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 illustrates the anticipatory application of the analytical toolkit developed and used in MAGIC, that is, Quantitative Story-Telling (QST) on explorations of the future based on the accounting method Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). This deliverable is intended for use both within the consortium and beyond. As regards the former, the various grammars developed as proof-of-concept in this report will serve as a point of departure for upcoming analyses in WP5 and WP6. As regards the latter, the deliverable also has the objective to illustrate the application potential of this innovative analytical toolkit for checking the quality of narratives used in policy making to other scientists as well as policy makers and civil society.
The report is publicly available on the project website: http://magic-nexus.eu/documents-repository.

3. Short Summary of results

The present deliverable relates to the objective of WP4 to structure the perception and representation of the Nexus using the approach of Quantitative Story-Telling based on the MuSIASEM accounting framework. In particular, it addresses the topics of Tasks 4.4 'Global Drivers', 4.5 'Planetary Boundaries', and 4.6 'Externalization'. In a series of exploratory analyses it illustrates MuSIASEM accounting and its potential for Quantitative Story-Telling for anticipation. Rather than claiming to generate plausible predictions of the future, the analyses aim to explore the feasibility, viability and desirability of assumed radical transformations. The deliverable covers the following three anticipatory applications:
(i) a dramatic decarbonisation in relation to energy supply for a sample of 6 EU countries, with consequences for required assets and investments;
(ii) a dramatic reduction in the externalization of food supply for a sample of 8 EU countries while considering water as an entangled variable, with consequences for agro-economic activities and labour requirement in an urbanizing EU;
(iii) a dramatic change in global population and dietary patterns, in relation to regional materialisations of planetary boundaries, with consequences for meeting regional biospheric constraints to self-sufficiency and interregional dependencies.

4. Evidence of accomplishment

The enclosed report.

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Deliverable 4.3

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1. Quantitative Story-Telling for anticipation

1.1. Introduction

In this report we present three exploratory exercises of Quantitative Story-Telling for anticipation, building on the tool-kit and analyses presented in Deliverable 4.2. In line with the theoretical foundations of MuSIASEM, the exercise of anticipation presented here is not meant to predict what will happen in the future, as the future states of complex systems are inherently unpredictable.

By moving away from the question of "What will happen?" and guiding our analysis using the question of "What if?" we can explore the feasibility, viability and desirability, of radical transformations that may happen in the future, without been trapped in the lock-in within the trajectories of changes associated with conventional predictions based on dynamical systems.

An analysis of congruence based on the sudoku effect over hypothesized future states implies not only checking whether certain aims are enough to meet certain goals in a given narrative but also checking whether underlying narratives are feasible, viable and desirable.

The three exercises will address anticipation on the following imaginable radical transformations:

- a dramatic decarbonisation in the EU (Chapter 2),
- a dramatic reduction of external food dependency in the EU (Chapter 3),
- a dramatic change in global dietary patterns (Chapter 4).

Each of the exercises starts with a consideration of relevant drivers, as main identified factors to be leading to changes in the state of the system focussed on. Aspects of these drivers are common for the three exercises, and addressed here.

1.2. Global drivers

The decision over the assumptions to be used to check the feasibility, viability and desirability of future states of the metabolic pattern of EU and the rest of the world was based on a consultation of the story-lines available in the document on Global Mega-Trends found in the State of the Environment Report of the Environmental European Agency (2015). The material produced by the EEA is very relevant for the MAGIC approach because their analysis is framed within the DPSIR (Drivers, Pressure, State Impact; Response) framework – this framework has been already discussed in Deliverable, 4.2.

The analysis of Global Mega-Trends is organized over 5 categories Social, Technological, Economics, Ecology, Politics (STEEP). In particular, in relation to the analysis of the nexus we focused on the following Drivers: (i) population size (Social), (ii) uptake of renewable energy technologies (Technological); (iii) trade protectionism (Economic); (iv) groundwater depletion (Environmental); (v) resistance against globalization (Political).

As explained in Deliverables 4.1 and 4.2 in the MAGIC analytical tool-kit *drivers* can be defined as factors determining expected changes in the metabolic characteristics of the studied metabolic patterns. These changes are reflecting either a changes in the size of the fund elements (absolute or relative) or a change in the metabolic relation between metabolized flows and fund elements processing them. More specifically:

1. Drivers can be related to changes in the total amount of metabolic rates inside the system:

(i) change in the population affecting the change in total human activity;

(ii) relative changes in size of the constituent components of the socio-economic system (how human activity is distributed across the different compartments of the society). A different profile of allocation of human activity across the different economic sectors can be determined either by changes in demographic structure – i.e. aging or immigration – or changes in the relative importance of economic sectors – i.e. industrialization or post-industrialization;

(iii) changes in the performance of the technology changing the productivity of production factors (labor, inputs such as energy, water, minerals).

These drivers are relevant for an analysis relevant of the socio-economic performance;

2. Drivers can be related to changes in the total density of metabolized flows inside the system:

(i) change in the population density;

(ii) change in the mix of primary sources and primary sinks;

(iii) changes in land uses.

These drivers are relevant for an analysis relevant of the ecological performance and environmental impact;

3. Changes in the level of openness/externalization of the system:

(i) quantity and quality of the imports.

These drivers are relevant for an analysis relevant of the ethical implications referring to the interaction across different social-ecological systems;

Using this rationale, we have translated the information gathered from the analysis of the megatrends into inputs of information used inside the MAGIC tool-kit.

In particular, in relation to the anticipatory story-telling about

- **food** – we have selected as relevant a set of assumptions about: (i) the mix of food products consumed in a country in order to guarantee a specific diet; (ii) the techniques of production; (iii) the level of imports.
- **energy** – we have selected as relevant a set of assumptions about: (i) the mix of primary energy sources required in a country to guarantee a specific supply of energy carriers; (ii) the techniques of production of energy carriers; (iii) the level of imports;
- **global limits** – we have selected as relevant a set of assumptions about; (i) population size; (ii) definitions of zones with common typologies of external limits; (iii) the level of economic development; (iv) dependence on import.

The assumptions used for the various exercise of anticipatory quantitative story-telling are listed at the beginning of the three exercises.

2. Radical assumptions on dramatic decarbonisation in energy supply for 6 EU countries

2.1. Introduction

We present here an exercise on anticipation building on the analysis of the state of the play presented in Deliverable 4.2 of eight EU countries in relation to their food and energy metabolism. In line with the theoretical foundations of MuSIASEM, the exercise of anticipation presented here is not meant to predict what will happen in the future, as the future states of complex systems are inherently unpredictable. By moving away from the question of "*What will happen?*" and guiding our analysis using the question of "*What if?*" we can explore the feasibility, viability and desirability, of radical transformations that may happen in the future, without been trapped in the lock-in within the trajectories of changes associated with conventional predictions based on dynamical systems. An analysis of congruence based on the sudoku effect over hypothesized future states implies not only checking whether certain aims are enough to meet certain goals in a given narrative – e.g. is the large scale infrastructure of renewable energy likely to reduce emissions? – but also checking whether underlying narratives – e.g. that a quick decarbonisation of the EU's energy sector is possible – are feasible, viable and desirable.

In this light, we refer to this anticipation exercise as an *anticipatory Quantitative Story-Telling* which is applied here to a quick decarbonisation of EU economies. In fact, many projections of EU's energy sector currently exist, the most notable, and the one most used as an input for decision-making, being the EU 2016 Reference Scenario, hereon referred to as EU16RS (European Commission, 2016). The EU16RS builds on the PRIMES energy model to predict changes in the patterns of production and consumption for each individual EU country, in the medium and long term (2030 and 2050 respectively). Our *anticipatory Quantitative Story-Telling* moves away from detailed predictions, yet we use some of the inputs from the EU16RS as inputs to check the assumptions. That is, we follow the assumptions found in that particular study regarding relative production and consumption mixes in EU countries so that we can compare the results of the EU16RS with the results of our exercise. A description of the assumptions used here is given in Section 2.3.

In conclusion this exercise wants to address the following issues that may result problematic for the feasibility, viability and desirability of a quick decarbonisation:

What would a rapid decarbonisation of the energy sector of Italy, Germany, Spain, UK, Netherlands and France entail in term of biophysical investments?

What are the current feasible, viable and desirable limits of the option space towards a total and quick decarbonisation of the energy sector?

According to the philosophy of Quantitative Story-Telling, rather than providing clear cut quantitative answers and predictions, we: (i) flag the existence of biophysical and social limits that, in our opinion, are currently underestimated in decision-making processes; and (ii) highlight areas which require more detailed metabolic analyses, suggesting that current master narratives underpinning decarbonisation discourses are severely flawed. Within EU contexts, in fact, the feasibility of a low-carbon transition is rarely questioned, on the contrary the endorsed narrative is that: "The low-carbon transition is feasible & affordable" (2050 low-carbon economy | Climate Action). For reasons of availability of the required data, in this study we are considering only 6 EU countries (Germany, France, Italy, UK, Spain, the Netherlands) rather than 8 - i.e. we took out of the sample Romania and Sweden.

2.2. The narratives about decarbonisation in EU policy

Before moving to the anticipation exercise, we briefly contextualise the role of decarbonisation within EU energy policy and its underlying narratives. At the moment, decarbonisation is arguably the primary goal of EU energy policy at large: it is, in fact, consistently framed as a double-edged sword capable of simultaneously solving the issues of energy security and of climate change. It is undeniable across EU energy policy documents that their shared goal is to work towards a transition away from (imported) fossil fuels and towards (local) renewable energy sources. The EU webpage on renewable energy states, for example, that "*By using more renewables to meet its energy needs, the EU lowers its dependence on imported fossil fuels and makes its energy production more sustainable*" (Renewable energy - European Commission).

Decarbonisation, then, is framed as a techno-political issue, requiring changes in technology and governance. The main tool towards decarbonisation, in this context, is the use of renewable energy, at best combined with carbon capture and storage (CCS) solutions.

The timings for such decarbonisation to take place are ambitious, with similar goals in relation to decarbonisation set by different frameworks, including:

- A 40% reduction in GHG by 2030 (12 years from now!) and 80% reduction of GHG by 2050, compared to 1990 levels;
- 27% of renewable energy in the EU by 2030 (12 years from now!);
- A drastic elimination of GHG emissions of the power sector, which can "**almost totally** eliminate CO_2 emissions by 2050" (2050 low-carbon economy | Climate Action);

The decarbonisation of the EU, then, is always framed within the green growth paradigm, as it will allows to "*boost Europe's economy thanks to the development of **clean technologies** and **low- or zero-carbon energy**, spurring growth and jobs*" (2050 low-carbon economy | Climate Action).

A metabolic analysis of the energy sector allows not only questioning the feasibility and viability of sustaining current consumption patterns while solely relying on indigenous renewable sources, but also questioning the timings associated with such a transition, by focusing on the fund elements (quantity and quality) needed to sustain a rapid decarbonisation of the energy sector.

2.3. The assumptions and the methodology used for the quality check

Similar to the EU16RS, we work within two timeframes: medium term (2030) and long term (2050). Rather than modelling the evolution of each countries' energy metabolism up to 2050, two snapshots of the system are taken at the chosen years.

The 2050 snapshot assumes the same level of decarbonisation for each country: 90% of all energy consumed is to be of renewable nature. This means that 90% of electricity consumption comes from renewable sources, and 90% of fuel consumption is from biofuels. We do not reach 100% levels of decarbonisation as, particularly for electricity, decarbonisation becomes exponentially harder to achieve as renewable integration increases. Thus results would be hyperbolically exaggerated in order to meet the last 10% of electricity consumption. The 2030 snapshot, then, shows varying levels of decarbonisation of each country depending on their initial conditions. Consumption patterns are assumed to remain the same and are scaled by Eurostat population projections up to 2050. The utilization factor of renewable technologies is assumed to improve in line with the EU16RS. All other elements remain the same as for the state of the play: that is, we use the same set of production factors associated to the energy system as those characterising the current metabolic pattern (as described in Deliverable 4.2). We start from the impredicative set of relations determining the dynamic equilibrium between supply and demand of fund elements across the different constituent components (the value of BEP "affects/depends on" the value of SEH) in the metabolic pattern of complex social-ecological system to study the limits to a rapid decarbonisation. That is, we argue that we by checking the limits to the use of available production factors we can provides policy-relevant insights about the feasibility, viability and desirability of quick changes in the existing metabolic pattern of EU countries. By answering the question "*What if?*" we can explore the option space of possible futures.

The methodological steps of analysis can be summed up as follows:

1. For consumption patterns we maintain 2012 levels of consumption and mix of energy carriers consumption per capita. Then, the information on the consumption per capita is scaled to an assessment of the overall consumption of the country following Eurostat population trends for each country for 2030 and 2050;

2. Snapshots of the characteristics of the energy sector given by the EU16RS study for the years 2030 and 2050 are converted from absolute to relative values to be used in the MAGIC tool-kit. For each EU-6 country, this leads to:

   (i) Percentages on the relative contribution of each electricity production mode towards total electricity production – this is broken down into the relative contribution of wind and solar power to renewable electricity, and the relative contribution of other electricity production modes to fossil electricity;

   (ii) Details on the total mix of energy carrier consumption (% of heat, fuels and electricity w.r.t. final consumption);

   (iii) Utilization factors of electricity production systems for 2030 and 2050;

   In terms of biofuels, little information is provided by the EU16RS. Therefore, we build on other existing reports to reach the following proxies for each country:

   (i) % of local crops used for biofuel production;

   (ii) Relative mix of biodiesel and bioethanol in final biofuel consumption;

   (iii) Types of local crops used for local biodiesel and bioethanol production.

3. For biofuels, we consider the agricultural production factors of the year 2012. We assume that the percentage of crops for each country remains the same as in 2012, by considering the two main crops. For example, in France biodiesels in 2012 were produced mostly from rapeseed, whilst bio-ethanol was produced predominantly by a mix of sugar beet (60%) and wheat (40%). We assume that the total amounts increase but the same percentages between the two crops hold in 2030 and 2050.

4. For electricity, we assume that additional renewable electricity will be covered by a mix of wind and solar power. The relative contribution of wind and solar power to the total renewable electricity production follows their relative contribution of the EU16RS. Similarly, the relative contribution of fossil energy to non-renewable electricity follows the EU16RS. What we changed in our analysis is the relative contribution of fossil and renewable

electricity to total electricity production, and the amount of electricity needed (based on population projections).

Conservative storage requirements have been assessed building on data from existing literature. For each country, a mix of storage technologies is assumed: first, the pumped hydro storage (PHS) potential is considered; then, it is assumed that PHS will be used up to its limit for each country, and that the remaining storage will be covered by lithium-ion batteries.

