EnAlgae
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EnAlgae Decision Support Toolset: Model Validation

Report WP3A16.01

Algae Growth Modelling Tool

Please check the options most appropriate to your needs, then press the "Grow" button:
There is more detail about the model here.
Menus in BLUE contain fixed standard values
Menus in RED allow you to customise your system more fully
Holding the pointer over ? will bring up more information
The graphs at the bottom show how biomass and biofuel-C areal production vary over a year.
You can see the actual values by holding the pointer over the world line.

My N:P ratio and nutrient concentration are ● Fixed n x f/2 ○ Custom	Fixed n x f/2	My own recipe
Dilution rate:	1/3	volume per day
Optical depth:	0.2m	
Lighting: ● Natural ○ Artificial	Latitude (° N)	Lighting Setup
Maximum growth rate:	Fast (1.386)	per day

Economics

Description	Amount
Total Return (€/yr)	2,645,452.6
Total Costs (€/yr)	1,161,01
Total Results (€/yr)	1,4
Selling Price (€/kg DM)	
Cost Price (€/kd DM)	

Energetic Algae ('EnAlgae')

Project no. 215G

Public Output

Report WP3A16.01 – EnAlgae Decision Support Toolset: Model Validation

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EnAlgae Decision Support Toolset: Model Validation

1 Introduction

One of the drivers behind the EnAlgae project is recognising and addressing the need for increased availability of information about developments in applications of algae biotechnology for energy, particularly in the NW Europe area, where activity has been less intense than in other areas of the globe. Such information can be of benefit in coordinating research activities, stimulating targeted investment to develop promising technologies and to guide key policy decisions. To make this a reality, EnAlgae has developed a Decision Support Toolset (DST) to enable improved evaluation of state of the art algal biotechnology and to compare alternative routes to utilising algal biomass.

With developing technologies, often there is a need for much time, investment and the exploration of experimental dead ends before the most effective methods become established. To speed this process up, modeling can provide a means to eliminate ineffective strategies and allow better targeting of resources towards more viable ones with great savings in time and expense. Hence, modelling can play a crucial role in guiding operational, financial and policy decisions. With that in mind, various modeling methods are at the core of the EnAlgae DST. There are four main areas supporting decision making:

- An online dashboard incorporating market and engineering models
- A growth modelling tool based on mechanistic principles
- A searchable map of algae initiatives in NWE
- GIS modelling to gauge the suitability of potential sites for algae production facilities.

However, to instil confidence in the guidance provided by the DST, it is necessary to test the models and information against reliable data. Here we outline the steps taken to validate the DST modelling against existing literature and against data generated from EnAlgae pilots in the NWE area.

1.1 DST Elements

Before examining the validation steps for each element, it is worthwhile to have a brief overview of the various functions of the DST, outlining the purpose of each one and its importance.

1.1.1 Dashboard

The DST dashboard comprises a description of cultivation and processing systems in the form of bio-economic models that combine an estimation of biomass production and resource consumption with an economic assessment that provides a detailed cost price analysis. Predicted outcomes depend upon the choice of cultivation system and the target end product, which in turn dictates the methods of downstream processing. Each scenario can be explored to compare the performance of each system type and to analyse the impact that various choices may potentially have on productivity and profitability. For microalgae cultivation technologies there are models for:

- Open pond systems
- Flat panel reactors
- Tubular photobioreactors

There is also a model describing the economics of offshore seaweed cultivation; further details on the macroalgae techno-economic model are provided by Dijk & Schoot (2014). Downstream processing economics are available for the following products:

- Methane
- Biodiesel
- Ethanol through wet milling

Each dashboard is based on a set of assumptions and presents inputs for user-defined variables. For a more detailed explanation of the background to the techno-economic dashboard models for microalgae production, see Spruijt et al. (2014).

1.1.2 Growth Modelling

The EnAlgae growth modelling tool is based on a well-founded mechanistic model of algal physiology and enables rapid calculation of biomass and biofuel feedstock production under a range of dynamic environmental conditions. The algae growth model is an acclimative, mechanistic structure describing variable stoichiometry (C:N:P:Chl) driven by multi-nutrient interactions (Flynn, 2001). In its description of cellular nutrient quota dynamics, growth under nutrient-limited conditions depends largely on the availability of internal nutrients for the cell to utilise. Limiting nutrients control much of the dynamics while uptake of any non-limiting nutrients is moderated (Flynn, 2001; Flynn, 2003).

Optimising for conflicting needs requires compromises in system design and operation and is a critical step toward achieving economic viability. High volumetric and areal productivity are mutually exclusive, as are high energy content (i.e. as feedstocks for biofuels) and enhanced growth for bulk biomass (Kenny & Flynn, 2014).

The user interface provides scope for experimentation to investigate how the interplay between these various factors can guide strategy to attain optimal solutions. The end user has control over light availability (whether artificial or natural), nutrient levels (in the form of dissolved nitrogen and phosphorus), harvesting rate and optical depth. The optimal combination of these options also varies according to location, growth characteristics of the chosen strain and the prime end product, whether the emphasis is on production of bulk-biomass or energy-rich components. Simple visualisations of the outcomes are also available.

1.1.3 Stakeholder Map

One of the foci of the EnAlgae project has been the completion of landscaping studies of academic and industrial research on algae cultivation and its use in general as well as for associated commercial activities. Information was gathered through a combination of direct interviews, questionnaires and desk research. A total of 283 organizations, including research institutions and companies, responded to the initial survey. The resulting reports, in particular the stakeholder overviews, serve as basis for an “Algae map” in EnAlgae’s searchable online database. The data from this survey are incorporated into the DST in the form of a searchable map, featuring a user-controlled portal to display the location, contact names and miscellaneous information on the respective algae stakeholders and their activities. Further details and a summary of the findings of the survey are provided by Sternberg et al. (2014).

1.1.4 GIS Data Modelling

The GIS data model enables the identification of potential microalgae production sites in the form of a map for open pond, tubular and flat panel cultivation systems. The user can choose pre-calculated scenarios regarding the availability of land for microalgae sites. For each potential site, information on area of the site, yield, access to roads and availability of nutrients are given. Different filters can be applied to display potential sites with specific properties. Nutrient sources for N, P, and CO2 can be found on the map, as well.

Within the DST the model is coupled to the techno-economic model developed in the Dashboard for the yield calculations. It feeds climate data for each potential site into the relevant techno-economic model and reads out the yield and other yield related attributes (e.g. N demand).

2 Dashboard Validation

2.1 Microalgae Cultivation

There is much overlap between the various techno-economic models describing microalgae cultivation in open ponds or tubular and flat panel photobioreactors. There are several key parameters and assumptions made that are common to all three. Therefore, to avoid unnecessary repetition, the critical parameters, data and assumptions used to construct all three microalgae techno-economic models (as outlined in Section 1.1.1) are considered collectively.

