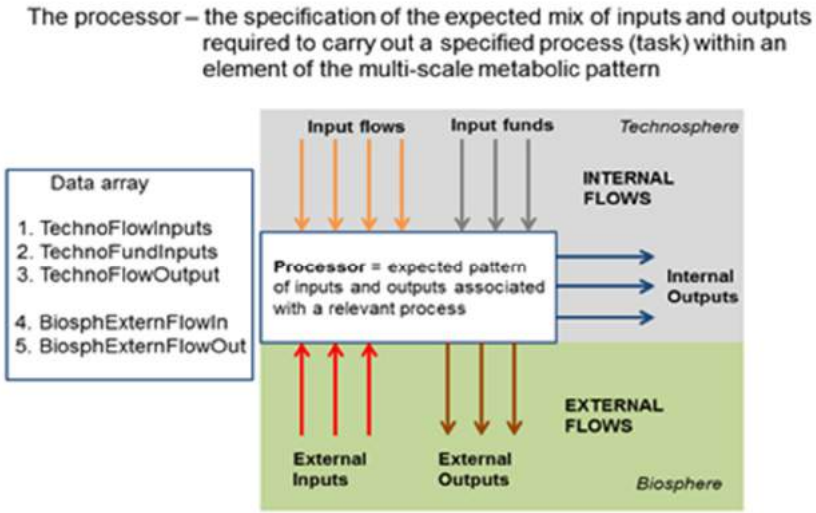


Figure 34. The logic of the formal representation of a processor.

A processor is an expected pattern (profile of inputs and outputs) associated with a specific metabolic task:

1. the required profile of internal inputs (controlled by the system) used in the production. These are the inputs (both fund and flows) coming from the technosphere entering in the upper part of the processor;

2. the required Primary Sources (in the biosphere) used for the production and the required Primary Sinks (in the biosphere) used for absorbing wastes and emissions. These are the inflows coming from the biosphere (not produced by human processes) and outflows going into the biosphere (not absorbed by human processes);

3. the supply of the useful output generated in the process, which must be useful for the system (otherwise it would not have been produced!).

Let's now compare two systems of agricultural production – as illustrated in Figure 35 – using the processor in order to understand an important feature of this epistemic tool.

The two systems described in Figure 35 are "irrigated corn in Iowa" and "rainfed marginal wheat in Nebraska". The categorization of the inputs and outputs follow the logic illustrated in Figure 33 and Figure 34. However, we provide in Figure 35 two non-equivalent way of describing the processor. The quantitative characterization given on the left side of the Figure for both systems is based on extensive variables – actual values of the flows per year - obtained by observing a sample of 10 hectares of the two systems of production. The quantitative characterization given on the right side is expressed using intensive variables (quantities of inputs required per unit of production) obtained by dividing the quantities of the various inputs by the quantity of the output.

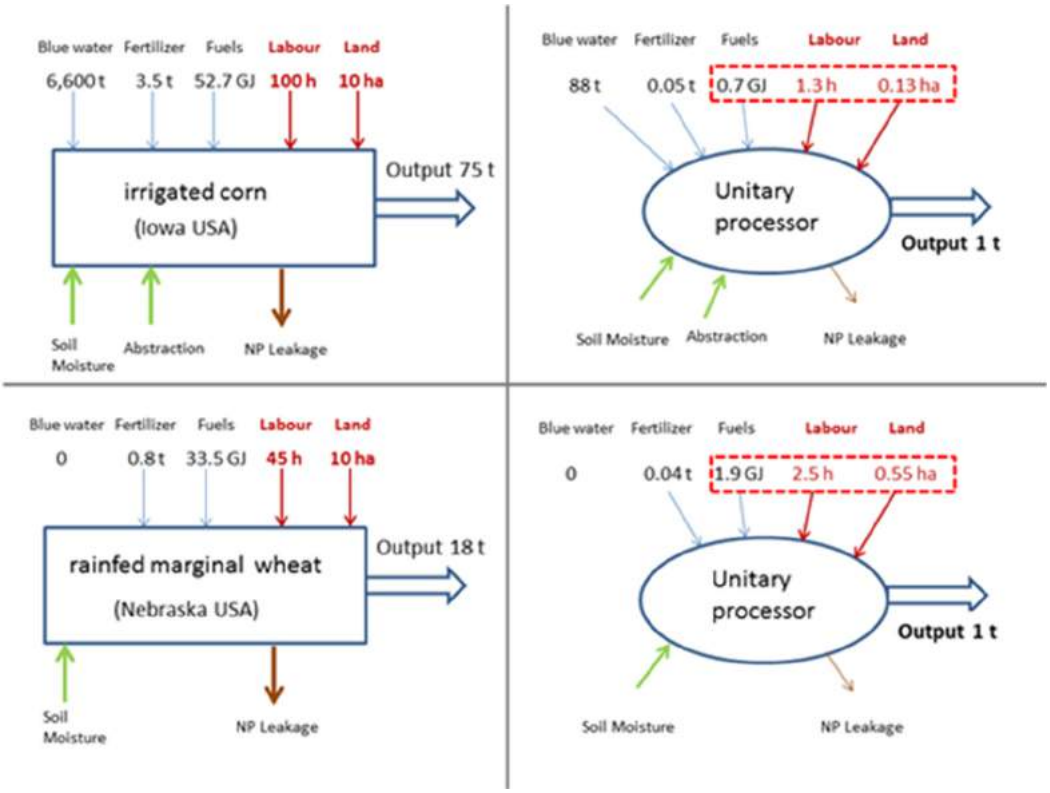


*Figure 35. Comparing two systems of crop production using the processor (data from Pimente and Pimentel, 1995).*

The two types of characterization can be used to generate different types of relevant information. The extensive characterization can be used to analyze issues relevant in relation to the scale of operation (how much land is required, the overall requirement of labor). The intensive characterization can be used for a qualitative analysis of the

performance of the two systems. For example the values indicated by the analysis given in Figure 35 based on unitary operations clearly indicate that the production of marginal land requires much more fuel, much more labor and much more land per ton of cereal than the production on good land. Moreover, if we multiply the quantities of inputs and outputs referring to metabolic activity taking place in the technosphere, we can provide an economic representation of these flows in terms of: (i) costs of the inputs (by multiplying the quantities required by the relative economic costs); and (ii) revenues of the outputs (by multiplying the quantities produced by their selling price).

### 5.2.2 Scaling across metabolic elements using the concept of processor

But there is another important feature of the processors described in unitary terms: they make it possible the scaling and the weighting across levels of analysis. This is illustrated in Figure 36. Let's assume that we want to study the metabolic pattern of a farm adopting a given mix (65% and 35%) of the two different crop production systems described in Figure 35 by using a scaling factor – either the total area of the farm, or the total production of the farm in terms of ton of cereals – we can calculate the profile of the other outputs.

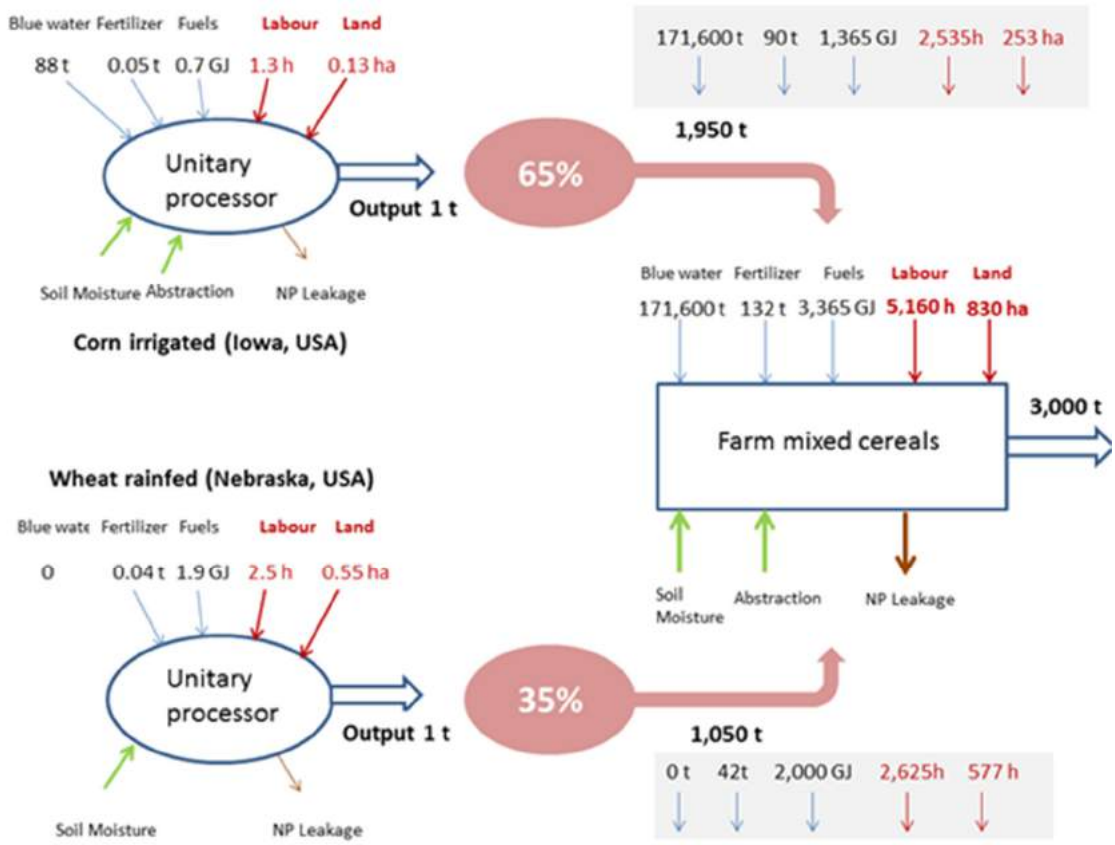

*Figure 36. The scaling and aggregating of the characteristics of crop production systems at a higher level of analysis: characteristics of the farm to which they belong.*

In conclusion by using the heuristic of the processor we can move through the analysis of the relations over the functional/structural components of a complex metabolic system – e.g. a social-ecological system. The information associated with processors can be scaled and integrated across levels and dimensions when moving across different metabolic activities:

* the specific profile of inputs and outputs relevant for characterizing elementary processes – e.g. breeding in animal production (Figure 37);

* the characteristics of different processors of a sequential pathway of elementary process can be combined into a processor describing the whole pathway (Figure 38) – e.g. breeding, rearing and fattening in beef production;

* the characteristics of a set of processors (reflecting the characteristics of sequential pathways) can be combined into a processor describing a production system (Figure 39) – e.g. different methods for producing beef can be combined together;

* the characteristics of a set of production systems required for expressing an emergent property (e.g. the supply system of animal production) can be combined together (Figure 40) – e.g. the various production systems used in animal production

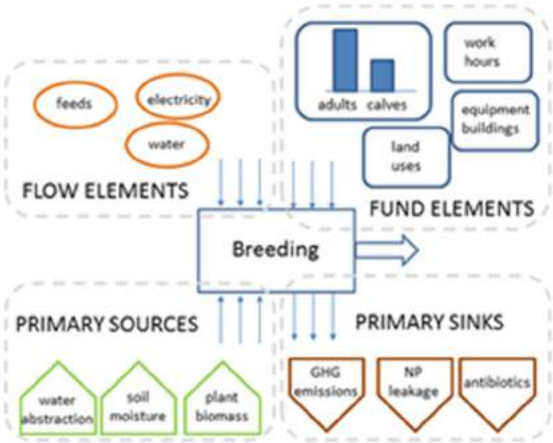


*Figure 37. The choice of the elements to be used to describe a elementary process in animal production*

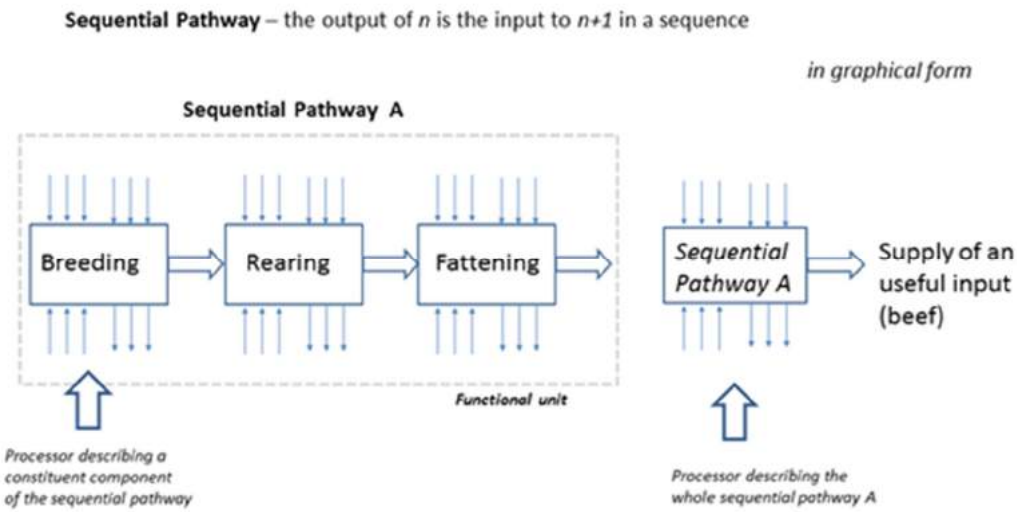


*Figure 38. The scaling of the characteristics of processors in a sequential pathway*

Depending on the technical requirements or economic demand (the definition of final causes) coming from the upper levels of the systems, the lower level functional elements can decide to produce a given required output in different ways. This reflect the diversity of possible technical solutions and the specific boundary conditions experienced locally by economic agents – e.g. beef can be produced in beef-lots or in organic way on pastures or in mixed systems. When establishing a relation between the characteristics of processors at one level to the characteristics of the upper level processor in the same constituent component, it is essential to respect the constraint of closure (the sum of the quantities of the various flows at level n must be equal to the quantities of the flows calculated at level n+1).

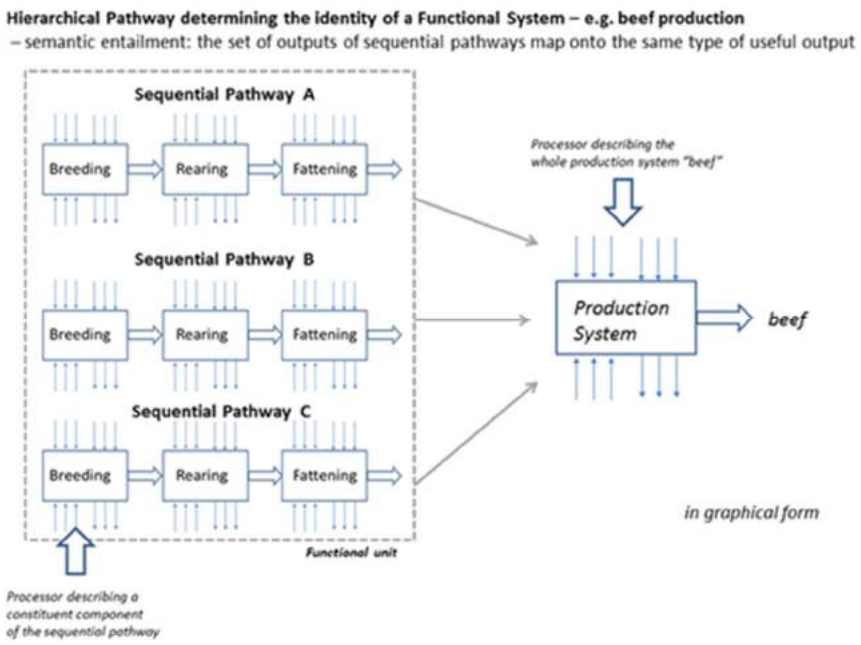


*Figure 39. The scaling sequential pathways à production system (beef)*

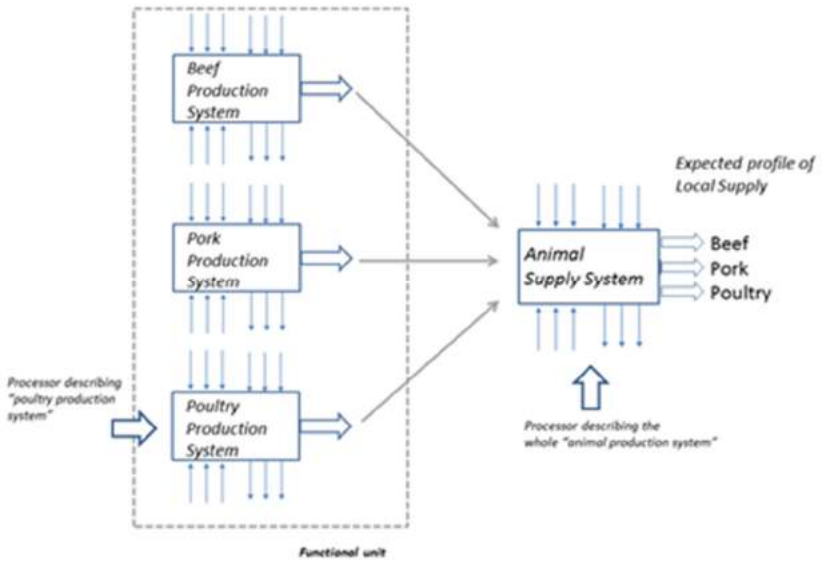


*Figure 40. The scaling production systems à supply system (animal production).*

Before moving to a systemic explanation of the quantitative assessment of the metabolic pattern of EU countries (Section 5.3) illustrated in this deliverable we present a brief illustration of the application of the concept of processor to the analysis of conversion taking place in the energy sector.

## 5.3 Using grammars to establish bridges across non-equivalent quantitative representations across scales and dimensions

### 5.3.1 Integrating different metrics used to measure energy and food flows in relation to the pre-analytic choice of non-equivalent levels of analysis

Coming back to the discussion on the epistemological problems faced when trying to describe in quantitative terms the characteristics of the coastline of UK across different scales - section 5.1.3 – Figure 32 – we face a similar problem when trying to characterize in quantitative terms the metabolic pattern. When defining water, energy and food across different categories of analysis - (i) primary sources and sinks; (ii) carriers; and (iii) end use - we cannot measure quantities of "water", "energy" and "food" if we do not declare first what we "mean" when referring to flows of water, energy and food. In turn the meaning of the measurement of water, energy and food depends on the questions we have to answer with the analysis. The epistemological predicament of multiple scale enters into play when different criteria of relevance (different policy questions) and different relevant attributes (different dimensions of analysis) have to considered simultaneously. In this situation, typical of sustainability studies, it becomes necessary to adopt and handle simultaneously quantitative assessments referring to non-equivalent descriptive domains – i.e. different definitions of what "water", "energy" and "food" mean when observed at different levels of analysis using different metrics . This is what has been done in the analysis presented here.

The MuSIASEM tool-kit organizes its quantitative characterization of the metabolic pattern of social-ecological systems across different levels of analysis and scales, in order to be able to identify different characteristics that are relevant in relation to different attributes of sustainability, that can only be observed at the chosen scale. In this study we have chosen to use three main levels of analysis.

**1. Level n/Level n-1 – the whole society and its constituent components**. At the highest level we view the system as a desired mix of outcomes and outputs – the societal pattern of production and consumption – across different constituent components (the functional components of the society). At this level policy decisions need to balance all aspects of societies interactions between the activities associated with production and consumption – i.e. how the internal funds and flows elements used to reproduced and operate structural and functional elements should be distributed across the constituent components of the society. Decisions at this level are highly complex. In fact, they are political decisions heavily value laden that balance issues such as food security, food prices, food quality, environmental impacts, local employment, and the balancing between the attention given to the various sectors. In analytical terms the questions to be answered at this level are always **contingent** – that is answers depend on the

questions asked. At this level it is not really important to have a detailed analysis of the nature of the metabolized flows as long as their representation makes it possible to catch in generic terms their quantitative and qualitative characteristics. For example for the diet we just look at the quantity and a quality factor (determined by the fraction of animal product in the total). For energy consumption we just keep the distinction between three classes of energy carriers (electricity process heat and liquid fuels). At this level of analysis we are just characterizing the pattern of consumption of the whole in relation to the pattern of consumption of the constituent components – this is what has been called – the End-Use Matrix . This type of analysis makes it possible to develop the indicator Bio-Economic Pressure reflecting how the total flows are allocated across different constituent components.

**2. Level n-1/Level n-2 – identification of the supply systems guaranteeing the required inputs to the metabolic pattern of production and consumption**. At this lower level the generic definition of a societal demand, used to carry out the analysis at the level n/n-1 is no longer sufficient. We need to better specify, by looking at a set of commodities, the nature of the supply system (what type of inputs is used to match the demand of both food and energy carriers). There are two categories of supply systems that have to be identified: (i) the mix of production systems used for generating the domestic supply of metabolized flows – domestic supply system; and (ii) the mix of imports used for matching the internal demand (in addition to the domestic production) – virtual supply systems associated with the production of imported commodities. In order to be able to assess these two supply systems we have to characterize the flows of food and energy (two flows relevant for the analysis of the Nexus) using categories that can simultaneously map onto: (i) a quantitative characterization of domestic supply in terms of a set of production systems expressing the supply; and (ii) a quantitative characterization of the level of openness of the society in terms of the profile of quantities of imported commodities.

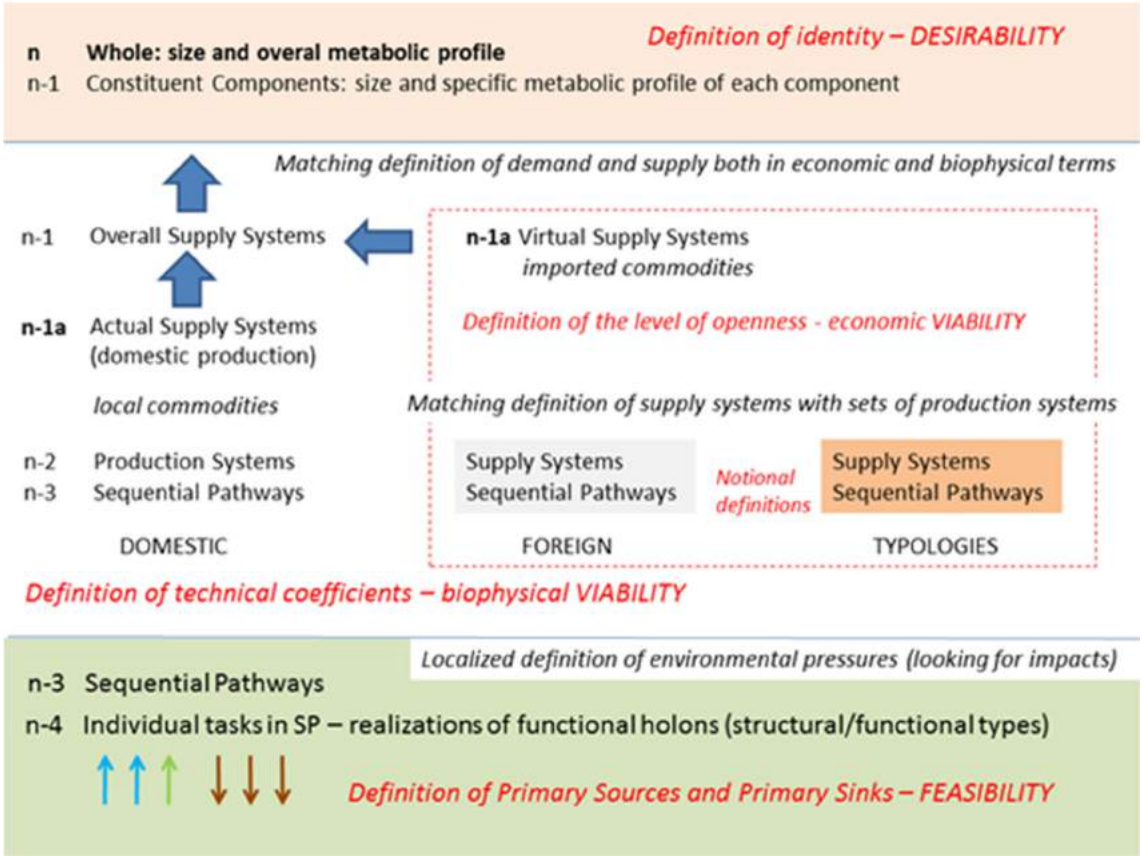


*Figure 41. The three non-equivalent metrics for food and energy used in the tool-kit.*

At this second level of analysis we have to select a set of common categories that can be used to identify and quantify both: (i) flows of food and energy commodities coming from domestic production (mapping onto a set of production systems); (ii) flows of imported food and energy commodities. In this way, it becomes possible possible to study the level of externalization of both secondary inputs required for the end use matrix (quantities of inputs that were required to produce the direct imports of energy and nutrient carriers) and of primary sources and primary sinks associated with the environmental pressure matrix (the primary sources and primary sinks used to produce the imported inputs in the countries of origin). With this type of quantitative analysis we can generate policy relevant information in relation to a discussion of the desired mix of outcomes and outputs in relation to the balancing between local production and imports. At this level, the study of the Supply System analysis makes a distinction between the fraction of the consumed commodities that is obtained through imports and the fraction that it is obtained through local production. The policy relevance of this level of analysis is obvious. Using this information it is possible to identify the effects of governance arrangements for trade (tariff and non-tariff barriers), the relative balance of support and regulation for agriculture, energy sector, manufacturing and services and

the “virtual resources” on which food imports depend (ghost land area, water footprint, embodied agrichemicals and labour, etc) an important piece of information in relation to a better understanding of the dependencies and potential security of supply issues. Finally, the analysis of the effect of externalization on the performance of the economy can clarify the confusion about the “improved performance” of developed economies: the overall efficiency of production systems in developed countries is being enhanced and the environmental impact is being minimized because of the massive reliance on imports. Last but not least, this level of analysis is essential for the identification of the set of categories of production systems that have to be considered when characterizing the local production of input. This set of production system has to be associated with the set of categories of imported commodities through a mapping across categories “Supply Systems” ßà Production Systems ßà Imports

**3. Level n-2/n-3/n-4 – localization of instances of productions systems in relation to the definition of environmental impact**. The analysis provided at the previous level makes it possible to establish a bridge between the representation of externalization through imports (level of openness) and the domestic production through the operation of production systems. However, the scale and the level of aggregation of the categories of accounting used for measuring food and energy commodities is still too high to make possible to contextualize the resulting environmental pressure into a specific assessment of environmental impact. Looking at the example of and the ability of moving down to track primary sources and primary sinks at the level of local production in order to have the possibility to contextualize the assessment of environmental pressure. Looking at the examples given in Figure 42 we can see that the category – animal product - used to describe the quantity and quality of food at the level n/n-1 maps at the level n-1/n-2/n-3 (when defining the commodities imported and the production systems used in the domestic supply) onto a set of three categories: “beef-milk”, “poultry-eggs”, and “pork-other”. Exactly like the category “electricity” defined at the level n/n-1 maps at the level n-1/n-2/n-3 onto a set of three categories: “baseload kWh”, “peak kWh”, and “intermittent kWh”. However if we want to assess the environmental impact of these system of production we have to add more information to the representation.

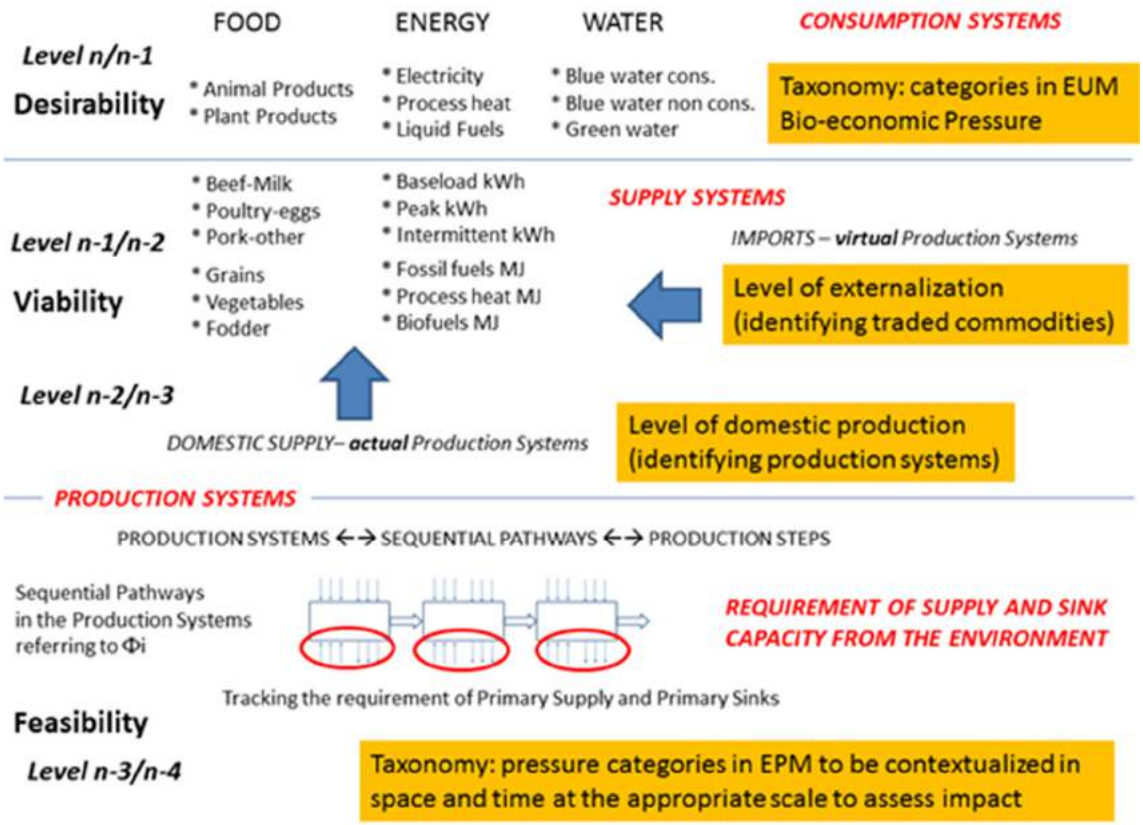


*Figure 42. Examples of different selections of categories of food and energy at different levels.*

For this reason we have to move down in the level of analysis in order to make possible a contextualization of the biophysical processes associated with the operation of the selected "Production Systems". That is a given production system – e.g. beef production – can be associated with a Sequential Pathway – e.g. a series of productive steps that are generating an expected output. The sequential pathway of beef production can be represented as a series of three production steps such as: "breeding" (the production of new calves), "weaning" (the capacitation of calves into young adults) and "fattening" (the production of final animals for production). The output of beef coming out from the last production steps (fattening) will not be possible without the expression of the entire production pathway. It should be noted that different typologies of Sequential Pathways can be realized within the same production system. For example, "breeding", "weaning" and "fattening" can be carried out using different methods – e.g. in intensive feed-lots , organic feed-lots, open pasture production. This means that below the level n-2 (the level making it possible to associate the set of chosen production systems with the set of commodities describing the imports) we can add another level of analysis - level n-3

– at which we can make a distinction between two notional representations: Production System ßà Sequential Pathways. But we can move the analysis down of another level to arrive at the level n-4 in order to be able to identify specific instances of productions steps that can be localized in space. This last movement of the analysis makes it possible to localize both in space and time the representation.

Instance of a production Steps ßà Local Environmental Pressures

Finally, when moving at the appropriate level of analysis we can define the requirement of primary sources and the requirement of primary sinks that are associated with the various steps of production in relation to the local availability. This contextualization is needed because the relation between an environmental pressure and an environmental impact can only be assessed when considering the relation between:

Local Environmental Pressures ßà Local Ecological Funds/Resource Stocks

As discussed in the Deliverabl 4.1 a given assessment of environmental pressure – e.g. “dumping 10 kg of salt in water” – can be very relevant – e.g. if the 10 kg of salt are dumped in a container of drinking water – or totally irrelevant – e.g. if the 10 kg of salt are dumped in the sea. It is the comparison between: (i) the primary sink (or primary source) capacity required by the environmental pressure; and (ii) the primary sink (or primary source) capacity available when considering the local environment of the specific environmental pressure that makes it possible to study whether a given environmental pressure has an important impact on the ecosystem or entails an important depletion of a stock of resource.

In relation to this point the issue of scale is essential, because depending on the type of ecological fund element associated with the pressure we may have different relevant scales to be considered. Emissions of GHG are referring to the whole atmosphere and therefore they can be summed even if coming from different spatial locations. Stress related to water metabolism (abstraction from aquifer or pollution of aquifer) have to be handled in relation to the geographic boundary of the affected aquifer. So the level of analysis required to contextualize the impact of an environmental pressure changes (this is a clear example of contingent assessment) depending on the purpose of the analysis – the definition of the environmental impact to be analyzed.

### 5.3.2 The overview of the network of transformation considered in the set of relations

In this section we provide an overview of the logic used to establish a set of numerical relations across the various representations. To do that we use the concept of grammars

(expected relations over functional elements expected to express an emergent property when properly combined) illustrated in Deliverable 4.1.

We can recall here the discussion in Section 5.2.2 about the use of processors for scaling across different levels of analysis. In this section we illustrate how the various functional and structural elements can be defined in the general representation and then how the various flows of inputs and outputs can be quantified to obtain a quantitative characterization of the metabolic pattern across different hierarchical levels. Going through the various levels of analysis described in Section 5.3.1 we can look first of all to the representation of the relations between functional elements on the interface: (i) level n/level n-1; and (ii) level n-1/level n-2. This is illustrated in the overview given in Figure 43.

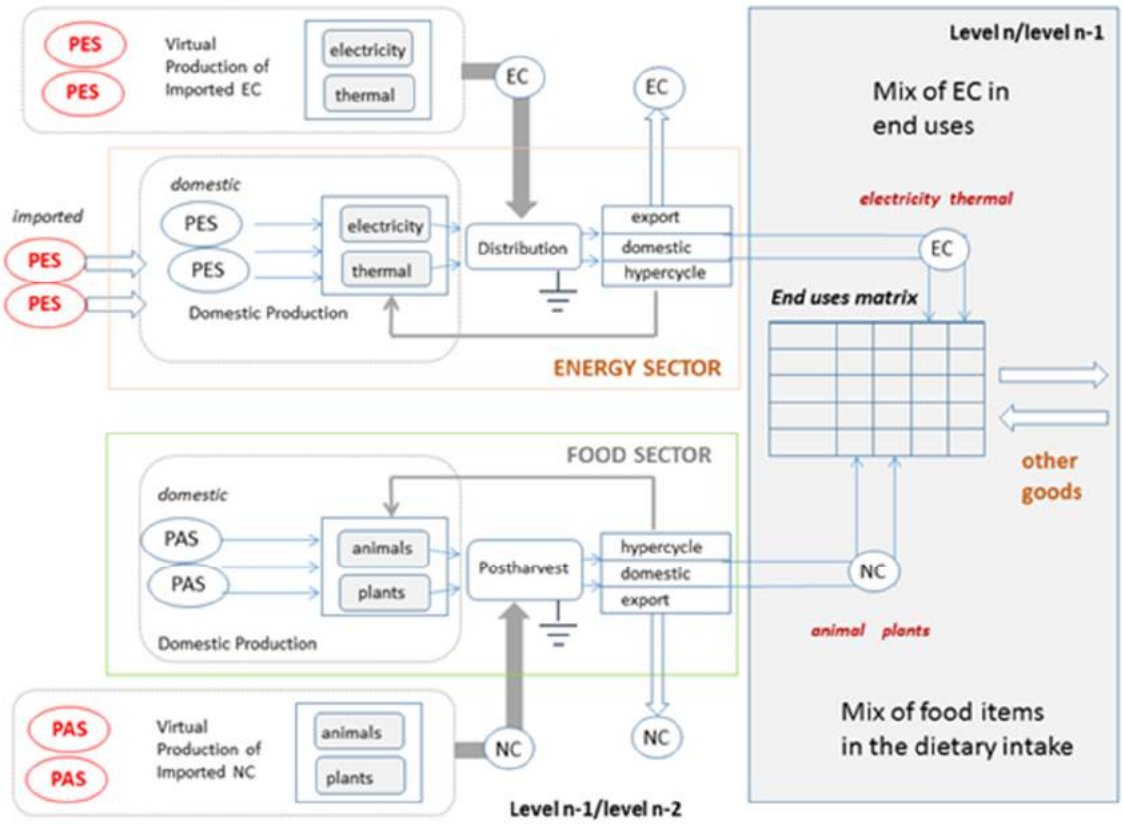


*Figure 43. An overview of relations over functional elements across the level "n/n-1" (on the right of the graph) and level "n-1/n-2" (on the left of the graph)*

In this overview we can see that the end use matrix (on the right) describe the distribution of the flows (as described in the metric #1 at the level n/n-1) inside the constituent compartments of the society and then on the left the series of process determining the supply of energy carriers and nutrient carriers to the society.

In the Figure PES stands for Primary Energy Sources, EC stands for Energy Carriers, PAS stands for Primary Agricultural Sources (water, soil, biodiversity, etc.) NC stands for Nutrient Carriers (food products). It should be noted that when coming to agricultural production the import of primary agricultural sources is in general negligible (but for seeds). This quantitative representation makes it possible to assess the level of openness of the supply system – to check the fraction of "energy inputs" and "food inputs" consumed by the society that are either domestically produced or imported. At the same time this distinction makes it possible to identify the type of production systems that are adopted to generate the same mix of food and energy inputs domestically produced. However, in order to be able to interface data referring to traded commodities (the mix of imports relevant for the internal consumption) and data referring to domestic production systems, we have to adopt a different quantitative representation of the flows based on a different metric – i.e. a new definition of different categories used for measuring quantities of "food" and "energy". This new selection of categories of accounting has to make it possible to track both: (i) the various flows included in the mix of commodities considered as "EC" and "NC" inputs; and (ii) the typologies of production systems used to generate the supply of these flows.