5. In terms of power capacity, we consider both the renewable power capacity for producing energy carriers to be built, and the construction of the required lithium-ion batteries. The investment of production factors needed for the construction of power capacity is discounted over the timeframe. **We do not consider the massive amount of energy required to also build the roads and transmission lines necessary to accommodate the added renewable electricity and to put in place the intermittent power plants**: the numbers therefore should be seen as an indication towards the direction of changes rather than an indication of their magnitude. However, part of the strength of the proposed protocol of accounting lies in its flexibility. Therefore the power capacity matrix proposed in this study can be easily used in the future, in a more detailed study, by including additional process steps and other infrastructure. We would just need to add additional processors to those used in the existing analysis.

2.4. The results of this exercise of anticipation

The state-of-the-play analysis presented in Section 3 of Deliverable 4.2 presents a state-of-the-play analysis of the energy sector of 8 EU countries, from a resource-nexus perspective. The analysis highlights underlying similarities across the selected EU member states, in particular their reliance on imports (further stressed when virtual energy imports are taken into account) and their reliance on fossil fuels. From a consumption perspective, making the crucial distinction between electricity and thermal energy carriers shows that fossil fuel dependence on EU countries is mostly due to their fuel consumption, with electricity accounting on average for 30% of total energy consumption. We build on the results of Section 3 of Deliverable 4.2 by producing and End-Use Matrix (EUM) and Environmental Pressure Matrix (EPM) for 2030 and 2050 in relation to the assumptions of decarbonisation described earlier, and compare the results with the 2012 analysis. A Power Capacity Matrix (PCM) is also introduced, collecting data regarding the amount of power capacity that would be needed to sustain such a decarbonisation transition.

2.4.1. End-Use Matrix (EUM)

Following the assumptions listed above, we calculate the investment of energy carriers and human activity required for the energy sector of 2030 and 2050, compared to 2012. Table 1 gives an example of the local and externalised EUM of the energy sector in 2012, 2030 and 2050 for Germany and the Netherlands, both in absolute terms and per capita.

When considering human activity (labour) to be allocated in the energy sector, we see how it increases for 2030 and 2050 not only locally, but also totally, since renewable energy systems and biofuels require a higher investment of labour than their fossil fuelled counterparts. It is important to note, however, that for biofuels we do not assume that fossil energy consumed in their production would have to be substituted by manual labour: this would significantly increase the amount of human activity invested in the energy sector. However, assuming a massive use of fuels (at the moment provided by fossil energy) in biofuel production implies that a large fraction of what is produced has to be reinvested in the internal loop of production. As investigated by Giampietro and Mayumi, 2009 the requirement of investment of fossil fuels in the production of fertilisers, the fuels needed to power tractors and to transport huge quantity of biomass can imply very low levels of energy-return-on-investment – e.g. 1.5/1 or even 1.1/1. This implies the gross production of 4 -10 litres of ethanol to get the net supply just 1 litre litres (an EROI of 1.5/1 entails a gross production of 4 litres to get a net production of 1 litre, an EROI of 1.1/1 entails a gross production of 11 litres to get a net production of 1 litre – Giampietro and Mayumi, 2009). This problem is often overlooked because the consumption of fossil energy (to be included among the energy inputs) takes place in the Sector of Manufacturing where the fertilizers and the other inputs used in the production of the biomass are produced. Needless to say, a non-linear increase of the difference between gross and net production translates into a non-linear increase in the requirement of primary sources in the phase of agricultural production (land, soil, water, labour). This means that the quantitative assessment of the processors associated with the production of biofuels is an area which requires further research.

Table 1. End-Use Matrix of the energy sector, local and externalised, DE and NL.

			Absolute			***Per capita***		
			HA (Mh)	**Electricity (PJ)**	**Thermal energy (PJ)**	**HA (h)**	**Electricity (GJ)**	**Thermal energy (GJ)**
Germany	**Local**	2012	349	264	360	4.3	3.3	4.5
		2030	947	455	155	11.2	5.4	1.8
		2050	1007	362	178	12.2	4.4	2.1
	Externalised	2012	186	236	906	2.3	2.9	11.3
		2030	67	1637	563	0.8	19.3	6.6
		2050	23	520	174	0.3	6.3	2.1
	Total	2012	535	500	1266	6.7	6.2	15.8
		2030	1013	2092	717	12.0	24.7	8.5
		2050	1030	882	352	12.5	10.7	4.3
Netherlands	**Local**	2012	65	52	182	3.9	3.1	10.9
		2030	140	701	241	7.6	38.1	13.1
		2050	227	344	139	11.8	17.9	7.2
	Externalised	2012	137	288	2309	5.2	17.2	138.0
		2030	40	211	87	2.2	11.5	4.8
		2050	7	0	3	0.4	0.0	0.2
	Total	2012	202	340	2491	9.1	20.3	148.9
		2030	180	913	328	9.8	49.6	17.8
		2050	234	345	143	12.2	17.9	7.4

The investment of electricity and thermal energy is more erratic. This is because the values are the result of different rates of production factors varying at different rates: the energy carriers invested in the production of electricity and biofuels, the energy carriers invested in the construction of renewable energy capacity and those invested in the construction of lithium ion batteries. The generation of renewable electricity does not require thermal energy consumption. Therefore, thermal energy consumed in the energy sector tends to decrease, while overall electricity consumption increases (showing a peak at 2030 due to the construction of power capacity).

Table 2. Local Human Activity per capita, 2012, 2030 and 2050 – Comparison between productive and consumptive compartments of the paid work (PW) sector.

		HA PW (h)	**HA productive (h)**	**HA consumptive (h)**	**Con/Prod**
DE	2012	711	16	695	43
	2030	718	23	695	30
	2050	719	24	695	29
ES	2012	650	33	617	19
	2030	663	46	617	13
	2050	680	63	617	10
FR	2012	626	23	603	26
	2030	631	28	603	21
	2050	636	33	603	18
NL	2012	740	20	720	36
	2030	744	24	720	30
	2050	748	28	720	26
IT	2012	610	28	582	21
	2030	618	36	582	16
	2050	629	47	582	12
UK	2012	758	12	746	62
	2030	762	16	746	46
	2050	764	18	746	41

From an end use matrix perspective, the largest change with the given assumptions is given by the investment of human activity. Table 2 shows a comparison of the investment of human activity in the productive vs. consumptive sectors of paid work in 2012 compared to 2030 and 2050. An indicator, making it possible to look at changes in the ratio of investment of human activity between consumptive sectors (determining BEP) and productive sectors (determining SEH) is shown in the last column on the right. All over the sample the quantity of HA per capita invested in the energy sector for the EU-6 increases by a factor of 3-5 depending on the country. This would also dramatically increase, as mentioned, when including the replacement of fossil fuels in the production of biofuels. It should be mentioned here that the method of accounting use here is underestimating the quantity of labour associated with energy security. In fact the hours of work accounted here in ES refers only to the technical work done in the technological sector. Another, larger, fraction of work is done in the offices of the companies distributing energy carriers – accounted in the Service Sector. Obviously we can expect that a major increase of labour in the technical areas of the energy sector will be reflected by an analogous increase in Service sector.

Moving to a description of the environmental pressure brought by a decarbonisation of the energy sector, we see how biophysical constraints rapidly pose feasibility and viability.

Table 3. Total land use of the energy sector, 2012, 2030 and 2050, compared to total arable land and total land (all per capita)

		LU biofuels (ha)	LU electricity (ha)	LU ES (ha)	Arable land (ha)	Total land (ha)
Germany	2012	0.01	0.01	0.02	0.15	0.43
	2030	0.07	0.03	0.11	71%	25%
	2050	0.19	0.07	0.25	170%	59%
Spain	2012	0.00	0.01	0.01	0.27	1.06
	2030	0.18	0.02	0.21	76%	19%
	2050	0.46	0.05	0.51	189%	48%
France	2012	0.01	0.00	0.01	0.28	0.84
	2030	0.05	0.03	0.07	27%	9%
	2050	0.13	0.06	0.19	67%	22%
Netherlands	2012	0.00	0.00	0.01	0.02	0.06
	2030	0.14	0.04	0.18	901%	300%
	2050	0.46	0.09	0.55	2755%	918%
Italy	2012	0.00	0.00	0.01	0.8	3.1
	2030	0.11	0.01	0.12	15%	4%
	2050	0.24	0.04	0.28	35%	9%
UK	2012	0.00	0.00	0.00	0.09	0.4
	2030	0.03	0.03	0.07	77%	17%
	2050	0.07	0.07	0.14	158%	36%

2.4.2. Environmental Pressure Matrix (EPM), local and externalised

In terms of feasibility and viability linked to environmental pressures, we focus on land use, water consumption and GHG emissions. The skyrocketing requirement in relation to land use (Table 3) is by far the first and most urgent matter to consider: replacing fossil fuels with biofuels, in fact, is definitely not feasible in the EU-6 due to land use limitations. The problem is further stressed when the land needed for renewable electricity is taken into account. Intermittent electric sources use less land than the one needed for biofuels but still their land requirement is not negligible. This is particularly worrying given the types of lands used for agriculture and electricity: the land needed for solar and wind power, given its slope, tends to be the same land needed for agricultural production. Moreover, we should not forget here the analysis provided in section 1 in which it is pretty clear that EU countries will be already in trouble if they would try to internalize inside their borders the production of food!

The last two columns of Table 3 show the total amount of arable and total land per capita for the reference year 2012, and what percentage of arable and total land is occupied by the energy sector in 2030 and 2050 when using EU16RS assumptions.

Table 4. Total GHG emissions per capita of the energy sector: 2012, 2030 and 2050.

		GHG emissions (t CO2 eq p.c.)
Germany	2012	7.29
	2030	10.00
	2050	2.52
Spain	2012	3.41
	2030	7.69
	2050	6.06
France	2012	1.58
	2030	4.65
	2050	0.81
Netherlands	2012	6.26
	2030	12.81
	2050	3.42
Italy	2012	3.50
	2030	10.78
	2050	3.32
UK	2012	5.77
	2030	6.39
	2050	1.48

It can be seen that, even without considering limitations such as wind speed, solar irradiance and slope, the amount of land use needed is not feasible, and quickly poses feasibility constraints, particularly if we consider the amount of arable land and how much of it is already in use by the agricultural sector. This analysis shows the key importance of using a GIS interface to carry out a proper feasibility assessment of land uses. However, even without using GIS these preliminary result give a taste of the magnitude of the issue and of how much land would be needed for a decarbonisation of the EU-6's energy sector.

In terms of water consumption, the green water for biofuels will certainly represent the most important type of consumption, although blue water consumed in the electricity sector (i.e. water consumed during cooling and hydropower processes) also increases in the considered assumptions. Total GHG emissions see an initial increase (2030), as a consequence of the emissions needed to build the power capacity, followed by a decrease (2050) as a consequence of the progressive use of alternative power capacity. Again, it is essential to note that our assessments tend to underestimate the level of emissions because of the very conservative levels of infrastructure considered in the analysis (e.g. we did not consider the emissions needed to extract and transport materials, for example). Again this application of Quantitative Story-Telling provides quantitative results useful to get an idea of the direction of change rather than its magnitude. We address the issue of power capacity and storage in the next section.

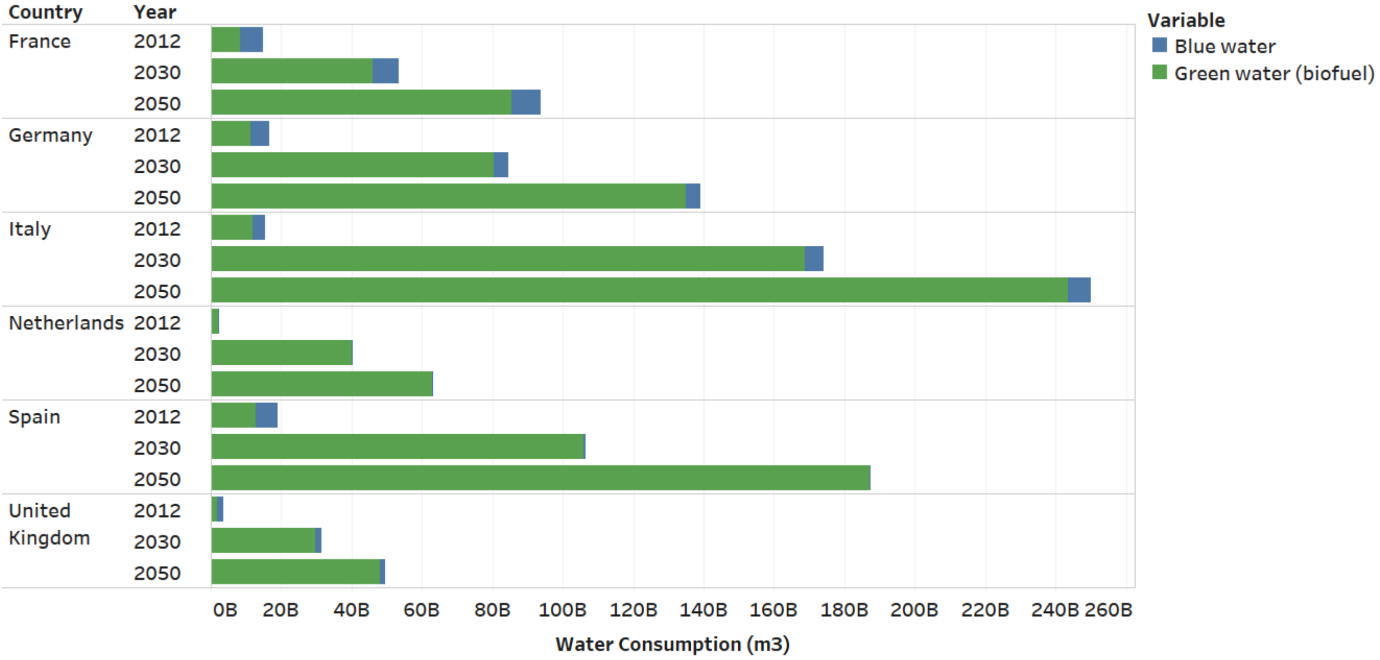


Figure 1. Blue and green water consumption of the energy sector – 2012, 2030 and 2050.