2.1.1 Critical Parameters

The choice of location (as selected by the end user from a dropdown menu) determines all climate data including global radiation, temperature, rainfall and day length.

An up-scaling equation is used for the calculation of capital good costs, labour requirement and extra land requirement for the associated equipment and infrastructure. The scaling parameter n enters as an exponent factor and is set at 0.6 in this instance, although it can be adapted to more applicable values if necessary. The default value for n originates from the chemical industry (see Section 2.1.2, Data & key assumptions used). However, no equivalent parameter has been firmly established for the algae industry. Hence, in the absence of a more appropriate value, the value $n = 0.6$ is used as typical.

Biomass composition is dependent upon the relative sizes of algae populations in the mixed culture. Furthermore, input prices can be modified to reflect market changes.

2.1.2 Data & key assumptions used

Several existing sources were referred to for guidance regarding physiological descriptions. Cell content profiles follow Becker (2007) while C:N:P content is based on data from the ECN Phyllis2 Database for biomass and waste (url: https://www.ecn.nl/phyllis2/). The temperature-growth relationship uses a description by James & Boriah (2010).

During cultivation, it is assumed that any digestate, flue gas and heat are available at no cost. As digestate from manure cannot be used directly to produce feed or food, hygienisation is required; such digestate needs to be refined. Furthermore, it is also assumed that, unless artificial CO_2 is added or if digestate is used as a nutrient source, algae growth is inhibited (e.g. if there is no extra CO_2, production level is restricted to 70% of maximum; this default value is considered typical).

When heat use is selected (switched “on” via a checkbox on the Dashboard), heat consumption is calculated under the assumption that the PBR is operated so that it is heated to a desired setpoint temperature during daytime and then cools down at night to the ambient air temperature. Otherwise, if heating is turned "off", then the ambient average air temperature is used as input to calculate the growth factor and the capital cost for heating equipment is consequently ignored. Heat balance formulas are based on Smith et al (1994) and Béchet et al (2011).

Photosynthesis is considered in terms of conversion of light to sugars based on a photosynthesis efficiency that varies according to the photobioreactor construction types. Factors that influence this conversion are temperature and CO_2 availability. The subsequent conversion of sugars to dry matter is influenced by the species composition of the culture and the expected dry matter composition of the species biomass (Vertregt & Penning de Vries, 1987).

Capital goods purchase costs are extrapolated from those for the Lelystad pilot facility. Scaling is factorised according to Sinnott et al. (2005) and is based on multiplication of 1,000 m^2 ponds. Ponds of this size are assumed to be the basic units to increase in size. When the installation is not in operation it is assumed that there are zero operational costs. The operational months can be end-user selected.

2.1.3 Sensitivity and Gaps

The cost and income from an anaerobic digester and/or any connected combined heat and power (CHP) engine are not included in this model yet. The prices at which the heat and flue gas can be supplied are set to 0 by default but can be altered if desired.

Scaling factors for labour costs remain best estimates for now due to a lack of data from practice.

2.2 Seaweed Cultivation

2.2.1 Effective Operating conditions

The focus of the model is on the production of brown kelps that are typically grown throughout winter and spring, with cultivation confined to offshore longline arrays similar to those employed by EnAlgae pilot operators (land based cultivation systems are excluded).

2.2.2 Critical parameters

The critical parameters in the model fall into two distinct categories; those which the end user can have full control over and those that are more influenced by external factors. Those that the end user can firmly control in practice are the choice of cultivation system (whether linear longlines or longlines with V-droppers), the farm size (that is, the number of longlines employed) and the combined use of longlines and/or hatchery. Parameters the user will have less control over in reality include the price of the harvested biomass and the cost price of plant material, if the latter is purchased from a third party supplier rather than grown within an on-site hatchery. As these are dictated by market forces, there is an option in the dashboard to select whether these costs are calculated by the model (cost price of plant material) or set by the user (cost price of plant material, price of the harvested biomass). Additionally, despite careful efforts, biomass yields cannot be guaranteed for a given system setup due to the exposed nature of offshore longline arrays. Hence, the dashboard enables the end user to enter their own chosen yield levels to explore the resulting scenarios.

2.2.3 Data & key assumptions used

The dashboard macroalgae model is constructed on the basis of input from EnAlgae pilot operators (explicitly, National University of Ireland Galway (NUIG), Ireland; Queens University Belfast (QUB) and Swansea University (SU), UK; Centre d'Etude et de Valorisation des Algues (CEVA), France) combined with reference to Edwards & Watson (2011).

Scale up is treated in a similar manner to the micro algae model (Sinnot et al., 2005) with the factor n entering as an exponent in the scaling formulae. In the context of macroalgae commercialisation, pilot data from a single existing farm suggests an appropriate value for the scaling factor to be $n = 0.8$.

This value is used for the capital good costs as well as the labour and boat lease costs (see below).

The capital good costs are mainly derived from Edwards & Watson (2011) with minor modification based on information provided by partners. The investment costs are based on one longline system with subsequent scale up calculated using the scaling formulae. Estimates of labour demand are mainly derived from data from CEVA based on a system of 4 longlines. Labour prices are derived from the Farm Accountancy Data Network (FADN 2015). In all cases it is assumed that a boat (including a skipper) needs to be hired to access the longline array; for a situation of four longlines the costs for the boat lease are estimated. In situations with more than 4 longlines the scaling formulae is used to estimate labour demand and boat lease costs.

The model offers the possibility to calculate the cost price of the plant material. This calculation is based on a hatchery producing 22000 m of seeded string on annual basis. A distinction is made between the production of plant material via gametophytes and direct seeding of zoospores. Transport costs of the biomass from the harbour to the processing site are included.

2.2.4 Sensitivity and Gaps

Due to the complexities of accounting for the effects of the natural environments on biomass yields, the model does not contain a module that simulates the growth of the seaweed based on environmental conditions (e.g. light, temperature, dissolved nutrient availability). Therefore, the achievable yield has to be set by the model user either based on experience or to test potential outcomes.

It does not account for a decreased life span or increased maintenance costs when using the facilities more intensively (combined use option). Additionally, the model does not account for further processing of the harvested biomass (e.g. drying).

The scaling factor has a significant effect on the results. Preferably the model results should be compared to a number of commercial farms differing in size. As seaweed growing in NWE is done on a very modest scale this has not been possible to date.

2.3 Downstream Processing

2.3.1 Critical parameters

The scaling parameter n (Sinnott et al., 2005) is set at 0.6 (it can be adapted to more applicable values). As in the cultivation process, this up-scaling equation is used for the calculation of capital good costs, labour requirement and extra land requirement for the associated equipment and infrastructure.

2.3.2 Data & key assumptions used

All models assume a selling price of algae, functioning as a raw material input price in the processing models.

The biodiesel and ethanol models are based on a base biomass weight of 10 tonnes of algae dry matter, with allowance for scale-up. Cell content in the biodiesel and ethanol models is based on data from Becker (2007) and Rebolloso Fuentes et al. (2000).