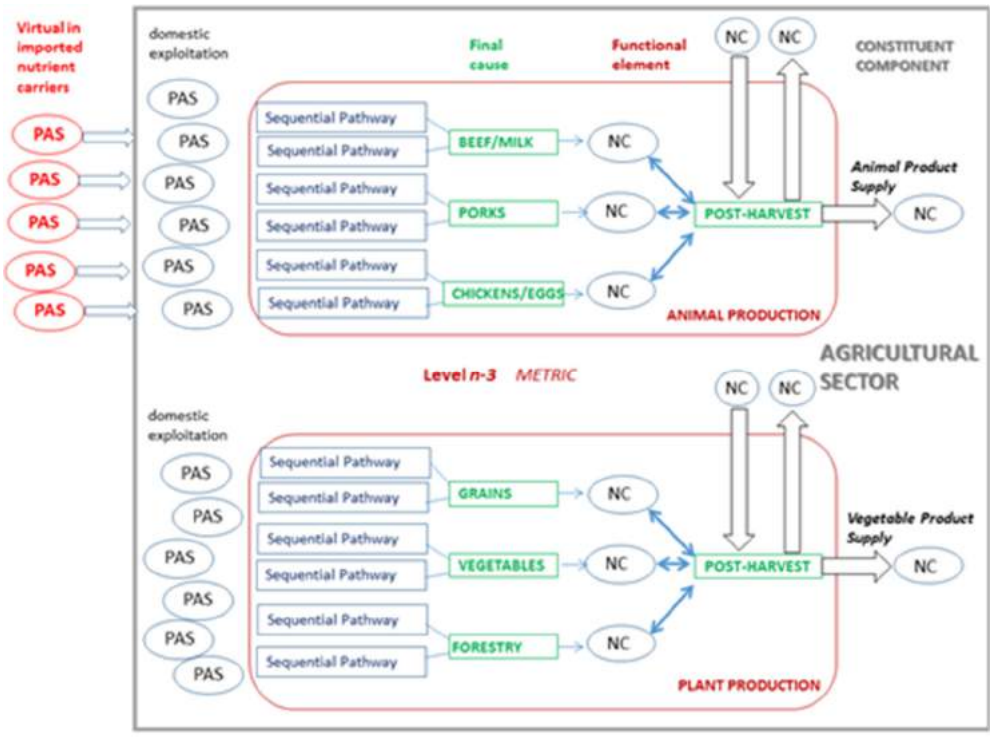


*Figure 44. The production systems used to generate Nutrient Carriers defined at the level n-3*

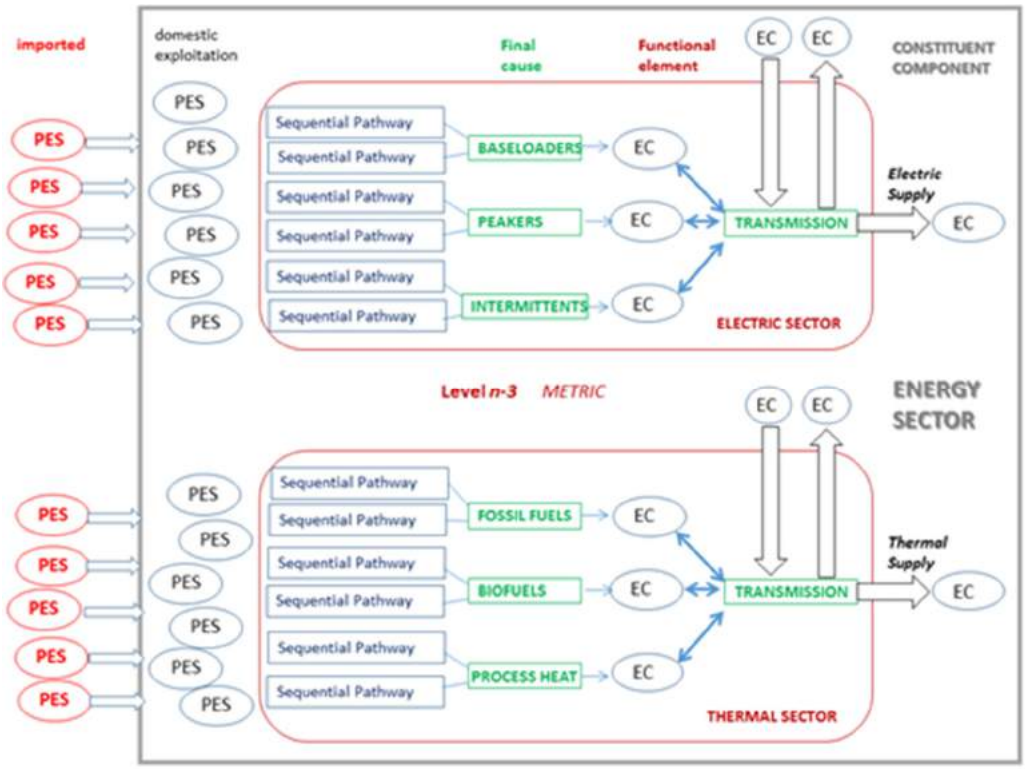

*Figure 45. The production systems used to generate Energy Carriers defined at the level n-3*

To achieve this task we have to "unpack" the definition of "animal products" vs "plant products" to generate a more detailed representation of these flows. This more detailed representation of the categories making up quantities of Nutrient Carriers is given in Figure 44. The analogous expansion of the representation to include more categories in relation to the production of Energy Carriers is given in Figure 45.

When finally coming to the movement to lower levels of analysis, the movement required to be able to contextualize and localize the generation of environmental pressures against the availability of primary sources and primary sinks (to check the potential negative effects on the environment) we have to generate another interface between two non-equivalent definitions of categories of accounting. As discussed in Section 5.2.2 this can be achieved using the special feature of processor. An example of a generic movement of non-equivalent quantitative representations across different levels is given in Figure 46.

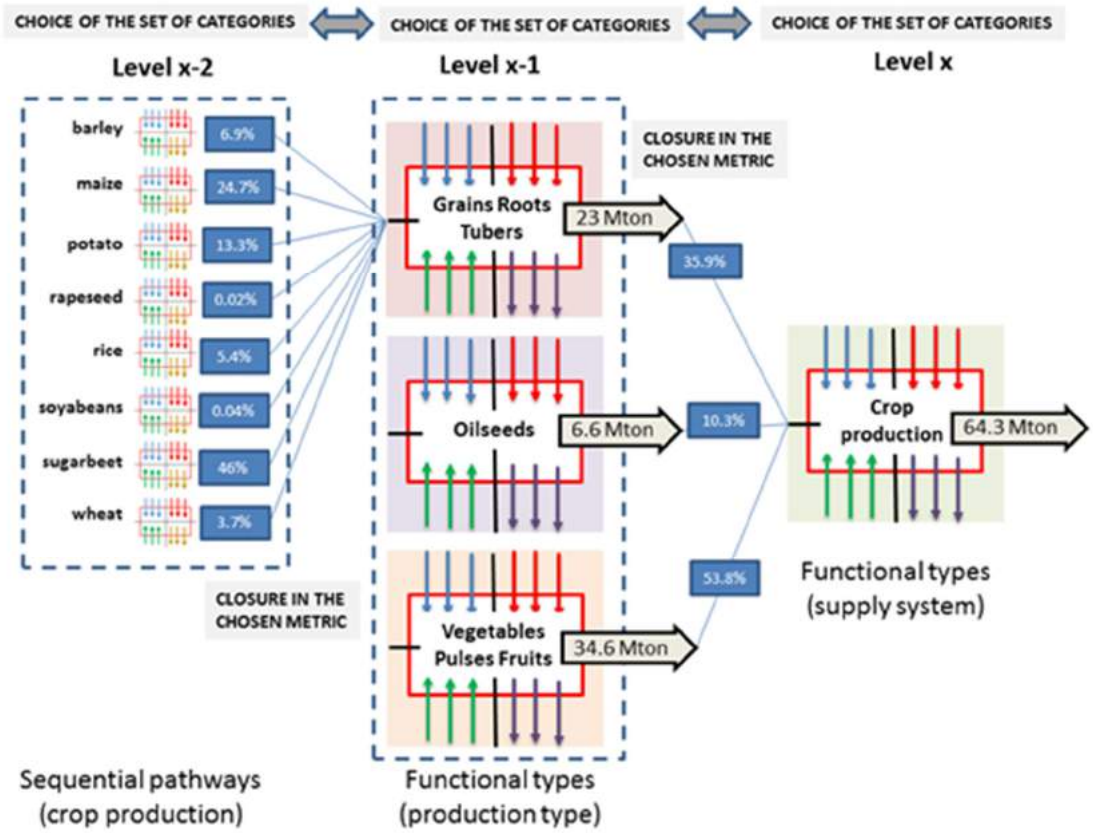


Figure 46. Example of accounting across levels by mapping accounting categories within a given taxonomy

Also in this case, we are in presence of a contingent decision of how to move to lower level characterization (the quantitative analysis based on this method can move to lower and lower levels when needed). The decision on where to stop depends on the type of question we want to answer. If we are dealing with an analysis of the stress on aquifers, then we have to focus on a level of analysis making it possible to use Geographic Information Systems in order to assess the aggregate supply capacity requirement and sink capacity requirement associated with the different land use categories – i.e. different processors describing the inputs and outputs per hectare of a given cultivation can be used to calculate the aggregate effect of the resulting environmental pressure.

### 5.3.3 How to move the quantitative information of processors across levels of analysis

In the previous section we explained that the quantitative characterization of the metabolic characteristics that is useful to discuss of "desirability" (at the level n/n-1) it is not useful to describe the level of openness (observable only at the level n-1/n-2). That is, the descriptive domain used to quantify energy, food and water consumption which is useful to describe the welfare of the people and political decisions about the structure of the economy is not useful to identify the flow of commodities (imports) and the set of production processes that guarantee the supply of inputs consumed by the society.

For this reason it is important to generate a different quantitative analysis at a different level (level n-1/n-2, and n-2/n-3) making it possible to estimate this different type of information. The information about the level of openness of the system (dependency on imports) is useful for: (i) economic reasons, security reasons and also for ethical reasons – i.e. to calculate the embodied quantities such as virtual energy, virtual labor, virtual water, land used by other social-ecological systems to produce the imported items; and (ii) technical reasons, it makes it possible to identify and categorize the typologies of production systems that are required to provide the domestic supply of the food and energy inputs.

Yet, the descriptive domain used to quantify the level of externalization and to identify the mix of required production systems does not provide the required discriminatory power for assessing the potential impact of environmental pressure. For this different task we have to be able to contextualize the processes generating environmental pressures to check the availability of primary source capacity and primary sink capacity. This task requires that the characteristics of a production process affecting the environment are quantified also in spatial terms (using GIS) considering the size and quality of the ecological funds supposed to absorb and neutralize the stress associated

with the environmental pressure. This additional analysis requires moving to a lower level of analysis (level n-3/n-4 and whenever needed to lower levels, n-4/n-5, . . . ).

In this section we illustrate how to aggregate across levels and scales the quantitative information associated with the representation of a processor organized in the data array presented in Section 5.2.

It is important to observe that when extracting the information referring to the requirement of Secondary Inputs (energy carriers, nutrient carriers, labor) we are handling data relevant for the analysis of internal constraints based on the data organized in the End Use Matrix. On the contrary when we extract information referring to requirement of Primary Sources and Primary Sinks we are handling data relevant for the analysis of external constraints based on data organized in the Environmental Pressure Matrix. This implies that when moving information across different levels of analysis we have to use to move the information across different data array describing processors at different levels. As illustrated in Figures 38-40 in section 5.2.2. it is possible to aggregate information from processors describing individual production steps into an information describing the processor at the level of the whole Sequential Pathway. Then to move up from the level of sequential pathways we have to hand le in a separate way the two data vectors: (i) the inputs coming from the technosphere entering into the processor from the upper part; and (ii) the inputs and outputs exchanged with the biosphere represented in the lower part of the processor. As illustrated in Figure 47 can use the information coming from the upper part of the processor to define the requirement of secondary inputs (an information relevant for the End Use Matrix) and the information coming from the lower part of the processor to define the requirement of primary sources and sinks (an information relevant for the Environmental Pressure Matrix). In this way, we can combine and aggregate the information coming from an entire set of sequential pathways that are considered to belong to a given production system. In the example given in Figure 47 we are considering the production system “peak electricity” made up of three sequential pathways: “Gas Fired Power Plants”, “Hydro Power Plants”, “Diesel Power Plants”.

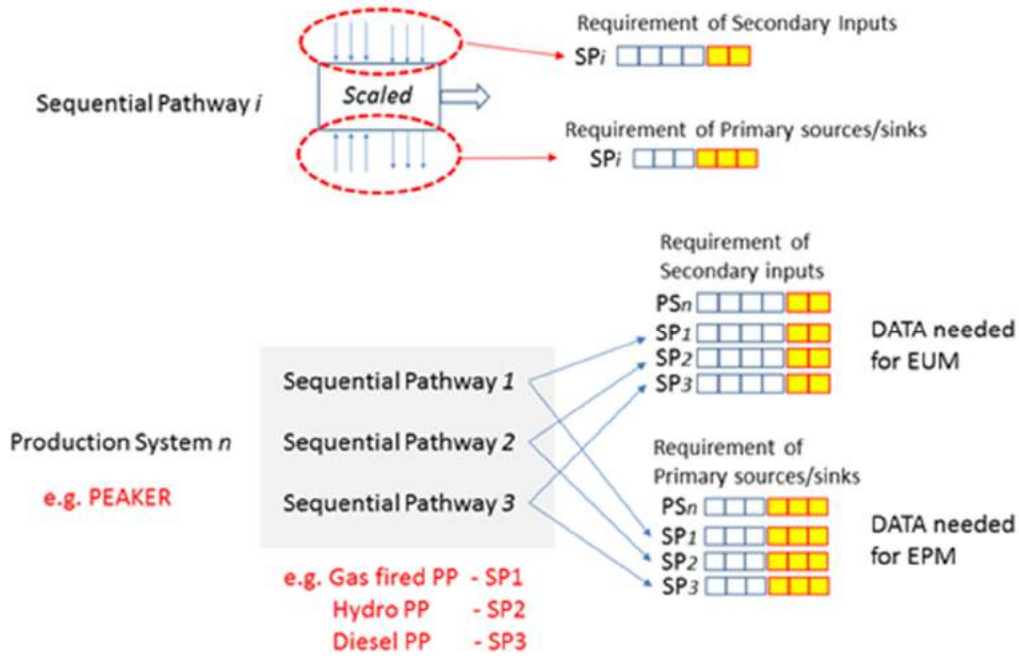


*Figure 47. Extracting from the processors the information needed to calculate $EUM_{LOC}$ and $EPM_{LOC}$*

By ordering the various vectors describing the requirements of secondary inputs of the various sequential pathways into a specific end use matrix we can generate a vector describing the requirement of secondary inputs of the Production System "Peaker". In the same way, by integrating the vectors describing the requirement of primary sources and sinks of the various sequential pathways belonging to the Production System "Peaker" we can calculation of the specific Environmental Pressure Matrix associated with the operation of the "peaker" production system.

This is a general method of aggregation that can be used to move the quantitative analysis across non-equivalent descriptions. The various rows of inputs describing the requirements of the constituent component of the functional element considered can be organized into a matrix (to keep record of the diversity of the information that is generating the emergent property of the whole – the sum of the quantities in the "total" the top level row. In this way, production systems can be described as functional elements inside the supply elements, seen as parts of the constituent components of the whole society. A self-explanatory view of this set of relation is given in Figure 48. The Figure is divided in two: (i) the upper part illustrates the handling of the quantitative information referring to the requirement of secondary inputs (useful for the End Use Matrix); (ii) the lower part illustrated the handling of the information referring to the requirement of Primary Sources and Primary Sinks (useful for the Environmental

Pressure Matrix). The movement of information across levels goes from left to right, starting from the level of production system (already indicated in Figure 47).

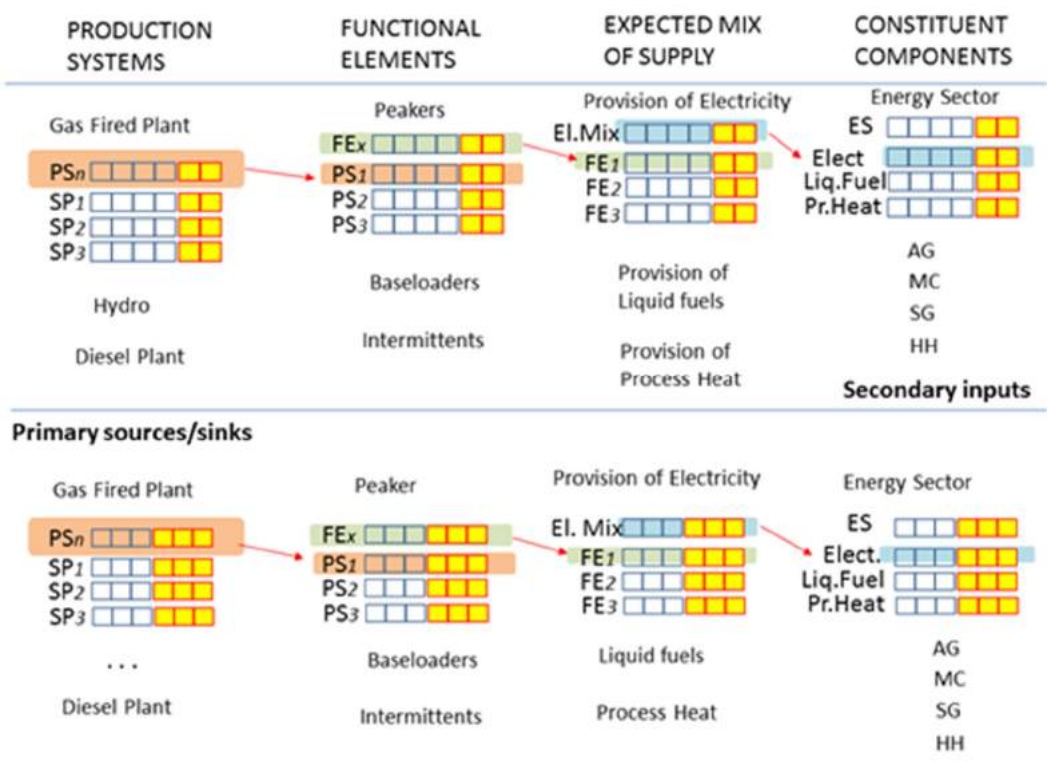


*Figure 48. An analysis of the recursive method of movement of quantitative information across levels*

We are using in Figure 49 an example taken from the analysis of the energy sector (as constituent component) and we describe below only the handling of the information referring to the requirement of secondary inputs (the information required for the End Use Matrix).

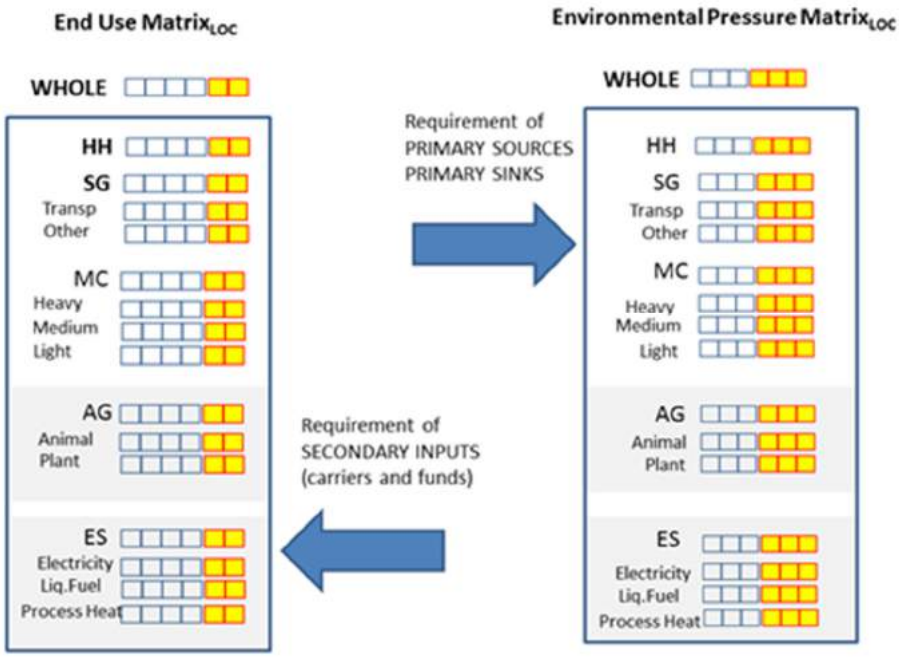


*Figure 49. An overview of $EUM_{LOC}$ and $EPM_{LOC}$*

The quantitative information gathered in this way, can be finally integrated in data arrays as Local End-Use Matrix ($EUM_{LOC}$) and Local Environmental Pressure Matrix ($EPM_{LOC}$) as shown in Figure 49.

### 5.3.4 How to deal with the assessment of the effect of externalization

The level of openness of the metabolic pattern of SES, when assessed in relation to economic narratives, does not refer to the interactions between the technosphere and biosphere – i.e. the conversion of primary sources into secondary inputs and the conversion of secondary inputs into end uses, requiring primary sinks. Rather the level of openness refers to the exchange of secondary inputs (imports and exports) across different Social-Ecological Systems. As explained in the previous sections, the analysis of the level of openness has to start from the identification of the imports and exports that have to be measured using a given selection of accounting categories in order to be included in the system of accounting of the proposed tool-kit. That is the definition of the quantities of imported flows has to coincide with the definition of the production system that are in use in the SES for producing them.

After having identified the flows of imports consistent with the system of accounting used to characterize the Local End Use Matrix and the Environmental Pressure Matrix (based on the identification of set of production systems establishing a relation between

the two), we are in a condition to generate assessments of the "virtual" requirements of both: (i) secondary inputs – e.g. what should be accounted in the end use matrix as secondary inputs required for the production; and (ii) primary sources and primary sinks, which can be associated with these imports – e.g. what should be accounted in the environmental pressure matrix as primary sources and primary sinks required for the production. For this estimation case we have to use a notional assessment based on the information associated with the characteristics of unitary processors (see Figure 34 in Section 5.2.1) – i.e. a description of the profile of secondary inputs and profile of primary sources and sinks per unit of flow supplied. The quantities of the various imports can be used to scale-up the information associated with the unitary processors describing the metabolic pattern of the respective production systems. In this way it becomes possible to generate an assessment of the virtual quantities that should be included in the Externalized End Use Matrix and the Externalized Environmental Pressure Matrix.

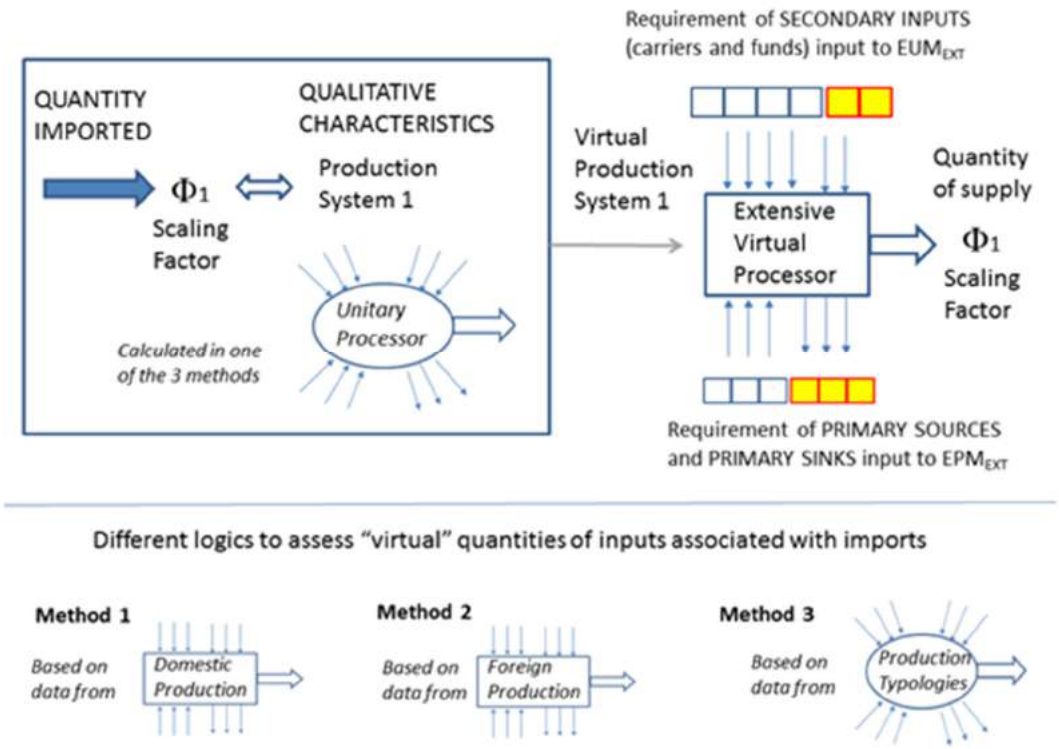


*Figure 50. An overview of the logic for the assessment of virtual production systems*

This mechanism of scaling, illustrated in Figure 50, flags again (on the bottom of the Figure) the unavoidable co-existence of three different rationales that can be used for the calculation of virtual requirements: (i) one can generate a unitary processor by renormalizing per unit of production the extensive processors (generating a unitary processor) of the production systems used in domestic production; (ii) one can generate

a unitary processor by renormalizing per unit of production the extensive processors of the production systems (generating a unitary processor) used in the exporting countries; (iii) one can generate a unitary processor by combining unitary processors of known typologies of productions. Again the choice of the method depends on the purpose of the analysis. Method (i) is good for studying the issue of security; Method (ii) is good for studying the issue of ethical concern for the exploitation of means of production of other Social-Ecological Systems; Method (iii) is useful for the exploration of possible scenarios of future state-pressure relations.

After having generated the profiles of requirements both for the Secondary Inputs and for the Primary Sources and Sinks it becomes possible to generated both an Externalized End Use Matrix ($EUM_{EXT}$) and an Externalized Environmental Pressure Matrix ($EPM_{EXT}$) that can be combined with the $EUM_{LOC}$ and an $EPM_{LOC}$ in order to generate an overall assessment of the EUM and EPM. The combination of the quantitative information across the 6 matrices is illustrated in Figure 51.

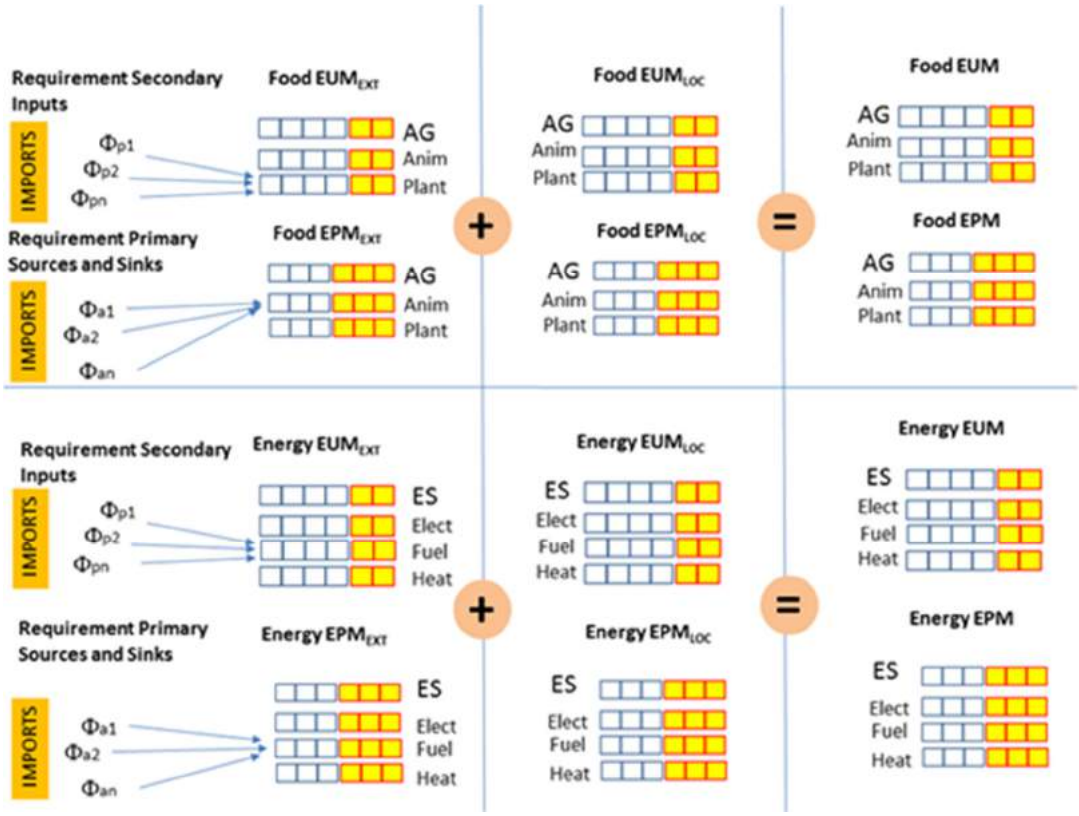


*Figure 51. The quantitative relations across the six matrices (only for food and energy)*

### 5.3.5 How to handle the issue of the re-export of imported flows

A problem faced when assessing the very large level of openness of EU economies is represented by the fact that some of European economies are very open in terms of trade of food and energy commodities. For example, the Netherlands is the second exporter of food commodities (when considering their economic value) in spite of the limited endowment of land of the country. As a matter of fact, the Netherlands economic export of food commodities is more than the economic export of food commodities of Canada and Argentina combined, two countries that have 80 times more arable land. Similar situations can be found also when looking at energy trade (again the Netherlands is a champion in terms of importing and re-exporting fossil energy products).

The analysis of the role of imports and exports in the metabolic pattern of countries presents a logical bifurcation. One can decide to add the imports to the consumption of the country and then to subtract the exports. In alternative one can assign two distinct metabolic role to the imported inputs. Imports represent inputs that are metabolized by the society (used in terms of useful transformation) for reproducing the functional and structural elements of a society. Therefore whatever import entering the economic process is "used" by society. There are two ways of using the import: (i) you can use food imports and energy imports for metabolic purposes (converting them in end use providing final biophysical outputs to the society); and (ii) you can use food imports and energy imports for economic purposes, generating added value by converting them in exported commodities. Our method of assessment assumes that in any case the imported flows are "metabolized" by the society either as biophysical inputs of processes generating end use and wastes (internal consumption) or as biophysical outputs re-exported and bringing economic gains to the economy. For this reason we are accounting the secondary inputs of energy and food of imports without subtracting the relative quantities of secondary inputs required for producing the exports. However, to avoid to destroy the information associated with the level of exports, we have split the constituent components "Agricultural Sector" and "Energy Sector" into two sub-sectors: $AG_{domestic}$ and $AG_{export}$ and $ES_{domestic}$ and $ES_{export}$. The logic of this split is that these two sub-Constituent Components play a totally different role in relation to the expression of the metabolic metabolism: (i) the supply of both $AG_{domestic}$ and $ES_{domestic}$ has the goal to cover the internal requirement of secondary inputs (in relation food and energy security); whereas (ii) the supply of both $AG_{export}$ and $ES_{export}$ has the goal to generate added value to be used by the SES. In the first case the supply refers to a biophysical secondary input required by the metabolic pattern, in the second case we are dealing with the generation of commodities whose physical nature is not directly related to the stabilization of biophysical metabolic processes in the SES. By using this distinction we can separate the quantities of the End Use Matrix and the Environmental

Pressure Matrix that are required for self-sufficiency and those that are used for boosting the economic performance.

When coming to the quantitative assessment of this split we adopted a simplified procedure to get a coarse assessment of the split of the requirement of Secondary Inputs and Primary Sources and Sinks across the two. In fact, the network of transformation taking place in the food and the energy system of EU countries is extremely complex (with joint productions and an extremely high level of openness of all processes). This means that it is impossible to track individual flows of secondary inputs of both energy and food in relation to their terms of trade. For this reason, we adopted the following method based on three steps:

1. Use the quantities of EXPORT, IMPORT, DOMESTIC SUPPLY and DOMESTIC CONSUMPTION resulting from the choice of the metric at the level n-1/n-2;

2. Define the ratios between two quantities: (i) EXPORT/(DOMESTIC SUPPLY + IMPORT) = x; and (ii) DOMESTIC CONSUMPTION/(DOMESTIC SUPPLY + IMPORT) = 1-x

3. Split the overall values of EUM and EPM in relation to the two sectors AG and ES as follows:

* the row $EUM\text{-}AG_{domestic} = AG \cdot (1-x)$; and the row $EUM\text{-}AG_{export} = AG \cdot x$

* the row $EUM\text{-}ES_{domestic} = ES \cdot (1-x)$; and the row $EUM\text{-}ES_{export} = ES \cdot x$

## 5.4 The approach makes it possible to check the robustness of available statistics

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**Energy**

The multi-level approach implemented by MuSIASEM allows checking for the quality of different data sources used at different levels. The metabolic behaviour of social-ecological systems varies across levels of analysis, and with the variation of behaviour there is an associated variation in relevant variables to be used in its description, and in the sources of data. In order to bridge higher level representations with lower level ones, MuSIASEM uses a scaling mechanism whereby types of lower level processes (structures) are aggregated and scaled up to reach a higher-level description, as explained in detail throughout this deliverable. In addition to being able to describe the behaviour of SESs at different levels, one of the strengths of the multi-level description

is that it allows commenting on the robustness of different data sources. Databases referring to individual processes and data available through statistical bodies tend to be used in isolated analyses, therefore their congruence is rarely checked. For the case of the energy sector, we obtain a description of the sector in two ways: from statistical bodies (Eurostat, in this case), and by up-scaling the behaviour of lower level processes (with data collected mostly through Ecoinvent). We refer to statistical data as top-down data, and to data at the level of processes (obtained through Ecoinvent, or through technical reports) as bottom-up data. Thus, we reach two descriptions of the same system obtained with different data sources.

Incongruences in the bottom-up and top-down system description can flag three types of inconsistencies: in the quality of statistical data, in the quality of bottom-up data, or in the quality of the relations used to up-scale bottom-up data. It is not always clear where the anomaly lies, and further descriptions of the energy system across different years and countries (a larger data set) will allow systematically checking for recurring inconsistencies. An initial appraisal of the energy metabolism of the EU-8 reveals how there are non-negligible differences between the data collected at different levels, particularly when it comes to the consumption of energy carriers within the energy sector itself. Part of the discrepancy can be explained by the different categorizations of data – Eurostat, for example, groups refinery processes under the manufacturing sector rather than the energy one. However, even when different categorizations are taken into account, discrepancies remain – the fuel consumption of the energy sector, for example, seems to be consistently either overestimated by bottom-up data, under-estimated by top-down data, or not scaled appropriately. For human activity, data remains within the same order of magnitude, confirming the validity of labour statistics and their reliability over statistics of energy consumption.

Water consumption in the energy sector, as collected bottom-up from Ecoinvent, varies greatly from water statistics in EUROSTAT as shown in the following Table. EUROSTAT datasets related to water use for energy do only account for cooling activities and other uses in electricity production. Therefore, the comparison is only possible between these two. As observed in the following Table, MuSIASEM bottom-up accounting estimates higher values in all cases but cooling activities in Germany and Spain. The most important differences are found in France and UK for consumptive uses and in the UK for non-consumptive, where MuSIASEM results are one order of magnitude larger than EUROSTAT reported values.

| Consumptive use for electricity (Mm3/Year) | Non-consumptive use for cooling (Mm3/Year) |
|---|---|

| | EUROSTAT | MuSIASEM | Difference | EUROSTAT | MuSIASEM | Difference |
|---|---|---|---|---|---|---|
| **FR** | 195 | 910 | -715 | 23562 | 27837 | -4274 |
| **DE** | 190 | 203 | -12 | 20112 | 12267 | 7845 |
| **IT** | Nav | 1255 | Nav | Nav | 33766 | Nav |
| **NL** | 17 | 67 | -50 | 6022 | 10744 | -4722 |
| **RO** | 9 | 48 | -39 | 1125 | 4710 | -3585 |
| **ES** | 32 | 98 | -67 | 6109 | 2472 | 3637 |
| **SE** | Nav | 197 | Nav | Nav | 5365 | Nav |
| **UK** | 26 | 255 | -229 | 6984 | 20760 | -13775 |

It is expected that further analyses bridging data sources across levels will result in crucial findings in relation to the quality of data used for energy analyses, and given the importance of multi-level and multi-scalar approaches for Nexus analyses, the importance of the quality and relations among different types of datasets should not be underestimated. In particular, the proposed multi-scalar approach may also be useful in determining to what extent the economy of scale plays a role, by reaching a satisfying level of detail in breaking down typologies according to their size, and up-scaling them.

Energy analysts should be aware of the categorizations used for energy statistics across different bodies, and statistical bodies should make their assumptions and categorizations clear and transparent. The notion that statistical data is always valid should be attenuated towards a more nuanced understanding of data, based on the view that the relevance and validity of a given dataset depends on the hierarchical level of analysis. Moreover, it would be advisable for the same statistical body to provide data referring to a range of Nexus elements, ensuring uniformity in Nexus analyses, whereas at the moment data is collected from different bodies implementing different sets of assumptions and techniques, making their comparability problematic.

**Livestock**

Similar as reported for the energy sector, the livestock sector experiences some inconsistencies with data, and especially when coming from different sources and from different aggregated (or hierarchical) levels. We summarize the problems faced below grouped in 3 main categories.