2.4.3. Power Capacity Matrix (PCM)

When discussing energy transitions or better radical transformations of the metabolic pattern of energy in terms of the practices of production and use of energy carriers, it is essential to account for the key role that fund elements (human activity, land and technology) play in making possible a change in the pace, density and quality of the required flows to be metabolized. In order to establish a proper accounting of changes in the various typologies of fund elements involved, we introduce a power capacity matrix (Tables 5, 6) assessing: (i) storage requirements needed to deal with intermittency; and (ii) new power plant capacity in the form of intermittent electricity sources. This information is needed in order to calculate the primary materials needed to build the batteries and the renewable power systems. In fact, if we want to change the flows of metabolized energy carriers we have first of all to change the fund elements that produce the energy carriers (the technology in the energy sector) and then the fund elements that transform the energy carriers in end uses (the technology in the rest of the society). This would be an essential task to study the feasibility, viability and desirability of such a gigantic transformation in relation to its speed.

In fact, talking of replacing the actual power plants based on fossil energy characterized by a very high utilization factor (e.g. a thermal or a nuclear power plant have an utilization factor in the order of 80%) with intermittent sources having a much smaller utilization factor (e.g. solar or wind may be operating with an utilization factor of 20/30% depending on the location), we have to build 3 or 4 times more MW of power plants than the existing one. Moreover if we want to replace the fleet of cars at the moment running on fossil fuels, we will have not only to build the entire fleet of cars and other vehicles (what about ships and airplanes?) but also increase quite a lot the consumption of electricity to power this new utilization of electricity for transportation. In relation to this point **the timing** of this energetic transformation (we prefer to use transformation than transition, because nobody can really know, at the moment, what the metabolic pattern of society will look like after this transformation …) is an essential factor to be considered. If we imagine a transformation done in less than 10/20 years, we are imagining an incredible effort of the economy that would have to mobilize and invest huge economic and biophysical resources to re-build from scratch the whole energy matrix and the vast majority of the prime movers used at the moment to express end uses in the society. This would only be possible imagining a sort of war economy.

Table 5. Power Capacity Matrix: Storage requirements.

		Wind (extra GW)	Solar PV (extra GW)	Storage (GWh)	PHS (%)	Li-ion (%)
Germany	2030	32	37	24107	24	76
	2050	100	109	44154	13	87
Spain	2030	4	14	11222	39	61
	2050	27	44	21609	20	80
France	2030	28	14	20938	26	74
	2050	87	45	41256	13	87
Netherlands	2030	4	14	5006	36	64
	2050	27	44	9930	18	82
Italy	2030	12	7	13614	27	73
	2050	36	59	29162	13	87
UK	2030	16	1	13614	27	73
	2050	121	16	29162	13	87

Table 6. Power Capacity Matrix: primary materials.

		Steel ('000 t)	Concrete ('000 m^3)	Silicone (t)
Germany	2030	7164	6	5
	2050	22123	17	13
Spain	2030	929	1	2
	2050	5938	5	5
France	2030	6293	5	2
	2050	19116	15	5
Netherlands	2030	929	1	2
	2050	5938	5	5

Italy	2030	2698	2	1
	2050	7917	6	7
UK	2030	3636	3	0
	2050	26648	21	2

In relation to the analysis of the feasibility, viability and desirability of this great transformation toward a low carbon economy we can use anticipatory story-telling to check the implications in relation to the need of building and replacing a large fraction of the existing fund elements. As example, we consider in the nest section a rough estimation of the effort that would be required to build an effective energy storage capable of integrating the supply provided by intermittent sources.

Energy Storage

Currently, Pumped Hydroelectric Storage is the predominant technology used for large scale energy storage (providing 99% of electricity storage in the EU). However, given its little potential for expansion (almost all the possibilities are already used in EU), it is expected that lithium ion batteries will contribute considerably towards future storage requirements. The amount of li-ion batteries that would be needed to accommodate the integration of renewable electricity is massive: the amount of lithium-ion storage needed for Germany alone in 2050 surpasses current global lithium-ion storage capacity. When looking at the need for primary materials lithium is not the only reason for concern. For example, taking the example of Germany, steel production for wind turbines would have to increase by 50% in 2050 compared to current levels, despite Germany being the EU country with highest steel production. It is essential to account for the energy that will be invested and GHG emitted from such steel production, needed for building the proposed PCM, in order to inform energy transition debates.

There is another very important observation to be made. Renewable and storage infrastructures have a limited lifespan and a limited recycling rate. Therefore their massive integration within the energy system would pose non-negligible issues in terms of waste management, and it will directly interfere with narratives of circularity. Moreover, when discounting the energy cost of their construction, if the life-span is short, we have a further reduction of the Strength of the Exosomatic Hypercycle because a share of labour, energy and other production factors will be always allocated to maintain the turnover of batteries and the power plants associated with renewable energy sources.

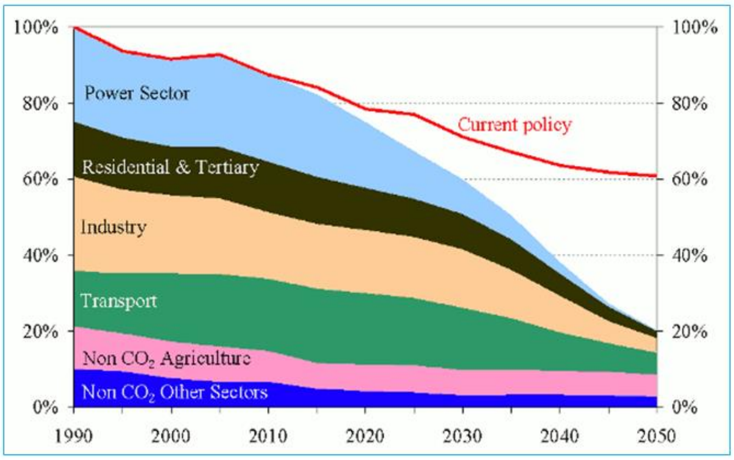
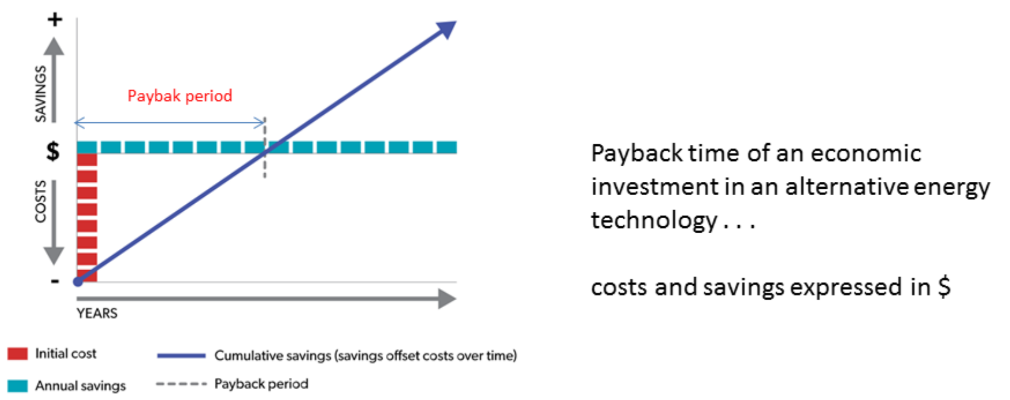


Figure 2. The narrative of linear reduction of emissions in the future of the EU.
https://ec.europa.eu/clima/policies/strategies/2050_en

We do not want to provide here a full estimate of the type of investment in terms of energy, material and emissions that would be required by the great transition to a low carbon economy, This would be a sterile exercise. This analysis should be carefully conducted by choosing the assumptions with relevant decision-makers. In fact, several aspects of the transition – the assumptions used to describe how we would like to have the transition - may have important consequences on the final results of this exercise. Depending on how radical we want the transformation and how the period of the change should be, we can imagine a scenario of “an economy of war for decarbonisation” in which society invests in making factories of factories, necessary to produce the enormous amount of power capacity required both on the production and the consumption side. What is important to observe here, in relation to this point, is the total lack of awareness of potential problems entailed by a great energetic transformation that is found when looking at the narratives used right now to describe the future of EU emissions. The standard narrative about future emissions is illustrated in Figure 2. Taking advantage of the reduction of emissions primed by the economic crisis of 2009, the emissions are expected to keep decreasing linearly more or less rapidly depending on the various assumptions.

However, when discussing the factors determining the acceptance of alternative technologies – e.g. in the case of more efficient appliances – the narratives used by the EU endorse the concept of payback time of the investment, which is not based on a linear reduction of cost for electricity. This concept is illustrated in the upper part of Figure 3.



https://www.resourcesandenergy.nsw.gov.au/energy-consumers/sustainable-energy/home-solar-battery-guide/will-a-battery-save-me-money/calculating-the-payback-period

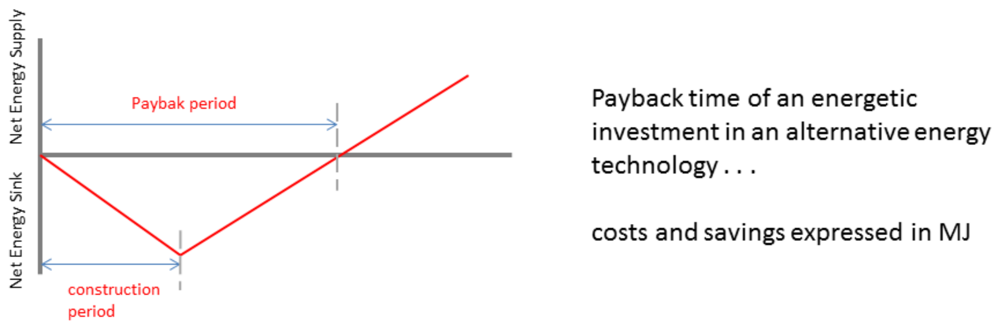


Figure 3. The payback time of investments in energy systems both in money and in energy terms.

In the economic payback narrative, after an initial investment (a net cost), the continuous savings provided by the more efficient appliance will generate an accumulate return for the investor that, after a given period of time, will pay back the initial cost.

It should be noted that in the field of energetics, the same concept has been proposed and used (since the 1970s!) to assess the energetic payback of building a new plant exploiting primary energy sources. This is illustrated in the lower part of Figure 3. Let's imagine to assess in this way the net energy balance related to the construction of a wind power plant. The construction phase should be considered as an accumulated loss (it is an energy sink). However, after becoming operational, the wind power plant starts slowly repaying the original energy investments to arrive to a point in which it represents a net provider of energy for society.

The same reasoning can be applied to the budget of emissions and the construction of new technology to avoid them. It is obvious that a massive and quick transformation of the energy sector away from fossil energy will have to be carried out, at the beginning, using fossil energy. Therefore, all the processes described in Table 5 and Table 6 – only for the construction of batteries … – will imply a major increase in CO2 emissions in the short-medium term. A visualization of the concept of payback time of fossil energy investment in emissions reducing technology is shown in Figure 4.

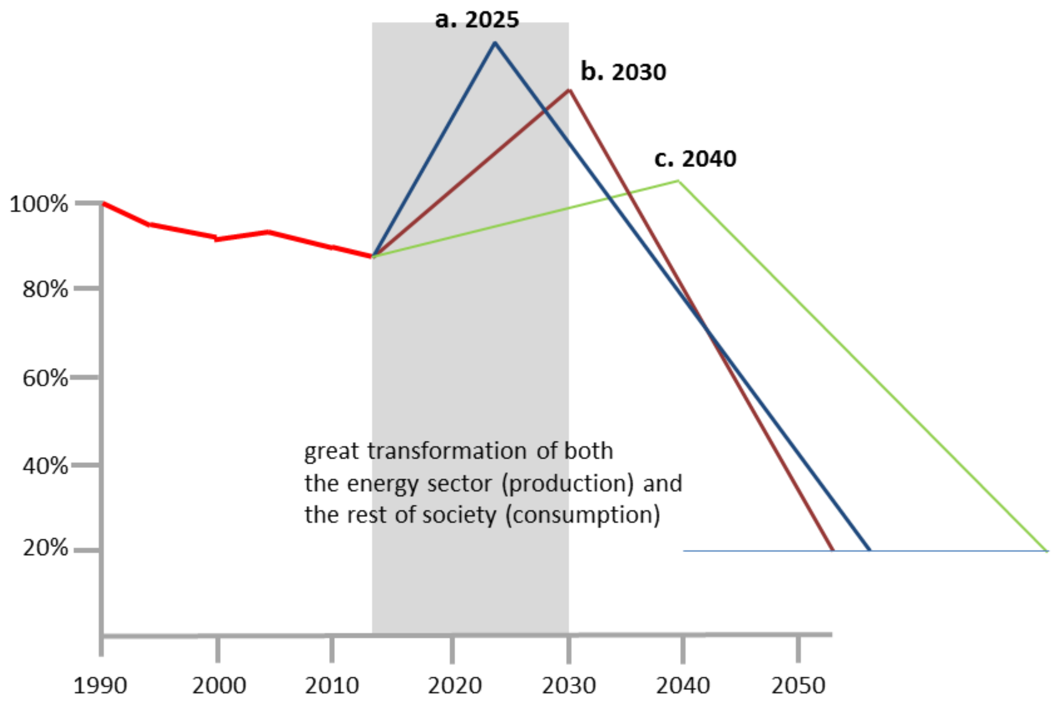


Figure 4. Possible descriptions of payback times of investments in low-carbon technologies in relation to emissions.

The graph shown in Figure 4 make explicit reference to the graph illustrated in Figure 2 with the standard narrative about the expected reduction of CO_2 emissions in EU. The graph in Figure 4 addresses the complication to be addressed in the analysis if we adopt the concept of payback time of reducing emissions investments. The initial increase in emissions is due to the heavy investments of fossil energy that are required to generate, in a short period of time, a totally new fleet of power plants, a totally new system of energy storage to handle intermittent sources and to power electric cars, a totally new generation of electric prime movers to substitute the existing ones power by fossil fuels, a major re-adjusting of the electric grid requiring gigantic distribution lines and a fine network of local infrastructures for a diffuse installation of alternative power plants. We did not even attempt to provide a quantitative assessment of the emissions that should be expected for this "great transformation" because, again, the results of this exercise are contingent on the assumptions used to describe the transformation.

Only considering changes associated with a very quick transformation (like path a. in Fig. 4 with the majority of the changes done for 2025 – a very unlikely assumption indeed!) we may expect a major surge of emissions in the short term. On the other hand, a slower transition – e.g. like path c. in Fig. 4 ending in 2040 - not only may lead to more efficient solutions, since it would allow incorporating in new designs and new solutions developed because of the experience done in the first steps, the progressive use of new constructed alternative energy plants and it could imply a lower initial surge of emissions. On the other hand, this would result in a later achievement of the objectives. Obviously, the trajectories shown in Fig. 4 are just speculations with no quantitative backup (they are not even quantitative story-telling!). A more detailed analysis should be done to verify the impact and the relevance of the different factors to be considered in relation to the policies to be adopted in relation to the different possible pathways.