Estimated investment costs for downstream processes for biodiesel and ethanol production are derived from a number of sources. Dryer costs are estimated by using the e-commerce website Alibaba.com, while investments costs for the ball mill for wet and dry milling are based on information in Balasundaram et al. (2012).

Scale up for the downstream process models uses the same upscaling equation applied to the models of the algae cultivation systems (see Section 2.1.1). The cost price for algae biomass (15 % dry matter) is assumed to be €10 per kg dry mass but can be changed to fit actual situations.

2.3.2.1 Assumptions unique to methane production

Methane production is via anaerobic digestion (AD). The resulting biogas density is calculated to be 1.232 kg/m^3, based on the mixture of biogas from a co-digester containing 52 % CH_4 and 48 % CO_2 by volume and with a methane density of 0.668 kg/m^3 and 1.842 kg/m^3 for CO_2. However, the AD system model assumes a minimum capacity of a co-digester of 1 million m^3 biogas per year, which requires that the digester has to be fed with 13,200 tonnes algae paste (assuming 15 % dry matter) with the resulting methane (green gas) production at 520,000 m^3 per year.

The selling price for bio-methane as a substitute for LPG is estimated at 0.22 €/m^3 (Voort et al., 2014). However, biogas (containing biomethane) needs to be refined to produce Compressed Natural Gas or bio-LNG.

2.3.2.2 Assumptions unique to biodiesel production

The input to the drying process step is assumed to be an algae paste of 15 % dry matter content. Estimates for the biodiesel refining equipment vessels and the transesterification reaction are taken from heuristic values for tanks (Coulson & Richardson, 1996) as well as process information for soybean biodiesel production (Haas et al., 2006).

The capacity of the ball mill as integrated in the biodiesel downstream process, is based on 12.5 tonnes dried algae paste (10 tonnes of 80 % w/w dry matter) and 8,000 operational hours. Electricity required for ball milling is 1.87 kWh/kg dry biomass (Balasundaram et al, 2012). The lipid extraction efficiency is assumed to be 95 % while loss during the transesterification phase is assumed to be 2 %.

The selling price for biodiesel and bioethanol as a substitute for diesel is estimated at 0.518 €/L (Voort et al. 2014).

The estimation for the selling price for protein-rich biomass (as a by-product of the biodiesel production process) is based on the soy price of €350 per tonne with a 50 % protein content. The assumption that algae equals soy bean in protein quality is unsubstantiated to date and requires testing.

2.3.2.3 Assumptions unique to Ethanol Wet Milling process

The description of the fermentation process for ethanol production is based on the following set of assumptions. Firstly, the efficiency of the whole process and with this the cost price, is influenced by the carbohydrate content of the algae paste. As a default value, the model assumes a high carbohydrate alga (for example, *Porphydrium cruentumm* has been described as having a carbohydrate content of 49 % w/w in the dry matter of the growth medium (Becker 2007)). In practice, about a third of this can be present outside of the algal cell, as polysaccharides (Rebolloso Fuentes et al., 2000). But for the model, the assumption of 49 % w/w carbohydrates is maintained as a 'best case' scenario. Secondly, it is assumed that 65 % of the carbohydrates are enzymatically hydrolysed to monomeric glucose, becoming available for ethanol fermentation by yeast. Some yeasts may be capable of fermenting xylose or arabinose to ethanol, but they do so less readily. Thirdly, the ethanol fermentation is assumed to be 100 % efficient, meaning that all available glucose is actually fermented to ethanol. As a consequence, a theoretical ethanol-from-glucose weight yield of 51 % (w/w) is applied in this instance. However, the dashboard interface enables the end-user to experiment with all of these parameters to study the effect on the end result. Energy requirements for the subsequent ethanol dewatering step are calculated on the basis of data from Vane (2008).

The wet ball mill costs are estimated using a quote for the Dyno Mill AP05 mill. Costs for the fermentation and distillation are both based on the investment costs for an ethanol pilot plant in Lelystad producing 150 thousand litres ethanol from corn per year, linearly scaled down to the base case of 10 tonnes dry matter algae. Based on the Lelystad bioethanol plant, enzymes cost are 6 €/L and yeast (DSM Fermiol) cost 9 €/kg.

2.3.3 Sensitivity and Gaps

The biodiesel model is generic and does not differentiate between saltwater and freshwater species – a washing or salt removal step may be required for marine species of microalgae prior to drying.

In this scenario, the model simplifies the process by examining the extraction of only one product, triacylglycerides from the algal biomass. In practice, other products such as pigments could be extracted simultaneously, and a second depressurisation step added to collect a different fraction. Owing to the huge diversity of microalgae, a single product probably is not correct but it is assumed here for simplicity reasons.

3 Growth Modelling Validation

3.1 Effective operating conditions

The mechanistic algae growth model itself can run for any non-(Ant)Arctic latitude but the DST version is limited in function to latitudes relevant to NWE (i.e. 45 – 60 ° N). While the model in its various forms can be adapted to describe growth in a variety of natural and man-made ecosystems, in this case it is primarily for open-pond cultivation but is also applicable to flat panel reactors where AP becomes production per panel unit area. The model simulates continuous, chemostat-style dilution and runs over one whole year (starting Jan 1st). The operating conditions of the growth modelling part of the DST are very much defined by the limits of the dropdown menu and slider options in the user interface.

3.2 Critical parameters

The most important parameter determining biomass production rates is maximum growth rate, U_m. For high biofuel production, the balance between light and Nitrate (N) availability is critical as to whether the system is light or nutrient limited. In most cases, the latter (stimulating lipid production) requires a low N concentration, typically only half times f/2 growth medium concentrations (f/2 provides 12.3 gN L^{-1} and 1.1 gP L^{-1}; Guillard & Ryther, 1962; Guillard, 1975), combined with a shallow optical depth of 7 – 10 cm. However, very shallow depths (3 & 5 cm) permit higher N levels while remaining N-limited.

3.3 Data & key assumptions used

A basic assumption is that the system is optimised with respect to CO_2, pH and temperature; the latter results from using a stain adapted to local conditions. Productivity, as directly calculated by the model, is in terms of carbon biomass, and use of these units provides the most reliable figures. The inclusion of conversion factors does provide some choice of preferred units for the end user but the subsequent calculations are less robust. For instance, to quantify simulated dry weight productivities, it is assumed that carbon accounts for 31% of dry weight (Heymans 2001). This figure is not constant for all strains and under all conditions. The C:dry weight ratio can be 1:2 (Geider & LaRoche 2002) or higher. However, the conservative value 0.31 was chosen to give a generous estimation of biomass dry weight to place an upper limit on productivity potential, even if this may be overestimating what can be produced in practice. This choice is supported by data generated by Silkina & Ginnever (unpublished) during trials for cultivation of *Scenedesmus sp*. and *Nannochloropsis oceanica* at the EnAlgae pilot facility in Swansea using a 5xf/2 growth medium (the corresponding biomass growth data from these trials are presented in Fig. 1). They measured the average %C content of the biomass produced as 29 ± 1.2 % for *Scenedesmus* and 32 ± 2.3 % for *N. oceanica*.