First, we face a problem of lack of data. The tool-kit developed in this deliverable of the project constitutes a major effort to gather and bring together heterogeneous data, from different sources and at different aggregated levels. This makes it tough to find the data on is looking for and requires a lot of assumptions. For instance, when performing the analysis of the livestock sectors for the 8 different countries, we realized that data from Romania is generally lacking. Different countries provide different data and in different way. Hence, once "standardized" the method for a country one may discover that such data is not available for another country. Moreover, country-specific detailed data is usually reported in the language of the country and many times inaccessible to the researcher. Also, countries store data in large, complex and continuously changing websites, which makes it difficult to localize and trace data sources.

In other occasions, data is not existing or not provided. For instance, we found a general problem in trade reporting. Data is many times missing or aggregated in such a way that impede proper interpretation. There was very little information related to how many animals were being imported and from where, especially in a format that could be related to animal numbers and weight. Also, there is hardly any information available on the hatcheries for poultry. This makes it difficult to quantify e.g. hatching rate, energy use or labour required. Another difficulty is defining a diet of the animals and tracing the feedstuffs. Diets are highly variable and many different sources provide (quite) different diets. Even when using data from feeding industry (access through personal contacts) it become almost impossible to trace which feeds were going where. To give an example, and as expressed by one of the data sources we used, some countries regarded the need to use default numbers as there were no more specific data available (FAO, 2017).

Considering that livestock sectors could be further split into farming systems (e.g. conventional/organic; different levels of intensity; etc.) depending on the research question, specific data may be missing or coming from different hierarchical levels. Hence, more susceptible to end up with inconsistencies (as explained below).

Second, a problem with definitions, aggregation of the data and uncertainty. This is quite a common problem when searching for data. Lack of clear definitions usually tend to lead to aggregation of data. For instance, many statistics group the beef sector and the dairy sector under the "cattle" umbrella; or the laying hens and the broilers under "poultry". This grouping or aggregation of data becomes problematic because each

sector is reared for a different purpose: have different functions. Hence, while grouping may make sense on the "similarity" between livestock types, it makes no sense from the "functionality" point of view. Another controversial definition is "young stock". Such definition is used for animals yet to be considered adult. However, and especially for cattle, it is many times unclear what does young stock really encompass: sometimes it refers to all animals that are not adults (i.e. <2 years old) and sometimes it refers to the early stage of growing (i.e. <1 year). This is the case of cattle and especially when referred to trade: EUROSTAT defined cattle numbers in young cattle, adult cattle and calves but then only sporadically disaggregated the data in this way when it came to trade.

The problem with uncertainty lay on the fact that sometimes data is based on provisional data (for instance for laying hens in Italy) and there are huge fluctuations between years difficult to explain. Also, sometimes data at a high aggregated level is not consistent: for instance, number of laying hens in Sweden becomes different when the source is the country, Eurostat or FAOSTAT. We found the same problem for broilers between Eurostat and FAOSTAT.

Third, as explained in detail in Appendix 2 (food processor and scaling up: animal processor) we selected 2 different ways to calculate the number of animals per livestock sector and 3 different ways to calculate the nutritional requirements of those animals. The differences between the two methods flag the necessity to check and validate the data collected and/or the process of collecting it. For instance, when aiming to put data together and check coherence, we observe some flows of "negative" livestock. We observe a negative number of parental laying hens placed (-3.2 million) in France; data on chicks placed for parental stock in Spain seems wrong (-6.7 million); or it becomes odd the difference between the amount of parental chicks needed in Italy (i.e. 250.000 chicks) compared to the imports (millions).

**Link to EUROSTAT**

The exercise conducted to elaborate this report allow to check the robustness of the data available in statistics, and it seems critical. This exercise flag the need to make available more of the raw data. Many times the data is presented aggregated and under different categories. Despite the process of creating indicators at a national or European level is needed, and indicators need to be reported, it is equally important to make the raw data available and allow others to analyze and draw conclusions from the data.

On the other hand, there is a need to critically check the robustness of the data reported. Together with the statistics, there is a need to report how data has been handled, if and how validity and uncertainty of the data has been checked, and finally, report which of

the indicators deserve a “label” of robust estimation or uncertain /handle with care estimation.

In this process, it is essential to reach consensus in data gathering across countries as well as in definitions. And later on, keep consistency of the definition across statistics and across different aggregated levels. When consensus of a common definition is not possible, it may indicate that aggregation of information may lead to a loss of information. In that case, and again, it becomes essential to maintain and provide the raw data and the information available.

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# Appendix 1. Practical guides from data gathering to number crunching: guide to energy accounting

## A1. Guide to energy accounting in the State-of-the-Play of EU-8

Authors: Ripa M., Di Felice L.

This guide illustrates how energy is included in the analysis of the State-of-the-Play (SoP) of European countries. Part 1 explains relevant concepts and energy accounting categories for the different analytical tools in the SoP. Part 2 details the data management process.

### A1.1 Energy in the analytical tools of the State-of-the-Play

In the following we provide a brief overview of how each level of the energy system is described in the proposed method of accounting and, crucially, how different levels are connected to one another. Figure A1.1 shows a description of the energy sector across hierarchical levels.

The energy sector is described by holons. The dual nature of holons means that they are simultaneously defined by function and structure at each level. However, functional descriptions of the system prevail at higher levels, while structural characteristics dominate lower levels of analysis. We briefly comment on each level, and on the relations between a given level and the ones above and below it.

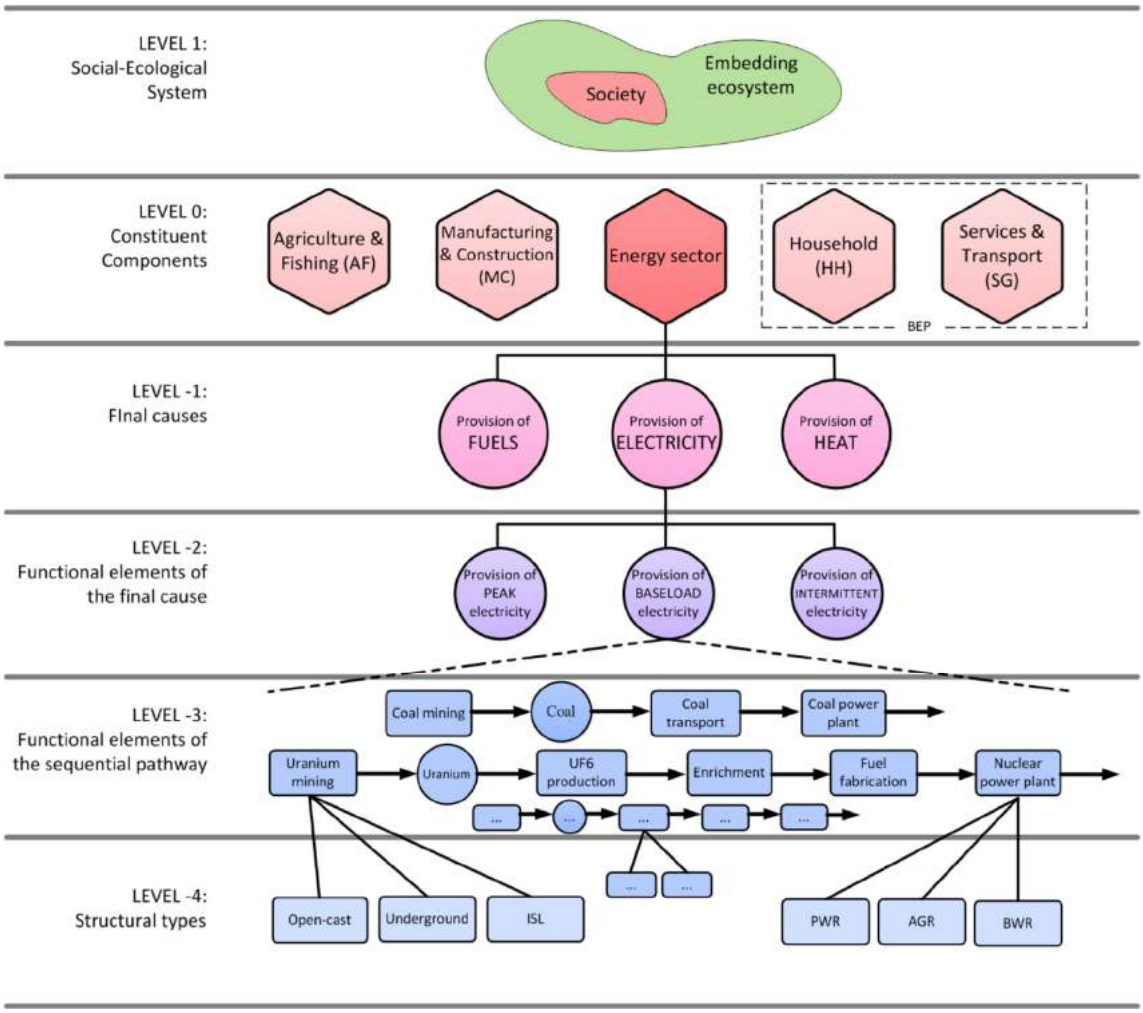



*Figure A1.1. Hierarchical organization of the energy sector. Simbols'key provided in the Appendix*

**Level 1: Social-Ecological System**

The Level 1 is occupied by the whole social-ecological system, i.e. society and its embedding ecosystem. This is the systems view, encompassing both the biosphere and the technosphere. The compartments of society are further split at the level below.

**Level 0: Constituent components**

Level 0 is our focal level of analysis. Here, society is broken down into its constituent components, i.e. the sectors of the economy: Agriculture & Fishing (AF), Manufacturing & Construction (MC), the Energy Sector (ES), Households (HH) and Service & Government (SG). The categories are not fixed and can be varied depending on the goal of the analysis. An end-use matrix (EUM) is used here to describe which food, water and

energy carriers are consumed by which sector. For congruence to be maintained, it is essential that the sum of the funds and flows allocated to and consumed by the constituent components is equivalent to the total funds and flows consumed by society at the Level 1. Focusing on the energy sector, it is then broken down into its three main functions: provision of fuels, provision of electricity and provision of heat.

**Level -1: Final causes required by society (demand side)**

At the level -1, we define the characteristics of the supply of the energy sector: that is, which mix of inputs is required by society. The mix of inputs is determined by the final cause of the energy sector – *what are the outputs of the energy sector used for in society?* – therefore the description is not static. The functions of the energy sector can be broken down at different grains depending on the goal of the analysis: here, we make the distinction between the provision of fuels, electricity and heat, given the different functions played by the three energy carriers within society. By declaring the final causes of the energy sector, this level links the one above, where the EUM collected how many ECs are consumed by the different constituent components, to the one below, where we describe how the ECs are produced. Thus, level -1 requires a qualitative rather than quantitative description.

**Level -2: Production systems (supply side)**

Moving down a hierarchical level, we provide a description of the supply side of the energy sector, through functional processors describing the patterns of flows and funds needed to produce the energy carriers which are then consumed by society. Therefore, this level is characterized by aggregated processors such as “production of heat”. The output of the functional processors, then, corresponds to the sum of the carriers consumed in the EUM at Level 0. As always, congruence among levels must be maintained: the funds and flows consumed by the production systems for each energy carrier must add up to the total consumption of the energy sector at the Level 0.

**Level -3: Sequential pathways**

At the level -3, the production systems are broken down into their sequential pathways – a series of processes connected through material entailment. A set of various sequential pathways maps into the production systems at level -2. Electricity, for example, may be produced with a mix of coal and nuclear power, and each type of production is associated to a unique pathway. For nuclear power, for example, a pathway could be: extraction of uraniumàtransport of uraniumàuranium refinementàtransport of nuclear fuel elementàelectricity generation in a nuclear plant. Sequential pathways are the expansion of the production system processors, therefore the funds and flows characterizing the processor for “production of electricity”, for example, is the sum of the funds and flows of each step of its sequential pathway.

**Level -4: Realized functional elements (not reported in Figure A1.1)**

The level -4 is populated by realized functional elements: that is, the functional elements which make up the unique sequential pathways of Level -3.

**Level -5: Structural elements**

At the lower levels of analysis the structural descriptions of holons prevails. Level -5 is populated by the different structural elements composing the functional elements of Level -4. There is no 1:1 mapping between function and structure: a coal CHP plant can simultaneously cover the function of heat and electricity generation, and a large hydropower plant can cover the function of either baseload or peak electricity depending on the context. The mapping between function and structure, thus, is open and flexible, in line with the MuSIASEM rationale. Examples of elements populating the Level -5 may include different type of nuclear plants, e.g. pressurized water reactors or boiling water reactors, or different types of coal mining techniques, e.g. opencast or underground coal mining.

A worked example of the aggregation of structural elements into functional ones, and of functional ones into a description of the energy sector (Level 0), is provided for the case study of Catalonia (Section 4.1).

### A1.1.1 The energy grammar

The concept of 'grammar' forces to declare the pre-analytical decisions about: (i) semantic and formal categories used for the accounting – primary energy sources (PES), energy carriers (EC), and production factors; (ii) the set of functional and structural elements of the power-supply system included in the analysis.

Since Figure A1.1 only showed some examples of the building blocks of the energy sector, we introduce here an image of the energy grammar. The energy grammar reflects a semantic mapping of the energy sector, meaning that information in the grammar is not split hierarchically. On the left side of the grammar, a specification of unique functional sequential pathways is shown (structures are not shown). At the right of the boxes showing the sequential pathways, the three energy carriers of the energy sector are shown, and linked finally to end uses. Both the hierarchical description of Figure A1.1 and the pathway description of Figure A1.2 are useful in understanding the application to follow.

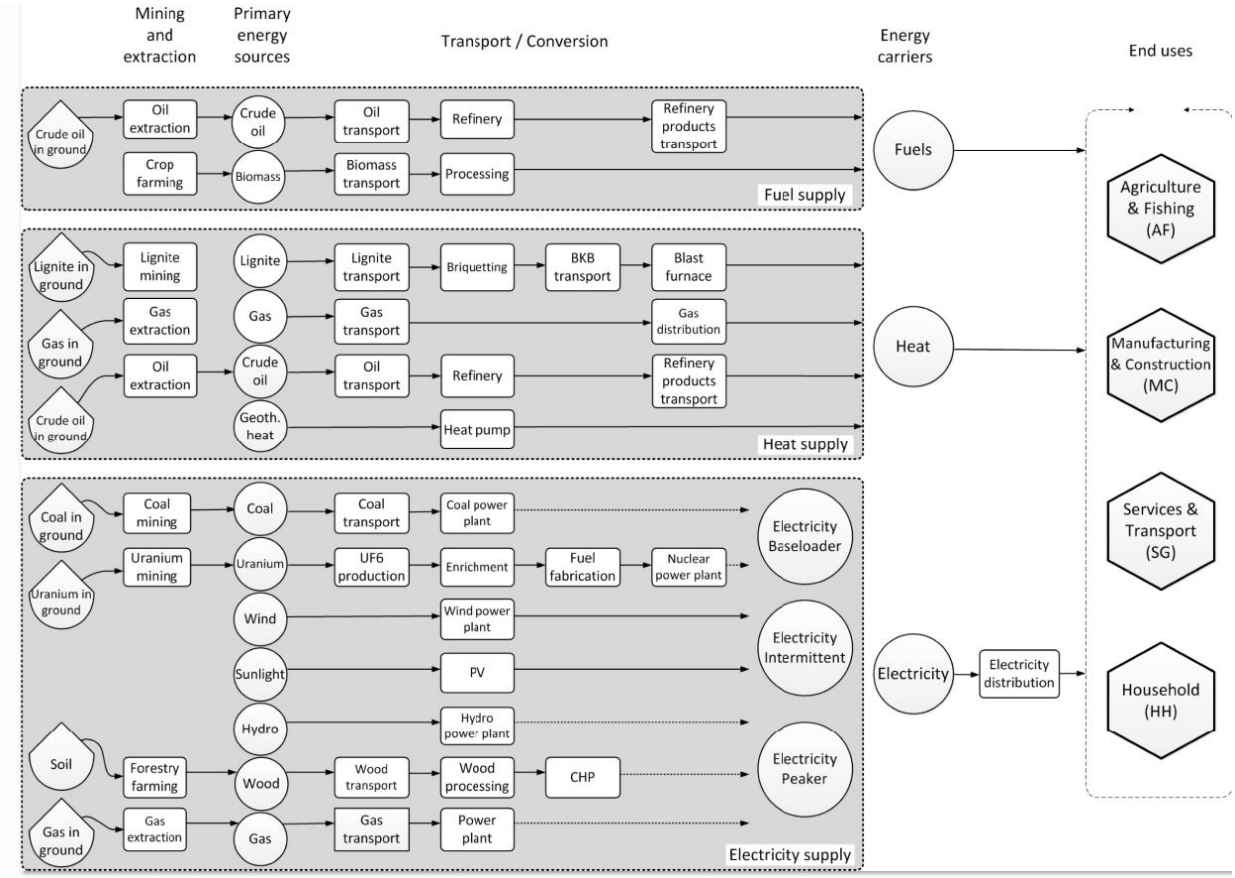



*Figure A1.2. Energy grammar. The key for symbols is reported in the Appendix. Transport steps are included in the grammar but not taken into consideration in the accounting.*

## A1.1.2 Energy processors

Each rectangular box of the previous figure (energy grammar) represents a processor that metabolizes inputs from both the technosphere and the biosphere, and produces outputs, both useful (to society) and released to the environment. Figure A1.3 shows an example of a structural processor (level -5) for a nuclear pressurized water reactor (PWR). The processor relates internal inputs and outputs, to external inputs and outputs. "Internal" refers to elements that are consumed or produced (flows), and maintained (funds) by the society under human control – they are metabolized inside the *technosphere*. "External" refers to elements that are produced or received (flows) by processes outside human control; they are metabolized outside the *technosphere* requiring a supply and sink capacity to be provided by the biosphere.

Therefore, the processor is associated with 5 sets of elements:

(1) Flows under human control (internal inputs), coming from the technosphere

(2) Funds under human control (internal inputs), going to the technosphere

(3) Flows extracted from the biosphere (external inputs)

(4) Flows discharged to the biosphere (external outputs)

(5) Flows generated for societal consumption, that maintain human funds (internal outputs)

What distinguishes processors from similar tools is their inclusion within a hierarchical organization of elements of complex systems. This means that processes are described in two dimensions rather than one, and can be disaggregated both horizontally, splitting a process into its various steps or functions, and vertically, splitting a process into its various mechanisms or structures. This means that, while functionality is not a material property of the system, functional processors can be built, representing inputs and outputs needed to carry out a certain task.

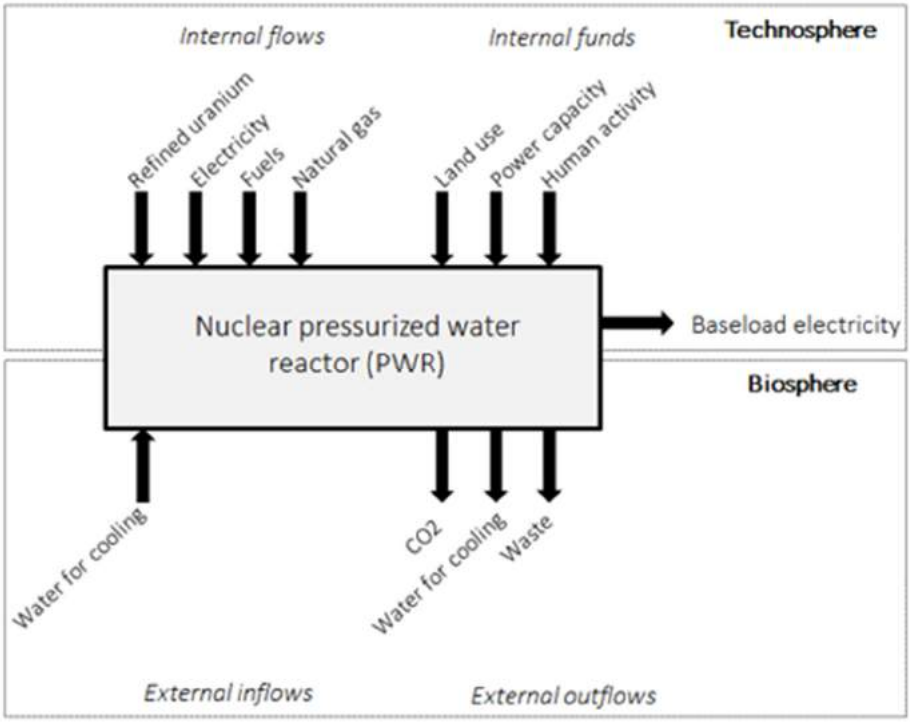



*Figure A1.3. Example of an energy processor*

A pattern of inputs and outputs is associated to each structural element: flows (electricity, fuels, water, $CO_2$ emissions and waste) and funds (labour and power capacity).

An overview of the top-down data used for the main functional energy processors is given in the following Table A1.1 (details about the sources of data and structural processors are given in the part 2: data management).

*Table A1.1. Overview of the top-down data in the energy processors*

| Dimension | Input/output | PRODUCT/ INDIC_SB | Processor | INDIC_NRG/NACE_R2 | Data source |
|---|---|---|---|---|---|
| Biosphere | Coal | 2115 | Coal Mining | B_100100 Primary production | Energy Balance |
| | | 2116 | Coal Mining | B_100100 Primary production | Energy Balance |
| | | 2117 | Coal Mining | B_100100 Primary production | Energy Balance |
| | | 2118 | Coal Mining | B_100100 Primary production | Energy Balance |
| Biosphere | Water | bottom-up | Coal Mining | | see 'bottom up accounting' |
| Biosphere | GHG emissions | bottom-up | Coal Mining | | see 'bottom up accounting' |
| Technosphere | Electricity | 6000 | Coal Mining | B_101310 Consumption in Coal Mines | Energy Balance |
| Technosphere | Heat | see Table A1.3 | Coal Mining | B_101310 Consumption in Coal Mines | Energy Balance |
| Technosphere | Fuel | see Table A1.3 | Coal Mining | B_101310 Consumption in Coal Mines | Energy Balance |

| | | | | | |
|---|---|---|---|---|---|
| Technosphere | Human Activity | V16150 | Coal Mining | B051 Mining of hard coal | Annual detailed enterprise statistics for industry |
| Biosphere | Lignite | 2210 | Lignite Mining | B_100100 Primary production | Energy Balance |
| Biosphere | Water | bottom-up | Lignite Mining | | see 'bottom up accounting' |
| Biosphere | GHG emissions | bottom-up | Lignite Mining | | see 'bottom up accounting' |
| Technosphere | Electricity | 6000 | Lignite Mining | B_101310 Consumption in Coal Mines | Energy Balance |
| Technosphere | Heat | see Table A1.3 | Lignite Mining | B_101310 Consumption in Coal Mines | Energy Balance |
| Technosphere | Fuel | see Table A1.3 | Lignite Mining | B_101310 Consumption in Coal Mines | Energy Balance |
| Technosphere | Human Activity | V16150 | Lignite Mining | B052 Mining of lignite | Annual detailed enterprise statistics for industry |
| Biosphere | Crude oil | 3105 | Oil extraction | B_100100 Primary production | Energy Balance |
| Biosphere | Water | bottom-up | Oil extraction | | see 'bottom up accounting' |
| Biosphere | GHG emissions | bottom-up | Oil extraction | | see 'bottom up accounting' |
| Technosphere | Electricity | 6000 | Oil extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |

| | | | | | |
|---|---|---|---|---|---|
| Techno sphere | Heat | see Table A1.3 | Oil extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |
| Techno sphere | Fuel | see Table A1.3 | Oil extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |
| Techno sphere | Human Activity | V16150 | Oil extraction | B061 Extraction of crude petroleum | Annual detailed enterprise statistics for industry |
| Biosph ere | Natural gas | 4100 | Gas extraction | B_100100 Primary production | Energy Balance |
| Biosph ere | Water | bottom-up | Gas extraction | | see 'bottom up accounting' |
| Biosph ere | GHG emissions | bottom-up | Gas extraction | | see 'bottom up accounting' |
| Techno sphere | Electricity | 6000 | Gas extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |
| Techno sphere | Heat | see Table A1.3 | Gas extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |
| Techno sphere | Fuel | see Table A1.3 | Gas extraction | B_101305 Consumption in Oil and gas extraction | Energy Balance |
| Techno sphere | Human Activity | V16150 | Gas extraction | B062 Extraction of natural gas | Annual detailed enterprise statistics for industry |
| Biosph ere | Uranium | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Biosph ere | Water | bottom-up | Uranium Mining | | see 'bottom up accounting' |

| | | | | | |
|---|---|---|---|---|---|
| Biosphere | GHG emissions | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Technosphere | Electricity | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Technosphere | Heat | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Technosphere | Fuel | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Technosphere | Human Activity | bottom-up | Uranium Mining | | see 'bottom up accounting' |
| Biosphere | Land | | | Crop cultivation for biofuel | |
| Biosphere | Blue Water | | | Crop cultivation for biofuel | see Food guide |
| Biosphere | Green Water | | | Crop cultivation for biofuel | see Food guide |
| Technosphere | Fertilizers | | | Crop cultivation for biofuel | see Food guide |
| Technosphere | Human Activity | | | Crop cultivation for biofuel | see Food guide |
| Technosphere | Crude oil | 3105 | Refining | B_101008 Transformation input in Refineries | Energy Balance |
| Biosphere | Water | bottom-up | Refining | | see 'bottom up accounting' |
| Biosphere | GHG emissions | bottom-up | Refining | | see 'bottom up accounting' |
| Technosphere | Electricity | 6000 | Refining | B_101307 Consumption in Petroleum Refineries | Energy Balance |

| | | | | | |
|---|---|---|---|---|---|
| Techno sphere | Heat | see Table A1.3 | Refining | B_101307 Consumption in Petroleum Refineries | Energy Balance |
| Techno sphere | Fuel | see Table A1.3 | Refining | B_101307 Consumption in Petroleum Refineries | Energy Balance |
| Techno sphere | Human Activity | V16150 | Refining | C192 Manufacture of refined petroleum products | Annual detailed enterprise statistics for industry |
| Techno sphere | Fuels (output) | see Table A1.3 | Refining | B_101108 Transformation output from Refineries | Energy Balance |
| Techno sphere | Coking coal | 2116 | Coking | B_101004 Transformation input in Coke Ovens | Energy Balance |
| Biosph ere | Water | bottom-up | Coking | | see 'bottom up accounting' |
| Biosph ere | GHG emissions | bottom-up | Coking | | see 'bottom up accounting' |
| Techno sphere | Electricity | 6000 | Coking | B_101312 Consumption in Coke Ovens | Energy Balance |
| Techno sphere | Heat | see Table A1.3 | Coking | B_101312 Consumption in Coke Ovens | Energy Balance |
| Techno sphere | Fuel | see Table A1.3 | Coking | B_101312 Consumption in Coke Ovens | Energy Balance |
| Techno sphere | Human Activity | V16150 | Coking | C191 Manufacture of coke oven products | Annual detailed enterprise statistics for industry |
| Techno sphere | Coke (output) | see Table A1.3 | Coking | B_101104 Transformation output from Coke Ovens | Energy Balance |

| | | | | | |
|---|---|---|---|---|---|
| Techno sphere | Coal | 2115 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | | 2116 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | | 2117 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | | 2118 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Lignite | 2210 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Gas/diesel oil | 3260 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Natural gas | 4100 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Solid biofuels | 5541 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Biogas | 5542 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Municipal waste | 5543 | Electricity production | B_101001 Transformation input - Conventional Thermal Power Stations | Energy Balance |
| Biosph ere | Water | bottom-up | | Electricity production | see 'bottom up accounting' |
| Biosph ere | GHG emissions | bottom-up | | Electricity production | see 'bottom up accounting' |
| Techno sphere | Electricity | 6000 | Electricity production | B_101301 Own Use in Electricity, CHP and Heat Plants + B_101302 Pumped storage power stations balance | Energy Balance |

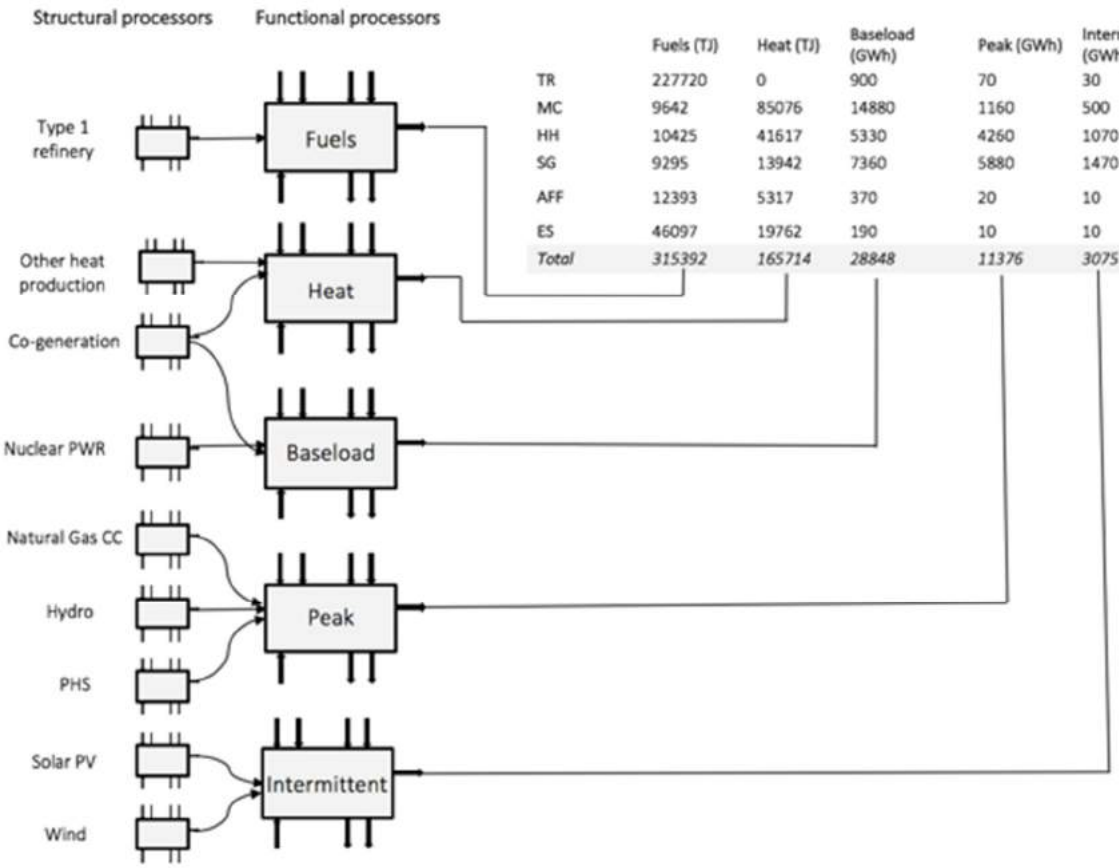
| | | | | | |
|---|---|---|---|---|---|
| Techno sphere | Heat | see Table A1.3 | Electricity production | B_101301 Own Use in Electricity, CHP and Heat Plants + B_101302 Pumped storage power stations balance | Energy Balance |
| Techno sphere | Fuel | see Table A1.3 | Electricity production | B_101301 Own Use in Electricity, CHP and Heat Plants + B_101302 Pumped storage power stations balance | Energy Balance |
| Techno sphere | Human Activity | V16150 | Electricity production | D3511 Production of electricity | Annual detailed enterprise statistics for industry |
| Techno sphere | Electricity (output) | 6000 | Electricity production | B_101101 Transformation output - Conventional Thermal Power Stations | Energy Balance |
| Techno sphere | Coal | 2115 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | | 2116 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | | 2117 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | | 2118 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | Lignite | 2210 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | Gas/diesel oil | 3260 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | Natural gas | 4100 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | Solid biofuels (excludin | 5541 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |

| | | | | | |
|---|---|---|---|---|---|
| | g charcoal) | | | | |
| Techno sphere | Biogas | 5542 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Techno sphere | Municipal waste | 5543 | District Heating | B_101009 Transformation input - District heating plants | Energy Balance |
| Biosph ere | Water | bottom-up | District Heating | | see 'bottom up accounting' |
| Biosph ere | GHG emissions | bottom-up | District Heating | | see 'bottom up accounting' |
| Techno sphere | Electricity | 6000 | District Heating | included in Electricity production | |
| Techno sphere | Heat | see Table A1.3 | District Heating | included in Electricity production | |
| Techno sphere | Fuel | see Table A1.3 | District Heating | included in Electricity production | |
| Techno sphere | Human Activity | V16150 | District Heating | D353 Steam and air conditioning supply | Annual detailed enterprise statistics for industry |
| Techno sphere | Heat (output) | see Table A1.3 | District Heating | B_101109 Transformation output - District Heating Plants | Energy Balance |
| Techno sphere | Electricity | 6000 | Electricity distribution | B_101400 Distribution Losses | Energy Balance |
| Techno sphere | Human Activity | V16150 | Electricity distribution | D3512 Transmission of electricity | Annual detailed enterprise statistics for industry |

| | | | | | |
|---|---|---|---|---|---|
| | | | Electricity distribution | D3513 Distribution of electricity | Annual detailed enterprise statistics for industry |
| | | | Electricity distribution | D3514 Trade of electricity | Annual detailed enterprise statistics for industry |
| Techno sphere | Natural gas | 4100 | Gas distribution | B_101400 Distribution Losses | Energy Balance |
| Techno sphere | Human Activity | V16150 | Gas distribution | D3522 Distribution of gaseous fuels through mains | Annual detailed enterprise statistics for industry |
| | | | Gas distribution | D3523 Trade of gas through mains | Annual detailed enterprise statistics for industry |

For sake of clarity, the lower part of the processors (inputs coming from biosphere) is accounted in the EPM, whilst the upper part of the processors (production factors from thechnosphere) is accounted in EUM.

Moving beyond mechanistic system descriptions, a functional grouping of structural processors is then performed. In the case of electricity production, the distinction among base-loader, peaker and intermittent is maintained by calculating the utilization factor of the different power plant (structural types). Once again the choice on how to adapt the framework depends on what is relevant for a given case study: fuels, for example, could be broken down into further sub-categories if needed.




| | Fuels (TJ) | Heat (TJ) | Baseload (GWh) | Peak (GWh) | Intermittent (GWh) |
|---|---|---|---|---|---|
| TR | 227720 | 0 | 900 | 70 | 30 |
| MC | 9642 | 85076 | 14880 | 1160 | 500 |
| HH | 10425 | 41617 | 5330 | 4260 | 1070 |
| SG | 9295 | 13942 | 7360 | 5880 | 1470 |
| AFF | 12393 | 5317 | 370 | 20 | 10 |
| ES | 46097 | 19762 | 190 | 10 | 10 |
| *Total* | *315392* | *165714* | *28848* | *11376* | *3075* |

*Figure A1.4. Example of aggregation of structural processors into functional*

An overview of the whole accounting is shown in Figure A1.5.

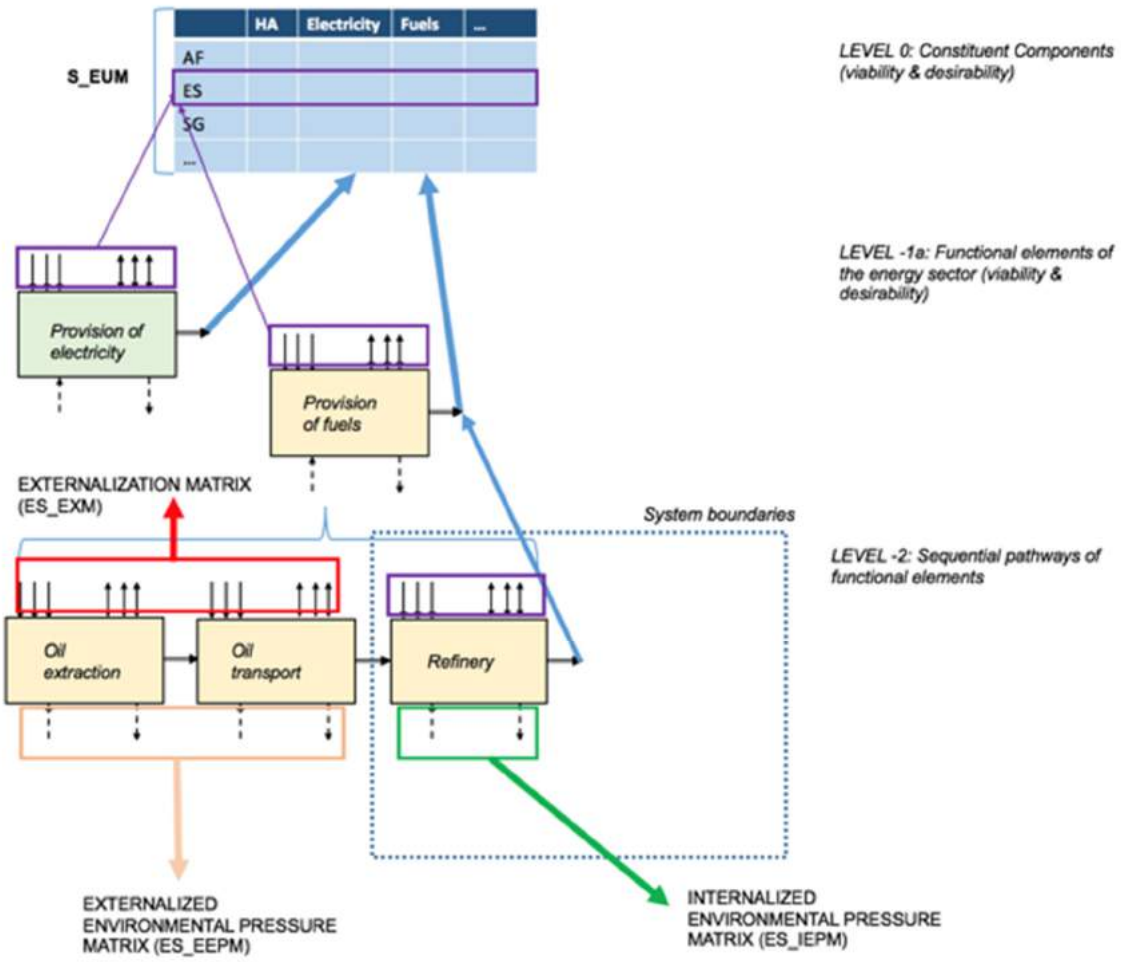



*Figure A1.5. Overview of the energy accounting through the different hierarchical levels*

### A1.1.3 Energy in the Local End-Use Matrix

The end-use matrix is the tool used to check the 'internal constrains'. In energy it accounts for the production factors (or secondary inputs from technosphere) necessary for the processes to operate properly and that include (i) electricity, heat and fuel, (ii) labor, (iii) water, (iv) other materials (as fertilizers in case of biofuels). In other words, we have to specify how much inputs – energy carriers and human labor – we have to invest in a given set of energy transformations (rectangular boxes in the energy grammar) under human control to get a net supply of energy carriers.