The main point of our exercise of anticipatory quantitative story-telling is that at the moment, when discussing of the policies that are needed to carry out a total re-building of the energy matrix of the European Economy, the idea that this massive re-building may generate a temporary increase in emissions in not even considered by those making future scenarios. This implies also that a discussion about the pros and cons of using different strategies and different timings cannot even be done because it is not even considered as relevant. This fact is certainly a reason for concern, especially when considering that the master narrative is that low carbon transitions are expected to take place in a decade or two.

2.5. Conclusions

Fuels are the primary source of energy consumption in the EU. The results clearly show how crop-based biofuels cannot be implemented as a large scale alternative to liquid fossil fuels. Moreover, we did not consider the worst part of the story: the heavy reliance on fossil fuels for the production of crops (for fertilizers) or fuels used by tractors. Even when adopting very conservative estimates we can say that the role played by biofuels in a future decarbonisation scenario is limited. Focusing on electricity does not make the situation improve much: renewable electricity requires huge amount of storage (more than ten times global storage capacity!) and a lot of primary materials. It will also increase the use of land and HA of the energy sector. A further electrification of the energy sector therefore may release the pressure on biofuels while simultaneously increasing the pressure on the electricity grid. We will explore in the activity of WP6 a similar Quantitative Story-Telling on the narratives about the innovation of electric vehicles, unpacking the trade-offs between biofuels and electrification.

Probably the most important contribution of this study is the introduction of a protocol of assessment that is based on the analysis of power capacity – the Power Capacity Matrix. In fact, when it comes to the analysis of transitions or better transformation of the energy system, it is crucial to consider: (i) how much infrastructure and technology are needed; (ii) what type of investment of production factors is needed to extract primary materials, treat them, transform them and transport them; (iii) the expected utilization factors of the specific typologies of power capacity that will be used (e.g. to substitute a power capacity with an utilization factor of 80% we have to build four times more power capacity with an utilization factor of the 20%!). By using the Power Capacity Matrix it becomes much easier to check the feasibility, viability and desirability of narratives indicating specific goals of decarbonisation (namely, the targets that are considered necessary for increasing security and reducing emissions).

The 2050 Energy strategy states that "*Decarbonising the energy system is technically and economically feasible. In the long run, all scenarios that achieve the emissions reduction target are cheaper than the continuation of current policies*." (2050 Energy strategy - European Commission). We are afraid that when integrating our analysis with economic variables we may find that such a statement it is not necessarily true. Overall, our anticipatory Quantitative Story-Telling suggests that, when considering the metabolic pattern of EU economies, decarbonisation narratives should be furthered problematized in the context of decision-making.

3. Radical assumptions on dramatically reducing externalisation in food supply for 8 EU countries

3.1. Introduction

In chis chapter, we will use the MAGIC tool-kit for anticipatory Quantitative Story-Telling about the feasibility space of a sample of EU countries in relation to food security considering water as an entangled variable. To gain anticipation we do not generate "predictions" of future changes but rather "radical assumptions" about future relations of "state-pressure" that are used for illustrative purposes.

We explore the following radical assumption in relation to the year 2050:

> *a dramatic reduction of the level of externalisation in relation to food supply* – the quantitative target is a reduction to only 10% (boosting of the End Use Matrix of 3.2) of the previously imported flows of food. This assumption requires that the 90% of the reduced imports must instead be produced inside the borders of the respective countries. In this way we can check the severity of external constraints in terms of primary agricultural sources;

The anticipation of possible troubles and constraints is obtained using Quantitative Story-Telling. That is, using the MAGIC tool-kit we are characterizing the implications of these assumptions in order to gain insights about:

(i) the limits of feasibility determined by external constraints;

(ii) the key role that externalisation plays in making the current metabolic pattern of EU countries possible; and

(iii) the quantity and quality of societal change that would be required (in relation to both viability and desirability) in order to achieve or maintain specifiable goals and aspirations in light of the existing trends of economic development.

3.2. Defining the food requirement used in the analysis

In the exercise of anticipation for the EU8 countries we assume a pattern of food demand (both in quantity and quality) found in available literature. These estimates reflect a foresight of regionalization (internalization of production), a continuation of agricultural trends over the past few decades, and an increased impact of climate change effects. Average annual growth rates (AAGRs) for bovine, swine, ovine, and poultry yields (both meat and animal products e.g. dairy) are applied for the 2012-2020 and 2012-2030 periods assuming an AAGR factor referring to the 2012-2020 period and to the EU-15, factors derived from the EU Agricultural Outlook (EC, 2017). A relatively conservative flat yield AAGR of 0.008 is assumed for all vegetal categories, derived in reference to developed countries and referring to the 2012-2030 period (Alexandratos and Bruinsma, 2012). Yield changes in 2050 are assumed to have reverted to 2012 levels, due to climate change effects. This assumption is again conservative in relation to the findings and projections of Ray et al. (2012) and Iizumi et al. (2017).

3.3. Defining the food supply according to conventional scenario analysis

Figure 5, below, reflects trends over changes in the food supply 1961-2012 (historic) with projections for the short-, medium-, and long-term (respectively: 2020, 2030, 2050), broken down by country (considering the EU-8). Colour details vegetal and vegetal products vs. animal products (*meat only*). The prediction of non-meat animal product supply (e.g. eggs and dairy products) assumes the same growth relation as meat supply. It is important to note that food supply is equivalent to total production plus imports of agricultural products. It is also important to note that a major source of the growth in food supply for select countries (e.g. Romania, the Netherlands) reflects the growth in agribusiness, not solely increasing food consumption. However, this agribusiness is presumed to occur 'regionally' as a EU internal affair (between European member states).

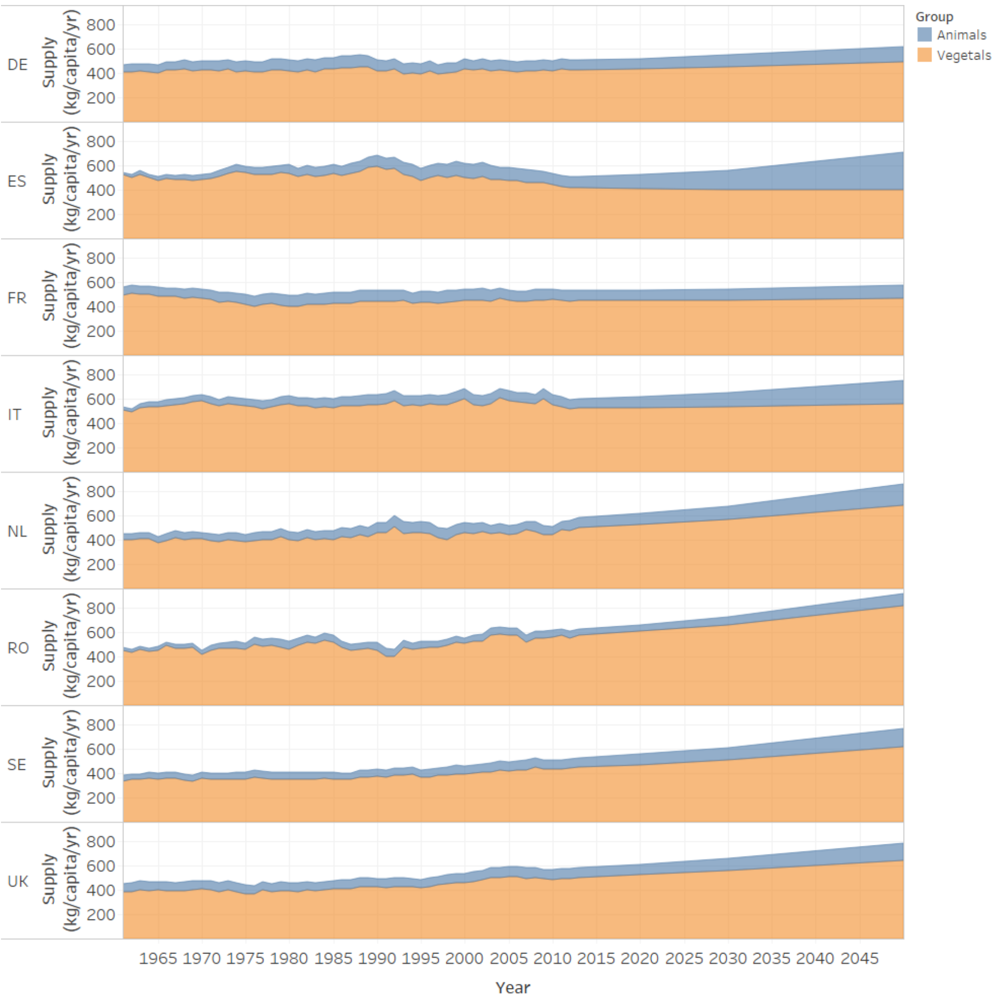


Figure 5. Changes in food supply 1961-2012 for the EU-8 with projections (2020, 2030, 2050).

The reasons for the predicted changes – some major, some minor – are varied. A number of descriptive examples follow. For Romania, mechanization catches up with the EU-15. Currently, Romania employs significantly more people in agricultural compared with the other EU-8 countries, but uses significantly fewer tractors, has significantly less irrigation equipped agricultural land, and exhibits low fertilizer application. The government currently provides subvention credits in accordance with the national 'Farmer' Programme (OECD, nd). In the current anticipations, agribusiness in Romania is seen to grow considerable (for example, importantly, with regard to hemp production and the hemp market). For Spain, the Spanish proclivity for meat consumption, rising importantly during post-Francoist Spain, compounds. This domestic consumption increase is mirrored by a significant increase in exports to foreign markets. For the Netherlands, agribusiness continues to thrive. In particular, a sharp increase in the level of re-export (import – modification – export, performed for economic reasons) is anticipated. In France, animal product consumption drops slightly at the per capita level while livestock production remains fairly steady, again for economic purposes. This trend reflects the view adopted by the Farm Europe think tank with regard to anticipated changes in European diet (Farm Europe, 2015).

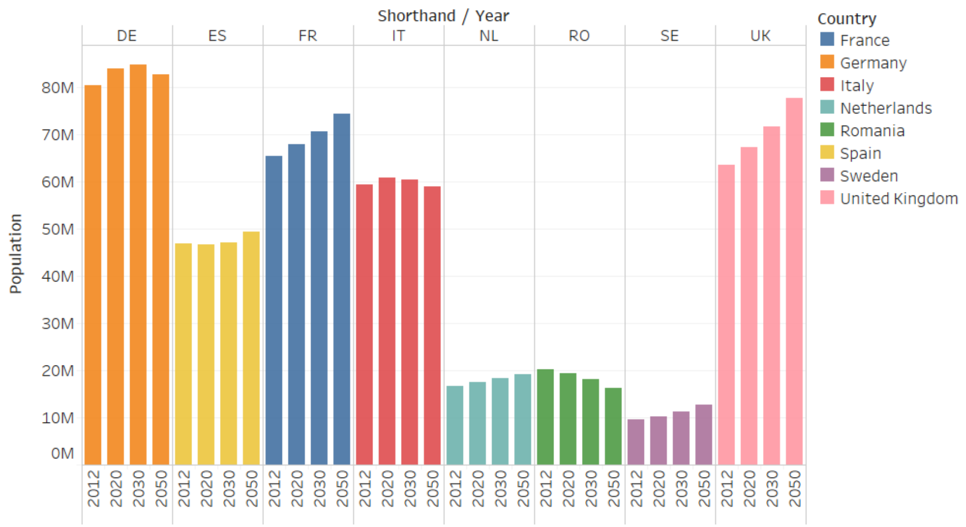


Figure 6. Current (2012) population along with projections (2020, 2030, 2050).

Changes in food production and consumption reflect also changes in population (Figure 6).

3.4. Internalization of imports by increasing domestic production – external constraints

We assume now to increase local production (and reduce imports) in relation to current (2012) levels by 5% in the short-term (2020), 25% in the medium-term (2030), and 90% in the long-term (2050). As was the case with yields and diet changes, these assumptions reflect a foresight of regionalization and increased effects of climate change. Figure *7*.7-10 reflect the anticipated changes of these developments (the first three – fertilizer, land, and water usage/consumption – refer to the Environmental Pressure Matrix i.e. the EPM whereas the last figure refers to the End-Use Matrix i.e. the EUM).

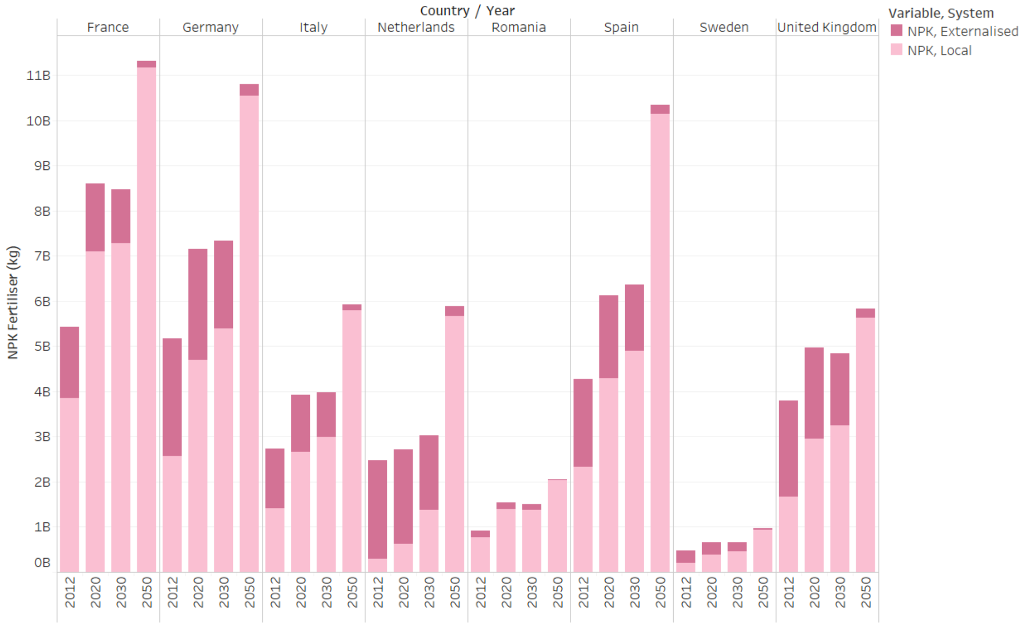


Figure 7. Fertilizer utilization (domestic vs externalized) under the chosen assumptions.