The model's effectiveness has been demonstrated repeatedly against independent data for various species and for diverse aspects of growth under varying conditions including (but not limited to) biomass growth dynamics (John & Flynn, 2000; John & Flynn, 2002), photoacclimation (Anning, et al., 2000; Flynn, et al., 2001), nutrient quotas and transport controls (Elrifi & Turpin, 1985; Flynn, 2008) production of dissolved organic matter (Biddanda & Benner, 1997; Clark, 1998; Flynn, et al., 2008) and applications to ecology (Fehling, et al., 2004; Flynn, 2010) including marine ecosystems (Lochte, et al., 1993; Jeandel, et al., 1998; Gall, et al., 2001a; Gall, et al., 2001b; Fasham, et al., 2006). In addition, a summary of data sets used to tune prototypes of the model has been compiled by Flynn (2001).

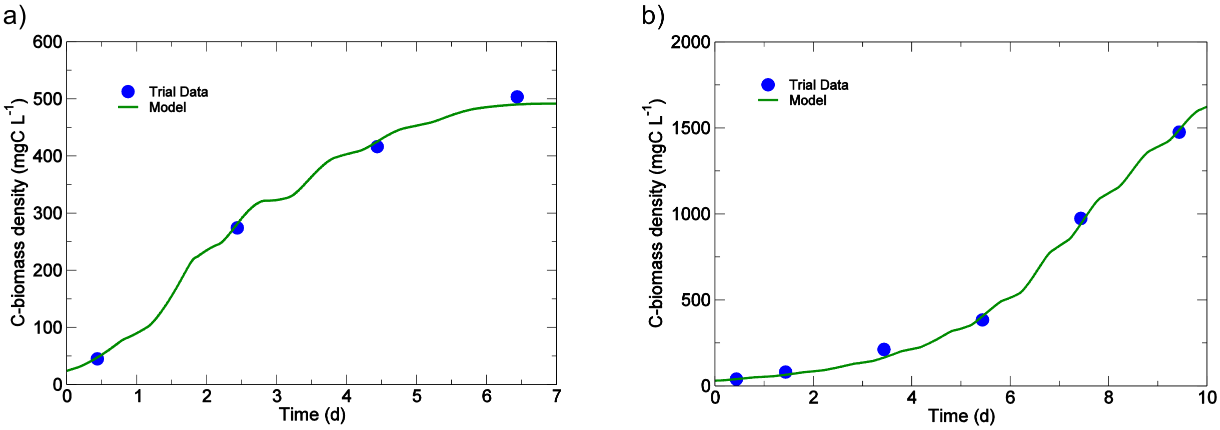

Fig. 1. Comparison of model prediction against data from growth trials at the Swansea EnAlgae pilot facility. Panel a) shows the DST model run with the default parameterisation against growth data for Scenedesmus. Panel b) shows the model tuned to growth data for Nannochloropsis (see main text for details).

Data sets from growth trials at the EnAlgae pilot facilities in Swansea and Lelystad have been used to test that the default DST growth model parameterisation is satisfactory. Data from the growth trials of *Scenedesmus* and *N. oceanica* grown in a closed tubular bioreactor under natural light with a high concentration 5xf/2 medium (62 mgN L^{-1}, 5mgP L^{-1}) were used to validate the model predictions for short term batch cultivation (a harvesting mode unavailable in the online user interface). With the default parameter settings, the model generates an excellent fit to the *Scendesmus* data (Fig 1a). To generate a comparable fit to the *N. oceanica* data (Fig 2a), it was necessary to tune the parameter describing the maximum chlorophyll:carbon ratio, $ChlC_m$, to a lower value than that used in the DST version; from $ChlC_m$ = 0.06 to $ChlC_m$ = 0.015. While still within the range of physiologically correct values, the implications for this change of value are considered in Section 3.4.

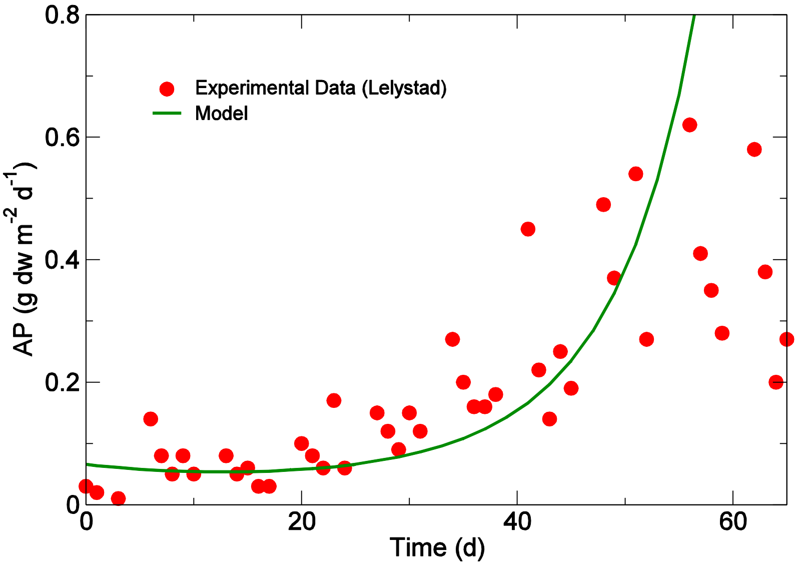

Fig. 2. Comparison of model prediction against data from growth trials at the Lelystad EnAlgae pilot facility. The data were collected between Jan and April 2013.

The model was then tested against data for a longer term trial at the Lelystad EnAlgae pilot facility. The culture was grown in a 0.8 m deep open-pond between January and April 2013. The model here is run with a discontinuous daily harvest, whereas in practice it was either not possible or not necessary to harvest every day. For most of the time, the model makes a reasonable approximation to the experimental data. However, it is apparent that, coincident with the time production should have increased sharply with the arrival of spring, the culture was contaminated (probably by predators) and rapidly crashed. Despite this, there is confidence that the model in its default parameterisation produces reasonable productivity projections.

According to the DST growth model, daily areal biomass productivity in NWE under natural light should average up to 1.9 gC m^{-2} d^{-1}, with an absolute daily peak of 3.1 gC m^{-2} d^{-1}. For comparison to real systems, in oceans areal production by fast growing phytoplankton at upwelling zones can reach 3-4 gC m^{-2} d^{-1} in short bursts during spring blooms (Field, et al., 1998), matching rates in shallow ponds (Flynn, et al., 2013). Kenny & Flynn (2014) ran a very similar model for biomass and biofuel production optimisation over a broader geographical region than NWE and demonstrated the model's headline predictions for biomass productivity are consistent with reported results (Fernández, et al., 1998; Garcia-Gonzalez, et al., 2003; Jimanez, et al., 2003; Olguin et al., 2003; Moheimani & Borowitzka, 2006; Huntley & Redalje, 2007; de Schamphelaire & Verstraete, 2009; Rodolfi, et al., 2009; Ritchie & Larkum, 2012).