The end-use matrix characterizes the pattern of consumption: when looking at internal constraints the investments of production factors under human control refer only to the

"biophysical costs" (i.e. viability) associated with the building, maintenance and operation of fund elements used in the exploitation process.

Depending on the hierarchical level taken into consideration, the data for EUM, as well as for EPM, were accounted top-down (mainly using Eurostat datasets) or bottom-up (from reports, LCA datasets, etc).

In particular, the data from level 0 to level -3 (excepted for the semantic split among peak, baseload and intermittent electricity) were accounted from top-down extensive data according to the algebra of accounting described in the following.

Algebra of the top-down accounting

Each sector (e.g. energy sector) can be formalised as an m x n matrix A

**Step 1: build 'domestic vectors'**

Let consider the processor a one-dimensional array $\mathbf{v_i}$ (i = 1, 2, . . . , m) where $\mathbf{v_{i,j}}$ (j = 1, 2, . . . , n) are the components of the vector $\mathbf{v_i}$ and represent direct biophysical requirements (e.g. primary and secondary inputs), from the biosphere and/or technosphere.

Each hierarchical level (**n**) can be described as a new one-dimensional array $\mathbf{v_i}$. Each of these arrays is an ordered collection of **k** real numbers $\mathbf{v_1, v_2, . . . , v_k}$, and is written as $\mathbf{v} = (\mathbf{v_1}, \mathbf{v_2}, . . . , \mathbf{v_k})$.

Therefore, the vector at level **n** can be described as the sum of the vectors at lower level **n-1**, according to the equation:

$$v_i = \sum_{v=1}^{i} v_{i-1}$$

**Step 2: build a unit vector**

The 'domestic' extensive vectors are then used to calculate normalized vectors by dividing each vector by a scalar **α**. A new vector, defined in reference to a unitary member, will be defined as:

$$\hat{v} = \frac{v}{\alpha}$$

where **α** is the scalar, e.g. the output (in physical units) of the processor according to its final cause.

**Step 3. Scaling up unit vectors to build new vectors (externalization matrix)**

The unit vectors are then scaled up to obtain new extensive vectors. Multiplication of a vector by a new scalar changes the magnitude of the vector, but leaves its direction unchanged. The new scalar is the imported flow which is used to re-scale the domestic unit vectors:

$$v' = \alpha' \hat{v}$$

Then it is possible to define a new matrix which represents the externalization matrix calculated using the vectors

## A1.1.4 Energy in the Externalized End-Use Matrix

The externalized EUM accounts for the use of resources in order to produce the energy commodities imported by EU-8 countries. Industrial and manufactured products are not accounted. Energy is accounted in the externalized energy processors following the algebra explained above. The total ECs uses in the EUM of the SoP will be thus the sum of direct ECs within the country for both domestic consumption and for exports, plus indirect ECs associated to imports.

*Boundaries definitions in the Externalization matrix (of the ES)*

The indirect energy component includes the energy embodied in materials and processes that are used to produce a product. Hence, one can progress infinitely upstream in counting all of the indirect energy. With each stage upstream, the indirect energy requirements become smaller. The boundary here must be well defined. The cutoff adopted for externalization truncation is here described by an equation.

The matrix can be defined as a sum of the following matrices:

$$A' = A'_{PES} + A'_{PES_{EC}} + A'_{EC}$$

Where is the matrix constituted of the row vectors

$$v'_{PES} = \alpha'_{PES} \hat{v}$$

Where corresponds to the direct import of PES (i.e. coal, gas, oil, etc) is the matrix including the row vectors

$$v'_{PES_{EC}} = \alpha'_{PES_{EC}} \hat{v}$$

Where corresponds to PES (i.e. coal, gas, oil, etc) requirements to produce the EC imported

### A1.1.5 Energy in the Environmental Pressure Matrix

It is possible to determine the pressure that the processes of the energy sector have on the environment: depletion of stocks, consumption of flows from the ecosystem, sink capacity and occupation of ecosystem funds. Primary Energy Sources (PES) expressed in physical units such as tonnes of coal, kilograms of uranium) – the use of PES makes it possible to bridge the assessments made using energy variables with assessment made with non-energy physical units. This analysis is useful for dealing with environmental impact and biophysical constraints.

The calculus performed to obtain the EPM are already reported in the Algebra of accounting.

An overview of the top-down data used to calculate EUM and EPM is given in Table A1.2, whilst a detailed de*scri*ption of the data sources used for the bottom-up accounting is given in the section A1.2.5.

## A1.2 Data Management

This part of the guide shows the process of data management combining both top-down statistics and bottom-up aggregation of energy used in different processors, alongside calculus procedures and main uncertainties affecting the interpretation of results.

*Premise*

The end-use matrix (meaning an array of flows and funds describing the metabolism of a system) requires the collection of data (e.g. energy, power capacity, human activity – i.e. working hours) from multiple datasets.

An overview of the sources of data is given in the Appendix where the data are hierarchically organized according to Table A1.2. A detailed list of assumptions is included in the Table A1.2 footnotes.

According to MAGIC Data Management Plan, the statistical learning process consist of the following steps:

Data production

The first cycle **Data production** includes the following four steps:

1. *Survey Sampling* for planning the way to collect data,

2. *Data Collection* for doing the operative part of field analysis,

3. *Data Validation* for assuring the quality of collected data,

4. *Data Imputation* for replacing missing data.

The analysis of the State of the Play (SoP) does not properly include a phase of data production (i.e. primary data coming from survey or field). The data used for the analysis were extracted from different sources and datasets and then processed. Therefore for data collection, data validation, check the metadata links listed in the following.

Conversely, Data Imputation has been been addressed in the section Pre-Processing.

## A1.2.1 Data extraction

The second cycle **Data Extraction** includes the following four steps:

1. *Data Selection* for filtering units and variables of interest,

2. *Data Transformation* for recoding and normalization,

3. *Data Organization* for assuring the coherence of data of interest,

4. *Pre-Processing* for preliminary descriptive statistics.

The sample are 8 EU countries (Spain, Italy, Germany, France, Romania, Sweedend, UK) and the reference year is 2012.

Data were extracted between October 2017 and January 2018 from different sources.

## A1.2.2 Data selection

### Energy data

The Energy Balances of Eurostat (Eurostat, 2012a) provides annual data on quantities for crude oil, petroleum products, natural gas and manufactures gases, electricity and derived heat, solid fossil fuels, renewables and wastes covering the full spectrum of the

energy sector from supply through transformation to final consumption by sector and fuel type. Also, annual imports and exports data of various energy carriers are included.

Data covers all major sectors of the economy that are involved in the production, trade, energy transformation and energy consumption (the energy sector, industrial sector, transport, commercial and public services, agricultural/forestry/fishing and residential).

Classifications, nomenclatures and correspondence tables are available at the Eurostat's classification server RAMON.

The classification of the economic activities both in carrying out the surveys and in presenting the results is in accordance to NACE Rev.2, i.e. each economic activity is defined by a seven digits code (e.g. B_102010) and a label (e.g. Residential)

Each energy product is denoted by a four digits code (e.g. 6000) and a label (e.g. Electricity).

They were downloaded in csv format and imported into excel for validation, imputation and extraction. Data units are TJ/year.

More info regarding the metadata can be found: http://ec.europa.eu/eurostat/cache/metadata/en/nrg_10_esms.htm

**Human Activity data**

Data on hours worked (human activity − HA) have been obtained from the National account employment data (Eurostat, 2012b) (nama_nace64_e) and Annual detailed enterprise statistics for industry (Eurostat, 2012c) (sbs_na_ind_r2).

National accounts are a coherent and consistent set of macroeconomic indicators: among them, data on total employment domestic concept (EMP_DC) were selected and downloaded in (thousands of) total hours worked (THS_HW) for all the NACE activities. Employment covers all persons engaged in some productive activity (within the production boundary of the national accounts). Employed persons are either employees (working by agreement for another resident unit and receiving remuneration) or self-employed (owners of unincorporated enterprises).

National accounts use aggregation levels of the NACE Rev.2 classification to define industry breakdowns (see above).

More info regarding the metadata can be found: http://ec.europa.eu/eurostat/cache/metadata/en/nama10_esms.htm

Structural business statistics (SBS) describes the structure, conduct and performance of economic activities, down to the most detailed activity level (several hundred economic sectors).

Among them, data on Labour inputs (coded as 16 xx x) were selected and filtered. In particular, data on Hours worked by employees (V16150) were selected and then downloaded for the following NACE activities: B051, B052, C191, D351, D3512, D3513, D3514, B052, B062, D353, D3522, D3523, B061, C192.

Annual detailed enterprise statistics for industry use aggregation levels of the NACE Rev.2 classification to define industry breakdowns (see above).

More info regarding the metadata can be found:

http://ec.europa.eu/eurostat/cache/metadata/en/sbs_esms.htm

**Energy Imports data**

Import datasets from Eurostat were used to calculate imports (Eurostat, 2012d, 2012e, 2012f, 2012g) of PES and EC for each country.

Classifications, nomenclatures and correspondence tables are available at the Eurostat's classification server RAMON.

Basic data on energy quantities are given in fuel specific units e.g. solid and liquid fuels in thousand tonnes, electricity in Gigawatt-hours, heat and gases in terajoules (TJ).

They were downloaded in csv format and imported into excel for validation, imputation and extraction.

More info regarding the metadata can be found:

http://ec.europa.eu/eurostat/cache/metadata/en/nrg_10_esms.htm

### A1.2.3 Data imputation: missing data

The energy and human activity data contained cells with missing values due to poor data quality or different level of disaggregation in Eurostat datasets. Two main issues were found: first, some HA data were missing because the information was either unavailable or withheld due to poor data quality (i.e. not disaggregated). In such cases, the known quantities of labour given by the lower level NACE codes were subtracted from those

provided by the higher level NACE code. In other cases, where energy use/labour for subsector was missing/not disaggregated (and it was not possible calculating it from higher level), input-output benchmarks from other countries were used to disaggregate the energy use of a higher level subsector and derive the energy use for a lower level subsector.

For a detailed description of missing data imputation, see Table A1.2.

*Table A1.2. Hierachical organization of data*

| | Hierarchical Organization (Level) | Name | Energy[i] | | Human Activity[ii] | |
|---|---|---|---|---|---|---|
| Whole | 1 | Country | B_102010 | Residential | | *calculated* |
| | | | B_101800 | Final Energy Consumption - Industry | C | Manufacturing* |
| | | | | | F | Construction |
| | | | B_102030 | Agriculture/Forestry | A | Agriculture, forestry and fishing |
| | | | B_102035 | Services | E + G-U | Services* |
| | | | B_101300 | Consumption in Energy Sector | B051 + B052 + D + C19 | |
| Costituent Component | 0 | Energy Sector (ES) | Electricity (n-1) + Heat (n-1) + Fuel (n-1) | | | |
| Functional Elements | -1 | Electricity | Extraction for El (n-2) + Processing (n-2) + Generation (n-2) + El Distribution (n-2) | | | |
| | -1 | Heat | Extraction for He (n-2) + Processing for heat (Level n-2) + District Heating (n-2) + He Distribution (n-2) | | | |
| | -1 | Fuel | Fossil fuels (Oil extraction + Refinery) + Biofuels (Crop farming + Processing) | | | |
| Sequential pathway for Electricity | -2 | PES extraction for El | B_101310 | Coal Mining (hard coal + lignite)[iii] | B051 | Mining of hard coal[iv] |
| | | | | | B052 | Mining of lignite |
| | | | | Uranium Mining & Fuel fabrication | | Uranium Mining & Fuel fabrication |
| | -2 | Processing for El | B_101312 | Consumption in Coke Ovens | C191[v] | Manufacture of coke oven products |
| | -2 | El Generation | B_101301 | Own Use in Electricity, CHP and Heat Plants[vi] | D351 | Production of electricity |
| | | | B_101302 | Pumped storage power stations balance | | |
| Sequential pathway for Heat | -2 | El Distribution | B_101400 | Distribution Losses | D3512 | Transmission of electricity[vii] |
| | | | | | D3513 | Distribution of electricity |
| | | | | | D3514 | Trade of electricity |
| | -2 | PES extraction for heat | B_101310 | Coal Mining (lignite)[viii] | B052 | Mining of lignite[ix] |
| | | | B_101305 | Consumption in Oil and gas extraction[x] | B062 | Extraction of natural gas[xi] |
| Sequential pathway for Fuel | -2 | Processing for he | B_101315 | Consumption in Blast Furnaces | | |
| | -2 | District heating | | District heating | D353 | Steam and air conditioning supply |
| | -2 | He distribution | B_101400 | Distribution Losses | D3522 | Distribution of gaseous fuels through mains |
| | | | | | D3523 | Trade of gas through mains |
| | -2 | Oil extraction | B_101305 | Consumption in Oil and gas extraction | B061 | Extraction of petroleum[xii] |
| | -2 | Refining | B_101307 | Consumption in Petroleum Refineries | C192 | Manufacture of refined petroleum products[xiii] |
| | -2 | Crop farming for biofuel | | | *bottom - up data* | |
| | -2 | Processing | | | *bottom-up data* | |

Footnotes of detailed assumptions:

[i] The Eurostat dataset Energy Balance 'nrg_101a' (Eurostat, 2012a) has been used to calculate the ECs (electricity, heat and fuels) for the different hierarchical levels. The sectors (INDIC_NRG sector) taken into account in the analysis are listed in the Table by means of an unique code (e.g. B_101310) and name (e.g. Coal Mining).

[ii] The Eurostat datasets 'nama_nace_64_e' (Eurostat, 2012b) and 'sbs_na_ind_r2' (Eurostat, 2012c) have been used for working hours for the level n+1 and n to n-2, respectively. The sectors (NACE_R2 sector) are specified in the Table by means of a unique code (e.g. B052) and a name (e.g. Lignite Mining).

[iii] Coal Mining (B_101310) includes the energy inputs (ECs) consumed both in Hard Coal and Lignite Mining, therefore, being ES only mining Hard Coal, the intensive values of ECs (EC consumed/TJ hard coal) have been used as benchmarks, scaled up (i.e. multiplied by the amount of hard coal mined in the country) and subtracted by the corresponding ECs in B_101310. This approach has been applied only to DE and RO, being the only countries mining both hard coal and lignite.

[iv] Missing data for Coal Mining (B051) in IT and RO has been calculated by assuming 35.5 h/TJ of hard coal mined from average values in DE, ES, UK: B051/ (2115+2116+2117+2118) B_100100

[v] Missing data for Coking (C191) have been calculated by assuming 3.3 h/TJ coking coal input to coking (this value comes from the average values – arithmetic mean - for IT and UK): C191 (working hours in Coking)/2116 $_{B_101004}$ (Coking coal input in Coking)

[vi] Due to missing data, the data for Electricity production (D3511) for DE and FR has been calculated bottom-up

[vii] Data on transmission and distribution for heat (D3522+ D3523) and electricity (D3512 + D3513 + D3514) were missing. Neverthless it seems reasonable considering that the more electricity and heat a country trades, the more human activity is requested, therefore 7E+02 h of transmission and distribution/TJ electricity traded and 1.9E+02 h of transmission and distribution/TJ heat traded are assumed for DE and FR

[viii] Coal Mining (B_101310) includes the energy inputs (ECs) consumed both in Hard Coal and Lignite Mining, therefore, being ES only mining Hard Coal, the intensive values of ECs (EC consumed/TJ hard coal) have been used as benchmarks, scaled up (i.e. multiplied by the amount of hard coal mined in the country) and subtracted by the corresponding ECs in B_101310. This approach has been applied only to DE and RO, being the only countries mining both hard coal and lignite.

[ix] Missing data for Lignite Mining (B052) in DE has been calculated by assuming 13.7 h/TJ of lignite mined from RO: B052/2210 $_{B_100100}$

[x] Oil and Gas extraction (B_101305) includes the energy inputs consumed both in Oil and Gas Extraction, therefore, the intensive values of ECs (EC consumed/TJ oil and gas) have been used as benchmarks, scaled up (i.e. multiplied by the amount of gas and oil extracted in the country, respectively)

[xi] Missing data for Gas extraction (B062) have been calculated by assuming 31.3 h/TJ gas extracted from average (arithmetic mean) values in IT and NL: B062/4100 $_{B_100100}$

[xii] Missing data for Oil extraction (B061) have been calculated by assuming 12.5 h/TJ oil extracted from average values in IT and NL: B061/3105 $_{B_100100}$

[xiii] Missing data for refinery where calculated:

- For DE and ES as C19 (available) – C191 (calculated as explained above)
- For FR, RO, SE an average value of 5.9 h/TJ oil input to refinery (this value comes from the average values of the other counties): C192 (working hours in Refinery)/ 3105B_101008 (Crude oil input in Refinery)

## A1.2.4 Data transformation

The accounting categories from the different databases need to be transformed into MuSIASEM categories.

Firstly the throughputs of the energy carriers (electricity, heat and fuel) consumed in the Energy Sector were obtained by aggregating (bottom-up-wise) the different forms of each of these energy carriers provided in the Energy Balances of Eurostat (Eurostat, 2012a) (nrg_101a) as shown in Table A1.3.

*Table A1.3. Classification of the energy products (nrg_101a) into energy carriers (Electricity, Heat, Fuel)*

| Energy Carrier Categorization | Code | Energy Product |
|---|---|---|
| **Electricity** | 6000 | Electrical energy |
| **Heat** | 2100 | Hard Coal Derivatives |
| | 2200 | Lignite Derivatives |
| | 2410 | Oil shale and oil sands |
| | 3214 | Refinery gas |
| | 3215 | Ethane |
| | 3220 | Liquified petroleum gas |
| | 3270A | Total fuel oil |
| | 4000 | Gas |
| | 5200 | Derived heat |
| | 5532 | Solar thermal |
| | 5541 | Solid biofuels |

| | | |
|---|---|---|
| | 5542 | Biogas |
| | 5543 | Municipal waste |
| | 5544 | Charcoal |
| | 5550 | Geothermal Energy |
| | 7200 | Waste non renewable |
| **Fuels** | 3234 | Gasoline |
| | 3235 | Aviation gasoline |
| | 3244 | Other kerosene |
| | 3246 | Gasoline type jet fuel |
| | 3247 | Kerosene type jet fuel |
| | 3260 | Gas/diesel oil |
| | 5546 | Biogasoline |
| | 5547 | Biodiesels |
| | 5548 | Other liquid biofuels |
| | 5549 | Bio jet kerosene |

Data on PES domestic production have been derived from Primary production (B_100100) and PES imports from Imports (B_100300) for coal, lignite, oil and gas (data on uranium mining were not available):

*Table A1.4: Example of data on PES domestic production, imports and exports (energy Balance)*

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 2115 | 2116 | 2117 | | 2118 |
| Coal Mining | Hard Coal | Anthracite | Coking Coal | Other Coal | Bituminous | Sub-bituminous Coal |
| Lignite Mining | Lignite | 2210 Lignite/Brown Coal | | | | |
| Oil extraction | Oil | 3105 Crude oil (without NGL) | | | | |
| Gas extraction | Gas | 4000 Gas | | | | |

And then converted in physical units by using the calorific value (calculated using the ratio between Imports in TJ from Energy Balance and Imports in physical units in Imports –annual data).

Data on PES requirements for processing (e.g. Refining, Coking) were derived from Trasformation Input (B_101000):

*Table A1.5. Example of data on PES requirement in processing (Energy Balance)*

| PES to process | Process | Energy Balance code |
|---|---|---|
| Coal | Coking | B_101004 Transformation input in Coke Ovens |

| | | |
|---|---|---|
| Oil | Refining | B_101008<br><br>Transformation input in Refineries |
| Gas, Coal, Lignite, etc | Electricity supply | B_101001<br><br>Transformation input - Conventional Thermal Power Stations |
| Gas | District heating | B_101009<br><br>Transformation input - District heating plants |

Data on ECs domestic production were derived from Trasformation output:

*Table A1.6. Example of data on EC supply in processing (Energy Balance)*

| EC from the process | Process | Energy Balance code |
|---|---|---|
| Coke | Coking | B_101104<br><br>Transformation output from Coke Ovens |
| Fossil fuels | Refining | B_101108<br><br>Transformation output from Refineries |
| Electricity | Electricity supply | B_101101<br><br>Transformation output - Conventional Thermal Power Stations |
| Heat | District heating | B_101109<br><br>Transformation output - District Heating Plants |

## A1.2.5 Data organisation

Data has been organized as arrays in Excel files following several structures.

Data were organized in end-use matrix, meaning an array of data regarding energy, human activity (i.e. working hours), PES for each subsector (e.g. Coal Mining B_101310).

Then the different subsectors were semantically assigned to the three final causes: electricity, heat and fuel provision.

Although some processes deliver more than one output addressing different functions (joint production dilemma), the allocation is here avoided by assigning these processes (subsectors) to a single functional compartment (Electricity, Heat, Fuel production). In particular:

- hard coal mining is allocated to Electricity functional compartment
- lignite mining in splitted into: electricity and heat (90% and 97% of lignite goes to electricity in DE and RO, respectively; while the rest going to briquetting is included into 'heat functional processor')
- natural gas extraction is included in heat functional processor
- CHP is included into Electricity processor
- oil extraction and refinery are included in the fuel functional processor

Nevertheless, the coherence is ensured on the upper level (ES) where the data are summed up (thus avoiding double accounting).

## A1.2.5 Data pre-processing

No descriptive statistics have been made. The calculation procedures used in the Energy Sectors follows the general algebra of accounting (see above for further details).

The characterization of the energy sector has been performed by using statistical data (mainly Eurostat) till level n-3, the characterization under this level has required a bottom-up accounting of the specific structural processor as specified in the following.

**Bottom-up Accounting**

The bottom-up characterisation of the energy sector is broken down into the characterisation of electricity production, and production of thermal energy. For the production of electricity generation, data is obtained mostly through the Ecoinvent

database. Refinery data, on the other hand, is collected mostly through technical reports.

Electricity generation

Each typology of electricity generation is described by the same pattern of funds and flows, including: human activity, electricity, heat, fuels, water input, water output, water consumed, and GHG emissions. We briefly describe how each input/output was obtained for different typologies.

Ecoinvent aggregations

Data on the consumption of heat, fuels and water in electricity generation processes was obtained through the Ecoinvent database, as well as GHG emissions. In order to do so, categories provided in Ecoinvent were mapped onto MuSIASEM accounting categories. The aggregations between Ecoinvent datasets and MuSIASEM categories for each variable are included below. For each typology of electricity generation, the Ecoinvent specific data sources is also listed.

Fuels

Fuel consumption: diesel, burned in electricity generating set (MJ).

Heat

Heat consumption: heat, central or small-scale, other than natural gas (MJ); heat, district or industrial, natural gas (MJ); heat, district or industrial, other than natural gas (MJ)

For processes where natural gas is the primary PES, the natural gas input, listed under ecoinvent as “natural gas, high pressure (m3)” is considered as a separate PES rather than heat.

Electricity

Electricity consumption: electricity (low voltage) (kWh); electricity (medium voltage) (kWh); electricity (high voltage) kWh.

Water

For water we define three categories: water input, water output and water consumed. Water consumed is secondary as it is simply water output minus water input. For water output and input, the following Ecoinvent categories are aggregated:

Water input: water, completely softened, from decarbonised water, at user (kg); water, decarbonised, at user (kg); water, cooling, unspecified natural origin (m3)

Water output: Water (m3) – under the category Elementary flows/Emissions to water/unspecified. Water output (m3) under the category Elementary flows/Emissions to air/unspecified is not accounted for.

All water is accounted for in m3. Ecoinvent categories in kg are converted to m3 (1 kg of water: 0.001 m3 of water).

GHG emissions

Emissions to air from Ecoinvent are converted into their CO2 equivalent, following the conversion values given by the 5$^{th}$ IPCC assessment report. The following emissions are taken into account: Carbon dioxide, fossil; Methane, fossil; Nitrogen oxides.

*Mapping between Ecoinvent data sources and MuSIASEM typologies*

The Ecoinvent datasets are listed below, in the format MuSIASEM typology: Ecoinvent dataset. For all types of electricity generation, the Ecoinvent database distinguishes across EU countries, however the distinction is secondary as it is based on the same primary set of data which is then slightly adjusted to a country's specification. Therefore, we use the same typology for all EU countries.

Natural gas combined cycle (CC) plant: electricity production, natural gas, at conventional power plant (Source: Faist Emmenegger, M. et al. 2007)

Small Hydro: electricity production, hydro, run-of-river (Source: Bolliger, R. et al. 2007)

Large Hydro: electricity production, hydro, reservoir, non-alpine region (Source: Bolliger, R. et al. 2007)

PHS: electricity production, hydro, pumped storage (Source: Bolliger, R. et al. 2007)

Natural Gas CHP: heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical (Source: Faist Emmenegger, M. et al. 2007)

Other CHP: heat and power co-generation, wood chips, 2000 kW (Source: Bauer, C. 2007)

Nuclear PWR: electricity production, nuclear, pressure water reactor (Source: Dones, R. 2007)

Nuclear BWR: electricity production, nuclear, boiling water reactor (Source: Dones, R. 2007)

Hard coal power plant: electricity production, hard coal (Source: Röder, A. et al. 2007)

Lignite power plant: electricity production, lignite (Source: Röder, A. et al. 2007)

*Handling other sources of bottom-up data*

For human activity, data is not available through Ecoinvent. A series of technical reports and secondary sources are used to estimate the labour required for electricity generation, as specified under the column "Source" of the full dataset available (see Appendix 4). Since most reports list data in the form of employees per year, the value was converted into hours by assuming 1800 working hours per person per year in the energy sector for the EU-8. Only direct employment (Operation & Maintenance) is considered.

Refineries

Refinery data is obtained from Spanish typologies, since complete reports indicating the amounts of funds and flows consumed by individual refineries are available through the Registro Estatal de Emisiones y Fuentes Contaminantes (online database available at http://www.prtr-es.es/). GHG emissions are listed in the form of CO2 equivalent so no conversion is necessary. Water is listed as water withdrawn and water released, mirroring the MuSIASEM categorization. Human activity is provided as number of employees, and converted as above by assuming 1800 of working hours per employee per year. Heat and fuels are aggregated following the MuSIASEM rationale (see Table A1.3).

For a complete overview of data sources for each variable, and formulas converting primary data into secondary data, the reader is referred to the dataset (see information on datasets in Appendix 4).

Water use and GHG emissions data

Due to the lack specific dataset (with adeguate level of disaggregation), data on water use in the energy sector have been calculated by bottom-up accounting. Water withdrawal and discharge and GHG emissions have been calculated by scaling up the intensive values (m3 and kg per kg of output extracted/mined, respectively) for hard coal mining (Ecoinvent 3.1 reference process: *hard coal mine operation*), lignite mining (Ecoinvent 3.1 reference process: *lignite mine operation RER*), gas extraction (Ecoinvent 3.1 reference process: *natural gas production*), oil extraction (Ecoinvent 3.1 reference process: *petroleum and gas production, off-shore*). According to IPCC Fifth Assessment

Report, the most important GHG for ES were taken into account (CO2, CH4, NOx), but country-specific data have been used in case of Electricity Generation and Refinery (calculated bottom-up). Emissions from natural gas distribution are included considering an average value of 90% CH4 in the distribution losses (could be higher). Emissions from bioenergy combustion are not accounted since they are considered as carbon neutral (as suggested by IPCC Guidelines) as well as emissions from indirect land use change (ILUC).

Biofuel Accounting

Since there are no specific datasets on bioenergy production, a bottom-up accounting was used in case of biofuels. In fact, the biofuel production is not included in the ES: the 'crop faming' phase is included in AF (Agriculture) and the 'extraction of oil' is included in MC (Manufacturing), therefore a bottom-up approach was used to calculate the production factors (i.e technical coefficients) needed to produce the domestic and the imported biofuels.

No specific datasets are available on the feedstock crops used for biofuel, therefore some assumptions were made on the domestic mix of crop feedstocks for biofuels:

| | **Biodiesel** | | **Bioethanol** | | |
|---|---|---|---|---|---|
| | Rapeseed | WCO | Wheat (and cereals) | Maize | Sugar beet |
| DE | 93% | 7% | 53% | 14% | 33% |
| ES | 93% | 7% | 49% | 51% | |
| FR | 91% | 9% | 32% | 12% | 56% |
| IT | 100% | | 64% | | 36% |
| NL | 70% | 30% | 100% | | |
| RO | 100% | | 100% | | |

| | | | | |
|---|---|---|---|---|
| SE | 100% | | 100% | |
| UK | 60% | 40% | | 100% |

Source of data: Ecofys, 2012

The intensive technical coefficients for domestic energy crops (i.e. rapeseed and soybean for biodiesel and maize, wheat, sugarbeet for biogasoline) have been taken from agriculture datasets (see Food guide for detailed info) and then scaled accordingly (they should be discounted by AF)[12].

As a matter of fact not all the crops used to produce biofuels within the country are cultivated domestically, therefore it has been assumed that on average 50% of crops is imported (excepted for NL assumed to be 80%).

Due to the lack of specific datasets and the very large presence of missing data in the current Eurostat statistics on biofuel imports (nrg_126a), some assumptions were made on the mix of imported crop feedstocks for biofuels. It has been assumed that an average of 80% of the imported biodiesel comes from EU (therefore the feedstock mix of the country is assumed) and 10% of the imported biodiesel comes from Argentina (mainly using soybean) and 10% from Eastern countries – Indonesia, Malesya, Cina – (produced using palm oil). The same approach has been adopted for bioethanol considering 85% coming from Europe and 15% from Brazil (therefore produced using sugarcane).

| | **Biodiesel** | | | **Bioethanol** | |
|---|---|---|---|---|---|
| | national mix | Soybean | Palm oil | national mix | Sugarcane |
| DE | 70% | 10% | 20% | 85% | 15% |

[12] Biofuel feedstocks needed for the domestic production of biofuel have been estimated by assuming that the largest share of biodièsel is produced from rapeseed and the largest share of biogasoline is produced from grains (e.g. wheat). Biofuel yields of 0.77 kg per kg of crop and 0.66 kg per kg of crop are assumed for biodiesel and biogasoline, respectively (Jungbluth et al., 2007).

| | | | | | |
|---|---|---|---|---|---|
| ES | 70% | 10% | 20% | 85% | 15% |
| FR | 70% | 10% | 20% | 85% | 15% |
| IT | 70% | 10% | 20% | 85% | 15% |
| NL | 70% | 10% | 20% | 85% | 15% |
| RO | 70% | 10% | 20% | 85% | 15% |
| SE | 70% | 10% | 20% | 85% | 15% |
| UK | 70% | 10% | 20% | 85% | 15% |

Source: Global CCS Institute

Moreover, the intensive technical coefficients for imported crop feedstocks (i.e. palm, sugarcane) were taken from Ecoinvent (Ecoinvent 3.1 reference process: *palm fruit bunch production* and *sugarcane production).* For further info: (Jungbluth et al., 2007).

Data on biodiesel and biogasoline processing (oil extraction/ fermentation/ esterification) were taken from Ecoinvent as well (Ecoinvent 3.1 reference process: *rape oil mill operation, esterification of rape oil, ethanol production from rye, dewatering of ethanol from biomass, from 95% to 99.7% solution state*). For further info: (Jungbluth et al., 2007)

## References

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Eurostat, 2012e. Imports - solid fuels - annual data (nrg_122a).

Eurostat, 2012f. Imports - electricity - annual data (nrg_125a).

Eurostat, 2012g. Imports - oil - annual data (nrg_123a).

Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J., 2007. Life Cycle Inventories of Bioenergy. ecoinvent report No. 17, Swiss Centre for Life Cycle Inventories, Dübendorf, CH

# Appendix 2. Guide to the food accounting in the State-of-the-Play of European countries

## A2.1 The semantic framing of the food accounting

*Authors: Serrano T., Cadillo-Benalcazar J., Ripoll-Bosch R.*

### A2.1.1 The food grammar

In the following Figure A2.1, we can see a representation of the food flow from the production to the consumption stages, and where the losses can be allocated. The agricultural sector is in charge of transforming primary agricultural resources (like the land or the fertilizers) into biomass, and then collect the food products from this biomass. Some losses occur at those transformations, but they are pre-harvest losses and are not accounted in the food flow. The food supply can be provided by the domestic production or by the imports of food. The food can have some different stages of processing into derived food products in the manufacturing sector, with some associated losses. And then the food can be consumed inside or exported to other countries. There are some distribution losses associated with the transport, which are part of the service sector. Finally, before the food intake by the people, there are some losses in the kitchens of households and restaurants (the last are part of the service sector), but they are not reflected in the food accountings as they occur after the purchase of the final food products.

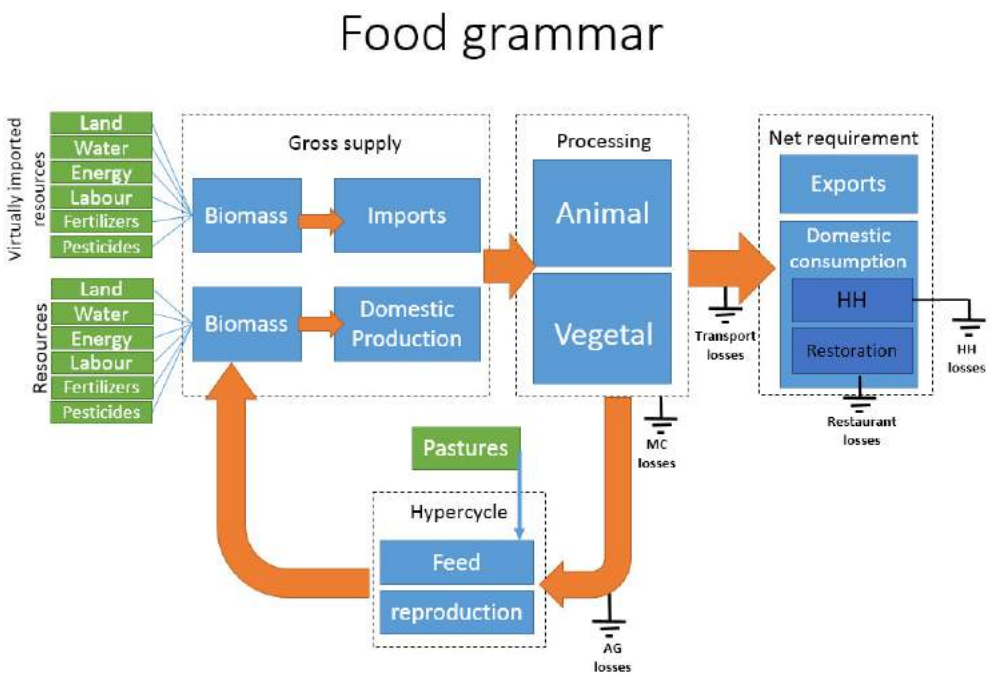


*Figure A2.1. General food grammar*

## A2.1.2 Hierarchical organization and functional compartments of the food sector

In the following Figure A2.2 we can see how we distribute the food sector along the hierarchical levels of organization with one example for the dairy production. In the case of food, the Agriculture and Fishing sector (AF) is the one in charge of producing the food. The food is firstly divided into the most significant differentiation of plant and animal products (level -1a). The next level -1b distinguishes among the aggregation of the most relevant farming system categories, that can be later sub-divided into more specific food production systems (level -1c). In the case of animal production, we can find the sequential pathways made of three stages of production (level -2). Then, for each food product category, we need a particular dictionary of and functional elements (level -3) that will be filled with data taken from a dictionary of structural elements.