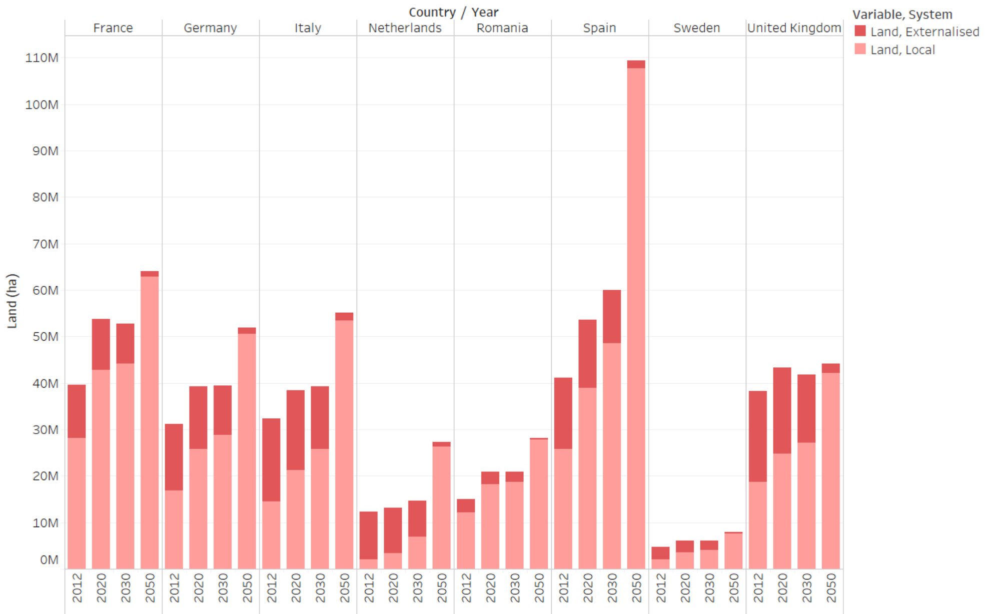


Figure 8. Land utilization (domestic vs externalized) under the chosen assumptions.

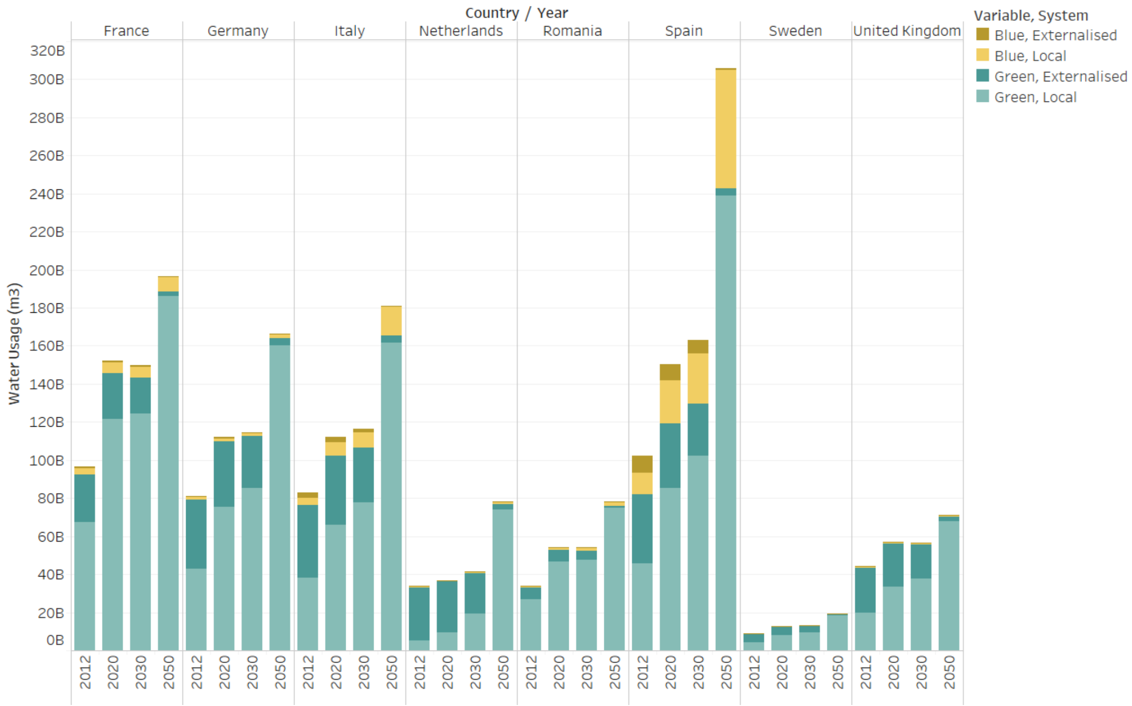


Figure 9. Water utilization (domestic vs externalized) under the chosen assumptions.

The results described in Figures 7-9 do not have the goal to provide predictions about the actual use of these production factors in the future.

It is important to observe that in order to observe the implications of the expected changes in these figures one has to compare the length of the bars referring to the local supply in 2012 and the predicted value in 2050. For example if we look at the anticipation of the order of magnitude of fertilizer utilization – given in Figure 7 – only focusing on the values associated with the light pink colour we obtain the comparison given in Figure 10.

Looking at the results, it is important to understand the meaning of this exercise of anticipatory Quantitative Story Telling. When looking at the use of fertilizers in the Netherlands we can see that in order to support the required growth in agricultural production (needed for internalize the imports), the Netherlands would need to apply 19 times more NPK fertilisers than it is already doing. Clearly this assessment is not a prediction. It does not make any sense (= it will not be either feasible, viable of desirable) to apply this quantity of fertilizer on an already stressed agro-ecosystem. First this increase would crash against ecological limits (the health of the soil and the impact on the water table) and second there are also economic limits (decreasing marginal return in terms of economic investments) to the density of application of fertilizers in agriculture. Increasing so much the load of fertilizers will simply kill the possibility of producing crops in the first place. The same discussion can be done looking at the anticipated requirement of land or water for other countries.

This is simply an exploratory study with the goal of illustrating a methodology. A more detailed and realistic study would be required, i.e. it would be necessary to move at lower level of analysis (as described in the Deliverable 4.2) in order to make possible the contextualization of indicators of environmental pressures to the specific availability of primary sources and primary sinks in space (using Geographic Information Systems) at the local level. That said, as a first exercise of anticipation and with a set of assumptions describing an official, expert agricultural forecast for the EU, we can say that described state-pressure expectations look very problematic in terms of feasibility.

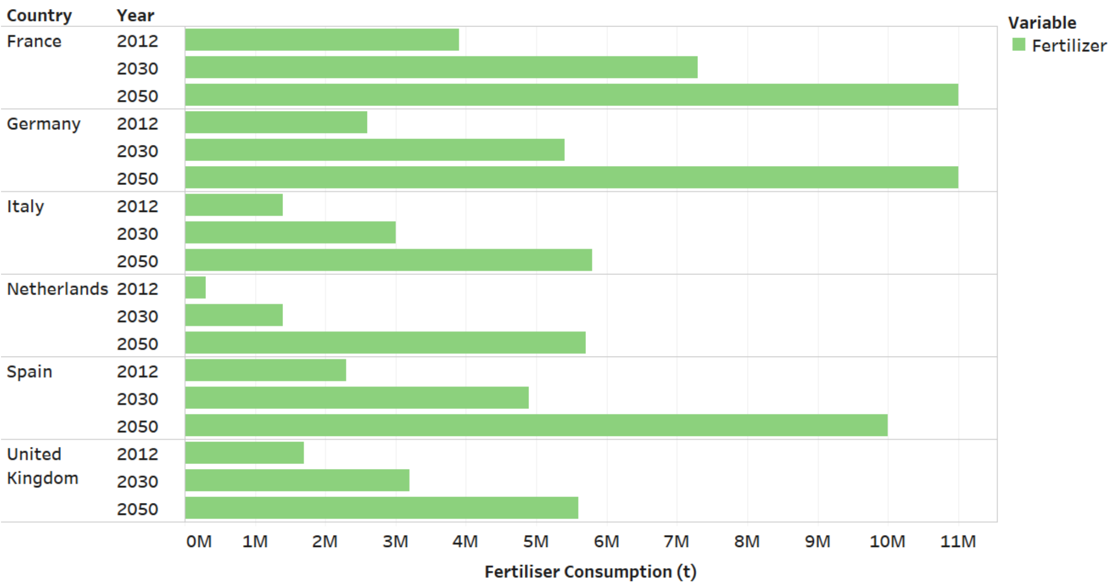


Figure 10. The comparison of the increase in the use of fertilizers in domestic production.

Considering that the environmental pressure determined by current agricultural practices in Europe is already dangerously high - harming the preservation of natural habitats required to preserve biodiversity, stressing the health of soils and the quality and the size of aquifers – the hypothesis of a massive internalization of the actual flows of food imports seems to be quite unfeasible in relation to external constraints.

3.5. Internalization of imports by increasing domestic production – internal constraints

So far our analysis did not consider the inputs that would be required by the society in terms of labour, energy, machinery and infrastructures – the factors relevant to calculate viability constraints. It should be noted that when looking at fertilizer this input is not only relevant for its potential environmental impact, but also because synthetic fertilizer (in particular the nitrogen content) is a major source of energy consumption in agriculture – the energy needed to produced fertilizers can be more than the operation of machinery and irrigation. Following the discussion over environmental feasibility, we can explore the factors that should be considered to check the viability of the EU-8 economies when considering the changes that would be required to match the requirement of food supply in the respective agricultural sectors. The projected changes will affect also the industrial sectors (stepping up the internal industrial production) implying substantial changes in the factors determining the bio-economic pressure (see the discussion in Deliverable 4.2). These changes may put into question the social desirability of the given assumptions. The explanations of the methodology used in the MAGIC tool-kit are explained in Deliverable 4.2. In relation to externalization we are considering here only manufacturing and construction (MC) and the agricultural (AG) sectors. That is, the effects of eternalization in the other sectors (ES and SG) are not considered among 'virtual imports' in the current account. The results presented in Figure 11 identify which types of sectoral changes would be needed to occur and needed to be accommodated by adjustment to the existing metabolic pattern.

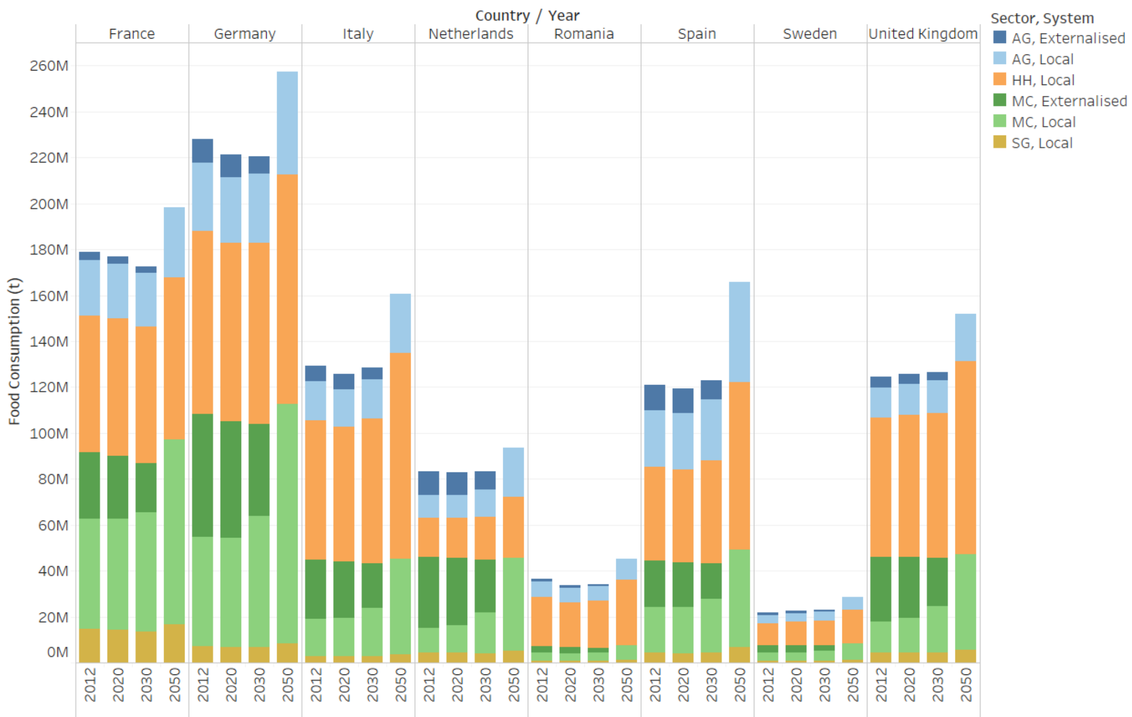


Figure 11. End-Use Matrix (EUM) over the chosen assumptions.

In the case of the Netherlands the MC and AG will have to process almost the double of the food processed at the moment. Again in order to compare the length of the bars "before" and "after" the internalization (to assess the expected changes) one has to eliminate the length of the bars of a darker colour.

3.6. Conclusions

Comparing the results relevant for a discussion around feasibility (Figure 7.7-10) with those relevant for a discussion around viability and desirability (Figure 11), one can have the impression that feasibility concerns should have priority. However, at this level of aggregation, it is difficult to assess the actual impact that adjustments in the structure of the economy of EU countries. EU countries will be required to accommodate inside their metabolic pattern a massive increase of activities to be invested in food production. This may have important consequences on viability: who will pay the enormous bill in the case of a major scaling-up of economic activities in the agricultural sector (an economic sector requiring at the moment already a heavy flow of subsidies ….). Over the course of the past two centuries, Europe has been eliminating farmers from the agricultural sector moving them to the industry, first, and to the service sector later. An internalization of the actual imports would require a dramatic increase in the requirement of labour in agriculture by 2050. Moreover, as discussed in the globalized scenarios, developed countries may result the only countries in the world capable of exporting food produced under the paradigm of industrial agriculture (monoculture produced with a lot of input and machinery). Indeed, it is difficult to imagine a smooth transition when considering the changes that a rapid mechanisation and intensification of agriculture will have on European societal metabolism. How much labour would be required in agriculture? What if this requirement will result much larger than the actual number of unemployed and therefore will require reducing work supply to the other sectors of the economy? What if many urban dwellers do not want to go to work in agriculture? What about the massive requirement of investments in infrastructures and services in rural areas if we will have to go back to a renaissance of rural areas?