The production of energy-rich storage carbon (carbohydrate, fatty acids) as feedstocks for biofuels is also simulated. The stoichiometric values of the parameters governing biofuel-C production (Flynn et al, 2013) are typical of experimentally derived values (Geider & LaRoche, 2002). It is assumed that all C-rich biomass will be extracted and converted into biofuel (in reality, it is highly unlikely this could be achieved). To convert biofuel-C from gC to L biodiesel, a typical diesel fuel carbon density of 720 gC L^{-1} is assumed (Miguel, et al., 1998). The growth model predictions for maximal biofuel production in NWE are comparable to calculations by (and communications to) Walker (2009).

The DST calculations determine the optimal depth for commercial cultivation of wild-strain (non-GM) phototrophic microalgae in a facility intended for multiple applications should be approximately 10 cm, a value consistent with that suggested by Garcia-Gonzalez et al. (2003) and Ritchie and Larkum (2012) who also place an upper limit on useable pond depth around 25 cm.

Atmospheric clearness data is from NASA's Surface Meteorology and Solar Energy database (url: https://eosweb.larc.nasa.gov/sse/). This clearness index determines the fraction of sunlight penetrating the atmosphere (accounting for cloud cover, dust, etc.) at each latitude and is averaged over the year. The model description of the temporal and spatial variations in irradiance has been tested against data in Walsby (1997) and data from Swansea & Lelystad pilots (unpublished) and found to be a good approximation (as an example, see Fig. 3).

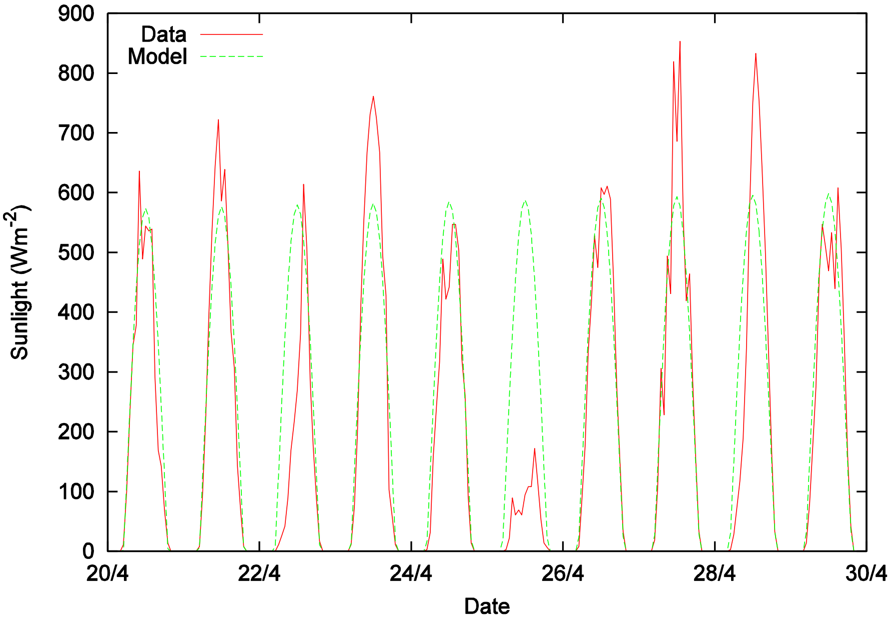

Fig.3. A comparison of the model descriptor of sunlight levels to irradiance data obtained at the EnAlgae pilot plant at Lelystad UR, Netherlands in April 2013.

3.4 Sensitivity and Gaps

Model parameters are set to typical values as there is a lack of suitable data to be able to make the parameterisation completely strain specific. Hence, the model is sensitive to the parameterisation. As an example, species with a lower *ChlCm* (as was the case for the data tuning in Fig 1b; see Section 3.3) will be less affected by self-shading, hence dense cultures in this case should be more productive as they are less likely to be light limited. Furthermore, the maximum and minimum values for the cellular nitrogen quota have a bearing on biofuel-C production. The parameter having the biggest impact on production is the maximum C-biomass growth rate, U_m, with suitable dissolved nitrogen levels being critical to biofuel production (maintaining the balance between having high enough levels to maintain growth but not so high as to make the culture light limited).

The main gap in the DST growth model is not having a suitably parameterised, strain-specific descriptor of temperature dependence on growth. Neither is predation nor multi-culture competition taken into account. This is potentially a serious issue for open ponds, where predator contamination can lead to culture crashes (see data in Fig. 2). While mechanistic models exist to explore these issues, sufficient data is not currently available to implement them meaningfully in this instance.

4 Stakeholder Map

4.1 Data & key assumptions used

Data was obtained via a comprehensive questionnaire, which was distributed among stakeholders identified in a preliminary scoping exercise. The questionnaire aimed to gather more information on focus, expertise and applied technology of the addressed institutions/companies. It was also designed in such a way as to allow its use as an information sheet in the EnAlgae web-based information portal. In cases where a direct response was not obtained, appropriate stakeholder information in the public domain was used for the landscaping study while additional information was collected through further personal communication with the respective stakeholders.

Prior to publication of the collected data about the different stakeholders and their activities it was necessary to obtain permission to publish the information in order to protect personal property rights. For this purpose all stakeholders were directly contacted. Requested adaptations and cancelations were taken into account.

4.2 Sensitivity and Gaps

The listed data and information cannot claim to represent an exhaustive overview of all stakeholders active in algae research and business. The reasons behind this are:

- It is a rather broad area and in some cases only very limited information is available about respective activities.
- There is lots of movement in this sector with regard to new start-ups and the closing down of business operations, making it difficult to give an up-to-date overview.
- If inadequate information could be found about certain institutions they were not included in this survey.

However, the landscaping study and with it the online “Algae Map” nevertheless represent the most important institutions active in this area, allowing conclusions to be drawn about the main fields of interests, technology and market opportunities for algal research in North-West Europe.

5 GIS Model Validation

5.1 Effective operating conditions

The data used as the basis for the GIS siting model covers the entire EU region but, in the specific context of the EnAlgae DST, only data relevant to NW Europe is analysed.

5.2 Critical parameters

The location of potential microalgae production sites is mainly determined by the chosen land use restrictions. The most important parameter for the yield calculation (coupled to the Dashboard model) is the photosynthetic efficiency which can be changed by the user. The yield is further affected by the chosen cultivation system.

5.3 Data & key assumptions used

Fig. 4 shows a model scheme of the GIS model for algae siting including the data used to model the availability of suitable land areas for potential microalgae sites and the data used to add information on climate (resulting in biomass yield), nutrient availability and road infrastructure.