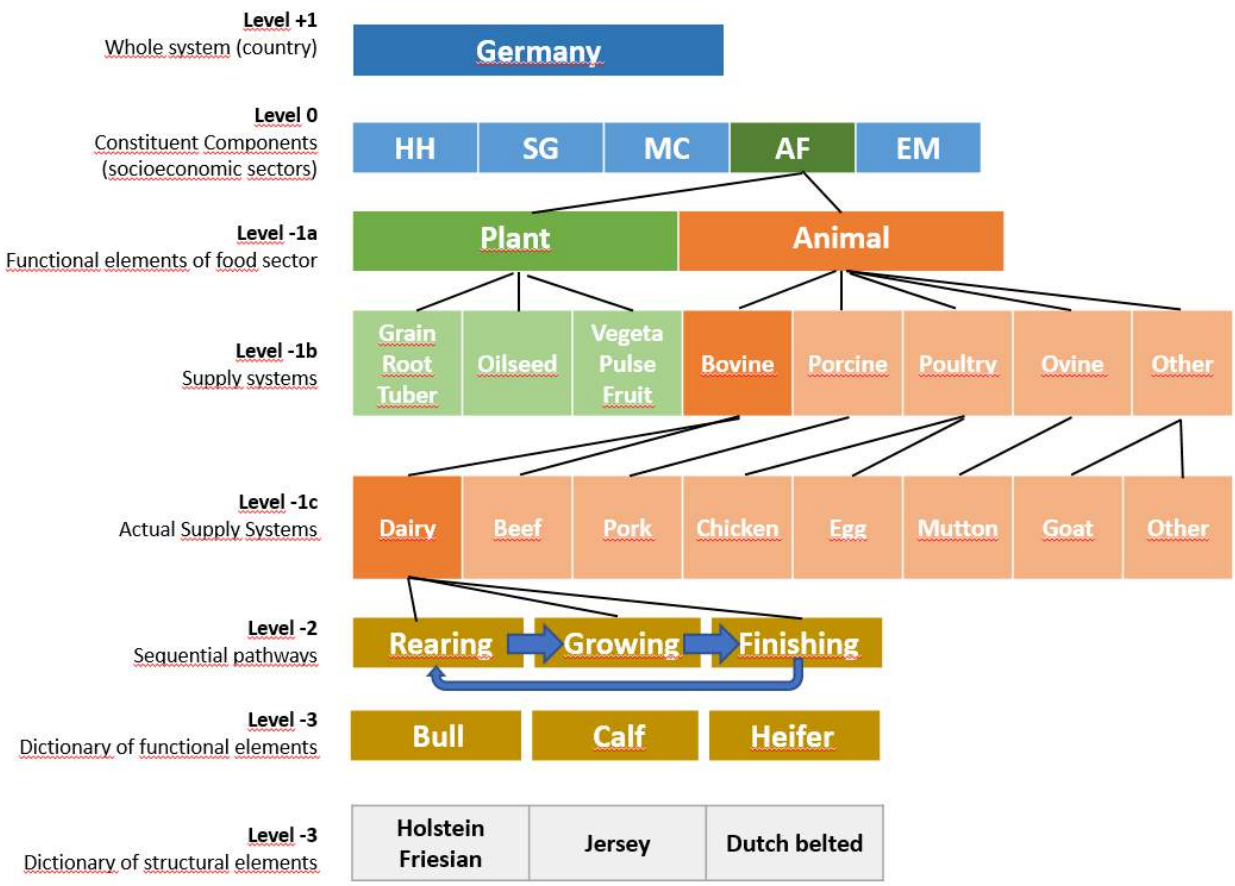


*Figure A2.2. Hierarchical organization of levels of aggregation for food with the example of the dairy sector.*

The classification of food products into functional categories is proposed as follows. For the plants we use three functional categories representing the main metabolic profile of plant farming systems:

1. **Grain, roots and tubers**. This category represent those plants with high nutritional content on carbohydrates and proteins, the crops that serve as the basics and provide most of the calorific content for the diet.

2. **Oilseeds**. These are the plants producing fats and oils, second in nutritional importance in the diets.

3. **Vegetables, pulses and fruits**. These plants are mostly used fresh, and they provide the rest of essential nutrients, but not so important in calorific terms.

For the animal products, we are grouping into five functional categories:

4. **Bovine**. Includes the meat products such as beef and all the dairy products coming from milk production.

5. **Porcine**. It basically includes pork.

6. **Poultry**. Includes chicken meat and egg production.

7. **Ovine.** Including the mutton and derived products that go to other uses than food.

**8. Other animals.** The rest of food products from livestock and game products are included here, such as mutton or rabbits, which are in general a small fraction compared to the previous animal products. Offals and fats are a large part of the animal products but cannot be distinguished into their animal origin in the statistics.

### A2.1.3 Food processors and scaling-up: plant processor

In the following figure A2.3 we can see an example of the representation of a formal processor for a crop (barley in Spain) normalized per unit of output. For the purpose of this study we were just able to provide data for the consumption of fertilizers, green water, blue water, land and labour required to produce crops. In the following sections we will explain how to produce and organize the data required to characterize these crop processors.

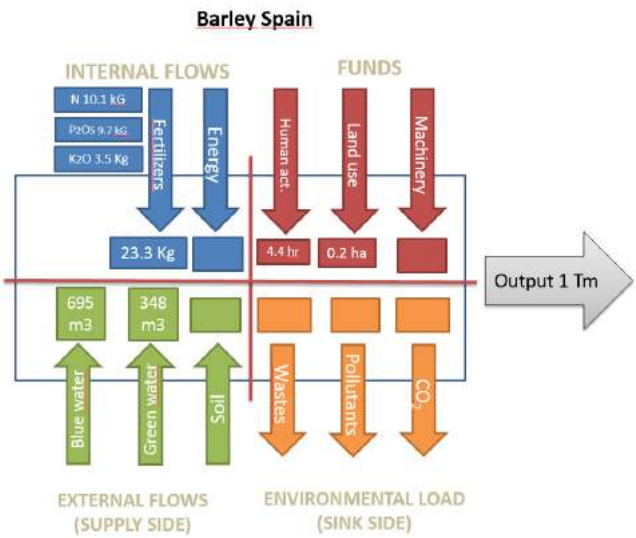


*Figure A2.3. Example of a plant processor (barley in Spain)*

**The scaling up of the plant products**

In the following Figure A2.4 we can see how we can select three categories of functional types representing the crop processors in the different hierarchical levels of organization. These categories of crops are in turn composed of a certain mix of processors of crops made of sequential pathways. The sequential pathways of crops could correspond to the stages of sow, maintenance and harvest of the crops, but there is not enough information at this level of disaggregation to reflect separately these processes, so the processors represented already account for all the stages together. Each crop will be using information from the bottom part using structural categories of the specific crop varieties that compose a functional crop category like wheat. The processors are aggregating across levels until we obtain the processor characterizing the total crop production in the system.

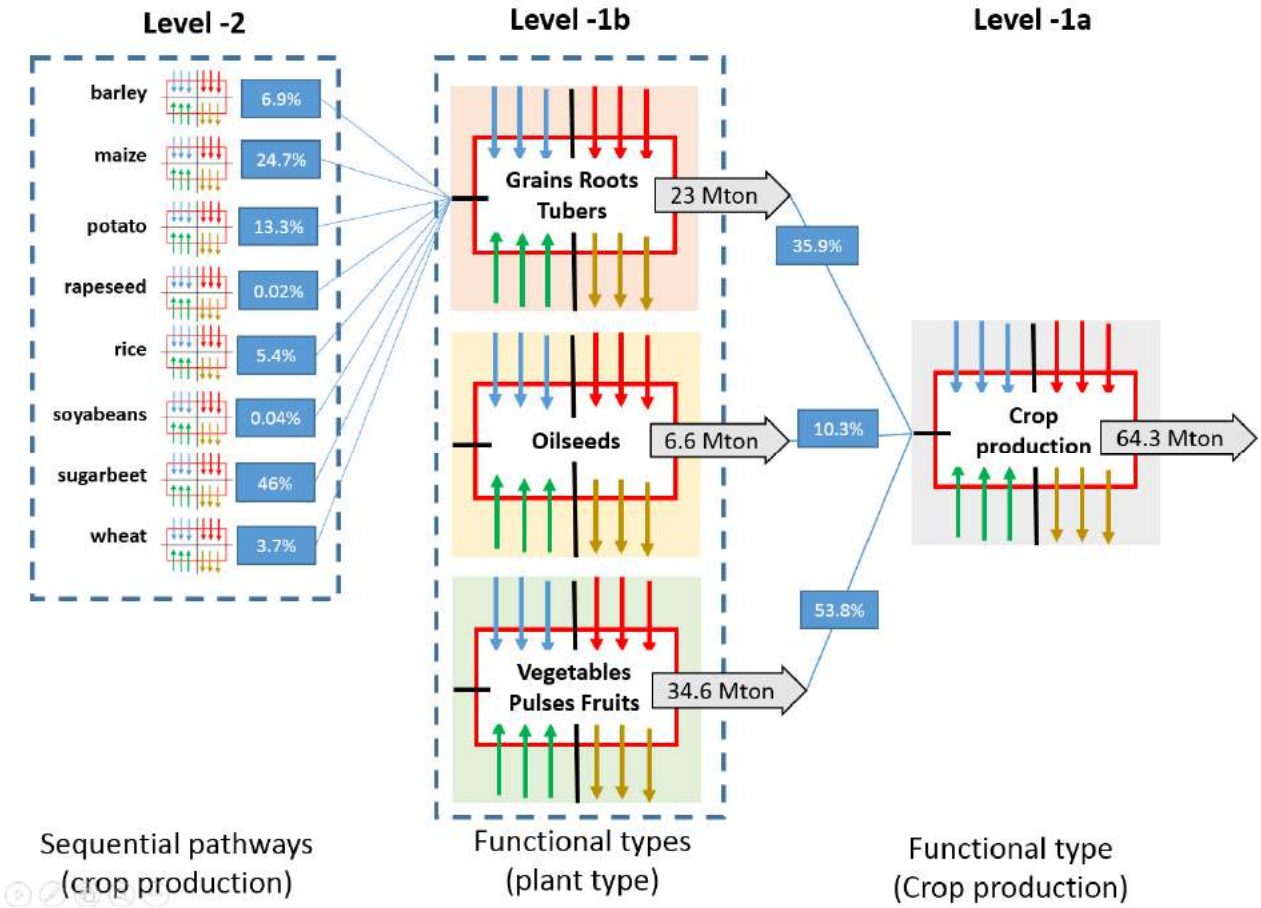


*Figure A2.4. Process of scaling-up of plants from structural categories into 3 functional types (Spain 2012).*

For characterizing the processors of the plant production systems, we have to choose a way to face the practical problem of gathering data for thousands of different crops, each one with different inputs requirements and techniques of farming in each country. It can be established and characterized a limited set of "prototypical" crop types covering all possible crops, the previously introduced 3 groups of: "Grains Roots Tubers", "Oilseeds" and "Vegetables Pulses Fruits". To select also a limited number of crops characterized in each country, which proportional mix will serve to provide the characterization of the functional categories of plants, as illustrated in the previous Figure A2.4. The selected crops categories are explained in the next section A2.2.5 Data transformation. According to the previous diagram and the processor in the previous figure A2.4, we can see that for characterizing the crop production in EU in terms of processors with the associated resources and outputs, we have to obtain data for the 1)food production quantity, 2) land, 3) labour, 4)green and blue water, and 5)fertilizers. All that information has to be gathered for the different crops in 8 different countries.

## A2.1.4 Food processors and scaling-up: animal processor

**Livestock importance and trends**

Livestock production is becoming an element central in the discussion of sustainable future. Livestock is a source of nutritious foods for the human population, among many other roles and functions for society across the globe. Gains in agricultural productivity in last decades have been meet through a process of intensification, generally characterised by an increase of the use of inputs (e.g. energy, artificial fertilisers or veterinary services) and by the use of inputs of better quality (e.g. feeds and especially concentrates). However, this process of intensification to boost agricultural production, including livestock production, has been controversial. While improving yields, livestock sector has also been recognised as a driver of environmental pressure, by means of intensive use of resources (e.g. land, nutrients or energy) and by loadings to the environment (e.g. emissions of greenhouse gases, leaching and eutrophication or biodiversity loss). Several scholars have pointed out that current livestock production systems may compromise global sustainability (Giampietro et al., 2001) by e.g. intensification of land-use (Erb, 2012), increasing reliance on use of fossil energy (Giampietro et al., 2001; Giampietro and Mayumi, 2000), soil degradation, water pollution and depletion, land use change, and habitat loss and fragmentation (Erb, 2012; Haberl et al., 2011; Sala et al., 2000). Moreover, the use of better feeds, especially grains and concentrates, to improve productivity of animals has entered in direct competition for food for humans. While the use of concentrates in livestock diets can indeed derive in higher yields, it is still more efficient is humans would directly eat such feeds. In other words, the use of concentrates to feed livestock would reduce the global food security.

The Earth's population is growing rapidly and becoming wealthier. This results in an increasing demand of resources in general. Not surprisingly, the increasing demand will also be for food and especially animal-source foods. It has been largely demonstrated that increasingly affluent population shift their diets including larger shared of animal source foods.

In the abovementioned context, it is expected that the growing population and the change in diets (Alexander et al. 2015) will put further pressure on global ecosystems, will be a driver of adverse global environmental change and hamper soil fertility in agricultural lands (Stavi & Lal 2013).

Hence, the livestock sector is a production system of major importance when assessing issues related to the NEXUS of food-land-water-energy-climate and even biodiversity.

**Diversity in livestock farming systems**

Livestock production, generally summarised as livestock sector, encompass a wide diverse variety of livestock farming systems. Livestock production in Europe has been shaped according to specific environmental and socio-economic contexts. Livestock are used in multiple ways for food production in Europe and worldwide (where may not only be raised to generate income, but for food self-sufficiency at the household level, as well as for transport, draught power, fertilization of fields with manure or for for their skins and hides). Livestock diversity and diversity in farming practices is essential to thrive in multiple contexts.

Four livestock species dominate with regards to food production for European citizens: ruminant species (i.e. dairy and beef cattle) and monogastric species (i.e. swine and poultry –broiler for meat and laying hens for eggs-). This distinction is key. Firstly, because they provide different source foods. While cattle provide dairy products and red meat, monogastrics provide withe meat and eggs. Secondly, because ruminants and monogastrics have different abilities to digest and metabolize feeds. While monogastrics have a stomach similar to humans and hence, may eat and compete for the same feedstuffs, ruminants are able to convert fibrous feedstocks (e.g. roughages, grasslands or by-products from harvested crops) into food of high nutritional value, that would otherwise be unavailable to humans.

Despite a generalized trend of intensification in animal production, which has led to a generalized use of concentrates regardless of the specie, the different ability of using feedstocks between monogastrics and ruminants has been and still is, a decisive factor when it comes to diversity in farming systems. In this sense, and unlike monogastrics, ruminants in Europe still make use of large shares of grasslands, either cultivated or (semi-)natural grasslands.

**The theoretical approach of MuSIASEM related to livestock sector**

MuSIASEM or Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism is a method of accounting used to analyze the metabolic pattern of social-ecological systems to study its feasibility (compatibility with external constraints determined by processes outside human control), viability (compatibility with internal constraints determined by processes under human control), desirability (compatibility with institutions and normative values). The MuSIASEM accounting tool was created by Mario Giampietro and Kozo Mayumi in 1997 (Ripa and Giampietro, 2017), and consists of a relational analysis of the functional and structural elements of a social-ecological system that together determine its metabolic pattern of water, energy and food. MuSIASEM is mostly based on the Georgescu-Roegen Fund-Flow model (Georgescu-Roegen, 1971) and it is based on maintaining coherence of the quantitative representations generated using different metrics across different scales and dimensions (e.g. economic, social, demographic, ecological, technical). It is designed to detect and analyze patterns in the societal use of resources and the impacts they create on the environment. This framework, therefore, allow bridging heterogeneous descriptions from various scientific disciplines, such as economics, demography, energy analysis, and ecology (Giampietro et al., 2001; Giampietro and Mayumi 2000).

This analytical approach describes systems over hierarchical scales and levels. The levels and scales refer to the different levels at which an analysis can take place, e.g. EU level, country level, regional level, farm level or animal level. The selection of scales is critical and respond to the level of analysis to be performed or, in other words, depends on the research question to be addressed. The strength of MuSIASEM lay in the ability to maintain coherence semantically (i.e. maintaining consistent definitions of elements taking part in the system) and numerically (i.e. maintaining consistent relationships between the numbers across scales. This means that despite levels and scales can all be ranked according to a certain hierarchy going from bottom-up (for instance, mapping out the livestock sector from primary data from on-farms surveys, i.e. from animals to entire livestock sector) or top-down (mapping out the livestock sector from secondary data and national statistics, i.e. from livestock sector to farm characteristics and to animals), they should always keep coherence and consistency. Variables are bridged using simple equations of congruence across hierarchical levels (Giampietro et al., 2001). The capacity to adjust the model in semantic terms (for instance, when studding the dairy sector in a country, one may decide to disaggregate the dairy sector into a lower scale such as organic/conventional, or into different provinces, better off 10% farms and the rest depending on the research question) and numerically (it does not really matter how you disaggregate the dairy sector as long as the numbers make sense). This confers great degree of flexibility for the application of the method and when analysing a system.

The metabolic pattern of a social-ecological system has to be first framed in semantic terms and then should be framed by the use of numbers. A social-ecological system is an adaptive self-reproducing and self-maintaining system in which we can differentiate between fund, flow and stock elements. Funds represent the size and definition of the system, and are transforming input flows into output flows (e.g. feed and water to milk) while remaining the same structure. The funds require a certain amount of maintenance and replacement in order to maintain the same production level. Flows are forms of matter and energy that are produced/consumed in the system (Fisher-Kowalski and Haberl, 2015; Serrano Tovar, 2014; Giampietro et al., 2009). Stocks are material/energy inputs coming from a source that is finite, that does not regenerate (or regenerate at a very low pace, over millennia) implying the depletion of that material/energy source when used.

A graphical representation of this explanation can be found in Figure A2.5. There, the metabolic pattern of the livestock sector of a given country is characterized. In a sense, the livestock sector becomes a social-ecological system as we defined it previously: is an adaptive self-reproducing and self-maintaining system. Livestock sector is adapting in time due to internal and external constraints; and is self-reproducing and self-maintaining because a livestock sector must always be there to ensure the production of outputs (i.e. meat, milk, eggs, or manure) and counting on adult producing animals that are replaced by young stock at the end of their productive life. Hence, livestock becomes a “fund element”, that requires of other fund elements to function (i.e. land or human activity), which metabolizes inputs flows (e.g. feeds, water, or certain types of energies) and input stocks (e.g. energy from fossil fuels or fossil P) into output flows (i.e. the products). In Figure A2.5, fund elements that are under control of humans (or coming from the technosphere) are depicted in red, while fund elements coming from “nature” (or coming from the biosphere) are depicted in green. Blue arrows become input flows (also from stocks) that are metablolised by the fund element or processor livestock sector into  products, depicted in black. Yellow arrows represent a discharge of loadings to the environment as a result of the process of transforming input flows into output flows.

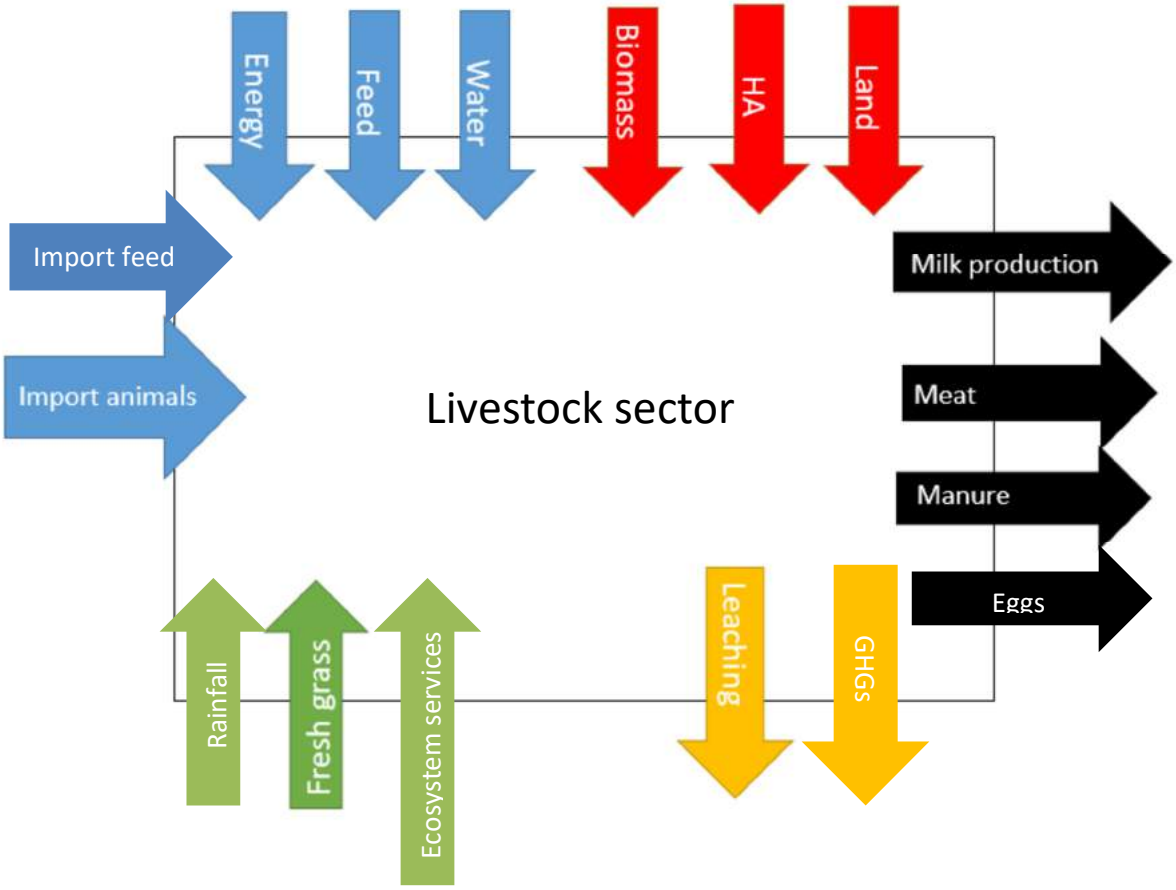


*Figure A2.5. Example of the metabolism of a livestock sector. Example subtracted from a plenary discussion between members of the MAGIC team about the representation of a livestock sector. The blue arrows represent input flows, the red arrows represent funds, the black arrows represent output flows, and the green and yellow arrows represent flows related to the environment.*

**Application of MuSIASEM to the livestock sector**

In order to study the applicability of the MuSIASEM accounting tool to the livestock sector we selected 8 EU countries as pilot case studies. The EU countries that were chosen for this study are: the Netherlands, Spain, France, Italy, Romania, Sweden, UK and Germany which presents a good overall division throughout the EU to represent the differences in size of the country, in intensity of production and aim of production (for internal consumption or export geared). The Netherlands was done more in-depth due to availability of data and to explore deepening in the methodology, whereas the other EU countries were done as a representation to check the applicability of the MuSIASEM. The main focus was to test the applicability of MuSIASEM to the livestock sector. We first started depicting the applicability of MuSIASEM to the dairy sector, and

subsequently applied to the beef, to the poultry (i.e. broiler for meat and laying hens for egg production) and to the pig sector. The small ruminant sector was dismissed at this stage due to its marginal contribution to food production in the EU.

This categorisation already illustrate the principles of working across scales or hierarchical levels. One could characterize the entire livestock sector such as in Figure A2.5 with the corresponding input and output flows, but could also characterize each individual sector dairy, beef, poultry and pig. The graphical representation of each sector would be depicted exactly the same way as Figure A2.5, but with the corresponding scaled input and output flows and fund elements required. After all, the sum of all feeding ingredients used in each individual sector or the need of working units in each sector should add up to the total feeds and working units of livestock sector in a given country.

To characterize the different livestock sectors, as explained previously, we defined all the different elements of the metabolism; processors, funds and flows. Moreover, we aimed to find a systematic way to characterize any production system. For the sake of "reproducibility" in different farming systems in different contexts; and for the sake of comparability between farming systems and farming sectors.

Hence, each given sector, considered as processor, was defined by three processors that have to take place in order to reproduce the given sector. This were, the adult animals, able to produce and reproduce. The newborn animals and its young stage. And the grown up young stock that will either become and adult reproductive animal, or will be sent to slaughterhouse to be transformed into meat.

This 3 processors that conform a given sector are represented in Figure A2.6 and Figure A2.7. Considering the dairy sector as an example, the 3 processors that compose the dairy sector are connected. The adult animals are kept produce the milk. To produce the milk the animals need to calve, and the calves are needed to produce the meat and to produce the future dairy cows. Hence, the processor calves unit is dependent on the amount of adult animals (given a certain fertility rate and a certain mortality). The processor Heifers unit is dependent on the calves unit (considering certain mortality rate). Finally, at the end of a "heifer" stage, animals can become adult productive/reproductive animals or be sold as meat to slaughterhouse. This condition is necessary for the reproducibility of the system and it is based on a biophysical basis (quantification). The disruption in the connectivity between the processors can be solved (and usually happen) by the imports and exports of animals. Import and export of animals can happen at any stage: sectors or farms that import adult animals, that sell surplus newborn calves to be fatten somewhere else or that fatten the claves to have a second source of income aside from dairy products. However, this only mean that this

very same process is happening somewhere else, and at a certain stage animals in that other place become a output product and become and input to this livestock sector. These 3 processors (or stages) can be reproduced in every livestock sector.

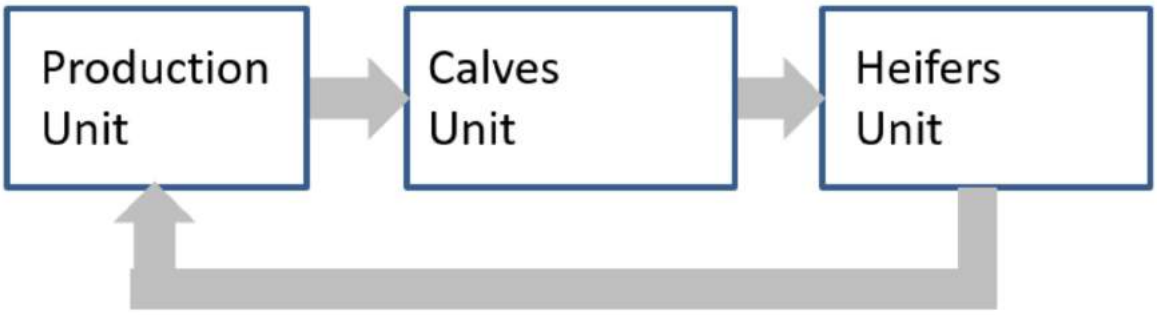


*Figure A2.6. A simplified view of the relational analysis of the processors of the dairy sector, production unit refers to the dairy cows*

Next, each processors can be defined with a specific metabolic pattern. Each processors require a certain amount of inputs (which may differ across processors. For instance, calves may require powder milk or dairy cows require energy for milking and milk storage, while the other processors do not) in order to produce a certain amount of output (which may differ across processors. For instance, while calves and heifers produce animals or living biomass as output, dairy cows produce meat from the calves and the replaced adults but also milk), each processor having a different metabolic profile, requires a different amount of input and possibly different forms of energy (Figure A2.8).

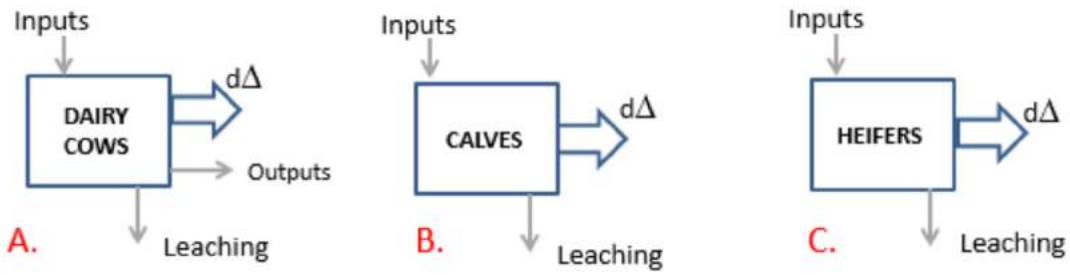


*Figure A2.7. The processors of the dairy sector all requiring a different amount of inputs to produce an output. dΔ = living biomass (kg).*

When combined, as illustrated in figure A2.8, we can see a generalization that there are three main stages in the animal production corresponding to the adults breeding, the early growing stages, and the stages for fattening and finishing.

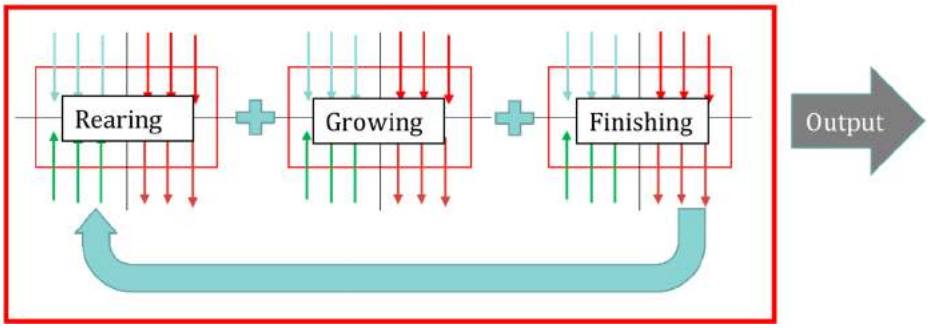


*Figure A2.8. Generic sequential pathway of animal production*

The processors livestock systems were here expressed as biomass of living animals (explained below), rather than number of animals. The expression in terms of living biomass allow for the comparison between the 3 processors, and allow for scaling the use of inputs and the production of outputs. Moreover, this facilitate the comparison across different livestock sectors.

The fund elements identified in the livestock sector were the live animals (expressed in kg of biomass. See explanation in section below), labour (working force expressed as human activity in hours) and land (agricultural land to produce the feed and grass expressed in ha). Fund elements not included in this calculation were buildings and machinery (tractors, milking or feeding engines).

The input flow elements identified in the livestock sector were feeds (disaggregated per feed type), consumptive water by livestock and energy (in the different forms of fuels, electricity or gas) and alive animals at different stages of production. Input flows not accounted for were use of drugs and veterinary treatments or bedding material.

The input flow elements identified were dependent on the livestock sector. For the dairy sector, we identified the output flows: milk and alive animals at different stages of production (for meat production, for replacement or for export). For the beef sector, we identified the output flows: alive animals at different stages of production (for meat production, for replacement or for export). For the pig sector, we identified the output flows: alive animals at different stages of production (for meat production, for replacement or for export). For the poultry sector we identified the output flows: eggs

(for consumption and for incubation) and alive animals at different stages of production (for meat production, for replacement or for export).

**Livestock as biomass**

The calculation of livestock as biomass was performed following two different approaches: A top-down approach, using data from statistics, and a bottom-up approach using calculating the biophysical potential for production.

The top down approach used secondary data (i.e. national statistics, FAOSTAT or EUROSTAT) to estimate the number of animals that belong to each of the 3 processors that describe each livestock sector. Secondary data was also used to estimate the amount of import and exports from each processor. Statistics provide the number of animals of each category. To estimate the total living biomass in each processor, we then multiplied the number of animals by its live weight. Note that live weight can differ between countries and differs in each processor. We estimated and used the average live weight of the animal within each processor for the calculations.

The bottom up approach used the total number of adult productive and reproductive animals to from secondary data to estimate the biophysical potential of the processor adult animals to generate the biomass of the subsequent processors and to estimate the productive potential. We used technical coefficients of fertility rate and mortality to estimate the potential of one processor to generate the subsequent processor. Then, this data was complemented by the existing data on trade (imports and exports).

The use of the two methods allow double checking the credibility of the data available. While we do not expect the data to be exactly the same (at this aggregated level), data should resemble one to the other in terms of magnitude.

Defining livestock biomass is critical, as most of the data available on inputs will finally be scaled to the total amount of biomass (or animal numbers).

**Calculation of feed requirements**

A very important particularity of the livestock production is that this sector use food from the plant production as feed for the animals. This implies that the animal processors are using a part of the outputs of the crop processors, and to account for the total resources required to produce animal products, it is necessary to also include the resources consumed by the plants that serve as feed for the animals. This is reflected in the Resource Matrix shown in Figure A2.9.

To properly account for the feed and its associated resources, we need to distinguish between those crops in the feed that are bought from outside the livestock farm, such

as the concentrates and grains, and the feed that is grown inside the farm or animal sector, such as the pastures, hay or some grains too. Therefore, it is possible to account for the crops coming from outside the animal sector, since we can characterize those processors in the plant analysis part, as long as we know the quantity and composition of the feed of the crops conforming it. On the other hand, that means that we also need to include in the processors of the animal production systems the land, water, fertilizers and labour required to produce the pastures, hay, silage or whatever feed that must be considered to be produced inside the animal sector. This is illustrated in the scheme of the following Figure A2.9.

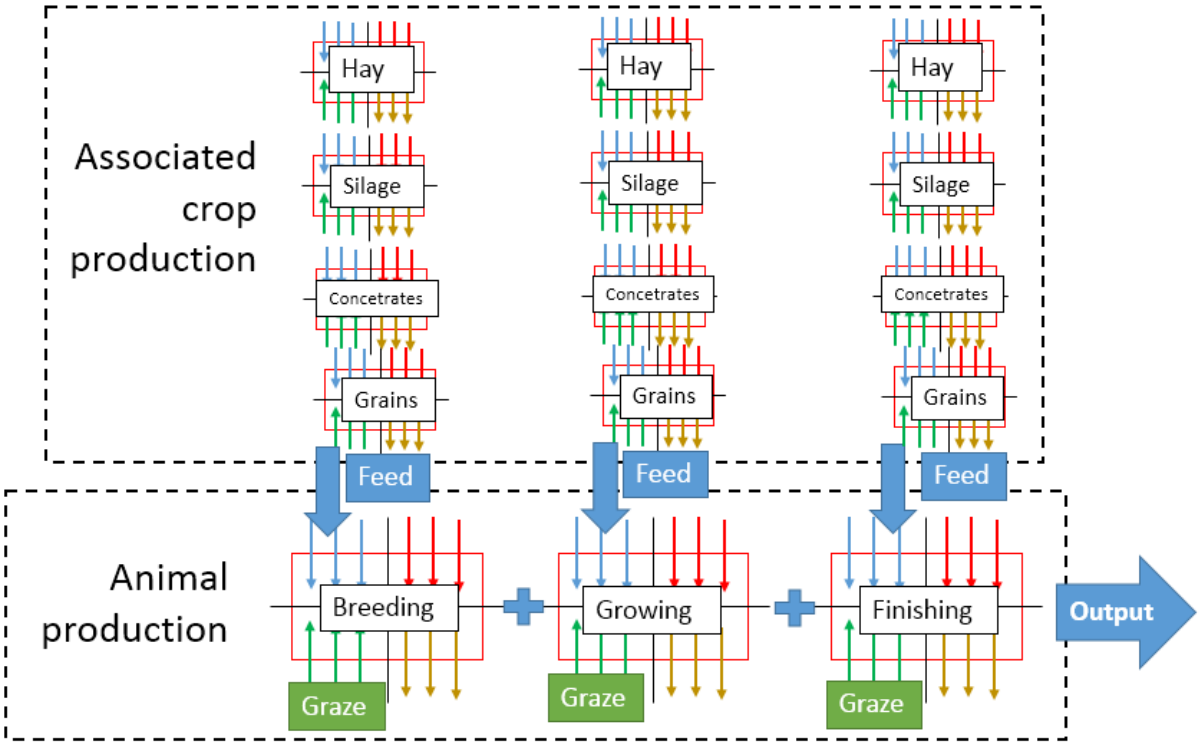


*Figure A2.9. Example of the plant processors used as feed in the animal processors.*

Likewise the biomass per processor, the amount of feeds that each processor require can also be estimated in different ways. Here, we used three ways to estimate the flow of feed inputs: based on biophysical nutritional requirements, on average nutritional requirements or based on average standard diet composition.

Based on biophysical nutritional requirements, we calculated the energy requirements of each processor based on bodyweight and performance of the animals. We based the calculations on the formulas developed by the IPCC (2006) and further developed by the FAO to estimate the emissions of greenhouse gases from livestock with the model GLEAM (FAO, 2017). Then, the amount of feeds actually used (in kg) was estimated using

a default diet (composition of feeds expressed in %) defined by GLEAM model (FAO, 2017) per processor and per country, and allocating the amount of feed required to fulfilling the calculated energy requirements.

Based on average nutritional requirements, we estimated the energy requirements of each processor based on research publications that characterize the energy requirements of animals reared under similar conditions as assumed in this report. Hence, the value is accurate, but is a fixed value, implying that is not able to capture potential changes in productivity level of the animals due to changes in management. Then, the amount of feeds actually used (in kg) was estimated using a default diet (composition of feeds expressed in %) defined by GLEAM model (FAO, 2017) per processor and per country, and allocating the amount of feed required to fulfilling the energy requirements determined in research publications.

Based on average standard diet composition, we estimated the amount of feeds actually used (in kg) by assuming that a standard diet described in publications would actually meet the energy requirements of the animals.

The three methods have their own advantages and limitations. The purpose of exploring 3 different routes was, 1) to test potential ways to calculate one of the most important flow inputs of the processors; and 2) to check for the coherence of results when applying the different methods.

**Calculation of land requirements**

Calculation of the fund element land requirements for the livestock sector is calculated using the information coming from the processor crop production. In other words, The crop production section describes what are the fund elements to produce crops. There, land is needed and describe the relationship in the crop processor between land and yield (among other flow elements). Since we here define the mount (kg) of feeds required, one can calculate the amount of land required from the processor crop production (i.e. yield per hectare).

The amount of land required for housing the animals is actually negligible compared to the land required to produce the feed. Hence, the land occupied by buildings is neglected in this study.

**Data and databases**

Data was primary obtained from open widely available data sources. For instance, FAOSTAT, EUROSTAT or data used for the calculations of greenhouse gases from livestock with the model GLEAM (FAO, 2017). Despite this data can be very generalist

and inaccurate, this also ensures the reproducibility of the study for (almost) any other country of the world.

Nevertheless, we also searched for country specific data to test whether we could obtain a more accurate result and the feasibility to get more accurate data in all EU countries. We soon discovered that that would not be possible. First, because some countries do not have such country specific accurate data (e.g. Romania). Second, because country-specific data is many times supplied in the language of that country. Hence, we could not retrieve most data due to the language barrier. Third, because countries do not collect the same type of information and especially they do not store or supply the information in the same way. Hence, it becomes very time consuming to trace all potential websites, links or reports that may contain the specific data required.