4. Radical assumptions on dramatic global dietary changes in relation to planetary boundaries

4.1. Introduction

In this chapter we link Quantitative Story-Telling to the concept of planetary boundaries and their regional appearance, as discussed in literature by Rockström et al (2009), Steffen et al. (2015). In MAGIC terms, the concept directly links to *external feasibility*, operationalizing biospheric constraints under arguably disputed assumptions.

The exploratory exercise focusses on global food supply by 2050, assuming population growth and dramatic changes in global dietary patterns, that could change along with globalization and increasing welfare. At the same time, increasing global food demands opens up concerns on food security, driving considerations on food self-sufficiency or mutual dependency between world regions as well as on changes in agricultural production systems and consequences on resulting biospheric pressures..

In conclusion this exercise wants to address the following issues that may result problematic for the feasibility, viability and desirability of global food supply in a radically changing world:

What are feasible, viable and desirable limits of the option space for regionally self-sufficiency in food supply?

What can regional externalization contribute to stretching limits of feasibility, and what are implications for viability and desirability?

4.2. Planetary boundaries to operationalise feasibility: biospheric constraints

Global society draws on natural resources by both consumptive (renewable and non-renewable water resources, fossil fuels) and non-consumptive (land) use of resources, and by using ecosystem services (diluting polluting emissions such as nitrogen (N), phosphorous (P) or sequestering emitted CO_2 and other greenhouse gases). Planetary boundaries were proposed by Rockström et al. (2009), updated in Steffen et al. (2015) as specifications and quantifications for global limits for human use of natural resources and ecosystem services to maintain within a safe operating space. Acknowledging for large uncertainties in the academic debate on environmental impacts and the robustness of the Earth's system to accommodate disturbances, limits are assessed with ranges of uncertainty, where a precautionary principle is proposed to denote safe and high-risk boundaries.

Limits to resource use and ecosystem services are intrinsically of a global or regional / local nature, depending on the underlying processes: climate change is a dominantly global process, whereas water pollution processes play at local or river basin scales. Therefore an analysis of the implications of planetary boundaries can only be carried out starting from a series of analyses of limits defined at local and regional scale that have to be aggregated to the global scale. In their precautionary assessment, Steffen et al. (2015) conclude that planetary boundaries for Land-system change, Climate change, Biospheric integrity and Biochemical flows transgressed bounds for the safe operating space, where the latter two have exceeded limits beyond the range of uncertainty (Figure 12).

Focusing on metabolic aspects of food production and consumption, the main related planetary boundaries for "control variables" are (in the terms of Steffen et al., 2015) Biochemical flows of nitrogen and phosphorus, Land-system change and Freshwater use. At the global scale for the current situation, biochemical flows are estimated by Steffen et al. (2015) to already go beyond the zone of uncertainty of safe operation of the natural metabolism of the earth system; land-system changes are estimated to be in the zone of uncertainty, whereas freshwater use at the global scale still remains within the boundary of safe operation. At the local or regional scale, all control variables are assessed to have transgressed the limits of safe operation for each aspect.

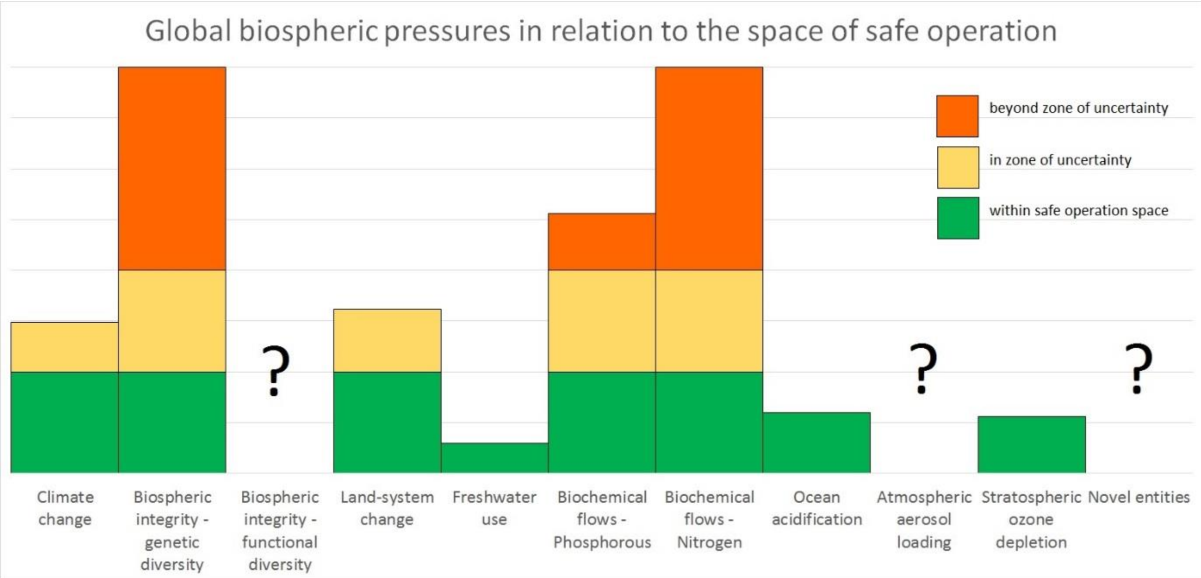


Figure 12. Planetary boundaries and the assessment of current human pressures at global scale.

Boundaries for Biochemical flows (N,P) are e.g. assessed to be transgressed in Northwestern Europe, part of the wheat-belt in the USA, and the North of China and India, and boundaries of Freshwater use are violated in the Middle East, Mediterranean countries in Africa and Europe, India, the North of China.

In terms of MuSIASEM, the boundaries of the range of safe operation translate into (*extensive*) limits to biospheric funds and flows into the biosphere. The opportunities for multi-scale functionality of MuSIASEM make it particularly useful to represent links of regional and global exceedances of limits. In this manner, the concept of Planetary boundaries links well to MuSIASEM.

For the planetary boundaries related most strongly to food production and consumption, quantifications found in literature include:

Land-system change

Steffen et al. (2015) consider 25% of removal of original forest cover to be the planetary boundary, specified at a regional resolution as 15% for tropical or boreal forest, and 50% for temperate forest. Limit relate to the relevance of land cover to climate feedbacks. A general limit of 10% for cropland is mentioned as well.

Alexandratos and Bruinsma (2012) describe a maximum expansion of cropland with sufficient potential, as constrained by factors limiting production, as well as spatial constraints from current land use to be forest, protected land and urban land. The estimated maximum expansion amounts to of 1.412 Mha globally; with 1.260 of current 1.559 Mha of cropland to be of sufficient crop production potential, this translates into a global 20% of land to be available and suited for cropping.

Where cropland expansions will merely go at the expense of natural or managed pasture areas, the opportunities of total agricultural land (as the combined area of cropland and pasture) to extend is constrained by forest, protected land and urban land to be modest.

Regionalization of the constraints presented by Alexandratos and Bruinsma (2012) are used in the present analysis.

Fresh-water use

Steffen et al. (2015) consider 4.000 km^3yr^{-1} to be the planetary boundary for consumptive freshwater use, where the current use is estimated to be 2.600 km^3yr^{-1}. Global precipitation is estimated at 113.000 km^3yr^{-1} (Bogardi et al., 2013), where some 40.000 km^3yr^{-1} becomes runoff flowing into oceans or is consumptively used by societies or ecosystems.

Richter et al. (2011) consider 80% of this flow to be required to sustain the environment (Environmental Flow Requirement, EFR), supporting aquatic ecology and dependent terrestrial ecosystem; this suggests 8.000 km^3yr^{-1} as a constraint for societal consumptive use. The 80% EFR constraint is also used in water footprint sustainability assessment (Hoekstra et al., 2011). Gerten et al. (2013) loosen the environmental flow requirement following Pastor et al. (2014), differentiating between high to low flow phases in the hydrological regime allowing a range of 30 to 60% of consumptive freshwater use, but also include restrictions to the feasibility to capture and/or utilize flow due to high flows or remote locations of the availability of flow, resulting in a planetary boundary of 2.600 km^3yr^{-1}, similar to current use.

In the illustration of MuSIASEM, we will use the Richter et al. (2011) approach, applied to the estimate of renewable water resources as reported in Aquastat (FAO, 2018a).

Biochemical flow: Nitrogen

Steffen et al. (2015) consider 62 TgN yr^{-1} to be the planetary boundary for new reactive nitrogen to be introduced the Earth system, stressing the regional diversity of the (fertilizer) inputs; the current input is estimated at 150 TgN yr^{-1}, well exceeding the boundary.

A critical factor in the assessment of maximum allowable nitrogen loads to the environment is the margin between natural and allowable nitrogen concentrations in surface water. This margin is assessed by Liu et al. (2012), suggesting 1,6 mgN/L for total nitrogen as a plausible value in the ranges found in cited literature. Values in literature may vary widely, as conditions for flowing (river) or stagnant (lake) water may be very different.

With a global runoff of 40.000 km^3yr^{-1} (Bogardi et al., 2012) the value suggested by Liu et al. translates into a planetary boundary of 64 TgN yr^{-1}.

In the current analysis we use the Liu et al. (2012) value, in connection to freshwater availability at regional scale.

Biochemical flow: Phosphorous

Steffen et al. (2015) consider 6,2 TgP yr^{-1} to be the planetary boundary for new phosphorous to be introduced the Earth system, stressing the regional diversity of the (fertilizer) inputs; the current input is estimated at 14TgP yr^{-1}, well exceeding the boundary.

A critical factor in the assessment of maximum allowable phosphorous loads to the environment is the margin between natural and allowable phosphorous concentrations in surface water. This margin is assessed by Liu et al. (2012), suggesting 0,43 mgP/L for total nitrogen as a plausible value in the ranges found in cited literature. Values in literature vary over orders of magnitude , as conditions for flowing (river) or stagnant (lake) water may be very different.

With a global runoff of 40.000 km^3yr^{-1} (Bogardi et al., 2012) this translates into a planetary boundary of 17,2 TgP yr^{-1}.

In the current analysis we use the Liu et al. (2012) value, in connection to freshwater availability at regional scale.

4.3. Scenarios of radical transformations

In order to illustrate how MuSIASEM can represent the nexus in the context of planetary and regional boundaries, assumptions of radical changes in drivers is introduced to create a set of scenarios focusing on food security. Population growth and welfare- or policy-induced dietary changes drive a possibly strong rise in global food demand up to 2050.

Drivers:

- Population of the planet in 2050 is assumed to reach 9.7 billion, following UN projections (United Nations, 2017).
- Three different diets: (1) a diet high in animal products; (2) a diet moderate in animal products; (3) a diet almost vegetarian (Table 7). In order to use robust assumptions we based the assessment of the mix of required primary food products (the overall consumption of primary products at the level of the whole country including the double conversion of plant products into animal products and the resulting post-harvest losses) using data from the FAO Food Balance Sheet. We considered as representative of the these three categories: (1) France; (2) Bulgaria; and (3) India respectively.

Growing demands can increase regional biospheric pressure, calling for externalization of such pressures by importing food commodities from regions with current potential to expand agricultural production. But it can also reduce opportunities to externalize when currently exporting regions will also be limited by biospheric constraints. Intensification of agricultural production may release pressure on land and water resources, but may also go along with increased nutrient use putting additional pressure on water quality.

Table 7. Scenario assumptions for dietary patterns and food supply.

	Food type	**France**	**Bulgaria**	**India**
Domestic supply quantity (1000 tonnes)	Grains-oils	8023448	6737675	2402711
	Roots	866203	304699	397069
	Vegetables-fruits	8788601	1954823	4500993
	Bovine	241137	36933	11729
	Porcine	322968	247980	2779
	Poultry	374769	316570	45652
	Other animal	598489	230833	95132
	Dairy	2605665	1785985	1023517
	TOTAL	21821280	11615499	8479582
	Total veg	17678252	8997197	7300773
	Total animal	4143028	2618302	1178809

Domestic consumption (kg/cap/yr)	Grains-oils	836	702	250
	Roots	90	32	41
	Vegetables-fruits	915	204	469
	Bovine	25	3.8	1.2
	Porcine	34	26	0.3
	Poultry	39	33	4.8
	Other animal	62	24	9.9
	Dairy	271	186	107
	TOTAL	2273	1210	883
	Total veg	1841	937	760
	Total animal	432	273	123

Scenarios distinguished are:

1: current situation

At a global scale and at the scale of regions, recent food production and consumption is assumed.

2: future with a high meat diet

Global food consumption is assumed to have a high-meat dietary pattern (current French diet); population is assumed at 2050 central UN projections. In the base version of the scenario, production practices are assumed to be at current levels.

3: future with a low meat diet

Global food consumption is assumed to have a low-meat dietary pattern (current Bulgarian diet); population is assumed at 2050 central UN projections. In the base version of the scenario, production practices are assumed to be at current levels.

4: future with an almost vegetarian diet

Global food consumption is assumed to have an almost-vegetarian dietary pattern (current Indian diet); population is assumed at 2050 central UN projections. In the base version of the scenario, production practices are assumed to be at current levels.

In the assessment, variations to the future scenarios are considered.

In the base version, regional agricultural practices (*"intensity levels"*) are assumed to take recent values, whereas the volume of regional food production is assumed to meet supply requirements of regional societies. The scenario are evaluated on the extent to which the various implied biospheric pressures (*"extensive variables"*) respect or violate regional or planetary boundaries. In MAGIC terms, the *feasibility* of the scenarios is tested.

In an intensification-variation of the scenarios, intensity levels of agricultural production are assumed to reflect production practices similar to the EU currently. Again, the volume of regional food production is assumed to meet supply requirements of regional societies. These scenario too are evaluated on the extent to which regional and planetary biospheric constraints are respected or violated. In MAGIC terms, the *feasibility* of the scenarios is tested.

In <u>downscaled variations</u> of the scenarios (both base and intensification versions), agricultural production is downscaled to meet regional biospheric limits of sustainable resource use. Irrigated production may be downscaled to meet freshwater constraints, overall crop and animal production to meet constraints on cropland availability and total availability of agricultural land, and on the capacity of regional freshwater resources to accommodate nitrogen and phosphorous loads generated in agricultural production. Where production in individual regions may end up to underfulfil regional food requirements, food production in other regions is increased when allowable within biospheric constraints. In this manner, downscaled scenarios are, by construction, *feasible* in MAGIC terms. The scenarios are evaluated on their *viability* and *desirability*. Here *viability* is assessed by considering the ability of scenarios to meet societal food requirements, and the plausibility of regional employment in agriculture. *Desirability* is assessed by considering regional food self-sufficiency, or reversely the external dependency of domestic food supply of regions.