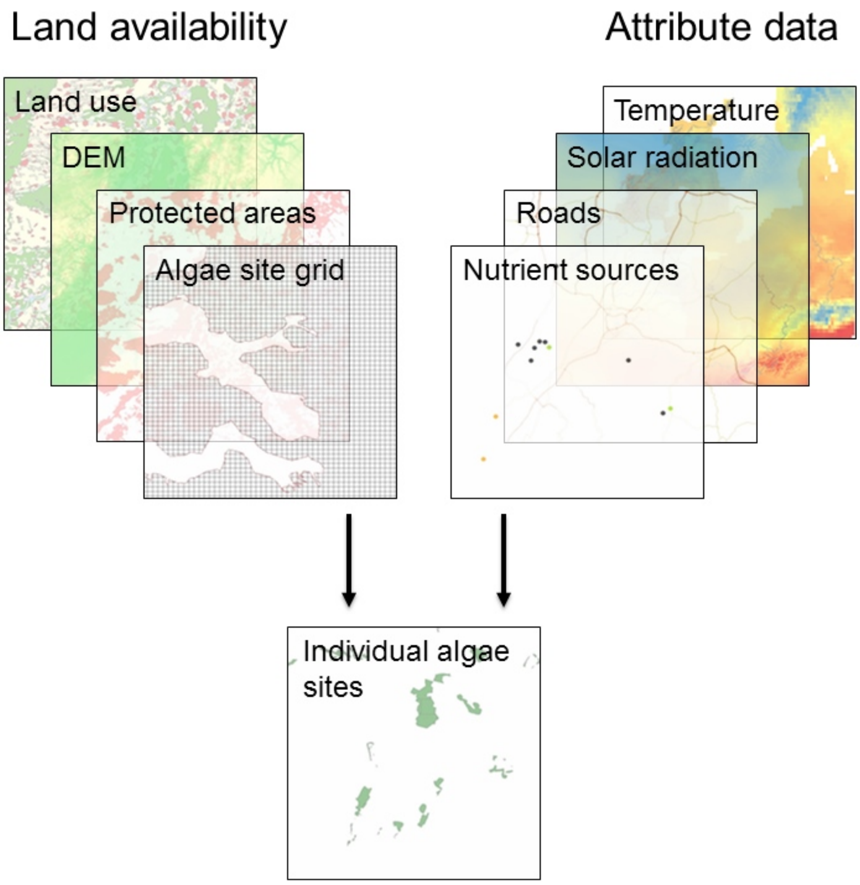

Fig.4. Scheme of the GIS model used for the identification of potential microalgae production sites divided into data regarding to land availability and additional attribute data.

In general, geographic data on administrative boundaries of the NUTS regions have been extracted for NWE from Eurostat (2006).

5.3.1 Algae Siting based on land availability

5.3.1.1 Siting Grid

To enable the identification of potential individual microalgae production sites, a random potential site grid had to be calculated. Each grid unit has a surface of 100 ha (1 km x 1 km). This spatial resolution is necessary to avoid extremely large potential sites. The grid is then intersected with the following data to exclude unsuitable or unavailable areas from the analysis.

5.3.1.2 Land Use Data

The Corine Land Cover 2006 seamless vector data (EEA, 2014a) has been used. In the default scenario, the CORINE land use categories pastures, bare rock, and sparsely vegetated areas were assumed to be available for microalgae sites, at least in principle. Other scenarios excluding productive land (i.e. pastures) or further including arable land can be chosen by the user.

5.3.1.3 Topological Data

The EU-DEM (EEA, 2014b) digital elevation model (DEM) has been used considering only tiles relevant for NWE. The spatial resolution of the raster data is 25 m x 25 m. The DEM has been used to identify mountainous areas according to Blyth et al. 2002. In the default scenario, mountainous areas were assumed to be unsuitable for microalgae sites. Furthermore, the DEM has been used to calculate the slope to identify areas with a suitable slope for open pond systems. A slope of less equal 2 % was assumed to be suitable for open ponds (compare U.S. DOE, 2010; Wigmosta et al., 2011; Quinn et al., 2012). Areas with a slope higher 2 % were consequently excluded as unsuitable for open pond scenarios.

5.3.1.4 Protected Areas

Vector data from the World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC, 2014) has been used. Protected areas were assumed to be not allowed for microalgae sites.

5.3.2 Site attribute data

5.3.2.1 Climate Data

Data on total solar radiation (monthly mean) has been taken from PVGIS-3 (Súri et al., 2007), with a spatial resolution of 1 km x 1 km. Data on monthly mean temperature have been calculated from the E-OBS dataset (Haylock et al., 2008; van den Besselaar et al., 2011). The E-OBS dataset provides daily mean temperature for Europe with a spatial resolution of 0.25° x 0.25° (approx. 20 km x 20 km, depending on latitude). Based on these data monthly means for total solar radiation and temperature have been calculated for each potential site. Within the DST the biomass yield is calculated using these site specific climate data with the help of the Dashboard model.

5.3.2.2 Nutrient Sources

Data on N, P and CO_2 sources in NWE have been extracted from the European Release and Transfer Register (E-PRTR) (EEA, 2014c). Amongst others, the dataset provides geographic coordinates, area of economic activity and nutrient emission amount in kg per year. For each potential microalgae production site the distances to the nearest N, P and CO_2 source are calculated.

5.3.2.3 Infrastructure and Administration

The dataset on road transportation infrastructure in Europe provided with the ESRI ArcGIS software license has been used. For each potential microalgae production site the distances to the nearest divided highway and to the nearest other road are calculated.

5.4 Sensitivity and Gaps

Geographic data are only representations of real objects. Accuracy of geographic data is therefore always limited and depends on factors such as the level of generalization or the chosen method of data gathering. Thus, there are occasions where the data used in the GIS model show differences in position and accuracy. For instance, there are inconsistencies between administrative boundary data, CORINE data and WDPA data which can result in deviations of about 200 m in some cases.

The slope data calculated from the DEM has a spatial resolution of 250 m x 250 m. The DEM has been resampled from the original 25 m x 25 m resolution to 250 m x 250 m prior to the slope calculation to reduce the local variance of the elevation and to increase calculation performance.

The E-PRTR lacks in geographic accuracy in a few cases. Furthermore, only large nutrient sources are compiled within the database: The E-PRTR includes facilities with CO_2 emissions to air higher than 100,000 $tCO_2\ y^{-1}$, N emissions to water (as total nitrogen) higher than 50 $tN\ y^{-1}$ and P emissions to water (as total phosphorous) higher than 5 $tP\ y^{-1}$ (European Commission, 2006).

The road data does not include small roads; the extra computational workload required to use very detailed road data (e.g. OpenStreetMap) can cause severe performance issues (e.g. very long calculation times, need for splitting data, etc.).