A general problem derived from the use of secondary data (i.e. statistics and existing databases) is that many times the information is provided aggregated or derives from a calculation. However, the raw data is not accessible, the exact formula used to obtain the final number is not provided or there is a lack of clear definitions on the type of data provided. For instance, many times it is reported the number of “cattle”. This number does not differentiate between “dairy” and “beef” cattle. That is a problem since dairy and beef serve to different purposes, are raised in different farming systems and have different herd structures. However, there is no way to get to the raw data. The definition of cattle is also controversial, as one does not know what it is actually considered “cattle”: only reproductive animals? Adult animals? If adult, when an animal is considered to become an adult? Last, the way a number is calculated is also important and not always reported. For instance, census of cattle is not too much of a problem if you report census from one point in time or the total number of animals during one year, since adult cattle have a lifespan longer than one year. However, it is crucial for e.g. poultry, because poultry farm has several rounds in a year. Hence it makes a difference whether you report census one point in time (i.e. number of places) or number of animals. That becomes important to determine the resources needed to reproduce the fund “animal biomass”.

#### Dairy

The method applied to define the biomass of living animals for the processor “Dairy cows” was multiplying the live weight data per animal provided by FAO (2017) times the number of animals (FAO, 2017). Note that live weight of the adult animals was differing quite a lot between the different countries.

The method applied to define the biomass for the processors “Calves” and “Heifers” was using the average live weight in the period 0-1 years for the calves and the average live weight in the period 1-2 years for the heifers provided by Veepro (Nov 2017) in the

"Heifer Growth Chart". Then, the average live weight per animal in each processor was multiplied by the total number of animals in each processor, to obtain the total biomass (in kg) per processor. Due to limited data availability of the other countries this study assumed that weight of calves and heifers did not differ over the different EU countries.

As a result of the two ways of accounting for the "live weight biomass" the data for some countries indicated that the heifers used for replacement weighed more than the dairy cows. However, for this study it was still the most accurate and country specific data that was found.

The of number of animals in processors "calves" and "heifers" under method "biophysical potential" was estimated using the formulas below:

The number of calves = Number of dairy cows * fertility rate * 50% (male/female)*mortality rate of calves.

The number of replacement heifers = Number of dairy cows * replacement factor

The number of heifers = Number of calves * mortality rate heifers – output flow of calves (calves imported – calves exported)

The number of heifers being output = Number of heifers – replacement heifers + heifers imported – heifers exported

This method was applied to all the different EU countries included in this study. The mortality rate for young stock provided by FAO (2017) for each country is set at 8%. This study divided mortality for heifers and calves to 4% for each box as there is no specific data available at this moment.

Energy requirements of dairy cattle were calculated using the IPCC (2006) and GLEAM (FAO, 2017) formulas. As average energy requirements for dairy cattle, we used from Remmelink et al. (2017). This data source provided an energy requirement for the three processors in "Voedereenheid Melk" (VEM) per animal. These results were then transferred to the unit MJ by dividing by 6.7, providing a net energy.

### Beef

The method applied to define the biomass of living animals for the processor "beef cows" was multiplying the average live weight data per animal provided by FAO (2017) times the number of animals (FAO, 2017). Note that live weight of the adult animals may differ between the different countries.

The flows between processors was calculated also be based on statistics on cattle numbers, meat production and cattle imports and exports. Numbers in heads were always converted to biomass using average live weights.

To calculate the “biophysical potential” of number of animals in processors “calves” and “heifers” under method “biophysical potential” was estimated using the formulas below:

The number of calves into Calves Processor = Number of Adult Cattle females * fertility rate *mortality rate of calves + imports – exports of calves

The number of replacement cattle = Number of Adult Cattle females* replacement factor

The number of young cattle in young cattle processor = Number of calves * mortality rate young cattle – + imports – exports of young cattle

The number of Young Cattle being output = Number of Young Cattle– replacement cattle

Since GLEAM does not differentiate between Calves and Young Cattle, we used the mortality of young females/males and divided in half. In GLEAM the mortality of female and male young cattle is defined at 10% so the mortality rate is 5% for Calves and 5% for Young Cattle.

We calculated the gross energy requirements based on Tier 2 IPCC methods (IPCC, 2006). We used the coefficient for non-lactating cows for calves. For the UK as well as for Europe, we assumed pasture housing conditions to calculate the net energy for activity and to assume digestibility percentage. We did not differentiate between male calves and female calves when calculating the feed requirements. We assumed that females in the adult cattle box are lactating while females in the young cattle box are not lactating and are not pregnant as we assumed the adult cattle box to be the reproductive herd. We assumed that milk fat content and milk production for dairy in GLEAM also applied for beef to calculate the net energy needed for lactation for female reproductive herd within the adult cattle box.

We then used the Dry Matter Intake (DMI) percentages found within GLEAM to determine the various ratios of the different types of feed in the diet. For Calves we assumed that part of the percentage is taken from milk so we removed the energy requirement needed for milk from the gross energy requirement and calculated the rest of the energy in feed based on the DMI percentages provided in GLEAM. From this calculate the kg/DMI per animal in the following way: 1) We found the GE MJ/KG

(Source: Feedipedia and Feedtables.com by INRA); 2) Using the equation Gross Energy in MJ per animal x %DMI/ MJ/kg of feed, we found the kg DMI/animal.

### Pig

The pig sector was calculated applying a similar method to the ones for the other sectors. Pig sector was also divided into 3 processors which included the adult herd (i.e. adult reproductive animals), the young stock (i.e. piglets up to 25 kg of live weight) and growing stock (i.e. pigs up to 100kg which will become part of the adult herd or will end up in the slaughterhouse for meat production).

To calculate the biomass of living animals in each of the processors of the pig sector, we multiplied the average live weight data per animal provided by FAO (2017) times the number of animals (FAO, 2017).

The feeding ratio of the different pig processors was defined according to the data provided in the GLEAM model (FAO, 2017) for each specific country.

### Poultry

The calculation of poultry sector was divided into laying hens (for egg production) and broilers (for meat production). Below, we first explain the methodology for laying hens and then for broilers.

### Poultry: Laying hens

The eight case studies represent a relatively high share of 73% of hens kept for egg production in the EU28. For the Netherlands, in-depth data was gathered to map the system for laying hens. The system is divided into three boxes: hatching, rearing (up to 17 weeks) and laying hens (17 weeks to slaughter). The parental stock is aggregated in the boxes, however, at the end a division is made between eggs for hatching and for consumption.

To map the system for the other countries herd data, feed composition and manure system were taken from GLEAM (FAO, 2017). Dutch data is used to compute the main inputs (e.g. feed, water, energy, antibiotics) and the output of manure. This data might not represent the local conditions given the high productivity and specialization of Dutch laying hen farms. Additional efforts would be needed to make it more context-specific and would require searching in national statistics or national egg industry reports. This is just a first approach.

In the case of poultry, census are usually provided aggregated. Hence it becomes difficult to determine the animals that form each processor. There are multiple options to allocate the animals, either by taking the total number of laying hens from EUROSTAT

or GLEAM and allocating them based on the division in the Netherlands, or allocating them based on the number of weeks they are kept in the system. We selected the EUROSTAT data in combination with the allocation based on weeks, as the Dutch allocation would be based on a high share of export.

One of the challenges in the laying hen production is that data is sometimes aggregated at poultry level (combining broiler and laying hen production as 'chicken' (e.g. FAOSTAT production and trade of live animals, and for meat)). Therefore, data on export and import of animals is limited. GLEAM formed an important source of data. GLEAM distinguishes 3 types of poultry production: backyard, laying hens and broilers. For laying hens, the production is assumed to be 'Fully market-oriented; high capital input requirements; high level of overall flock productivity; purchased non-local feed or on-farm intensively produced feed. Layers housed in a variety of cage, barn and free-range systems, with automatic feed and water provision' (GLEAM, 2017). Within the countries the share of production systems from enriched cage, barn, free-range and organic systems varies. Whereas in Spain, France and Italy enriched cage systems are most common, in Germany and the Netherlands the most common system is barn production and in the UK this is free range production. How this is considered in GLEAM is not clear. In addition, differences exist between single-tier and multi-tier systems, and between brown and white hens.

For the laying hens sector we had to make several assumptions, such as 1) molting doesn't take place, meaning we assume hens are kept for 1 round of production and slaughtered afterwards. 2) Most recent data is used, but this can mismatch with data of earlier years. Moreover, some data, especially on trade, is provisional. 3) Backyard systems are not included. Only for Romania some backyard production was included in GLEAM. 4) The required input of a system (i.e. layers) could be better matched with the output of another, when correcting for the mortality (i.e. rearing).

### Poultry: Broliers

Similar to the laying hen sector, the eight case studies represent a relatively high share of 74% of the EU28 broiler production. For the Netherlands, in-depth data was gathered to map the system for broiler production. The system is divided into three boxes: hatching, broilers and parental animals. The parental stock consists of both rearing and adult animals.

Annual laid eggs in GLEAM is considered to be the same for broilers as for layers. This has an important impact on the number of parental animals needed. Data of the Dutch broiler sector shows that parental animals of broilers produce 160 eggs per parental hen, whereas GLEAM assumes a production of 301 eggs per hen. For the Dutch system we used the Dutch data, resulting in a higher number of parental animals needed, which

is also confirmed by the number of farms and animals shown in statistics. While the ratio parental animals to broilers based on the Dutch statistics is 18%, according to GLEAM this is just 4%. For the other countries we used GLEAM, to maintain consistency with the other case studies and because information on the productivity in the other countries was not easily accessible. Moreover, other countries might not import and export as much compared to the Dutch broiler system.

We used the number of broilers and parental animals from GLEAM to allocate animals into the three boxes. In which we assumed: total number of broiler animals = parental female + parental male + estimate number of parental animals in rearing + broilers for meat. GLEAM animal numbers were used, however, in some cases large differences were found compared to the EUROSTAT data on broiler numbers of 2013. Moreover, if one looks at the number of animals per farm, based on the EUROSTAT data, there are large differences between countries. This has large implications for the efficiency in terms of labour and transport. The reference values used (for the Netherlands) will not reflect conditions with very low numbers of animals per farm.

*Table A2.1. Number of animals per farm – calculated from EUROSTAT data of 2013.*

| | |
|---|---|
| Germany | 21399 |
| Spain | 4755 |
| France | 5450 |
| Italy | 11405 |
| Netherlands | 79000 |
| Romania | 21 |
| Sweden | 33167 |
| United Kingdom | 61135 |

Similar as to the laying hen cases, herd data, feed composition and manure system were taken from GLEAM (FAO, 2017). Dutch data is used to compute the main inputs (e.g. feed, water, energy, antibiotics) and the output of manure (Dutch data is given in blue font colour in the Excel sheets). This data might not represent the local conditions given the high productivity and specialization of Dutch broiler farms. Additional efforts would be needed to make it more context-specific and would require searching in national statistics or national broiler industry reports.

Similar as with laying hens, one of the challenges is that data is sometimes aggregated at poultry level (combining broiler and laying hen production as 'chicken' (e.g. FAOSTAT production and trade of live animals, and for meat)). Therefore, data on export and import of animals is limited. GLEAM formed an important source of data. GLEAM

distinguishes 3 types of poultry production: backyard, laying hens and broilers. For laying hens, the production is assumed to be 'Fully market-oriented; high capital input requirements; high level of overall flock productivity; purchased non-local feed or on-farm intensively produced feed. Broilers assumed to be primarily loosely housed on litter, with automatic feed and water provision.' (GLEAM, 2017). Similar as in laying hen production, a transition towards more animal friendly systems is taking place in several countries. In broiler this transition entails changing from fast to slow growing broilers, a transition from 41 days to 56 days, which means that instead of 7.4 rounds per year, a farmer can only produce 5.6 rounds per year. Additional animal welfare standards in countries in the Netherlands require lower stocking densities. Altogether this is contributing to a substantially lower production capacity compared to fast growing broilers. This recent development is most likely not fully represented in the numbers used in GLEAM and in the Dutch reference values.

For the laying hens sector we had to make several assumptions, such as 1) molting doesn't take place, meaning we assume parental animals are kept for 1 round of production and slaughtered afterwards. 2) Most recent data is used, but this can mismatch with data of earlier years. Moreover, some data, especially on trade, is provisional. 3) Backyard systems are not included. Only for Romania some backyard production was included in GLEAM.

**Externalization**

The openness of a system or externalization of a system is a very important aspect in order to provide a full overview of the metabolism of the system. Externalization, as described extensively previously, related to all resources a system needs to import in order to function and deliver the expected outputs. Imports, therefore, refer to resource that come from outside the system. "Outside the system" depends on the formal definition of the processors and the definition of the boundary of the system.

In the current assessment, externalization can be explored in each particular livestock sector (i.e. dairy, beef, pig and poultry), of the total animal or livestock sector or as a country. In the livestock sector, openness is especially relevant in the case of 1) life animals, i.e. animals that are imported or exported from the system under study. Animals could enter the system at any stage of the productive life. For instance, as adult reproductive animals as replacement, but also young stock to be fattened or already fattened animals to be slaughtered. 2) feed, i.e. feed components that come from other agricultural sectors within a country or from outside the country. In a sense, how feed self-sufficient are the farms and/or the country. 3) energy to carry out all the activities required to rear animals.

The externalization becomes very interesting to establish comparisons between sectors and between countries. For instance, the calculation of feed required externally to reproduce the specific livestock activity would also allow the calculation of land required elsewhere to maintain the production system. Also in terms of feed, which systems become more self-sufficient and which ones more dependent on other sectors to function. This is a key question on sustainability (Ripoll-Bosch et al., 2014), not only for the socio-ecologic system under study but also for the pressure that might be causing the socio-ecologic system from where the externalized resources come from.

**Visualization and integration of results**

The procedure described above allow for the representation of each livestock sector in each of the 8 countries. Moreover, it allows for the analysis and integration of results at different scales.

As explained in section 5.2.2 (Scaling across metabolic elements using the concept of processor) it is possible to trace (up-scale and down-scale) across different hierarchical levels and analyze the element of interest. For instance, the analysis could address the livestock sector at more European level, by aggregating the 8 different countries. A down-scaling would provide and analysis of the livestock sector at a country level. And further disaggregation or downscaling would provide an analysis of each livestock sector within the country, and further, an analysis of the different processors (i.e. the sequential processors) within a sector.

As an example of the disaggregation per livestock sector within a country can be seen in Figure A2.10, were there is the representation of the dairy sector in the Netherlands.

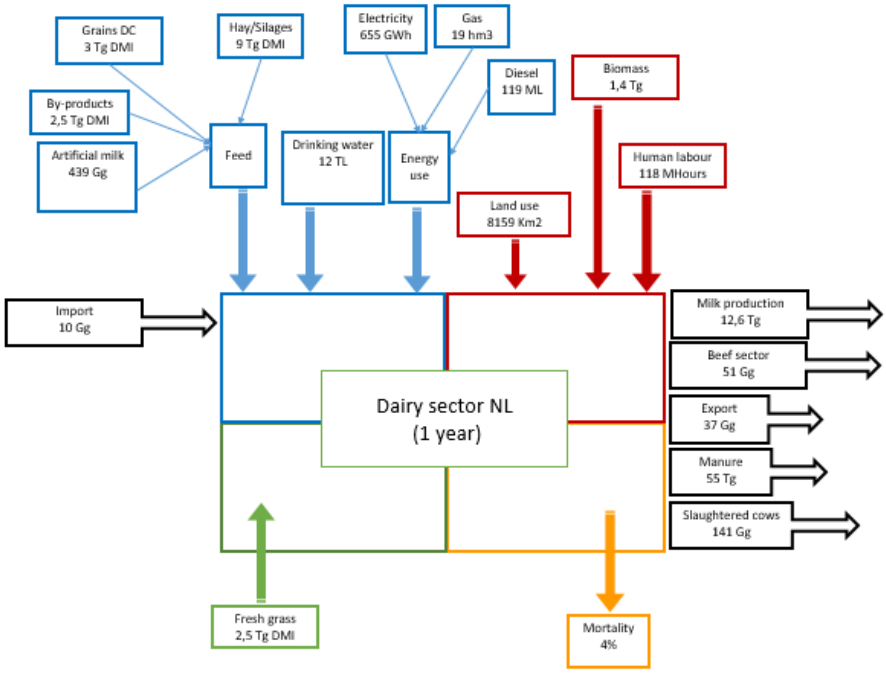


*Figure A2.10. Example of animal processor (dairy sector).*

As we can see in Figure A2.10, the processor is compiling information about:

· Different categories of feed, water and energy that come from the technosphere, and also some imported live animals to replace the dead or sold ones (in blue).

· Labour, land and the biomass (numbers of animals time their weight) as fund elements (in red).

· Fresh grass from the pastures inside the farm (in green).

· A waste element made of the dead animals that is disposed to the environment (in yellow).

· A set of different outputs to be used by the rest of the socioeconomic system as a result of the dairy production, including milk, meat, live animals and manure (in black).

A further disaggregation into the 3 main stages of production in livestock (i.e. the sequential processors, corresponding to the adults breeding, the early growing stages, and the stages for growing and finishing) would provide the Figure A2.11, when

calculating the amount of livestock biomass with a top-down approach, or the Figure A2.12 when calculating the amount of livestock biomass with a bottom-up approach.

First, as we see, the figure of each processor resembles the aggregated figure for the dairy sector. However, each stage is characterized by very different processes, resources and quantities of fund elements, and even more complicated, there are imports and exports of live animals with other systems in each one of these stages.

Second, we realize that number differ when using one or another method. The definition of the number of animals (or "amount of livestock biomass") is critical as most of the flows (inputs and outputs) are usually available in literature and statistics in unitary terms, as coefficients (not in absolute terms). This means that many flows are scaled to the total livestock biomass (or numbers). Hence, determining the size of the processor (i.e. livestock biomass) is crucial.

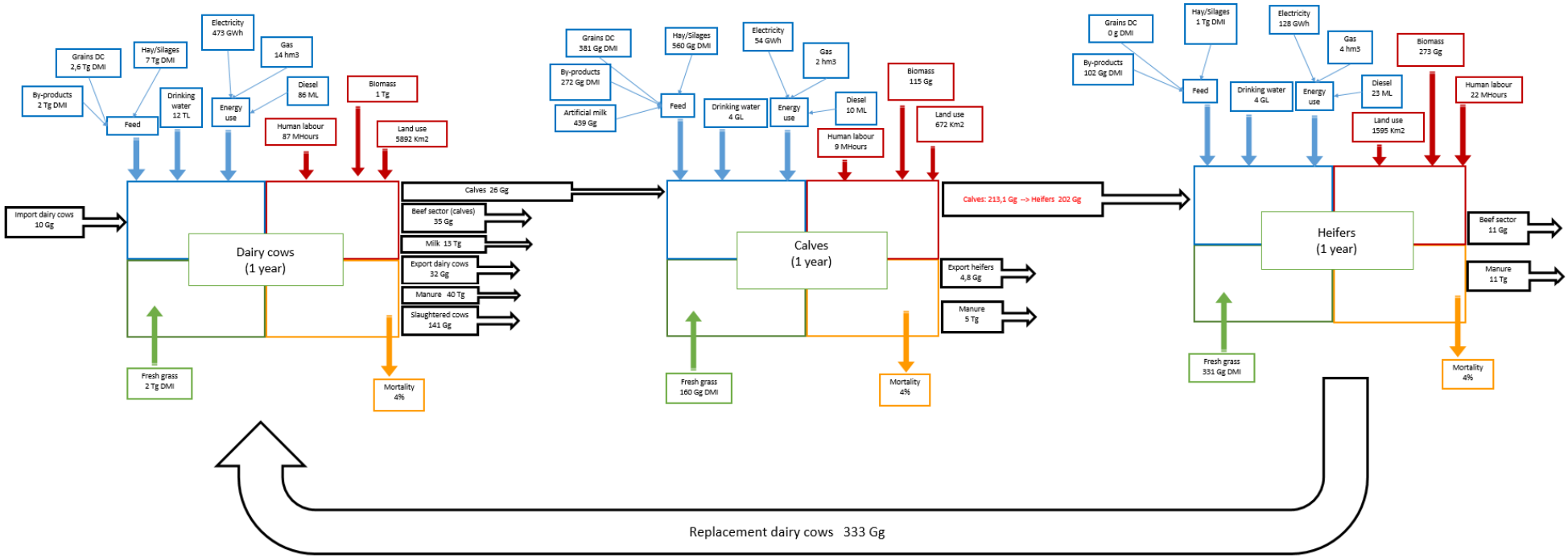


*Figure A2.11. Example of full representation of animal processors in the sequential pathways (dairy sector in Netherlands). The yearly metabolism of the Dutch dairy sector based on statistics (top-down approach).*

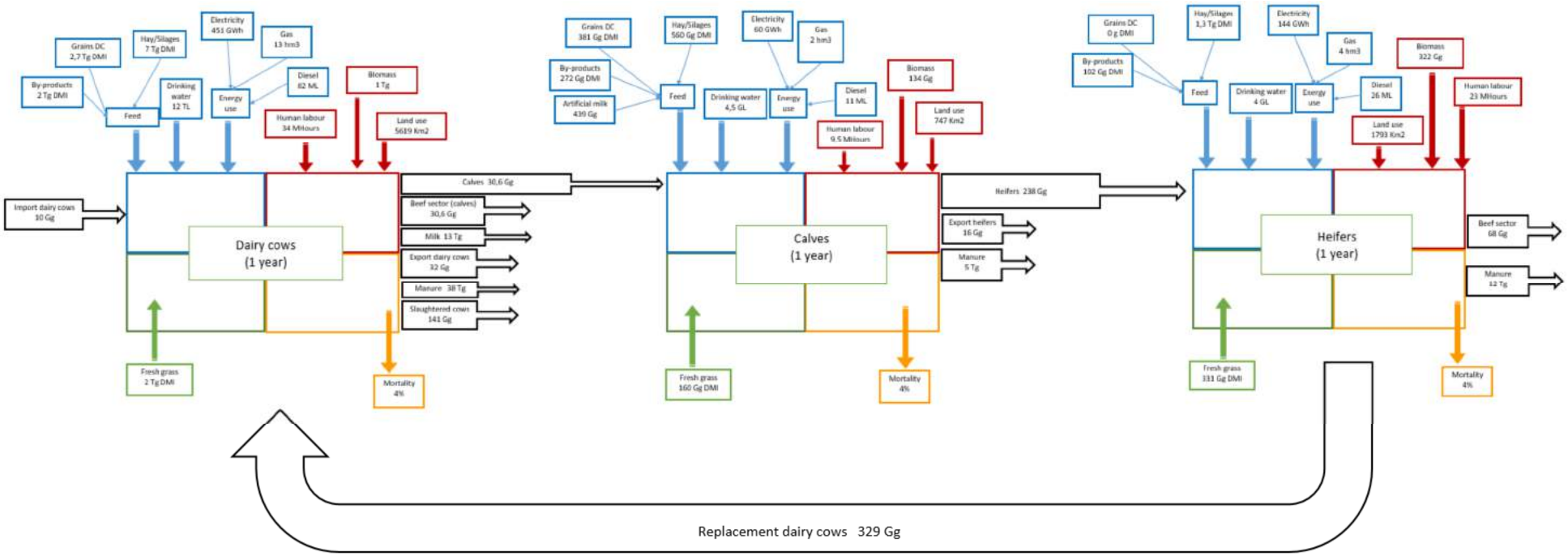


*Figure A2.12. Example of full representation of animal processors in the sequential pathways (dairy sector in Netherlands). The yearly metabolism of the Dutch dairy sector based on biophysical potential (bottom-up approach).*

**The scaling up of the animal products**

Bovine, caprine and ovine are the only animal categories consuming roughages from pastures, hays and silages. Chickens and pigs are not ruminants and eat feed made of crops. Blue water is the water withdrawal for drinking and maintenance purposes, and green water is the soil moisture appropriated by the plants composing the roughages, so only ruminants entail green water consumption.

The offals and fats are a by-product and their quantities in statistical sources do not distinguish among animal origin. But it is possible to estimate the associated resources using the proportional quantities of the rest of food categories and the coefficients per unit of food output.

The feed quantity is also important because it will provide the data about food virtual imports on how much crops and associated resources must be used to feed the imported animal products.

### A2.1.4 Food in the matrices

In this first part, it will be shown how the results for the information about food are expressed in the final matrices, with the End Use Matrix (EUM) divided into the Domestic End Use Matrix (EUMdom) for food and the Externalized End Use Matrix (EUMext), and the Environmental Pressure Matrix (EPM) divided into the Domestic Environmental Pressure Matrix (EPMdom) and the Externalized Environmental Pressure Matrix (EPMext).

In this case, the End Use Matrices are filled mainly using statistical data from “top-down”. The Environmental Pressure Matrices have to be built using data from “bottom-up” about the inputs required in each of the processors corresponding to the selected categories of food, which are later combined with top-down data about the quantities of food to scale-up to the extensive values at country level. This means that the processors obtained from bottom-up information are providing technical coefficients (intensive variables) about the resources required to produce different food products, but we use the information from top-down about food quantities to scale up the information to extensive values at the different levels of aggregation.

**Domestic End Use Matrix**

As explained in Section 3, we are representing the food products in the End Use Matrices (EUM) as a set of two main functional categories of food –plants and animals- split into the relevant constituent components of the system under analysis. For the allocation of the food flow into the constituent components we will follow the food grammar shown in the previous Figure A2.1. In the following Table A2.2 we can see an example of the

final result for a EUMdom with the food values among the socioeconomic sectors of one of the 8 EU countries analysed.

*Table A2.2. Domestic End Use Matrix of food.*

| Country | Year | Sector | Plants (Mton) | Animals (Mton) |
|---|---|---|---|---|
| **France** | 2012 | AG | 22 | 2.4 |
| | | MC | 48 | 0.13 |
| | | SG | 14 | 0.24 |
| | | ES | N/A | N/A |
| | | HH | 35 | 25 |
| | | TOTAL | 120 | 28 |

The data source used in this case comes from the Food Balance Sheets (FBS) from FAO, which already provides a split of food allocation that can be useful for our purposes. In the following lines it will be explained how to re-aggregate this data into the categories useful for our analysis.

For sake of simplicity and clarity, the EUM only reflects the two main categories of food: the “plant” and the “animal” food products. We decided to name “plant” instead of “crops” or “vegetables” terms since there are few food plant products that are not cultivated, just gathered from the wild. And the word “vegetable” in English is usually used to name only the fresh and green vegetables from the vegetable gardens.

The food values in the EUMdom are reflecting how much food is consumed by the population in their diet, which is allocated to the Household sector (HH). Note that this is the total food quantity arriving as food to the people, before possible losses for preparing and cooking the food in the kitchens (that can suppose a large part), so this number does not exactly reflect the final amount of food (nutrients) eaten in the diet of the population. We could provide an estimation of the food in the population’s diet

using for example the data about food losses found in FAO (FAO 2011). But in this case, we just need to reflect the total amount of food consumed by the people including losses, so that it matches with the rest of food quantities allocated to other sectors.

Please note that, differently from other dimensions (like energy or water), the rest of food is allocated to the productive sectors of the EUM not because they are eating food, but in terms of other uses of food and losses in other activities of those sectors. In this case, the food categories from the FBS of FAO are allocated as follows[TST1] :

· The category "Food" from FBS is the food finally consumed by the population. We allocate it only to the HH sector, although some food is eaten in the restoration sector, which is part of the SG. This quantity is obtained after the production, imports, exports, stock change, and different losses.

· The category "Losses" from FBS is allocated only to the SG sector, since what FAO consider losses are mainly occurring in the storage, distribution and transportation, which are activities of the SG sector, and excluding losses before and during harvest.

· The categories "Processing" and "Other Uses" from FBS are allocated to the MC* sector. "Processing" for FAO means the part of the food that is transformed into other food type, such as sugarcane into sugar or olives into oil. This is tricky because it implies double accounting, since the quantity in Processing will be also repeated in other food categories of the FBS. However, for the purpose of this EUM, it provides on the other hand a very useful indicator about the size and importance of the food processing sector of the country, that otherwise would be no indicator about it. So, depending of the purpose of the analysis this category should be kept or removed. The term "Other uses" refers to the use of agricultural products for non-food purposes, such as oil used for soap, so this is also part of the manufacturing industry.

· In the category AF of our EUM we will not include the food produced by the agricultural and fishing sector (important!), but only the part of the food that is "consumed" by this sector. That means the food that is required to produce more food, reflected in the FBS as the categories "Feed" and "Seed". Losses before and during harvest in the agricultural sector are already excluded from the food balance sheets, so we do not need to estimate that part for the EUM.

· The "Export quantity" from FBS is allocated to the EXPfood sector.

· And the sectors ES, and EXPenergy of the EUM are not food end users, so food data is not applicable there.

Of course this allocation of data into the socioeconomic sectors implies big assumptions. However, this provides a good quantitative approximation useful to map the consumption and allocation of food in the economic system.

**Externalized End Use Matrix**

For the EUMext we can use the three methods described in the previious section 3. In the cae of food, we need to account both for the direct imports of plant products (primary products and derived products), the direct animal imports in the form of meat, eggs and dairy, the direct live animal imports, and also for the indirect use of plants products as feed for the imports of animal products and live animals, and the indirect use of animals in other countries to produce the final animal products imported (virtual imports of food).

In order to know where the food is coming from and how much is remaining in the analysed system, it is useful to visualize the data about the **exchanges** of food with other countries summarized in a matrix as the following Table A2.3. The EUMext is very useful because offers a quick image of the **dependencies** from abroad of food products when compared to the domestic production. Additionally the exports can be checked to get the the level of domestic consumption and trading of the food (maybe the country exports most of the production or it re-exports the imported food).

*Table A2.3. Externalized End Use Matrix of food.*

| Country | Year | Sector | Plants (Mton) | Animals (Mton) |
|---|---|---|---|---|
| **GERMANY** | 2012 | Imports | 83[TST2] | 12 |
| | | Externalized (virtual imports) | 63 | 0.77 |
| | | Exports | 60 | 19 |
| | | Domestic consumption | 118 | 27.6 |

Items in this Table are again filled with statistical data from top-down, as described in detail in the following section A2.2. Data management.

**Domestic Environmental Pressure Matrix**

The following Table A2.4 shows an example of data that can be later used as indicators of environmental pressure on the extraction of natural resources and the disposal of wastes to the ecosystem to produce the food of a country.

*Table A2.4. Domestic Environmental Pressure Matrix of food.*

| | | | **Fund supply capacity** | | | **Fund sink capacity** | |
|---|---|---|---|---|---|---|---|
| **Country** | Year | Food category | Land **(mha)** | Water withdrawal **(hm3)** | Soil moisture **(hm3)** | NPK **(mton)** | Manure **(kton)** |
| **Italy** | 2012 | Plants | 10 | 3500 | 32000 | 1.4 | N/A |
| | | Animal | 4.2 | 470 | 6300 | N/A | 775 |
| | | TOTAL | 14.2 | 3970 | 38300 | 1.4 | 775 |

In the case of food, we provide an example of information for a list of environmental pressure variables: land (including pastures), water withdrawal, soil moisture, fertilizer use and manure (that serves to calculate the leakage to the ecosystem). Please note that is required a series of calculations to estimate the part of these resources that pressure the environment. After completing the EPM, one could use the indicators to generate environmental impact assessments, however, this assessment use context-dependent variables, so it must be included the characteristics of the ecosystems affected.

**Externalized Environmental Pressure Matrix**

The EPMext (Table A2.5) shows an estimation of how many resources is a country saving through the imports of food from other countries (labour, land, water and fertilizers). Alternatively, it could show how many resources are consumed in other countries by the food imported to our country, reflecting the environmental pressure provoked in other territories that have to produce our food. For this last estimation we would have to check, for each food type, where the imports come from and how is the use of resources in that country (for labour, land, water and fertilizers) for the production of that food type, that is all processors of food for all countries exporting to our analysed country. In this example we are showing the first option, using the values of the domestic technical coefficients times the food imported or virtually imported.

As previously mentioned, the only food products that can be considered as virtually imported are the plants that the imported livestock is eating as feed in other countries, so it pertains only to the "Grains Roots Tubers" category of food.

*Table A2.5. Externalized Environmental Pressure Matrix of food.*

| | | | **Fund supply capacity** | | | **Fund sink capacity** | |
|---|---|---|---|---|---|---|---|
| **Country** | Year | Food category | Land **(mha)** | Water withdrawal **(hm3)** | Soil moisture **(hm3)** | NPK **(mton)** | Manure **(kton)** |
| **Italy** | 2012 | Plants | 15 | 2400 | 34000 | 1.3 | N/A |
| | | Animal | 2.8 | 320 | 4300 | N/A | 508 |
| | | TOTAL | 17.8 | 2720 | 38300 | 1.3 | 508 |

## A2.2 Data Management for food accounting

### A2.2.1 Data extraction

To analyse the food systems of the 8 EU selected countries (France, Germany, Italy, Netherlands, Romania, Spain, Sweden, United Kingdom), 2012 was the reference year. Data were extracted between October 2017 and March 2018 from different sources.

### A2.2.2 Data selection

For the food production from plants origin, it was considered production (in tonnes), the yield (tonne/ha), the harvested area (ha) from FAOSTAT database (FAO, 2017). To stablish the food use, the food openness (imports and exports) and allocation of food into the different sectors (AG, MC, SG, HH, ES), it was Food balance Sheets from (FAO, 2017). FAOSTAT was also used to check the origin country for imports and the destination country for exports. On the other hand, (Eurostat, 2017) data was used to check the origin country for imports and the destination country for exports for live animals.

For the food production from animal origin it was considered both the food production from live animals (milk, eggs) and from slaughtered animals (bovine meat, porcine meat,

poultry meat and ovine meat). Each of the elements composing these two categories are expressed in tonnes and were gathered from (FAO, 2017). From this same database was obtained the stock for each animal type that serves to determine the animal population and allocate them to the production systems considered in each selected country (see A2.2.4 Data transformation). Regarding the inputs for the animal processors, it was used (Mekonnen and Hoekstra, 2010a) to establish the blue water used as drinking water and service water for the animals for each type of farming system. To establish the farming systems, the type and quantity of used feed, the weight of living animal and the life stage, it was used the benchmarks given by the GLEAM model (FAO, 2010).

Regarding the technical coefficients of transformation from derived plants products to primary products, (e.g. the extraction percentage of soya meal from soya grains), and also for the technical coefficients of performance for the animal production (percentage of bovine meat obtained from a living animal), data was gathered from (FAO, 2017).

Regarding the data corresponding to the different inputs of the food processors, it was used:

· Blue and green water were expressed in m3/tonne of product, gathered from (Mekonnen and Hoekstra, 2010b, 2010c).

· For the use of fertilizers, benchmark values were calculated for N, P2O5 and K2O (expressed in kg/ha), applied for each category of food product (see section A2.2.5 Data organization). These data were gathered from (IFA, 2017; FAO, 2017) and checked with experts.

· Human activity was stablished by benchmark of crop category (hours/cultivated hectare) and for animal type (hours/animal type). Data was taken from (ICEADR, 2017; FAO, 2017;MAPAMA, 2017; SAC Consulting, 2016) and checked with experts.

· Data about manure produced by different animal types was taken from (FAO, 2017).

### A2.2.3 Data imputation

For Romania, it was used benchmark values from Slovakia due to the lack of data about the use of fertilizers per type of crop in Romania.

Due to the lack of enough of labour data for each crop type in each of the 8 selected countries, benchmark values from United Kingdom were used for Sweden, Germany and Netherlands. Data was available for Spain, Italy, France and some cases for Romania. In the case of animals, it was used the benchmark values from United Kingdom to all the

rest of countries analysed, due to the lack of data. However, values were discussed with experts and improved to each country to adapt and amend them. In any case, values were standardize to the values provided by (Eurostat, 2017) and (FAO, 2017).

### A2.2.4 Data transformation

**Transformations for plant systems**

To analyse properly the included products in the domestic consumption, products were divided into primary products (e.g. soya beans) and derived products (e.g. soya meal and oil). From this classification, derived products were transformed into their corresponding primary product. For this transformation were used the extraction coefficients of each selected country (FAO, 2017). However, to avoid a double accounting in the derived products from domestic production, it was checked its primary equivalent with the quantities provided by the "Processed" category of the FAO FBS. Since in most of cases the quantity of food in the Processed category of FBS was higher to its primary equivalent, derived products from domestic production were not considered in the EPM. In case of the quantity of the primary equivalent was significantly higher than the one in the Processed category, the difference was assumed as an imported product, and therefore it was included in the EPM estimations.

**Transformations for animal systems**

GLEAM model is structured to allocate the animal population by farming system. These farming systems are: a) *Grassland based* and *Mixed systems* for each bovine and ovine livestock used for dairy and non-dairy; b) *Backyard systems, Intermediate systems* and *Industrial systems* for the porcine livestock; c) *Backyard systems, Layers y Broilers* for the poultry. However, since that data was not available, it was established the percentage of food product used for each production system respect to the total produced with default values. For instance, for France 2010, grassland system for dairy provided 10%, grassland system for non-dairy was 6%, mixed system for dairy was 50%, and mixed system for non-dairy was 34% for bovine meat. The total produced meat in the different farming systems was allocated using these percentages. The goal of this estimation is to establish the inputs used in each farming system (feed used) and the animal population by type (adult females, adult males, replacement females, replacement males, fattening females, fattening males). The total amount of animals obtained was compared to the stock provided by (FAO, 2017), and there were no significant differences. The rest of meat products was estimated similarly. In the case of eggs and milk, it was used the same production ratio than its corresponding meat product, therefore, the only reference elements were the meat products in this case.

GLEAM model provides the animal feed by farming system divided into three categories: roughages, grains and agroindustrial by-products. These categories were disaggregated into their corresponding elements according to the GLEAM manual and its Excel application(FAO, 2010). Once the disaggregation was undertaken, the elements were re-aggregated according to its industrial processing. These new categories are:

- Direct corresponding to a primary product.
- Indirect corresponding to a derived product
- Wastes including straws from cereal crops.

Once this classification was done, it was decided to exclude the wastes from the EPM estimation to avoid a double accounting. The other two categories were processed similarly as described in section A2.2.4.1.