A coarse distinction of the world into regions is chosen, both to allow focus on the EU and to indicate transgressions of boundaries that are violated at regional scales rather than globally (Figure 2). Therefore, the regional distinction is separating out the EU, distinguishes between relatively lower and higher productive areas (correlating with income), and distinguishes between currently water-scarce and more water-abundant areas.

Relative productivity was operationalized using yield-gap data in GAEZ 3.0 (Fischer et al., 2012), water scarcity was operationalized using data on availability of renewable water resources from Aquastat (FAO, 2018a).

Regions distinguished (see Figure 13):

- **EU-Med**: EU-Mediterranean
- **EU-Rest**: remaining EU countries
- **HighWat**: Higher-yield water-adequate (North America, Brazil and East Asia)
- **LowWat**: Lower-yield water-adequate (rest of Latin America, West and Central Africa, Russian Federation and former CIS, Southeast Asia)
- **LowDry**: Lower-yield water-scarce (North and East Africa, Southern Africa, Middle East, Middle East, India and Southwest Asia, Mexico)

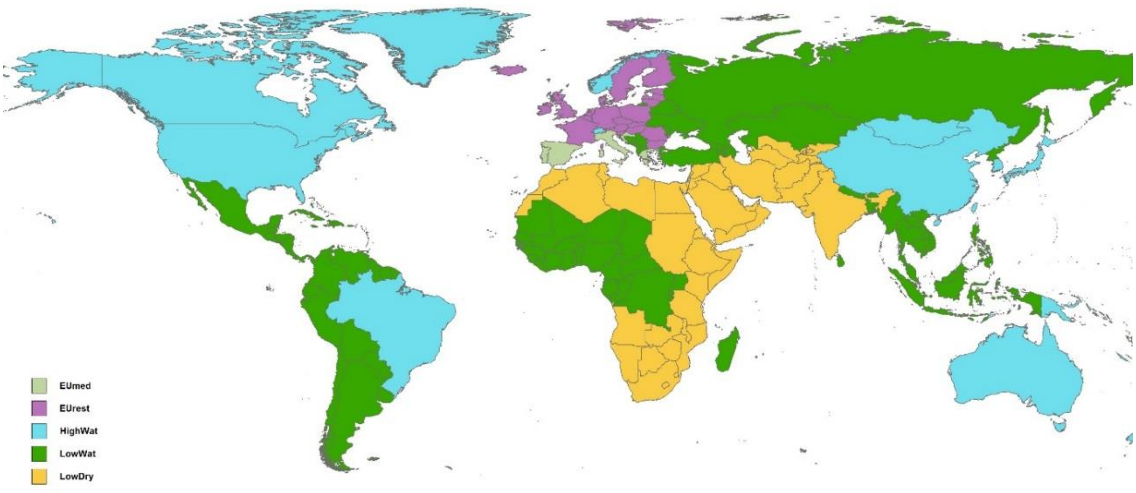


Figure 13. Regions used to coarsely distinguish EU, water endowment and intensity of crop production.

Intensity levels by region used in the analysis, characterizing production systems, were based on data from literature:

- Crop yields, freshwater use for irrigated and rain-fed production: Mekonnen and Hoekstra (2011), crop- and country-specific values representative for year 2000, a.o. based on FAOSTAT (FAO, 2018b); for the intensification scenarios, regional yield gaps (Fisher et al., 2012) are assumed to reduce to current EU level yield gaps,
- Nitrogen, phosphorous loads: crop- and country-specific grey water footprints from Mekonnen and Hoekstra (2011), combined with updated data on global nitrogen and phosphorous loads Mekonnen and Hoekstra (2015, 2018); for the intensification scenarios, fertilizer application rates are assumed to be at current EU levels,
- Pasture requirements of animal products: Bouwman et al. (2005) values for grass dry matter requirements, representative for year 1995, and Mekonnen and Hoekstra (2011) values for productivity of managed grasslands; for the intensification scenarios grass dry matter yields are adapted similar to crop yields,
- Employment in agriculture: ILO (2017).

4.4. Feasibility of regional self-sufficiency under radically increased food demands

This section considers the feasibility of the scenarios built on radical assumptions, by assessing the degree to which boundary values for the various biospheric pressures are respected or violated.

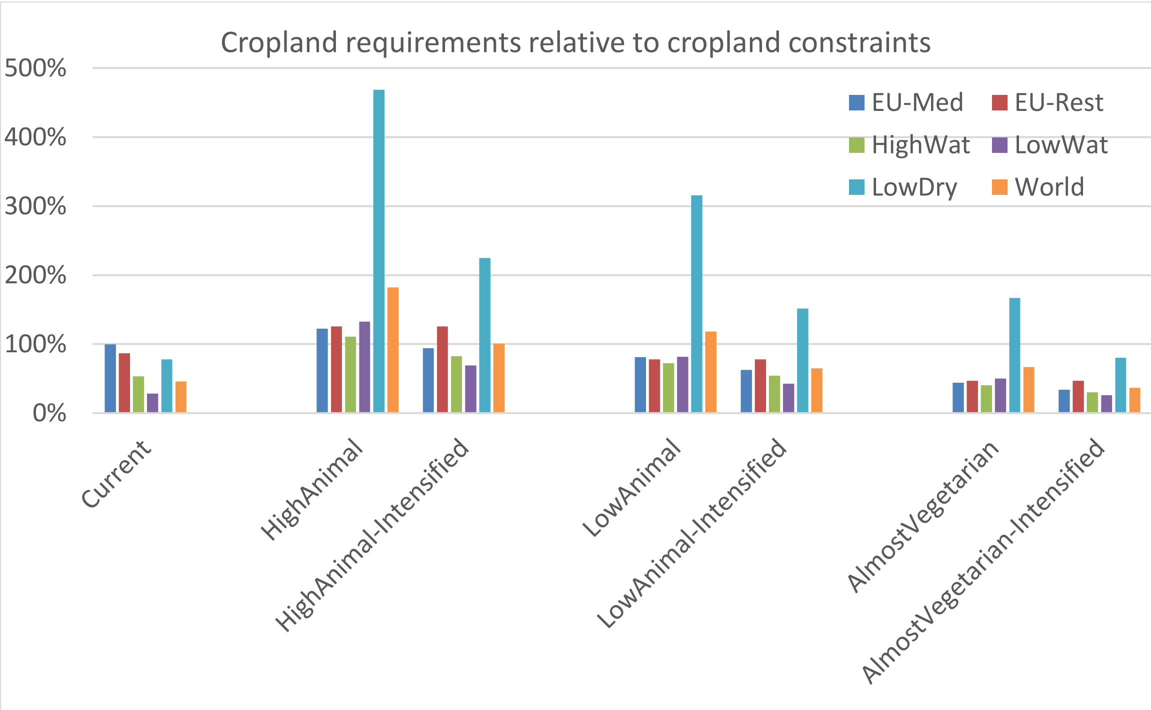


Figure 14. Assessment of cropland requirements for domestic production to supply food requirements, relative to the constraint to regional of global potential cropland. Values above 100% indicate the necessity for imports for regions, and biophysical infeasibility for regional food self-sufficiency.

Cropland

The availability of sufficient cropland is found to be a relevant *feasibility* issue in most of the scenarios (Figure 14), where the regional limit to cropland availability (100% in the figure) is exceeded regionally and globally in several instances.

Where cropland use is respecting constraints to boundaries to cropland availability for the *Current* scenario, boundaries are transgressed globally for the *HighAnimal* scenario (without and with assumed increases in the intensity level of production) and in the *LowAnimal* scenario. Regionally, in Europe, the *HighAnimal* scenarios show infeasibility. For the low income water-scarce region, all scenarios show an infeasibility to be food self-sufficient, transgressing available cropland resources with a factor of up to 5, except for *AlmostVegetarian-Intensified*.

Both dietary changes towards less animal sourced foods and intensification in production have a large effect on meeting cropland constraints.

Total agricultural land

The aggregated requirement for agricultural land from cropland and pasture is not found to lead to additional violations of land constraints; they are found to occur in the same scenarios and regions where cropland is limiting. In some cases violations of total agricultural land are larger than cropland violations in relative terms. Results are not emphasized here, as grassland requirements are more coarsely describe than cropland requirements.

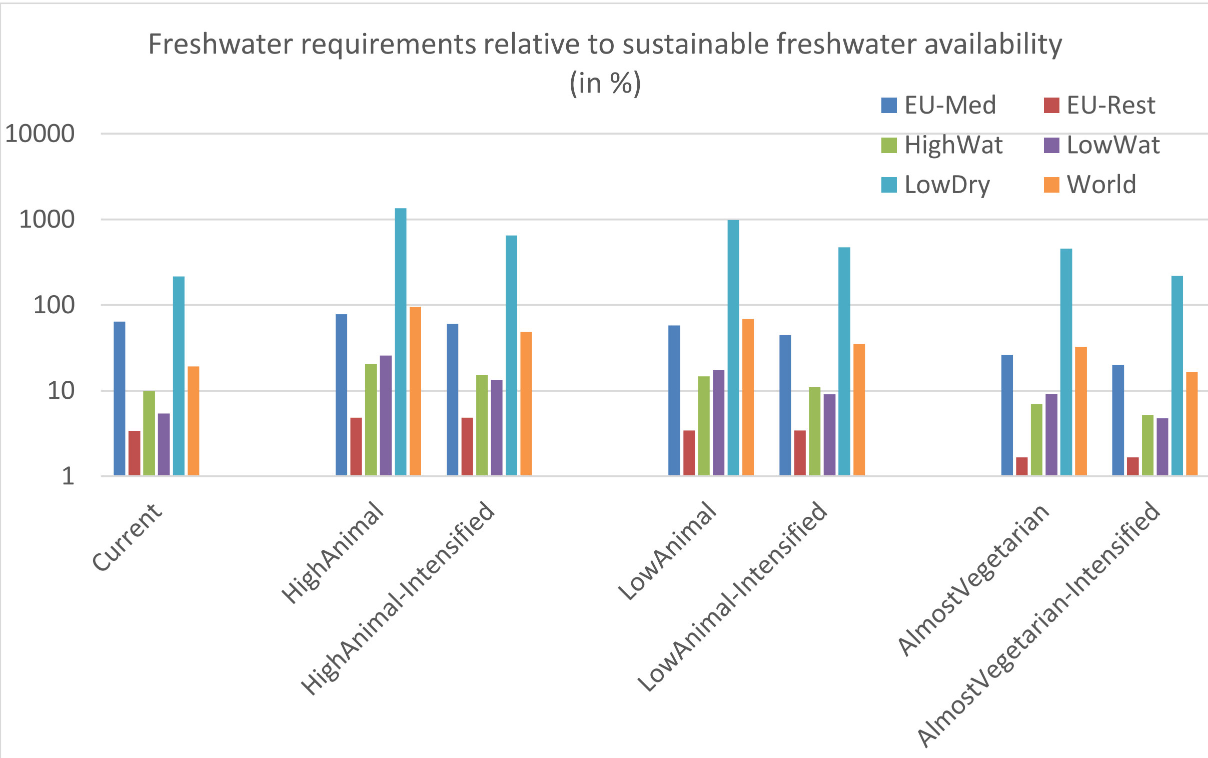


Figure 15. Assessment of freshwater requirements for domestic production to supply food requirements, relative to the constraint to regional of global sustainable freshwater availability. Values above 100% indicate the necessity for imports for regions, and biophysical infeasibility of regional food self-sufficiency. Note that the y-axis is at a logarithmic scale.

Freshwater

The sustainable availability of sufficient freshwater resources is found to be a relevant *feasibility* issue in all scenarios (Figure 15) for the LowDry region, where the regional limit to freshwater availability (100% in the figure) is exceeded; exceedances are so excessive in some scenarios, that a logarithmic scale is used.

Most regions remain within the range of feasible freshwater use. Mediterranean EU is close to the constraint in the *HighAnimal* scenarios, indicating that at a smaller scale constraints may be transgressed.

Regional exceedances of the constrains are restricted to the LowDry region. Already in the *Current* scenario, sustainably available freshwater resources are overused by a factor of 2, meaning that current consumptive freshwater use does not comply with environmental flow requirements, as operationalized in the scenarios. For the *HighAnimal* scenario (without and with assumed increases in the intensity level of production) exceedances are by a factor above 13 and 6 respectively. In the *LowAnimal* scenarios factors of exceedance are nearly 10 and 5, and in the *AlmostVegetarian* scenarios 4,5 and 2. Food self-sufficiency of this region is therefore severely limited by freshwater availability in all scenarios.

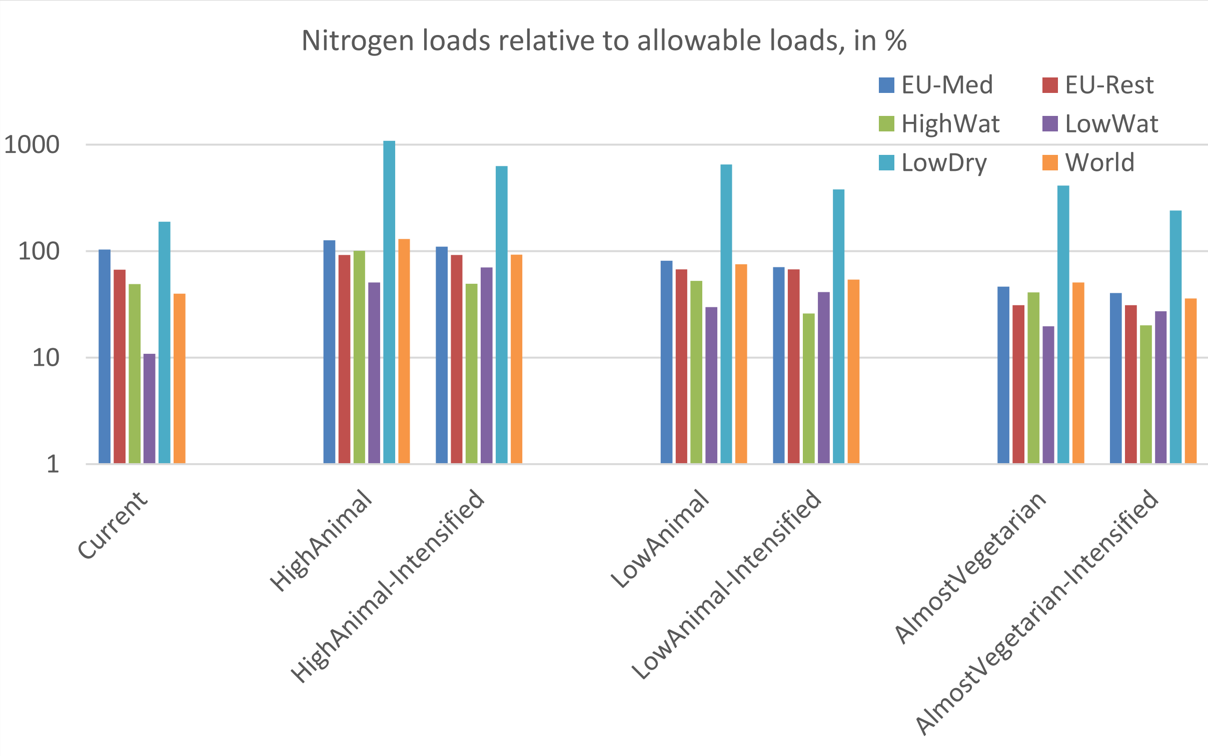


Figure 16. Assessment of nitrogen loads generated by domestic production to supply food requirements, relative to the constraint from the capacity of freshwater to accommodate human-induced loads. Values above 100% indicate the necessity to externalize production, and biophysical infeasibility of regional self-sufficiency. Note that the y-axis is at a logarithmic scale.