6 Pathways for enhanced DST development

The EnAlgae Decision Support Toolset provides end users with unprecedented access to information enabling them to gauge the current status of algal biotechnology in NW Europe. However, it is vital that progress continues to be made in this field. The DST has a role in this development, by identifying both the most promising pathways for technological advancement and where knowledge gaps need to be remedied but also reflecting subsequent progress by enhancing its functionality. The scope for the latter is already promising. The DST in its current form displays a subset of full range of functionalities of the models which underpin its operation. This section outlines ways in which it is possible to enlarge the DST functionality with only minor modifications of existing models and also by improving the effectiveness of these models through continued scientific investigation.

6.1 Opportunities for Future Knowledge Creations

6.1.1 Dashboard Models

The bio-economic models on different photobioreactors (be it open ponds, tubular reactors or flat panels) could be improved on the “bio” side by more in depth modelling on the production side. This would make the tool stronger with more use for day-to-day monitoring. Also, the interaction with predators in the open pond systems would need to be included to increase practical day-to-day use. But this would require more data on this interaction.

For a better underpinning of the scaling factor more data are needed from commercial facilities (for both micro- and macroalgae production) differing in size.

Incorporating a suitable and effective description of growth dynamics into the model requires a better understanding of variations in cellular stoichiometry (C,N,P,Chl) over the whole growth period, from seeding to harvest. This can be achieved using elemental analysis but demands data to be sampled more frequently than has been the case to date.

A better elaboration of the combined use of longlines and/or hatchery will improve the model as the combined use is an important factor affecting the cost price. This refers to an estimation of the life span and maintenance costs depending on the intensity of the use. Additionally, it can be considered to add the economics of the ‘second’ use (e.g. shellfish or second seaweed crop) of the installations in order to estimate the results for the total farm.

6.1.2 Growth Modelling

The growth model needs a better handle on temperature dependence; a descriptor for this currently exists but suitable and adequate data to parameterise and test the model robustly is lacking. There also exists an untested descriptor for cellular photodamage but a better understanding of effects of nutrient deficiency on photosystem repair mechanisms is needed. Tied in with this is the need for an improved descriptor of secondary pigments. Also an improved understanding of effects of CO_2 enhancement of growth, effects of salinity, pH. Progress is also needed in modelling of DOC, fractionation of C-rich components and proteins. There is also scope to include predator prey interactions in open ponds but, again, a lack of suitable data prevents a reliable implementation of this. At the moment, the DST growth model provides very much a ‘best case’ scenario; improving these needed descriptors will lead to more realistic simulations if, in general, less optimistic.

6.1.3 Stakeholder Map

The “Algae Map” offers the opportunity to North-West European algae stakeholders to make new entries or to adapt outdated information. If the “Algae Map” becomes more known in the algae sector and the stakeholder use this option to work with the map, the data base, which the map is based on, would become much more comprehensive, up-to date and therefore more valuable for all users.

6.1.4 GIS Data Modelling

Small nutrient sources are of particular interest for small scale microalgae cultivation. It would be therefore of high value to compile a database including geographic coordinates and nutrient quantities for e.g. biogas plants (N, P, with a CHP also for CO_2) or municipal waste water treatment plants (N, P). So far, the needed data is split into small and incompatible databases.

6.2 Opportunities for Expanded Capabilities and Functionalities

6.2.1 Dashboard Models

Coupling the economic model to a mechanistic description of seaweed growth would greatly enhance the usefulness of this tool and would enable end users to explore scenarios more applicable to the environmental conditions specific to their locality. The micro-algae dashboard displays a limited number of variables to be varied by the user to provide information about the effect these variables have on the micro-algae economics. There are more variables in the model that could can influence the economics but for reasons of user convenience the functionalities are limited. For more advanced users, more advanced dashboard functionalities could be developed. For instance, additional functionality incorporating end-user defined weather data or algae species would enhance performance. Furthermore, comparisons between photobioreactors (e.g. displaying production across the months of a year or even different years) would improve this.

6.2.2 Growth Modelling

Implementation of an optimisation algorithm is possible, e.g. calculate dilution rate and depth for a given system to optimise biofuel production. It would be good to add an option for wastewater treatment to optimise for N and/or P uptake.

Ideally would like to be able to select strain from a dropdown list and strain-specific parameters are automatically selected for simulations. This requires a full parameterisation for a range of species.

The DST version of the model currently only runs in continuous (chemostat-style) mode with dilution averaged over the year. Options for seasonally optimised discontinuous dilution or short-term batch cultivation would add flexibility.

6.2.3 Stakeholder Map

The addition of other search function in the online map could increase the use of the map as data overview.

6.2.4 GIS Data Modelling

Further coupling with the techno-economic model (more data input needed!) would be an interesting (though challenging) option to calculate site specific economics. Furthermore, the model could be extended to assess the microalgae biomass resource potential in NWE.

7 Gauging the Contribution to Future Action Guidance

The aim of the EnAlgae DST is to provide state of the art knowledge to facilitate decisions that will shape the future progress of algal biotechnology in NW Europe. To that end, validation of the various models above provides a foundation for the DST to make a valuable contribution to subsequent developments in this field, and increasingly so as model descriptors are subsequently improved.

7.1 End User Development

Despite the fact that the models comprising the DST take contrasting and complimentary approaches, the combined results from all of these DST elements should impress on end users the enormous scale of infrastructure (open ponds) and resources (water, nutrients, energy) required to produce enough feedstock for biofuels to satisfy even a fraction of NWE’s transport fuel needs, even accounting for the optimistic results of what are often best-case scenarios. If, on the other hand, the end user is considering other markets for the end product, the growth modelling tool will provide a useful means of determining strategies for optimised biomass production prior to implementation although some caution is needed in relying too heavily on the guidance provided. For instance, factors which may lead to sub-optimal production need to be more fully accounted for both within the DST itself but also by end users. The dashboard models are especially of interest to those seeking information on production costs and the build up of this across different cost factors. Energy costs make up a large part of total costs and the model well illustrates this. This should lead to improved cost awareness and will inform discussions on future directions of industry development.

The stakeholder map provides valuable information to the end user concerning the location and nature of any organizations in the NWE region with a connection to algal biotechnology, either commercial or academic, and their main field of interest.

For those that have an interest in investing in algal biotechnology and developing its commercial potential, the GIS model enables the end user to find potential locations for the construction of microalgae production sites. Site specific data give guidance on the maximum yields that may be expected. The different filter options enable the user to find potential sites tailored to their unique specifications.

7.2 Energy Production

The DST provides a sober verdict on algae as a potential source of bioenergy for the NWE region. The mediocre biodiesel production rates for NWE that the growth model predicts suggest that cultivating algae exclusively as an energy source is not a viable strategy. Also, it should encourage investors to pursue more promising options for sustainable energy production elsewhere, either from algae but as a by-product within an integrated biorefinery (Voort et al., 2014) or by means of unrelated technologies. Production cost specifications supply the end user with information that will enable them to give thought to developmental directions to be taken to decrease production costs considerably.