**Transformation of the food flow**

To establish the volume of food imports (or exports) per food category and country of origin (or destination), food products were classified using the trading database from (FAO, 2017) according to the classification seen in section A2.2.5 Data organization. Using this classification, it was selected a ratio for each origin country for the imports (or destination country for the exports). This ratio was applied to the corresponding values of imports and exports from FBS.

## A2.2.5 Data organization

A list of items aggregated was used from FAOSTAT Commodity Group (FCG) (see the following Table A2.6) with the goal of standardizing the MuSIASEM accounting process and to obtain a better adaptation to the databases from the main international organizations. The advantages of using this list are, firstly, that it is possible to go down to the level of plants and animals, and in second place, it is possible to allocate for each category the corresponding elements of flows and funds, obtaining the information for the processors. On the other side, these processors are the reference units that will integrate to the part of local production and imports to estimate the local and externalized environmental pressure. Finally, the matching between the data explained along this overall section A2.2 and the food flows until the allocation to the end uses are done according to the food grammar explained in Section A2.1.1.

*Table A2.6. Top-level classifications of the FAOSTAT Commodity Group used in the hierarchical classification of agricultural sector commodities*

| FAOSTAT Commodity Group (FCG) |
|---|

1. Cereals and cereal products
2. Roots and tubers and derived products
3. Sugar crops and sweeteners and derived products
4. Pulses and derived products
5. Nuts and derived products
6. Oil-bearing crops and derived products
7. Vegetables and derived products
8. Fruits and derived products
9. Fibres of vegetal and animal origin
10. Spices
11. Fodder crops and products
12. Stimulant crops and derived products
13. Tobacco and rubber and other crops
14. Vegetable and animal oils and fats
15. Beverages
16. Livestock
17. Products from slaughtered animals
18. Products from live animals
19. Hides and skins
20. Other livestock products

### A2.2.6 Data preprocessing

No descriptive statistics have been made. The SoP is a descriptive analysis itself of all variables integrated. See section A2.1.4 to see a detailed explanation about the use of data and sources into the different categories.

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# Appendix 3 Guide to water accounting in the State-of-the-Play of EU-8.

*Author: Cabello V.*

This guide illustrates how water is included in the analysis of the State-of-the-Play (SoP) of European countries. Part 1 explains relevant concepts and water accounting categories for the different analytical tools in the SoP. Part 2 details the data management process.

## A3.1 Water in the analytical tools of the State-of-the-Play.

### A3.1.1 The water grammar

The metabolic pattern of a social-ecological system consist of the linked analysis of the supply and consumption of different resources, and the pressures and impacts on ecosystems derived from those patterns. In the case of water, supply refers to the generation of water sources mostly by environmental funds (i.e. the eco-hydrological cycle) and their transformation into useful water. The consumption side focuses on the direct and indirect end uses of water required for a society to reproduce its socioeconomic functions[13]. The analysis of pressures on ecosystems are key in the water dimension since water connects social and ecological systems being a vehicle for such type of relations.

Compared to energy and food, water accounting for the national scale has some important differences to be taken into account in the methodology. First, the water sector of a country is not a relevant economic sector (in labour or monetary terms). The water sector consists in a myriad of public and private water supply utilities, specific for different end users, and public water administrations. They are a relevant sector at the regional scale but for the country level they are considered a subsector within the services and government sector. On the other hand, water contributes to many different supply and consumption activities in all socio-economic sectors. This is because water has multiple useful attributes (Madrid et al., 2013). That is to say, water is not only quantitatively consumed (i.e. evapotranspired) like energy and food. On the contrary, some use its quality, its temperature, its location or its potential energy, for instance. In these type of water uses, what is transformed are those attributes (water is polluted, warmed or changed in location). For this reason, there are several types of water flows in MuSIASEM processors in addition to consumptive use of water.

[13] Indirect water uses refers to virtual water or water that is considered embeeded in the products for which it was directly used.

Finally, the accounting of water imports and exports is also very different to food and energy because water is not directly imported or exported to other countries unless there is a transfer. Water coming through transboundary basins could be considered an import but we rather considering as imports only those flows generated by either trade or policies, not by natural hydrogeography. In this regard, the main type of water imports and exports are associated to indirect uses or virtual water embedded in imported products (mainly food, PES and EC).

The water grammar for the analysis of direct water uses within a country is presented in the following Figure A3.1.

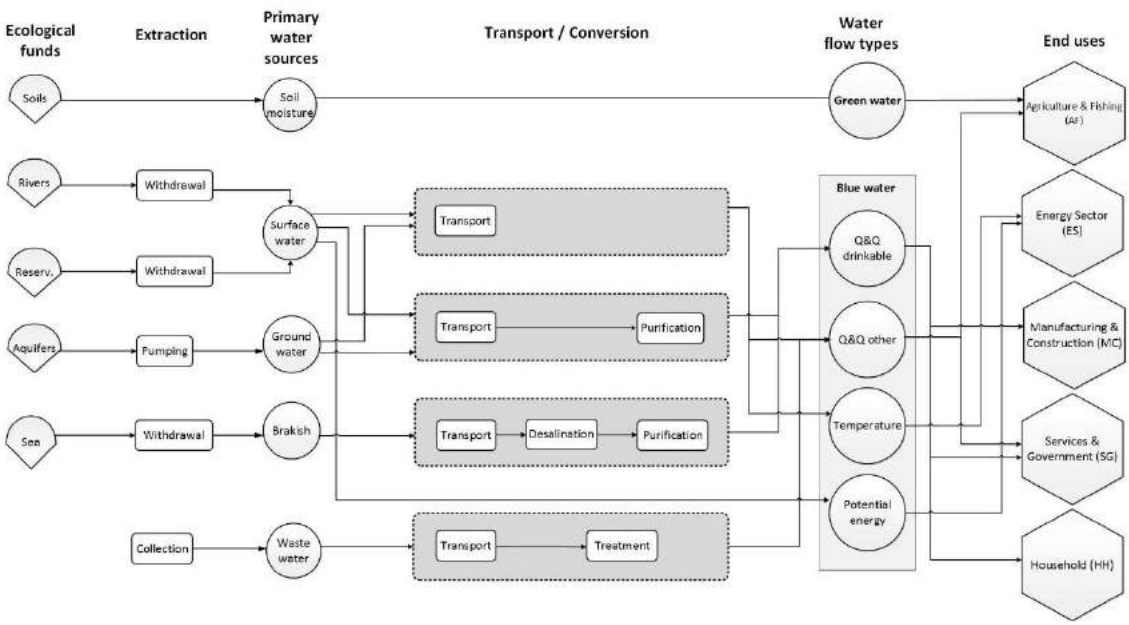



*Figure A3.1. Water grammar. Key for symbol reading in provided in the Appendix. Q&Q – Quantity and Quality use*

The grammar assimilates the categories from the energy and food accounting while acknowledging the above-mentioned specificities of water. From left to right the following categories are proposed: ecological funds from which water is withdrawn, primary water sources, transportation/conversion processes to bring water to useful quality for different sectors, resulting water flows for those sectors, and final end uses. The category of 'water flows types' (the analogous to energy and nutrient carriers) refers to qualitatively different sets of attributes of water required for different end uses. A taxonomy of five categories is proposed (Figure A2.2): green water directly evapotranspired from soil moisture; blue water (extracted from water bodies) - quantity and quality consumption, which can be drinkable water or other quality; blue water-temperature use for cooling mainly; and blue water-potential energy use for hydroelectricity

generation. For the sake of simplicity, Quantity & Quality uses are considered 'Consumptive blue water uses' in the aggregated matrices while Temperature and Potential energy uses are considered as 'Non-consumptive blue water uses'.

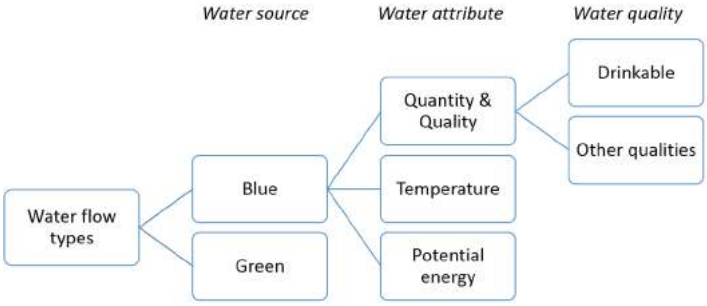



*Figure A2.2 - Typology of water flows used in different end uses*

Available international statistical sources (AQUASTAT, EUROSTAT) do not provide an adequate disaggregation of water uses in different subsector that would enable a bottom-up accounting of the water grammar. For this reason, the water accounting in this deliverable does only follow the multi-level approach in the case of water uses for food and energy production. That is, water is accounted in food and energy processors through alternative data sources that enable a bottom-up aggregation, as described in the corresponding guides. For the rest of sectors (HH, SG, MC), water is accounted in a top-down fashion. The integration of these two accounting procedures is provided in Part II of the guide. In the following sections, we explain the water related accounting categories in the different analytical tools (processors and matrices) characterizing the SoP of EU-8 countries.

## A3.1.2 Water in food and energy processors

Processors are used to characterize the metabolic pattern of a society from a production point of view. From this perspective, water can play different roles in the sequential pathways for food and energy supply: it can be an input from the environment, an input from another component within the social system, an output to the environment in the form of pollution or emissions, and sometimes an output to other social systems. Thereby, water accounting is coupled to the multi-level analysis of the food and energy sequential and hierarchical pathways as described in the food and energy guides. These different roles of water are expressed in general accounting categories in Table A3.1.

*Table A3.1. Water accounting categories in MuSIASEM processors*

| Categories | Acronym | Description | Units |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Withdrawal.<br><br>Can be decomposed into water sources, carriers and end uses. | WW | Water extraction from water bodies (surface, groundwater, brackish or sea). It is an environmental pressure and goes in the lower-left quadrant of the processor and it is considered a pressure. | Mm3/year |
| Green water use | WGU | Water used directly from soil in plant evapotranspiration. It is an environmental pressure and goes in the lower-left quadrant of the processor and it is considered a pressure. | Mm3/year,<br><br>m3/cap, m3/ha |
| Gross water use. Can be decomposed into water sources, carriers and end uses | GWU | Blue water that reaches the end user after transportation from withdrawal point. In practice, the difference with WW is very low and there is no data available for large analytical scales so they can be equated. | Mm3/year,<br><br>m3/cap, m3/ha |
| Net water use. Can be decomposed into water sources, carriers and end uses | NWU | Blue water that is effectively used by an end user within a territory. The difference with GWU is easy in agriculture because NWU equals plant transpiration while the rest is irrigation returns. In the case of urban or industrial uses the different is due to losses in the end user supply chain. NWU are equivalent to Water Footprints of production processes. This category goes also in the upper-left quadrant of the processors. Depending on the case, one might be more interested in considering GWU, NWU or both of them. | Mm3/year,<br><br>m3/cap, m3/ha |
| Returns. Can be decomposed into types of generator. | RET | Water that returns to the hydrological system from supply chains, including for instance irrigation returns. Losses happen in several steps of water supply and consumption chain. | Mm3/year |
| Wastewater.<br><br>Can be decomposed into types of generator. | WTW | Water that is qualitatively transformed and requires treatment in another processor before discharged into the water bodies or reused. This category goes in line with other outputs in the processors within the technosphere. | Mm3/year |
| Discharges.<br><br>Can be decomposed into type of discharge and types of generator. | DIS | Water that returns to the environment after is usage in the same basin where it was withdrawn with one or more water attributes transformed, usually water quality is deteriorated. It can be point (urban and industrial) or diffusive (agriculture) pollution to different types of water bodies (aquifers, rivers or the sea). This category goes in the lower-right quadrant of the processors and it is considered a pressure. | Mm3/year,<br><br>m3/cap, m3/ha |
| Virtual water<br><br>Can be decomposed into types of water flows | VW | Virtual water is defined as the water embedded in the outputs of a process. Therefore, the water used in order to produce a unit of food or energy products is its virtual water. Usually only consumptive water uses are considered virtual water. In this accounting also non-consumptive uses are considered virtual water flows. | Mm3/year,<br><br>m3/cap |

The general water accounting categories described in Table A3.1 can be further specified and disaggregated into subtypologies when describing food and energy processors. In what follows we represent them in some relevant generic processors.

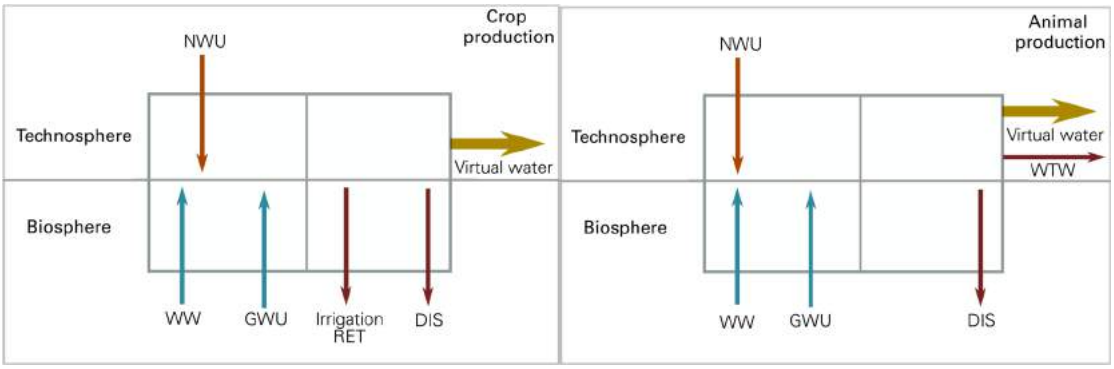



*Figure A2.3 - Water accounting categories in some relevant processors for food supply*

In irrigated crop production processes, water is both withdrawn from water bodies and directly used from soil moisture (green water). Blue water use is the share of withdrawal that does not return to water bodies. The sum of blue and green water uses is the virtual water embedded in the crops produced. Finally, water returns from irrigation and in the form of diffusive pollution (leaking nitrogen, pesticides and other agrochemicals). In the case of rain fed crops and pastures, only green water is used, which equals the virtual water content. Diffusive pollution is generated by rain percolation.

Coming to animal production, we find very diverse production processes as shown in the food accounting guide. Roughly, we can consider withdrawals as direct extractions for animal drinking and farm maintenance. Sometimes this water comes from public supply in the form of drinkable water (another social processor). Some types of animal production processes, such as pig farms, produce important volumes of highly pollutant wastewater, which requires treatment also in another processor. Finally, diffusive pollution is generated in some animal production mainly is pasture land from excrements leakage.

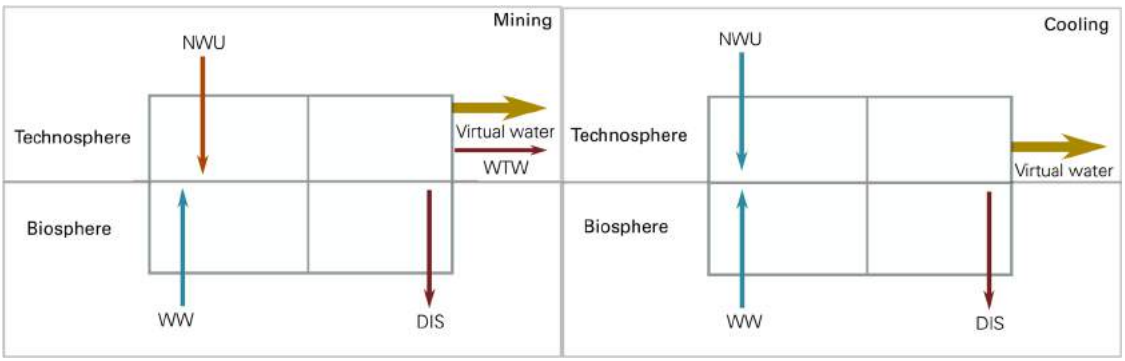



*Figure A2.4 - Water accounting categories in some relevant processors for energy supply*

Water uses in energy production are multiple as there are many processes involved along the energy sequential pathways. Figure A2.4 sketches the processors for two relevant examples. A processor for mining for PES might include withdrawal, net water uses, wastewater for treatment and discharges (either point or diffusive). Cooling is the second most important water use in energy generation after hydroelectricity. Water withdrawal is disaggregated into two categories of net water uses: non-consumptive use of water temperature that is later discharged into water bodies, and consumptive evaporation of a share of that water flow.

The case of hydroelectricity generation is a special one. It is the single largest user of water. However, it does not consume water quantity or quality, neither it withdraws water from the river. Hydroelectricity causes severe environmental impacts while under construction. However, once in operation, water simply flows through the power plant. Therefore, we have considered this water use as non-consumptive blue water use but not as a pressure to add to withdrawal and discharges.

### A3.1.3 Water in the Local End-Use Matrix

The EUM is used to characterize the metabolism from a consumption point of view, by quantifying the amount of resources used in a country in order to maintain the different socioeconomic sectors. As explained above, there is no water sector within the EUM but water is used in all sectors. The EUM for water is formalised as an **m** x **n** matrix ***W*** where rows are the sectors and columns are water flow types. Each item in *W* is the direct Water Throughput ($WT_i^j$) by sector *i* of water flow type *j,* obtained through the hierarchical pathway or aggregation of water uses at lower analytical levels as shown in Table A3.1, and measured in Mm3 per year or $m^3$/cap. Further calculus details are given Part II of the guide (Table A3.2).

*Table A3.2. Water Throughput calculus for the different sectors and water flow types*

| | Blue water consumptive uses (BC) | Blue water non consumptive uses (BNC) | Green water (G) |
|---|---|---|---|
| AF | $WT_{AF}^{BC} = WT_{Crop}^{BC} + WT_{Animal}^{BC}$ | Not considered | $WT_{AF}^{G} = WT_{Crop}^{G} + WT_{Animal}^{G}$ |
| ES | $WT_{ES}^{BC} = WT_{PESMining}^{BC} + WT_{Refinery}^{BC} + WT_{Electricity}^{BC}$ | $WT_{ES}^{BNC} = WT_{Cooling}^{BNC} + WT_{Hydroelectricity}^{BNC}$ | $WT_{ES}^{G} = WT_{Biofuel\ crops}^{G}$ |
| MC | $WT_{MC}^{BC} = WT_{Mining}^{BC} + WT_{Construction}^{BC} + WT_{Manufacturing}^{BC}$ | Not applicable | Not applicable |
| SG | $WT_{SG}^{BC} = WT_{Drinkable\ for\ commercial}^{BC}$ | Not considered | Not considered |

| | | | |
|---|---|---|---|
| HH | $WT_{HH}^{BC} = WT_{Drinkable\ for\ residential}^{BC}$ | Not considered | Not considered |

## A3.1.4 Water in the Externalized End-Use Matrix

The externalized EUM accounts for the use of resources in order to produce the food and energy commodities imported by EU-8 countries. Industrial and manufactured products are not accounted. Water is accounted in the externalized food and energy processors in a similar way than for the local ones as described in Table A3.1. Water inputs in externalized processors are accounted as indirect imports, classified in the same type of water flows types. For example, the externalized non-consumptive water use is the water required for hydroelectricity production and cooling activities in order to produce imported EC in a given country, assuming the technical coefficients from the country. The total water uses in the EUM of the SoP will be thus the sum of direct water uses within the country for both domestic consumption and for exports, plus indirect water uses associated to imports.

## A3.1.5 Water in the Environmental Pressure Matrix

The EPM is used to characterize pressures on ecosystems generated by food and energy supply. There is no EPM specific for water but water is accounted as the aggregated pressures from food and energy processors (lower part of the processors, flows in and out from ecosystems).

Water related pressures in the EPM for the SoP are described in the following Table A3.3. An important assumption made in the analysis of energy pressures is that hydroelectricity is not accounted in withdrawal and discharges. As explained, the pressures and impacts generated by this activity are of a different nature. Therefore, hydroelectricity is accounted as a non-consumptive use in the EUM but not as a pressure in the EPM.

*Table A3.3. Water related pressures in food and energy processors*

| | Fund stressed supply capacity | Sink stressed supply capacity |
|---|---|---|
| Energy | Withdrawal<br>$WW = \sum_i WW$<br>i= PES mining, refineries and biorefineries, electricity generation processors (no hydro) | Discharges<br>$WW = \sum_i WW$<br>i= electricity generation processors (no hydro) |
| | Soil moisture, equal to green water | |

| | | |
|---|---|---|
| | use in biofuel crop production | |
| Food | Withdrawal<br>$WW = \sum_{crop} WW + \sum_{animal} WW$ | Not considered |
| | Soil moisture, equal to green water use in crops and pastures | Not considered |

The local and externalized EMP follow exactly the same procedure, aggregation of pressures from processors involved either in local production within a country or in producing food and energy commodities that are imported into the country.

The analysis of water related pressures becomes more meaningful at the regional level when these pressures can be related to the level of impact on ecosystems, providing a comprehensive operationalization of the DPSIR framework.

### A3.1.6 Water sources matrix

The link of water consumption to supply capacity is not provided in the SoP matrices. This is a joint assessment that becomes more relevant when moving down to lower geographical scales such as river basins. However, at the national level we can compare the patterns of water consumption to that of water sources and available resources to understand some system constraints. As shown in Table A3.4, most water supply in EU-8 comes from surface water withdrawal. Some countries have started to introduce alternative water resources but these are far from becoming relevant in the national pattern. The EU-8 country with highest withdrawal is Italy albeit there is not further data on how this is splitted into sources. Spain on the contrary has annual data showing its large contribution to European overall water metabolism, both from surface and groundwater sources.

*Table A3.4. Primary water sources in the EU-8 countries (Mm3/year). Sources: EUROSTAT for withdrawal, and AQUASTAT for desalination and reclamation data.*

| **Country** | **Total withdrawal** | **Surface** | **Groundwater** | **Brackish** | **Desalination** | **Reclamation** |
|---|---|---|---|---|---|---|
| France | 30008 | 23554 | 6455 | 4803 | 12 | 411 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Germany | 32959 | 27211 | 5749 | 0 | 0 | 42 |
| Italy | 53750 | Nav | Nav | Nav | 97 | 45 |
| Netherlands | 10805 | 9787 | 1018 | 0 | 0 | 8 |
| Romania | 6453 | 5880 | 573 | 0 | 0 | 0 |
| Spain | 37405 | 30521 | 6884 | 205 | 100 | 49 |
| Sweden | 2426 | 2235 | 191 | 551 | 0.2 | 0 |
| United Kingdom | 7955 | 5754 | 2201 | 7880 | 33 | 146 |

## A3.2 Data management for water accounting in the State of the Play.

This part of the guide shows the process of data management combining top-down statistics and bottom-up aggregation of water used in different processors, alongside calculus procedures and main uncertainties affecting the interpretation of results.

### A3.2.1 Data selection

The selected sample are 8 EU countries (Spain, Italy, Germany, France, Romania, Sweden, UK) and one year 2012. Data was collected between 20/12/17 and 31/01/18 from four different sources (last access March 2018).

- EUROSTAT – WATER http://ec.europa.eu/eurostat/data/database

From the Eurostat Database, the following datasets were downloaded for the 8 countries and for the available years from 2010 to 2015[14].

- Water resources: long-term annual average
- Fresh water abstraction by source - million m³
- Water abstracted by sector of use
- Water made available for use
- Water use from public water supply and self-supply NACE Rev. 2 activity

[14] The firs list of datasets that you see in the water section (Energy & Environment – Environment – Water) does not include all downloaded datasets. One needs to look for the tag water in the searching option to access a larger a list.

- Water use balance *env_wat_bal* http://ec.europa.eu/eurostat/web/products-datasets/-/env_wat_bal

They were downloaded in csv format and imported into excel for validation, imputation and extraction. Data units are Million cubic meter/year. The data are produced by the National Statistics units of the member states who are asked to fill up the following template on a year basis: ec.europa.eu/eurostat/ramon/coded_files/OECD_ESTAT_JQ_IWA_Master.xls

The reporting is volunteer and therefore there are important disparities between the countries and many missing data. Caution is recommended about the interpretability of the data due to different interpretation of accounting categories and accounting methods by the different member states. Metadata does not cover an explanation of the process for collecting the data but there is manual linked in CIRCAB.

- AQUASTAT FAO http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

From Aquastat database, the following datasets were downloaded for the 8 countries and for the available years in the periods 2008-2012 and 2013-2017:

- Water use withdrawal by sector
- Water use withdrawal by source

They were downloaded in csv format and imported into excel for validation, imputation and extraction. Data units are $10^9$ cubic meter/year and m3/cap/year.

The dataset by sector includes data for all countries sampled, but only total withdrawal, not uses, and the categories are very large (municipal, industrial and agricultural, including another for irrigation). There is no distinction between consumptive and non-consumptive uses. The dataset by source contain data for all countries but Italy which only provides total withdrawal, desalinated and reclaimed. The datasets gather different types of sources or estimations, described in the metadata as:

| | |
|---|---|
| **No symbol** | Data come from one national source (report, publication, official website, etc.) |
| **L** | Modelled value |
| **I** | Internal estimate (previously known as F) |
| **K** | Aggregate value, either an aggregate of more than one source, or a calculated value depending on values with mixed symbols that include "external" values (E) or aggregate values (K) in addition to at least one value without a K or E symbol |

**E** External value (reported by another international agency*)

Time grain are referred to periods of 4 years (2008-2012; 2013-3017) although there is a year of reference indicated, ranging from 2000 to 2013. Only Romania has data for the two periods indicated. Therefore, the general the quality of the data is rather low and interpretation is limited by the accumulated technical and methodological uncertainties. However, they are useful for comparison and for imputation of missing data in EUROSTAT datasets.

- WATER FOOTPRINT STATISTICS (for food processors)
  http://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/

Coefficients of blue and green water footprints of biofuels, crop and animal products were used for the bottom up accounting of water use in the agricultural sector. These datasets are available at the product water footprint statistics databases and shall be referenced as:

- Mekonnen, M.M. & Hoekstra, A.Y. (2011) The green, blue and grey water footprint of crops and derived crop products, *Hydrology and Earth System Sciences*, *15*(5): 1577-1600.
- Mekonnen, M.M. & Hoekstra, A.Y. (2011) The green, blue and grey water footprint of crops and derived crop products, *Hydrology and Earth System Sciences*, *15*(5): 1577-1600.
- Mekonnen, M.M. & Hoekstra, A.Y. (2012) A global assessment of the water footprint of farm animal products, *Ecosystems*, *15*(3): 401–415.

The databases contain estimations of consumptive water uses for primary crop and animals products in $m^3$/kg, following the water footprint indicator methodology. They have been considered the technical coefficients of Net Water Use in agricultural processors. Water use for biofuel crops have been included within energy processors. These datasets are obtained through grid-based global models for water balance aggregated through a set of assumptions. Despite providing rough estimations at the country level, they are standardized models and their technical and methodological uncertainty is much lower than in official statistics. A detailed description of the management of data collection and validation from these databases is provided in the energy and agricultural guides.

- ECO-INVENT DATABASE (for energy processors)
  https://www.ecoinvent.org/database/database.html

Coefficients of water used in energy production (mining, hydroelectricity, cooling, biofuels…) were used for the bottom up accounting of water use in the energy sector. These data are available in the Eco-Invent Database that contains input-output data for hundreds of production processes. While the data comes from multiple studies and sources, it is standardized in Eco-Invent serving as the core database in Life-Cycle Assessments. A detailed description of the management of data collection and validation from this database is provided in the energy guide.

### A3.2.2 Data imputation

Within EUROSTAT datasets, only four countries have complete datasets for more than one year and include 2012: Spain, France, Romania and the Netherlands. Germany has available data for several years only for the datasets on water use but not on water withdrawal, which is only accounted in 2010. Therefore, 2010 was chosen as accounting year for Germany. In the case of UK, data is only available for 2011. No data is available for Italy and Sweden in EUROSTAT datasets. The data for these two countries was obtained from AQUASTAT datasets, using benchmarks from similar countries (Spain for Italy, Germany for Sweden) for disaggregated larger categories into the different sectors.

### A3.2.3 Data transformation

The accounting categories from the different databases need to be transformed into MuSIASEM categories. To do so, a revision of methods was performed and adjustments made to the data. Some of assumptions were made in this regard. They are summarized in Table A3.4 together with formulas for different accounting procedures.

In the case of Eurostat data, we consider water use by sectors as equal to the GWU category in MuSIASEM whereas withdrawals are equal to WW (see Table A3.2 for definitions). AQUASTAT data equals WW but we assume it equal to GWU in the EUM. In practice, the difference between WW and GWU is negligible at the country level.

Water footprint statistics equate the NWU category in MuSIASEM processors since they only refer to consumptive uses. A coefficient of irrigation efficiency at the country level was used to estimate GWU for the agricultural sector, which can be compared with top-down values from both EUROSTAT and AQUASTAT.

Eco-Invent datasets for energy processors include categories of water withdrawal and discharges. As shown in Tables A3.3 and A3.5, water uses in the energy sector include consumptive, non-consumptive and green water. Consumptive blue water uses include mining for PES and refineries because water quality is significantly transformed and requires an additional treatment in a separate processor. In these cases, water withdrawal in the processors was considered equal to GWU. Electricity production also consumes water, mainly evapotranspiration in cooling and hydro processors. This volume is calculated as the aggregated difference between withdrawal and discharge in the sector processor. Non-consumptive uses refer to the water that is not quantitatively or qualitatively consumed in cooling and hydroelectricity production and is obtained by aggregating discharges in those processors. This is the largest part of water uses. Green water uses refer to the production of biofuel crops.

### A3.2.3 Data organisation

Data has been gathered in Excel files following the structure of EUM and EPM for upper analytical levels as shown in the deliverable databases. For the water accounting, the final matrices are calculated by the aggregation of three submatrices: i) the EUM and EPM for water in energy supply; ii) the EUM and EPM for water in food supply; iii) the EUM for water in the rest of the sectors. They can be found within the water database.

### A3.2.4 Data preprocessing

No descriptive statistics have been made. The SoP is a descriptive analysis itself of all variables integrated.

*Table A3.5. Summary of methods for water accounting in the EUM. WT = Water Throughput; WF=Water Footprint; Y=Yield; WU=Water Use; WW=Withdrawal; DIS=Discharge*

| **End use matrix categories** | **Water flow type** | **Subsector** | **Data source & formula** | **Comments** | **Assumptions** |
|---|---|---|---|---|---|
| Agriculture and fishing (AF) | Blue water consumptive use | Crop production | Top down: Eurostat water use in agriculture | | =Gross Water Use |
| | | | Bottom up: $WT = \frac{\sum_i^{crop} WF*Y}{Efficiency}$ | Water for biofuel crops discounted | =Net Water Use, a coefficient of efficiency required to match GWU |
| | | Animal production | Bottom up: $WT = \sum_i^{animal} WF * \mathrm{Y}$ | | |
| | Green water | Crop production | Bottom up: $WT = \sum_i^{crop} WF * Y$ | Water for biofuel crops discounted | |
| | | Animal production | Bottom up: $WT = \sum_i^{animal} WF * Y$ | | |
| Energy sector (ES) | Blue water consumptive | Electricity production | Top down: Eurostat<br>$WT = WU_{electricity} - WU_{cooling}$ | The differences vary depending on the country. Hydroelectricity not included | =Gross Water Use<br>Water not used for cooling is consumptive use. |
| | | | Bottom up: Eco-Invent<br>$WT = \sum_{i}^{electricity} WW - DIS$ | | |

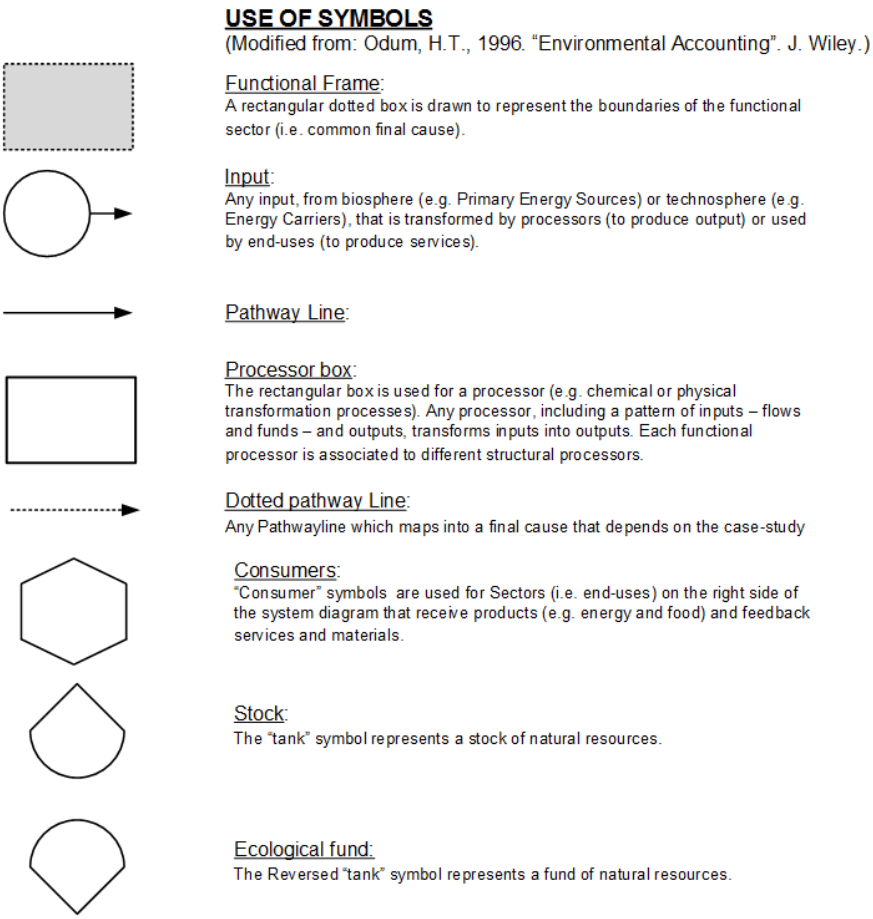
| | | | | | |
|---|---|---|---|---|---|
| | | Mining for PES | Bottom up: Eco-Invent $WT = \sum_i^{PES\ mining} \quad WW$ | | Consumptive use because water quality is transformed |
| | | Refinery and biorefinery | Bottom up: Eco-Invent $WT = \sum_i^{Refinery} WW + \sum_i^{Biorefinery} WW$ | | |
| | Blue water non consumptive | Cooling | Top down: Eurostat water use for cooling | Hydroelectricity not included | Non consumptive because once cooled down it is returned to water bodies or recycled |
| | | | Bottom up: Eco-Invent $WT = \sum_i^{Cooling} \quad DIS$ | | |
| | | Hydroelectricity | Bottom up: Eco-Invent $WT = \sum_i^{Hydro} \quad DIS$ | Water outflow from hydroelectricity processors | |
| | Green water | Biofuels | Bottom up: $WT = \sum_i^{crop} \quad GWF$ | | |
| Manufacturing and construction | Drinkable | Manufacturing | Eurostat category of manufacturing | Water used for oil and biofuel refining discounted and added to the energy sector | |
| | Blue water consumptive | Mining and construction | Eurostat category of construction + mining | Water used in mining for PES discounted and added to the energy sector | |
| Services and government | Blue water consumptive | | Top down: Eurostat category and AQUASTAT municipal water | These categories are likely interpreted in a different manner by different member states | Share calculated for AQUASTAT municipal water in the case of Italy |

| | | | | | |
|---|---|---|---|---|---|
| Households | Blue water consumptive | | Top down: Eurostat category and AQUASTAT municipal water | | and Sweden. Green water use in urban areas not considered. |

## References

Madrid, C., Cabello, V., Giampietro, M., 2013. Water-Use Sustainability in Socioecological Systems: A Multiscale Integrated Approach. Bioscience 63, 14–24.

## Appendix: Symbols key for grammars



# Appendix 4: The State of the play of EU8 countries

A continuation we present the Figures that summarize the results of the state of the play of the 8 EU countries analyzed in this report.

First, we present the End Use Matrix (EUM) of each of the 8 countries, and the then their Environmental Pressure Matrix (EPM).