Nitrogen loads

The sufficiency of freshwater resources to accommodate nitrogen loads from agriculture is found to be a relevant *feasibility* issue in all scenarios (Figure 16) for the LowDry region and for some scenarios for Mediterranean EU, where the regional limit (100% in the figure) is exceeded; exceedances are so excessive in some scenarios, that a logarithmic scale is used.

Most regions remain within the range of allowable nitrogen loads. Mediterranean EU exceeds the constraint in the *Current* scenario (marginally) and in *HighAnimal* scenarios by 25 and 10%, indicating that at a smaller scale constraints may be significantly transgressed.

Regional exceedances of the constrain is found in the LowDry region for all scenarios. Already in the *Current* scenario, allowable nitrogen loads are exceeded by a factor of 2, meaning that freshwater pollution reaches serious levels. For the *HighAnimal* scenario (without and with assumed increases in the intensity level of production) exceedances are by a factor of 11 and 6 respectively. In the *LowAnimal* scenarios factors of exceedance are nearly 6 and 4, and in the *AlmostVegetarian* scenarios around 4 and 2,5. Food self-sufficiency of this region is therefore severely limited by water quality constraints.

Phosphorous loads

The sufficiency of freshwater resources to accommodate nitrogen loads from agriculture is not found to be limiting agricultural production in the scenarios for the aggregated regions considered. Not, that in densely populated areas, a significant contribution to total phosphorous loads may come from domestic wastewater, not included in the current assessment. Also note that the margin between natural and critical total phosphorous concentration in freshwater, crucial in determining the load that can be accommodated, is very uncertain, see Liu et al. (2012) for discussion.

Overall, it can be concluded that, in this assessment, regional self-sufficiency is *infeasible* in all scenarios. In order to achieve feasibility, either external dependency could be accepted (see the downscaled scenario below), further intensification could be introduced that does not transgress biospheric boundaries, or driving factors like population growth and dietary patterns could be altered to relieve human pressure on the biosphere.

4.5. Viability and desirability of regionally feasible food production and supply

This section studies the downscaled scenarios, that represent feasible regional agricultural production volumes, trying to fulfil regional as well as global food requirements (Figure 7). Production may be downscaled, as compared to the scenarios presented above, to comply with regional biospheric constraints. In regions where production is not limited by these constraints, production may be upscaled to fulfil global food requirements, compensating for regions where constraints are limiting.

In the *HighAnimal*, *HighAnimal-Intensified*, and *LowAnimal* scenarios, global food requirements cannot be met, meaning that the scenarios are not *viable*, in MAGIC terms. Underfulfilment of the food requirement is around 50% in the *HighAnimal* scenario and 15 to 20% in the *HighAnimal-Intensified*, and *LowAnimal* scenarios.

In the *HighAnimal* scenario, neither region is self-sufficient, with EU food supply shortages between 20 and 25%, the LowWat region at 40% and the LowDry region above 90%. Only the HighWat region is close to fulfilling demands (production gap of 10%).

In the *HighAnimal-Intensified* scenario, the water-adequate regions HighWat and LowWat can produce more than what is regionally required, EU is still below self-sufficiency and the water-scarce region can only supply 16% of its own food requirement.

The *LowAnimal* scenario is quite similar, except that EU can now contribute to release underfulfilment of food requirement on LowDry. Global supply increases from 81% to 85% of demand.

The *LowAnimal-Intensified, AlmostVegetarian*, and *AlmostVegetarian-Intensified* scenarios do succeed in fulfilling global food requirement. Where the LowDry region can only supply 27%, 25% and 41% of its regional demand respectively, other regions can compensate. This leads to the other regions producing 40% (*LowAnimal-Intensified, AlmostVegetarian*) or 32% (*AlmostVegetarian-Intensified*) above their regional demands, to export to LowDry. In the *LowAnimal-Intensified* scenario, EU-Rest feasibility limits its contribution to supply LowDry with food.

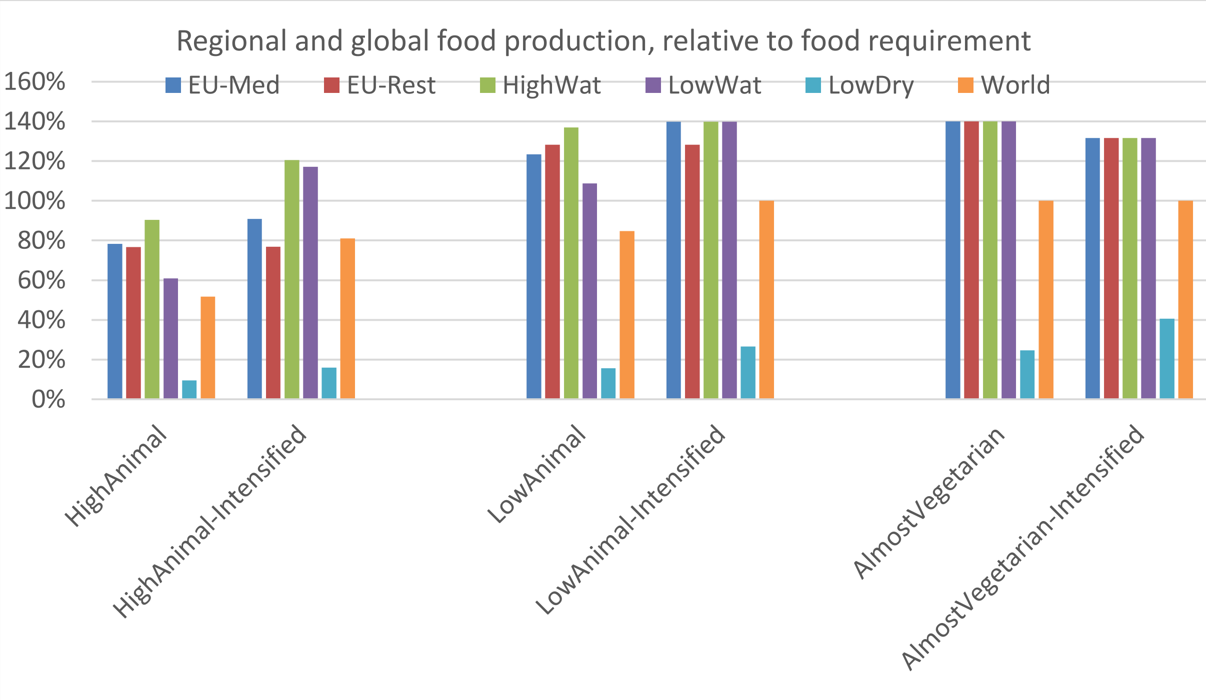


Figure 17. Regional and global food production for the set of scenarios, relative to the regional food requirements. Production below 100% indicates that biospheric constraints limit production to fulfil regional requirements, production above 100% indicates regional contributions to compensate for a lack of food self-sufficiency in other regions.

Overall, it can be concluded that only the *LowAnimal-Intensified, AlmostVegetarian*, and *AlmostVegetarian-Intensified* scenarios are *viable*, in producing flows of food products to society that is required to sustain the anthroposphere.

Other *viability* concerns related to labour and the level of investment in agriculture

In our scenarios the labour requirement in agriculture remains relatively high in EU and it becomes very high in water endowed countries for the scenarios with increasing consumption of animal sourced foods and current production systems(between 20-40% of the work force), when compared with the expected values of work force in agriculture in developed countries (below 4%). In the water-scarce region, even the *AlmostVegetarion* scenario requires over 20% employment in agriculture. Therefore, these values are not compatible with the projection of a developed world in 2050 in which the majority of the population also in developing countries will be urban. Employment requirements are more modest under the *Intensified* assumptions, Moreover, it should be noted that achieving a high productivity of land and labour in agriculture (the type of productivity assumed in the *Intensified*-scenarios) requires an enormous amount of fixed investment (machinery and infrastructure) and circulating investment (fertilizers, irrigation, pesticides), not even mentioning the biophysical costs in the post-harvest phases, when assuming 90% of the population living in cities. The agriculture in developed countries is the economic sector with the highest investment per worker, the lowest economic return of the economic investment. This is the reason why, within the

EU, the economic viability of agriculture is heavily dependent on subsidies. For this reason, it is not clear, whether developing countries will be able to arrive to a point, in 2050, in which they will be able to afford: (i) to generate the same level of economic investment per worker as experienced in EU countries; and (ii) to generate the same level of economic surplus in the other sectors of the economy making it possible to sustain their agricultural sectors with a constant flow of economic subsidies.

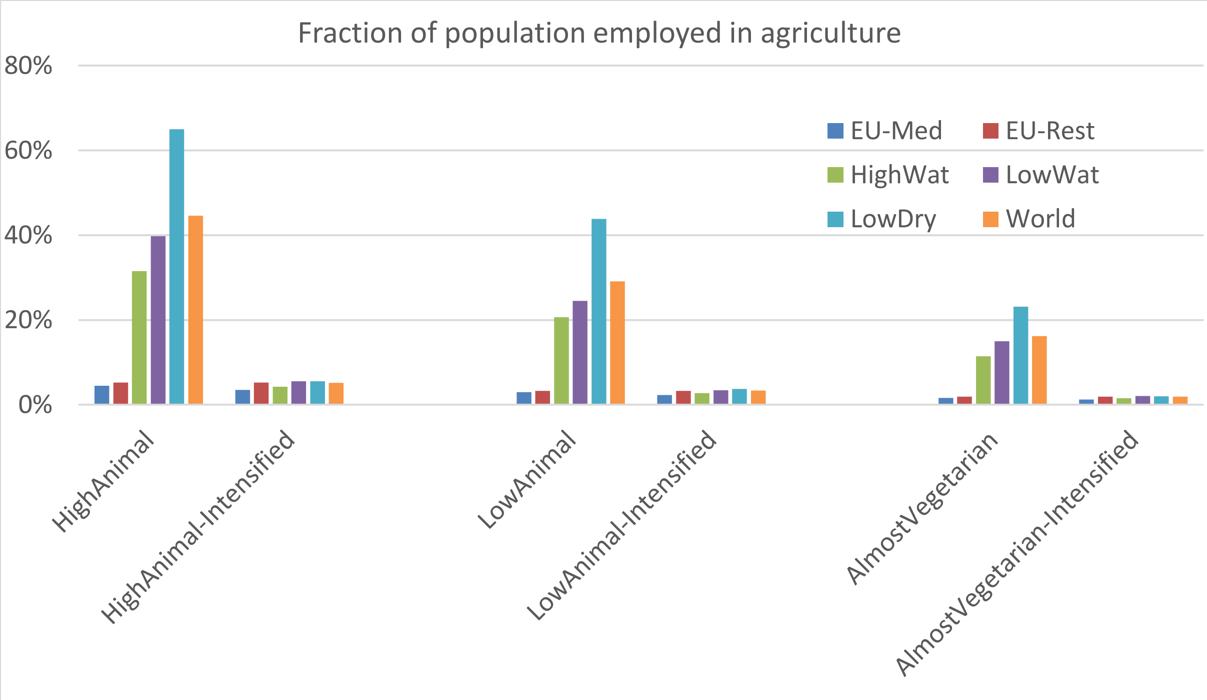


Figure 18. Regional employment rate in agriculture, for the downscaled scenarios. Scenarios assume production to be limited by biospheric factors, not by labour availability.

Other *desirability* concerns related to the terms of trade of food commodities in the future

The LowDry region has to import 60 to75% of its food requirements in the three scenarios and as a result they will become extremely dependent on external supply. Looking at the need of compensating gaps between requirement and supply with international trade, it is questionable whether regional societal metabolic patterns are consistent with such high commodity fluxes. For instance, the EU rather than becoming an exporter of large volumes of staple foods may find more convenient to supply diets richer in meat to its internal EU consumers. This will be extremely likely if the export of their staple food will be to countries that may not be able to guarantee the same prices paid within EU. Other regions may compensate for the fact that EU (that has the possibility of producing more) will not export, but still their decisions about exporting food surplus will imply a direct competition between “the rich” capable of maintaining diets rich in animal products and “the poor” forced on vegetarian diets. Moreover, the tendency to reduce the intake of animal-sourced foods in high-income regions, and to refrain from moving to more animal-sourced foods in developing regions may also be considered as undesirable by many. Many LowDry regions, as memory of their “low population density past”, do have dietary habits based on diets rich in meat. Again we want to repeat that the scenarios considered here do not have the goal of providing any prediction of what will happen in the future. However, our anticipatory Quantitative Story-Telling indicates that the increase in the world population to 9.6 billion will require major adjustments in the existing patterns of: (i) consumption of food products, (ii) trade of food commodities, and (iii) production systems in agriculture. The narrative that up to 2050 the agricultural system of EU will keep running smoothly without major perturbations is highly questionable.

4.6. Conclusions

The coarse analysis on global and regional food security illustrates the potential of MuSIASEM to perform the accounting of flows in the biosphere and anthroposphere, and to substantiate the assessment of feasibility, viability and desirability of depicted future or historic situations.

The analyses shown can feed into Quantitative Story Telling, specifying narratives on, for instance,

- global drivers to threaten global society to violate planetary boundaries,
- intensification of human-controlled processes to contribute to (but not altogether solve) food security,
- changes in dietary patterns to relieve human pressures on the world's natural resources, nearing or remaining within boundaries of biospheric integrity,
- externalization to be the only solution to safeguard food supply regionally but at a price of high dependency on a more volatile and "overconnected" market. At the level of the planet humans cannot import and therefore globalization is a zero-sum game (rich vs poor).

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