In the GIS model, since only the biomass yield is calculated the contribution to energy production further assumptions are needed to analyse the contribution to energy production. For the case of biodiesel production this could be estimated by multiplying the biomass yield with an assumed biodiesel output per biomass of microalgae.

7.3 Energy Consumption

The dashboard techno-economic models provide the best guidance for gauging energy consumption. These models explicitly calculate the amount of electricity needed to produce the algae. In this case, it is the direct energy input which is of concern. Note that any indirect energy input (for instance, that which might be associated with the capital goods production etc.) is disregarded Hence, the techno-economic models calculate the kWh being used per kg of algae dry matter produced based on all the electrical equipment needed.

Energy consumption is not explicitly quantified within the growth model. However, comparisons of production utilising either natural or artificial light should enable end users to make best use of natural resources. Also, considering the balance of production to pond volume (reducing de-watering requirements) and to dilution rate (minimising nutrient consumption, water usage and, hence, the electricity needed to pump the water) will allow end users to make a crude estimate of energy consumption and provide guidance as to how to minimise this while maintaining acceptable levels of production.

Energy consumption is not quantified in the GIS model.

7.4 Impact

The growth modelling part of the DST provides a robust way to calculate production of algae, in terms of its carbon biomass, and to make a realistic estimate of algal biodiesel production potential for NWE. It supplies strong evidence that growing algal solely as a feedstock for biofuels is not a viable option for NW Europe. The message should be that, if algal biofuels are to have any future, it needs to be as a part of a suite of products made by implementing an integrated biorefinery approach.

The stakeholder map improves transparency in the algae sector of NWE and provides a means for operators to raise their profile.

The GIS model shows that restrictions regarding the availability of land for microalgae production sites are crucial for the identification of potential microalgae production sites. It further shows the variability in the attributes of the potential sites, e.g. in nutrient availability and availability of infrastructure.

8 Conclusion

The EnAlgae Decision Support Toolset provides end users with access to sufficient information to enable them to make an educated evaluation of alternative technological pathways towards energy production from algal biomass. The GIS model provides information on potential microalgae production sites with a high spatial resolution and the stakeholder map enable end users to build on existing bases and to identify exploitable market place gaps. The techno-economic Dashboard models allow comparisons of pathways to commercial viability and the growth modelling tool gives guidance on how to optimise productivity. The DST has addressed some of the knowledge gaps surrounding algal biotechnology in a NW European context but has also highlighted where further developments can and need to be made. As such, the EnAlgae DST can contribute guidance for key policy decisions such as where to focus future research activities and into which technologies investment should be targeted most effectively.

If one message comes loud and clear from the EnAlgae DST it is that cultivating algae exclusively as feedstock for biofuels is not a viable strategy for NW Europe; a more promising approach appears to be in harnessing energy from algae as a co-product from an integrated biorefinery process. The DST validation process instills confidence in the reliability of the guidance provided.

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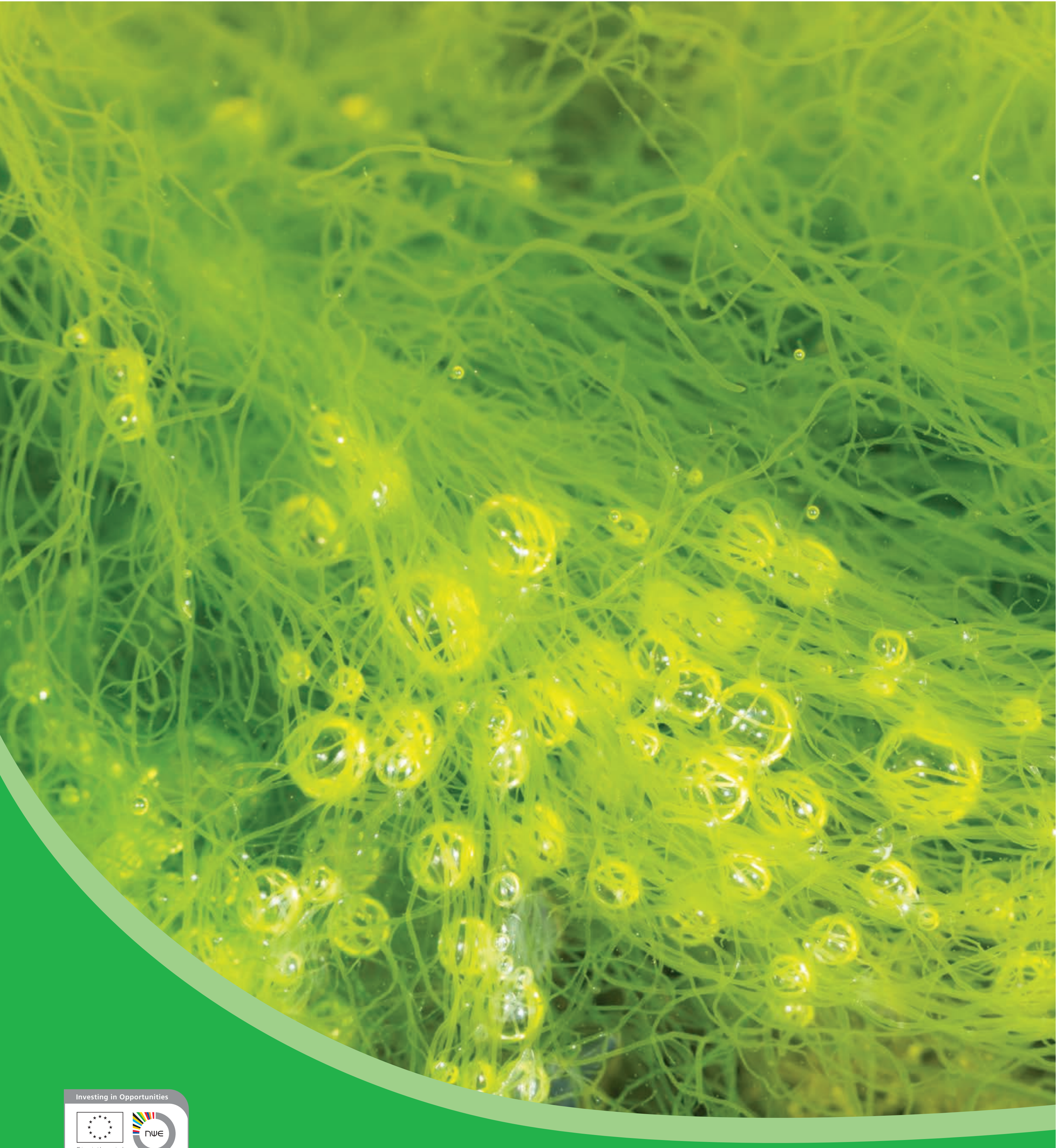

Investing in Opportunities

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EnAlgae is a four-year Strategic Initiative of the INTERREG IVB North West Europe programme. It brings together 19 partners and 14 observers across 7 EU Member States with the aim of developing sustainable technologies for algal biomass production.

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