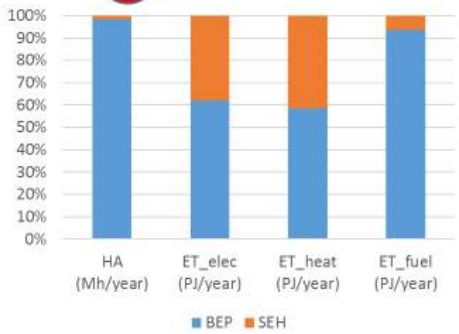
# STATE

FRANCE (2012)

POPULATION 65.3 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 1.29 | 1.04 | 1.25 | 0.7 | 0.86 | 1.28 | 1.26 | 1.25 | 0.68 | 1.04 | 1.02 |
| HOW | 1 | TOTAL CONSUMPTION | 2967 | 626 | 35 | 42 | 45 | 328 | 1790 | 1186 | 39 | 0.705 | 33000 |
| | 2 | EXTERNALIZATION | 767 | 85 | 4 | 9 | 19 | 51 | 417 | 431 | 10 | 0.174 | - |
| | | Total consumption/ domestic production | 1.35 | 1.16 | 1.14 | 1.26 | 1.72 | 1.18 | 1.30 | 1.57 | 1.34 | 1.33 | - |
| WHY | 3 | FOR SECURITY | 1839 | 428 | 31 | 34 | 39 | 301 | 1627 | 618.9 | 39 | 0.705 | - |
| | 4 | FOR EXPORT | 1128 | 198 | 3 | 8 | 6 | 27 | 163 | 567 | 0.0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1810 | 423 | 28 | 32 | 39 | 254 | 1248 | 394 | 8760 | 5311 | 33000 |
| AF | 18% | 9% | 2% | 1% | 5% | 18% | 0% | 99% | 0.30% | 83% | 2% |
| MC | 40% | 0% | 23% | 32% | 1% | 13% | 0% | 0% | 1.00% | 0.38% | 18% |
| ES | 0% | 0% | 13% | 8% | 0% | 18% | 100% | 1% | 0.03% | 0.44% | 2% |
| SG | 12% | 1% | 30% | 16% | 51% | 32% | 0% | 0% | 5.57% | 8.45% | 79% |
| HH | 29% | 90% | 32% | 43% | 43% | 19% | 0% | 0% | 93% | 7.52% | - |

*Figure A4.1. End Use Matrix (EUM) describing the state of the play of France*

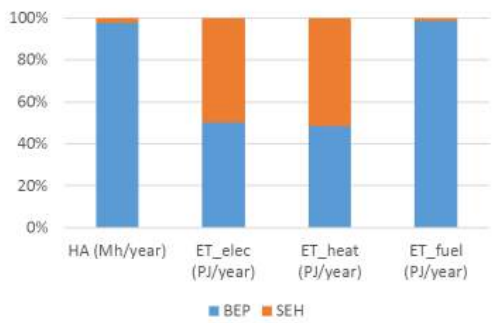
# STATE

GERMANY (2012)

POPULATION 80.3 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 1.00 | 1.22 | 1.12 | 0.91 | 0.93 | 0.63 | 1.08 | 0.87 | 0.55 | 0.67 | 1.16 |
| HOW | 1 | TOTAL CONSUMPTION | 2300 | 734 | 31 | 55 | 49 | 161 | 1541 | 825 | 32 | 0.453 | 37500 |
| | 2 | EXTERNALIZATION | 1160 | 157 | 3 | 6 | 11 | 13 | 370 | 345 | 14 | 0.180 | - |
| | | Total consumption/ domestic production | 2.02 | 1.27 | 1.11 | 1.12 | 1.30 | 1.09 | 1.32 | 1.72 | 1.75 | 1.66 | - |
| WHY | 3 | FOR SECURITY | 1509 | 494 | 28 | 46 | 42 | 153 | 1262 | 572 | 32 | 0.453 | - |
| | 4 | FOR EXPORT | 791 | 240 | 3 | 9 | 7 | 8 | 279 | 253 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1430 | 488 | 27 | 44 | 42 | 141 | 959 | 333 | 8760 | 2728 | 37500 |
| AF | 21% | 6% | 2% | 1% | 5% | 10% | 0% | 96% | 0.16% | 76% | 1% |
| MC | 37% | 1% | 37% | 41% | 1% | 43% | 0% | 0% | 2.00% | 0.72% | 27% |
| ES | 0% | 0% | 12% | 10% | 0% | 16% | 100% | 4% | 0.05% | 1.13% | 2% |
| SG | 5% | 2% | 27% | 14% | 41% | 1% | 0% | 0% | 5.86% | 14.5% | 70% |
| HH | 37% | 91% | 23% | 34% | 57% | 30% | 0% | 0% | 92% | 7.58% | - |

*Figure A4.2. End Use Matrix (EUM) describing the state of the play of Germany*

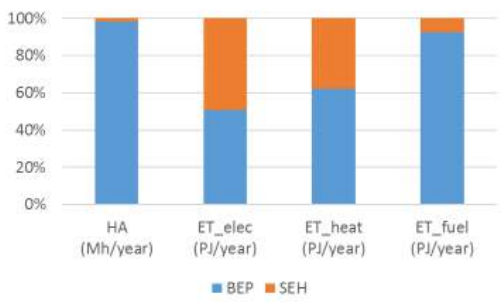
# STATE

ITALY (2012)

POPULATION 59.4 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 0.79 | 0.80 | 0.78 | 0.84 | 0.84 | 1.05 | 1.25 | 0.95 | 1.19 | 0.86 | 0.84 |
| HOW | 1 | TOTAL CONSUMPTION | 1821 | 480 | 22 | 51 | 44 | 270 | 1784 | 900 | 68 | 0.586 | 27200 |
| HOW | 2 | EXTERNALIZATION | 830 | 170 | 4 | 14 | 4 | 46 | 480 | 384 | 26 | 0.307 | - |
| HOW | 2 | Total consumption/ domestic production | 1.84 | 1.55 | 1.25 | 1.37 | 1.09 | 1.21 | 1.37 | 1.74 | 1.62 | 2.10 | - |
| WHY | 3 | FOR SECURITY | 1278 | 426 | 22 | 47 | 29 | 245 | 1571 | 633 | 68 | 0.586 | - |
| WHY | 4 | FOR EXPORT | 543 | 54 | 0 | 3 | 15 | 25 | 213 | 267 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1201 | 422 | 20 | 42 | 29 | 203 | 1148 | 363 | 8760 | 2786 | 27200 |
| AF | 22% | 3% | 2% | 0% | 5% | 25% | 0% | 99% | 0.45% | 83% | 2% |
| MC | 22% | 0% | 36% | 26% | 2% | 8% | 0% | 0% | 1.00% | 1.12% | 21% |
| ES | 0% | 0% | 12% | 11% | 0% | 9% | 100% | 1% | 0.04% | 0.70% | 2% |
| SG | 3% | 2% | 30% | 18% | 32% | 16% | 0% | 0% | 5.37% | 8.25% | 75% |
| HH | 52% | 95% | 21% | 44% | 61% | 43% | 0% | 0% | 93% | 6.99% | - |

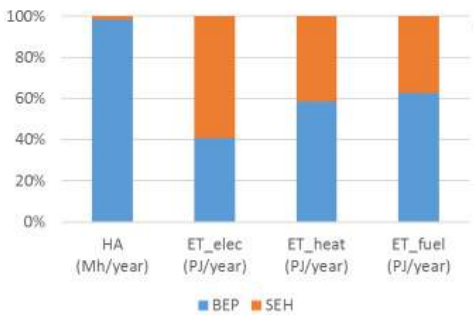
*Figure A4.3. End Use Matrix (EUM) describing the state of the play of Italy*

# STATE

NETHERLANDS (2012)
POPULATION 16.7 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 2.49 | 2.41 | 1.42 | 5.05 | 3.47 | 1.41 | 0.60 | 0.81 | 1.44 | 1.18 | 1.25 |
| HOW | 1 | TOTAL CONSUMPTION | 5740 | 1451 | 39 | 306 | 182 | 363 | 851 | 769 | 82 | 0.799 | 40400 |
| | 2 | EXTERNALIZATION | 3970 | 475 | 17 | 138 | 86 | 26 | 513 | 580 | 56 | 0.622 | - |
| | | Total consumption/ domestic production | 3.24 | 1.49 | 1.78 | 1.82 | 1.89 | 1.08 | 2.52 | 4.07 | 3.17 | 4.52 | - |
| WHY | 3 | FOR SECURITY | 2187 | 548 | 35 | 74 | 39 | 351 | 760 | 252 | 82 | 0.799 | - |
| | 4 | FOR EXPORT | 3553 | 903 | 4 | 232 | 143 | 12 | 91 | 517 | 0 | 0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1970 | 530 | 26 | 67 | 39 | 326 | 302 | 62 | 8760 | 1767 | 40400 |
| AF | 26% | 11% | 7% | 8% | 3% | 6% | 0% | 91% | 0.25% | 62% | 2% |
| MC | 32% | 0% | 29% | 26% | 3% | 76% | 0% | 0% | 1.00% | 1.33% | 18% |
| ES | 0% | 0% | 12% | 16% | 0% | 2% | 100% | 9% | 0.04% | 0.21% | 3% |
| SG | 12% | 2% | 32% | 20% | 52% | 2% | 0% | 0% | 6.79% | 26% | 77% |
| HH | 29% | 87% | 21% | 29% | 42% | 14% | 0% | 0% | 91% | 10% | - |

*Figure A4.4. End Use Matrix (EUM) describing the state of the play of Germany*

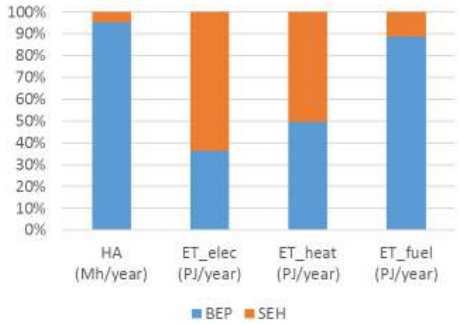
# STATE

ROMANIA (2012)

POPULATION 20.1 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 0.74 | 0.62 | 0.41 | 0.52 | 0.34 | 0.48 | 0.46 | 1.64 | 4.38 | 1.28 | 0.25 |
| HOW | 1 | TOTAL CONSUMPTION | 1703 | 374 | 11 | 32 | 18 | 123 | 660 | 1552 | 250 | 0.864 | 8100 |
| HOW | 2 | EXTERNALIZATION | 337 | 43 | 1 | 3 | 4 | 10 | 41 | 271 | 39 | 0.143 | - |
| HOW | 2 | Total consumption/ domestic production | 1.25 | 1.13 | 1.10 | 1.09 | 1.28 | 1.09 | 1.07 | 1.21 | 1.18 | 1.20 | - |
| WHY | 3 | FOR SECURITY | 1318 | 357 | 10 | 30 | 13 | 114 | 622 | 1289 | 250 | 0.864 | - |
| WHY | 4 | FOR EXPORT | 385 | 17 | 1 | 2 | 5 | 9 | 38 | 263 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1274 | 356 | 10 | 29 | 13 | 105 | 583 | 1064 | 8760 | 7213 | 8100 |
| AF | 26% | 3% | 1% | 1% | 5% | 37% | 0% | 97% | 2.33% | 95% | 4% |
| MC | 13% | 1% | 35% | 32% | 5% | 8% | 0% | 0% | 2.00% | 0.34% | 30% |
| ES | 0% | 0% | 27% | 18% | 1% | 25% | 100% | 3% | 0.08% | 0.26% | 4% |
| SG | 3% | 1% | 16% | 6% | 60% | 3% | 0% | 0% | 4.09% | 2.13% | 62% |
| HH | 57% | 95% | 21% | 43% | 29% | 27% | 0% | 0% | 91% | 2.53% | - |

*Figure A4.5. End Use Matrix (EUM) describing the state of the play of Romania*

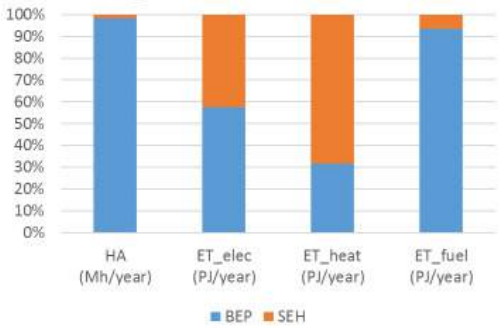
# STATE

SPAIN (2012)

POPULATION 46.8 Million

| | | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | Relative to EU 8 countries | 1.06 | 0.80 | 0.86 | 0.61 | 0.82 | 1.95 | 0.55 | 1.46 | 1.11 | 1.41 | 0.72 |
| HOW | 1 TOTAL CONSUMPTION | 2446 | 483 | 24 | 37 | 43 | 500 | 788 | 1382 | 63 | 0.953 | 23300 |
| HOW | 2 EXTERNALIZATION | 1040 | 114 | 2 | 11 | 10 | 130 | 20 | 494 | 30 | 0.326 | - |
| HOW | Total consumption/ domestic production | 1.74 | 1.31 | 1.11 | 1.40 | 1.31 | 1.35 | 1.03 | 1.56 | 1.92 | 1.52 | - |
| WHY | 3 FOR SECURITY | 1662 | 415 | 23 | 30 | 34 | 376 | 741 | 904 | 63 | 0.953 | - |
| WHY | 4 FOR EXPORT | 784 | 68 | 1 | 7 | 9 | 124 | 47 | 478 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1506 | 404 | 21 | 28 | 34 | 278 | 722 | 581 | 8760 | 6266 | 23300 |
| AF | 32% | 12% | 1% | 2% | 4% | 66% | 0% | 95% | 0.36% | 92% | 3% |
| MC | 28% | 0% | 26% | 43% | 2% | 6% | 0% | 0% | 1.00% | 0.37% | 21% |
| ES | 0% | 0% | 15% | 22% | 0% | 8% | 100% | 5% | 0.02% | 0.76% | 3% |
| SG | 4% | 6% | 30% | 7% | 63% | 5% | 0% | 0% | 5.63% | 4.87% | 74% |
| HH | 36% | 82% | 27% | 25% | 30% | 15% | 0% | 0% | 93% | 2.16% | - |

*Figure A4.6. End Use Matrix (EUM) describing the state of the play of Germany*

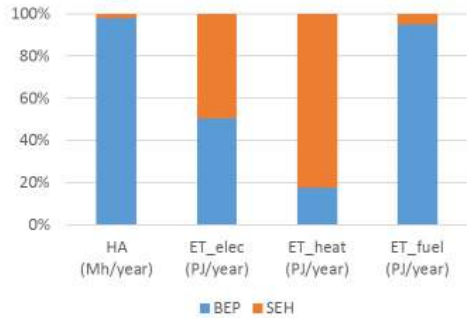
# STATE

SWEDEN (2012)

POPULATION 9.5 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 0.83 | 1.01 | 2.43 | 1.08 | 1.45 | 2.25 | 5.31 | 0.77 | 0.74 | 1.93 | 1.43 |
| HOW | 1 | TOTAL CONSUMPTION | 1920 | 608 | 67 | 66 | 76 | 578 | 7561 | 729 | 42 | 1.309 | 46100 |
| | 2 | EXTERNALIZATION | 870 | 173 | 6 | 20 | 19 | 32 | 496 | 295 | 13 | 0.276 | - |
| | | Total consumption/ domestic production | 1.83 | 1.40 | 1.09 | 1.43 | 1.34 | 1.06 | 1.07 | 1.68 | 1.46 | 1.27 | - |
| WHY | 3 | FOR SECURITY | 1419 | 510 | 55 | 48 | 39 | 532 | 6367 | 559 | 42 | 1.309 | - |
| | 4 | FOR EXPORT | 501 | 98 | 12 | 18 | 38 | 46 | 1194 | 170 | 0 | 0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1330 | 507 | 54 | 42 | 38 | 503 | 5949 | 333 | 8760 | 10328 | 46100 |
| AF | 27% | 2% | 1% | 3% | 2% | 1% | 0% | 99% | 0.27% | 31% | 1% |
| MC | 26% | 0% | 38% | 66% | 4% | 30% | 0% | 0% | 2.00% | 0.51% | 22% |
| ES | 0% | 0% | 11% | 13% | 0% | 49% | 100% | 1% | 0.06% | 2.63% | 2% |
| SG | 7% | 1% | 23% | 4% | 47% | 3% | 0% | 0% | 6.65% | 60% | 75% |
| HH | 41% | 97% | 27% | 14% | 47% | 17% | 0% | 0% | 91% | 5.39% | - |

*Figure A4.7. End Use Matrix (EUM) describing the state of the play of Germany*

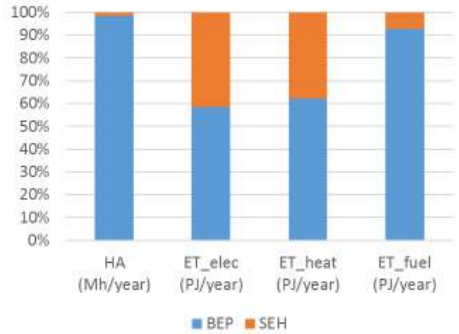
# STATE

UNITED KINGDOM (2012)

POPULATION 63.5 Million

| | | Quantities p.c./year | Food | | Energy | | | Water | | | Funds | | Money |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non Consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
| | | Relative to EU 8 countries | 0.57 | 0.77 | 0.77 | 0.93 | 1.00 | 0.31 | 0.36 | 0.49 | 0.49 | 0.93 | 1.24 |
| HOW | 1 | TOTAL CONSUMPTION | 1316 | 463 | 21 | 56 | 53 | 80 | 510 | 460 | 28 | 0.633 | 40100 |
| HOW | 2 | EXTERNALIZATION | 844 | 129 | 1 | 11 | 17 | 4 | 19 | 216 | 13 | 0.313 | - |
| HOW | 2 | Total consumption/ domestic production | 2.79 | 1.39 | 1.06 | 1.24 | 1.47 | 1.05 | 1.04 | 1.89 | 1.85 | 1.98 | - |
| WHY | 3 | FOR SECURITY | 1095 | 411 | 21 | 42 | 38 | 79 | 507 | 390 | 28 | 0.633 | - |
| WHY | 4 | FOR EXPORT | 221 | 52 | 0 | 14 | 14 | 1 | 3 | 70 | 0 | 0.0 | - |

5 DESIRABILITY




6 VIABILITY

| Quantities p.c./year | Plant (kg) | Animal (kg) | Electricity (GJ) | Heat (GJ) | Fuel (GJ) | Blue Water Consumption (m3) | Blue Water Non consumptive Use (m3) | Green Water Consumption (m3) | Human Activity (hr) | Land Use (ha) | GDP (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic use | 1042 | 404 | 21 | 38 | 38 | 75 | 488 | 207 | 8760 | 3199 | 40100 |
| AF | 17% | 6% | 1% | 1% | 0% | 9% | 0% | 99% | 0.12% | 85% | 1% |
| MC | 20% | 1% | 26% | 21% | 6% | 5% | 0% | 0% | 1.00% | 0.44% | 18% |
| ES | 0% | 0% | 14% | 17% | 1% | 13% | 100% | 1% | 0.05% | 0.74% | 3% |
| SG | 5% | 4% | 27% | 14% | 52% | 12% | 0% | 0% | 7.07% | 8.30% | 79% |
| HH | 58% | 89% | 31% | 48% | 41% | 60% | 0% | 0% | 91% | 5.95% | - |

*Figure A4.8. End Use Matrix (EUM) describing the state of the play of United Kingdom.*

**PRESSURE**

FRANCE (2012)

POPULATION 65.3 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0 | 0.01 | 0.01 | 0 | 0.3 | 0.05 | 567 | 10 | 0.01 | 1.8 | 0 | 1.03 | 518 |
| | Food | | | | | | | | 60 | 60 | 0.43 | 59 | 25 | | |
| EXTERNALIZED | Energy | 0.26 | 0 | 1.27 | 0.73 | 0.0159 | 0 | 0.1 | 49 | 5 | 0.01 | 2.37 | 0 | 0.13 | 47 |
| | Food | | | | | | | | 21 | 387 | 0.174 | 24.57 | 5.75 | | |
| | Total consumption/ domestic production | >1000* | - | 128.0 | 74.0 | >1000* | 1.0 | 3.0 | 1.1 | 1.4 | 1.4 | 1.4 | 1.2 | 1.1 | 1.1 |
| TOTAL | Energy | 0.26 | 0 | 1.28 | 0.74 | 0.02 | 0.3 | 0.15 | 616 | 15 | 0.02 | 4.17 | 0 | 1.16 | 565 |
| | Food | | | | | | | | 81 | 1314 | 0.6 | 83.57 | 30.8 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.9. Environmental Pressure Matrix (EPM) describing the state of the play of France*

**PRESSURE**

GERMANY (2012)

POPULATION 80.3 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0.15 | 1.23 | 0.03 | 0.14 | 0.00 | 0.28 | 0.04 | 370 | 21 | 0.01 | 1.9 | 0 | 6.73 | 347 |
| | Food | | | | | | | | 16 | 16 | 0.208 | 32 | 16.6 | | |
| EXTERNALIZED | Energy | 0.65 | 0.08 | 1.4 | 1.12 | 0.0033 | 0 | 0.12 | 35 | 4 | 0.01 | 2.72 | 0 | 0.56 | 34 |
| | Food | | | | | | | | 6 | 318 | 0.18 | 32 | 5.79 | | |
| Total consumption/ domestic production | | 5.33 | 1.07 | 47.67 | 9.00 | >1000* | 1.00 | 4.00 | 1.11 | 1.67 | 1.9 | 2.02 | 1.4 | 1.08 | 1.10 |
| TOTAL | Energy | 0.8 | 1.31 | 1.43 | 1.26 | 0.0033 | 0.28 | 0.16 | 405 | 25 | 0.02 | 4.62 | 0 | 7.29 | 381 |
| | Food | | | | | | | | 22 | 776 | 0.388 | 64 | 22.1 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.10. Environmental Pressure Matrix (EPM) describing the state of the play of Germany*

**PRESSURE**

ITALY (2012)

POPULATION 59.4 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0 | 0.09 | 0.14 | 0 | 0.26 | 0.01 | 204 | 3 | 0 | 0.3 | 0 | 3.04 | 181 |
| | Food | | | | | | | | 83 | 83 | 0.24 | 24 | 13.1 | | |
| EXTERNALIZED | Energy | 0.46 | 0 | 1.21 | 1.21 | 0 | 0.04 | 0.05 | 2 | 3 | 0.01 | 1.44 | 0 | 0.47 | 2 |
| | Food | | | | | | | | 47 | 360 | 0.3 | 22 | 8.59 | | |
| | Total consumption/ domestic production | >1000* | - | 14.44 | 9.64 | >1000* | 1.15 | 6.00 | 1.17 | 1.70 | 2.3 | 1.96 | 1.7 | 1.15 | 1.01 |
| TOTAL | Energy | 0.46 | 0 | 1.3 | 1.35 | 0 | 0.3 | 0.06 | 206 | 6 | 0.01 | 1.74 | 0 | 3.51 | 183 |
| | Food | | | | | | | | 130 | 873 | 0.55 | 46 | 21.7 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.11. Environmental Pressure Matrix (EPM) describing the state of the play of Italy*

**PRESSURE**

NETHERLANDS (2012)

POPULATION 16.7 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | FUND STRESS SUPPLY CAPACITY | | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0 | 0.07 | 4.79 | 0 | 0.15 | 0.01 | 288 | 17 | 0 | 0.9 | 0 | 4.57 | 285 |
| | Food | | | | | | | | 20 | 172 | 0.12 | 18 | 29.6 | | |
| EXTERNALIZED | Energy | 1.89 | 0 | 4.76 | 1.82 | 0.0007 | 0.08 | 0.18 | 37 | 7 | 0.02 | 4.61 | 0 | 1.69 | 37 |
| | Food | | | | | | | | 18 | 424 | 0.62 | 130 | 17.3 | | |
| | Total consumption/ domestic production | >1000* | - | 69.00 | 1.38 | >1000* | 1.53 | 19.00 | 1.18 | 3.28 | 6.35 | 8.12 | 1.6 | 1.37 | 1.13 |
| TOTAL | Energy | 1.89 | 0 | 4.83 | 6.61 | 0.0007 | 0.23 | 0.19 | 325 | 24 | 0.02 | 5.51 | 0 | 6.26 | 322 |
| | Food | | | | | | | | 38 | 596 | 0.74 | 148 | 47 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.12. Environmental Pressure Matrix (EPM) describing the state of the play of Netherlands*

**PRESSURE**

ROMANIA (2012)

POPULATION 20.1 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0.77 | 0.19 | 0.54 | 0.01 | 0.4 | 0.01 | 152 | 40 | 0 | 0.3 | 0 | 2.73 | 125 |
| | Food | | | | | | | | 56 | 1241 | 0.6 | 38 | 20.6 | | |
| EXTERNALIZED | Energy | 0.07 | 0.05 | 0.33 | 0.15 | 0.0015 | 0.01 | 0.04 | 8 | 4 | 0.01 | 0.73 | 0 | 0.12 | 7 |
| | Food | | | | | | | | 11 | 271 | 0.143 | 7.3 | 3.43 | | |
| | Total consumption/ domestic production | >1000* | 1.06 | 2.74 | 1.28 | 1.15 | 1.03 | 5.00 | 1.09 | 1.21 | 1.26 | 1.21 | 1.2 | 1.04 | 1.06 |
| TOTAL | Energy | 0.07 | 0.82 | 0.52 | 0.69 | 0.0115 | 0.41 | 0.05 | 160 | 44 | 0.01 | 1.03 | 0 | 2.85 | 132 |
| | Food | | | | | | | | 67 | 1512 | 0.74 | 45.3 | 24 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.13. Environmental Pressure Matrix (EPM) describing the state of the play of Romania*

**PRESSURE**
SPAIN (2012)
POPULATION 46.8 Million

| | | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity p.c./year | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0.09 | 0 | 0 | 0 | 0 | 0.23 | 0.01 | 293 | 42 | 0 | 1.2 | 0 | 3.24 | 269 |
| | Food | | | | | | | | 406 | 846 | 0.55 | 50 | 21.3 | | |
| EXTERNALIZED | Energy | 0.49 | 0 | 1.45 | 0.76 | 0.0032 | 0 | 0.14 | 16 | 3 | 0.02 | 4.41 | 0 | 0.17 | 16 |
| | Food | | | | | | | | 215 | 494 | 0.326 | 41 | 9.67 | | |
| | Total consumption/ domestic production | 6.44 | - | >1000* | >1000* | >1000* | 1.00 | 15.00 | 1.33 | 1.56 | 1.63 | 1.89 | 1.5 | 1.05 | 1.06 |
| TOTAL | Energy | 0.58 | 0 | 1.45 | 0.76 | 0.0032 | 0.23 | 0.15 | 309 | 45 | 0.02 | 5.61 | 0 | 3.41 | 285 |
| | Food | | | | | | | | 621 | 1340 | 0.876 | 91 | 31 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.14. Environmental Pressure Matrix (EPM) describing the state of the play of Spain*

**PRESSURE**

SWEDEN (2012)

POPULATION 9.5 Million

| | Quantity p.c./year | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0 | 0 | 0 | 0 | 0 | 2.11 | 0.05 | 831 | 42 | 0.01 | 2.2 | 0 | 1.68 | 567 |
| | Food | | | | | | | | 10 | 392 | 0.216 | 21 | 13.5 | | |
| EXTERNALIZED | Energy | 0.24 | 0 | 2.59 | 0.12 | 0.0177 | 0 | 0.18 | 94 | 16 | 0.01 | 2.39 | 0 | 0.15 | 90 |
| | Food | | | | | | | | 4 | 232 | 0.276 | 29 | 9.34 | | |
| | Total consumption/ domestic production | >1000* | - | >1000* | >1000* | >1000* | 1.00 | 4.60 | 1.12 | 1.57 | 2.27 | 2.35 | 1.69 | 1.09 | 1.16 |
| TOTAL | Energy | 0.24 | 0 | 2.59 | 0.12 | 0.0177 | 2.11 | 0.23 | 925 | 58 | 0.02 | 4.59 | 0 | 1.83 | 657 |
| | Food | | | | | | | | 14 | 624 | 0.49 | 50 | 22.8 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.15. Environmental Pressure Matrix (EPM) describing the state of the play of Sweden*

**PRESSURE**

UNITED KINGDOM (2012)

POPULATION 63.5 Million

| | | STOCK DEPLETION | | | | | FUND STRESS SUPPLY CAPACITY | | | | | FUND STRESS SINK CAPACITY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quantity p.c./year | Hard Coal (t) | Lignite (t) | Oil (t) | Gas ('000m3) | Uranium (kgU) | Wood Biomass (t) | Crop biomass (t) | Withdrawal (m3) | Soil moisture (m3) | Land use (ha) | NPK (kg) | Manure (kg N content) | CO2 (t CO2 eq.) | Water Discharge (m3) |
| LOCAL | Energy | 0.25 | 0 | 0.66 | 0.65 | 0 | 0.08 | 0.01 | 337 | 2 | 0 | 0.2 | 0 | 5.44 | 328 |
| | Food | | | | | | | | 11 | 241 | 0.29 | 26 | 19.3 | | |
| EXTERNALIZED | Energy | 0.74 | 0 | 1.19 | 0.81 | 0.0032 | 0.03 | 0.05 | 2 | 1 | 0 | 0.75 | 0 | 0.33 | 2 |
| | Food | | | | | | | | 5 | 209 | 0.3 | 34 | 10.3 | | |
| | Total consumption/ domestic production | 3.96 | - | 2.80 | 2.25 | >1000* | 1.38 | 6.00 | 1.02 | 1.86 | 2.03 | 2.33 | 1.5 | 1.06 | 1.01 |
| TOTAL | Energy | 0.99 | 0 | 1.85 | 1.46 | 0.0032 | 0.11 | 0.06 | 339 | 3 | 0 | 0.95 | 0 | 5.77 | 330 |
| | Food | | | | | | | | 16 | 450 | 0.59 | 60 | 29.6 | | |

To be assessed using lower level analysis

**STOCKS**

Reduction of the size and quality of reserves

**FUNDS**

| | |
|---|---|
| Terrestrial Ecosystems (health) | Global Atmosphere |
| Marine Ecosystems (health) | Local Atmosphere |
| Freshwater Ecosystems (health) | Human (health) |
| Rivers, Lakes, Groundwater (health) | Soils (health) |

*Figure A4.16. Environmental Pressure Matrix (EPM) describing the state of the play of United Kingdom*

# Appendix 5: The databases

The data handled in MAGIC consist mainly of bio-economic and socio-economic data. According to the Data Management Plan, data is being stored in a repository to support the applications of WP4, WP5, and WP6.

Data repository is continuously updating and gradually expanding.

In line with MAGIC's Data Management Plan, all data sets will be made available at the end of the project in the data repositories: https://zenodo.org/communities/magic/ and/or https://nextcloud.data.magic-nexus.eu/ .

# Appendix 6: Glossary

| | |
|---|---|
| Complexity | A property used to describe systems which, due to their nature, demand multiple non-equivalent descriptions (Rosen, 1977). Complex systems are non-mechanical (non-deterministic) and have a non-formalisable causal structure. Complex systems are impredicative (see *impredicativity*). If a system is not *complex* it is *simple* (which says little to the fact of whether or not the system is *complicated*). |
| Contingent representation | A relational analysis of *impredicative* relations. For example, when studying the historic relation between population and the technology of food production: was it the shortage of food that determined an increase in productivity in agriculture? or was it the increase in productivity in agriculture that generated an increase in population that resulted in shortage of food? The representation of a set of impredicative relations is necessarily pluralistic (it is impossible to provide a unique or deterministic representation of causality for a set of impredicative relations). When studying a *complex system*, a clear perception of a given direction of causality is the result of a pre-analytical choice adopted to eliminate the intrinsic *impredicativity* – e.g. the assumption that the size of population as an independent or a dependent variable of technological progress. *Relational analysis* may be used to provide a set of possible *contingent representations* useful for the exploration of the option space in relation to different hypotheses of causal relations – e.g. studying the relation among the dynamics of population growth, technological progress, and the effects of external constraints. In this way it becomes possible to explore the robustness of different narratives relevant for different criteria of sustainability – e.g. *feasibility*, *viability*, and *desirability* (see *Quantitative Story-Telling*; *Impredicativity*). |
| Desirability | Refers to the compatibility of a metabolic pattern with the normative values, goals and expectations of the people living in a respective society. One of the three conditions of sustainability checked by the MuSIASEM tool-kit (along with *Viability* and *Feasibility*). |
| Feasibility | Refers to the compatibility of a metabolic pattern with external constraints. The end-uses operating within a metabolic pattern require a supply capacity for primary inputs (whose availability depends on processes outside human control) and a sink capacity for resulting emissions (whose processing can degrade the *fund* elements |

of an embedding ecosystems). This pattern of internal transformations entails a pattern of primary *flows* (interfaces with the biosphere) that must be compatible with the characteristics of the metabolic processes taking place in the embedding ecosystems as well as the larger bio-geochemical cycles determining the stability of boundary conditions. One of the three conditions of sustainability checked by the MuSIASEM tool-kit (along with *Viability* and *Desirability*).

Flow — See *Flow-fund model*.

Flow-Fund model — Proposed by Georgescu-Roegen to avoid confusion in the quantitative representation of the sustainability of economic processes. The identification of what should be considered a 'flow', 'stock', or 'fund' depends on the pre-analytical choice of a scale of analysis and based on the following criterion: (i) a *flow* element is associated with a quantity of metabolised flows that either disappears or appears within the duration of the analysis (e.g. a quantity over time); (ii) a *stock* element is associated with a quantity of accumulated flows that changes over the duration of the analysis (e.g a quantity of time); (iii) a *fund* element is associated with a metabolic agent who's size remains constant during the duration of the analysis. See Section **Error! Reference source not found.** for a more detailed discussion; see Georgescu-Roegen (1971).

Fund — See *Flow-fund model*.

Hypercycle — An autocatalytic loop in which the output is greater than the input. Involves the characterisation of the quantity and quality of the flows metabolised by a dissipative component of society. Hypercycles are a key factor determining the characteristics of the dynamic budget of metabolic patterns.

Holon — An epistemic device used by humans to organise their perceptions when observing a multi-causal external world. A holon is a notional coupling of a functional type (e.g. a father) and a structural type (e.g. a specific person having children) used to identify a relevant agent observed in the external world. The concept implies an unavoidable level of ambiguity as the mapping between the two types is never 1:1 (it is fuzzy – many persons can be a father and the same person can

express many other functional types – i.a. a professor, a taxpayer, a cigarette smoker). See *Notional data*.

Impredicativity

*Impredicativity* is a property possessed by an object whose definition depends on that same property. Impredicativity is a standard predicament faced when studying autopoietic systems (a class of systems capable of producing themselves). What is defined at the end of the process is actively involved in determining its own definition (autopoiesis). Therefore, when dealing with autopoietic systems it is unavoidable to find contrasting perceptions in which: A ➜ B, but, with a change of scale, B ➜ A (aka the chicken-egg paradox). Impredicativity is unpopular among quantitative modelers because it generates a logical bifurcation in the definition of (i) what should be considered a relevant agent (dependent or independent variable in the model); (ii) what should be considered the right scale to be used for analysis (something which blurs the definition of 'before' and 'after'); and (iii) what should be considered the correct direction of causality used to provide an explanation over the relations between agents and phenomena perceived in the external world. With regard to point (i): the choice of what should be considered depends on the point of view used for the perception, e.g. governments rule on citizens on a daily basis (over a time duration of a year), whereas citizens rule over the government at election time (over a time duration of ten years). With regard to point (iii): are farmers needed to reproduce rural communities or are rural communities needed to reproduce farmers? Impredicative processes cannot be perceived in a substantive way and therefore they cannot be fully formalised in a deterministic 'objective description'. See also *Contingent representation*.

Metabolic pattern of social-ecological systems

Refers to the integrated expression of two sets of transformations of material and energy flows: (i) referring to the interaction of the socio-economic process (the technosphere) with its ecological context (the biosphere). This set of transformations is described as expected profiles of primary inputs (taken from the biosphere) and primary outputs (wastes and emissions discharged into the biosphere); (ii) referring to the activities taking place inside the technosphere required for expressing the set of functions reproducing the identity of a given *social-ecological system*. These activities are associated with a transformation of secondary inputs into secondary outputs

| | |
|---|---|
| | either re-used inside the technosphere as secondary inputs or dumped into the biosphere as wastes. |
| MuSIASEM | Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. An accounting framework proposed by Giampietro and Mayumi (2000) and suitable for the integrated analysis of societal metabolism seen as a complex adaptive system. Finds its roots in a wide range of academic disciplines i.a. hierarchy theory, non-equilibrium thermodynamics, cybernetics, autopoiesis, theoretical ecology, bio-economics, post-normal science, semiotics, bio-semiotics, logics, *relational analysis*, integrated assessment, participatory integrated assessment, and multi-criteria decision analysis. See also *Relational analysis*. |
| Nexus, Resource | The intractable entanglement between select resources considered most precious and inseparably linked with human wellbeing. Most frequently refers to the water-energy-food (WEF) resource Nexus in the context of resource security. Often includes additional or alternative dimensions i.a. minerals or land instead of food. |
| Notional data | Notional data refers to a quantitative representation of a non-material element as described in a system of control. A human activity system can be defined as a *"notional system (i.e. not existing in any tangible form) where human beings are undertaking some activities that achieve some purpose"* (Patching, 1990) |
| Quantitative Story-Telling (QST) | A method of quantitative analysis used to explore the option space of the metabolic pattern of *social-ecological systems* generating *contingent representations* of its *feasibility*, *viability* and *desirability* using *relational analysis*. The various representations depend on the assumptions and definitions used to characterise the factors determining the feasibility, viability and desirability of the system under analysis. |
| Relational Analysis | The field of study "*how any system is organised to the extent that it can be analyzed into or built out of constituent components. The characteristic relationships between such constituent components, and between the components and the system as a whole, comprise a new and different approach to science itself, which we may call the relational theory of systems"* (Rosen, 1991). Born from the work of Rashevsky (1954). |

| | |
|---|---|
| Scenario | An anticipation of a future system state characterised in a manner different than standard forecasting and foresight methods. Answers the question 'what can happen?' in a manner informative for decision makers. See the anticipatory systems ((M,R)-systems) of Rosen (2012) and fictional expectations of Beckert (2013). In the guise of fictional expectations Beckert introduces scenarios as "present imaginaries of future situations that provide orientation in decision making despite the incalculability of outcomes" (Beckert, 2013, p. 325; cited by Poli, 2017). |
| Social-Ecological System | The concept of *social-ecological systems* evolved from the seminal work of Holling, Folke, Berkes. A social-ecological system may be defined as 'the complex of biophysical processes taking place in a geographical area, that is controlled in an integrated way by the activities expressed by a given set of ecosystems and a given set of social actors and institutions'. See Holling (1998, 2001), Berkes et al. (2001), Gunderson and Holling (2002), and Berkes et al. (2003). |
| Societal Metabolism | See *Metabolic pattern of social-ecological systems*. |
| Viability | Refers to the compatibility of the metabolic pattern of a society with the internal constraints affecting the processes under human control. Internal constraints may be analysed in relation to several dimensions: (i) the technical dimension – the capability of constructing and operating the specific processors capable of carrying out the required set of activities associated with the expression of societal functions; (ii) the economic dimension – the capability of economic agents to break-even in their economic activities; (iii) the institutional dimension – the capability of organising, and defining the activities required to operate the processors across different levels of organisation and different scales. One of the three conditions of sustainability checked by MuSIASEM, along with *feasibility* and *desirability*. |