GLOBAL RESOURCE MODELLING

OF THE

CLIMATE, LAND, ENERGY AND WATER (CLEWS) NEXUS

USING THE OPEN SOURCE ENERGY MODELLING SYSTEM (OSEMOSYS)

INTERNSHIP REPORT

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INDEX NOTE

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ABSTRACT

The development of a global model incorporating Climate, Land, Energy and Water (CLEW) parameters and interconnections was undertaken using the Open Source Energy Modelling SYStem. The model was to be a simplistic representation of the nexus systems and include the most relevant mechanisms between them. Two separate modules on land use and materials were created and combined with an already existing energy module. Water and climate parameters were added to all modules and they were combined to the global CLEWs Base model. Three scenarios were run on the separate sector modules and the combined model. Results from the comparison of the separate and combined modules indicate that the CLEW approach is applicable even on a simplistic, highly aggregated scale. Differences in resource allocation were observed when the same parameters were run in the single sector modules and in the combined base model. However, to make the model provide a representative image of global resource conditions additional data and parameters will be required.

The resulting global CLEWs model provides a wide range of potential applications and can be easily expanded. As an open source tool it could act as an educational instrument or for policy support and be adapted to different geographical boundaries and detail.

ACKNOWLEDGEMENTS

ACRONYMS AND ABBREVIATIONS

CLEWs: Climate, Land, Energy and Water strategies
CO_2:   Carbon Dioxide
EC: European Commission
EJ: Exajoule (10^{18} Joules)
FAO: Food and Agriculture Organisation of the United Nations
GAEZ: Global Agro-ecological Zones of the FAO
GHG: Greenhouse Gases
Gt: Gigaton (10^9 metric tons)
IEA: International Energy Agency
IEA ETP: Energy Technology Perspectives of the International Energy
                 Agency
IIASA: International Institute for Applied Systems Analysis
IRENA: International Renewable Energy Agency
JISEA: Joint Institute for Strategic Energy Analysis
KTH dESA: Division for Energy Systems Analysis at the Royal Institute of
                 Technology Stockholm
NPP: Net Primary Productivity (indicator for biomass production
                 potential)
OSeMOSYS: The Open-Source Energy Modelling SYStem
UNDESA: United Nations Department of Economic and Social Affairs
US EPA: United Stated Environmental Protection Agency

CONTENTS

KTH DESA

KTH dESA is the division of Energy Systems Analysis at the Royal Institute of Technology in Stockholm, Sweden. It is a relatively young division having been created in 2011 with the appointment of Prof. Mark Howells at its head. Located on KTH's central Stockholm campus the division is part of the Department of Energy Technology in the School of Industrial Engineering and Management and can draw on close ties to other research and teaching efforts in the fields of engineering, systems design, modelling and policy analysis among others.

Figure 1: Logo of the division of Energy Systems Analysis at KTH

Despite its recent establishment KTH dESA has already been able to build a strong network of institutional and industry partners on a Swedish and international level. Its associate professors Dr. Holger Rogner at the International Institute for Applied Systems Analysis (IIASA) in Vienna and Dr. Morgan Bazilian, deputy director of the Joint Institute for Strategic Energy Analysis (JISEA) at the National Renewable Energy Laboratory of the United States further strengthen dESA's international activities.

Current research projects include Multi-Resource Modelling, Climate-Land-Energy-Water Nexus strategies (CLEWs), Smart Energy Modelling, Open Source Modelling Efforts with OSeMOSYS, Accelerated African Energisation, Sustainable Energy Development and Energy Security research. Most of the projects are collaborations with one or several of the research and business partners of the division. Recent work was done for the International Renewable Energy Agency (IRENA) on African Power Pools, for the United Nations on CLEWs and for the World Bank on energy planning and sustainability, to name but a few.

The team at KTH dESA currently consists of the head of the division, two affiliate professors, three doctoral students, four researchers and several Masters students, trainees from partner institutions and research interns.

INTRODUCTION

The world is projected to have a population of 9.3 billion people by 2050 and over ten billion by 2100 (UNDESA, 2011). How will this change energy systems and markets? Currently there are still a billion people undernourished and/or without access to safe drinking water and 2.5 billion who are deprived of modern forms of energy and/or sustainable sanitation (Martin-Nagle, Howard, Wiltse, & Duncan, 2012) and that is not likely to change soon (Howells & Roehrl, 2012; Nierenberg, Hebebrand, Shapiro, Milder, & Wheeler, 2012). If sufficient policies are put in place and sustainability can be achieved for the global scale, then humanity as a whole can be "living well and within the limits of the planet". This message from the 'Vision for 2050' (WBCSD, 2010) is a call to action for a better future. However, one has to be aware that in the present "Anthropocene" human activities significantly shape the Earth System (Brito & Stafford Smith, 2012; Howells et al., n.d.). There are complex interconnections between resources, such as ground water and biomass availability, and processes such as climate change or geochemical flows (Rockström et al., 2009). Any approach to sustainability and modelling of future scenarios should take into account the most important of these interlinkages. If the objective is to avoid reaching global ecosystem tipping points that could result in a sharp increase in catastrophic events or deteriorating socio-economic resilience of society, human activities must operate within "planetary boundaries" (Downing et al., 2012; Rockström et al., 2009; Steffen, Crutzen, & McNeill, 2007).

From a sustainable development perspective, social and economic aspects are as important as environmental ones. Most importantly, the plight of the world's poor is persistent. The needs for an affordable and accessible energy supply continue to be huge in developing nations. Increasing wealth alters consumption patterns as people in these countries strive for a higher living standard, raising ethical questions on which kind of development model is to be pursued (Howells & Roehrl, 2012). Changes in resource availability could have their worst effects on poor populations (Downing et al., 2012; Hope, 2006; IEA, 2012a; WEC, 2010). Thus, extreme events' influence on poverty, food security and conflict potentials should be taken into account for the optimisation of energy systems (Ahmed, Diffenbaugh, & Hertel, 2009). On the other hand, it is important to highlight the point that providing universal access to clean and affordable energy services does not significantly increase pollution loads on the global scale of planetary boundaries. Global environmental issues are almost exclusively the consequence of "excessive" consumption of resources by a minority (Chakravarty et al., 2009; Howells & Roehrl, 2012).

THE CLEWS NEXUS

The Climate, Land, Energy and Water (CLEWs) nexus is an integrated systems approach that investigates interconnections between the different resource sectors or "silos" and tries to determine the effects changes in one silo might have on the others. The fact that CLEWs are central to development has been stated many times,

not least in the "State of the Planet Declaration" (Brito & Stafford Smith, 2012). With regard to critical thresholds or tipping points one has to be aware that changes in only one part of the Earth System can potentially affect other sectors. Bazilian et al. (2011) exemplify the Energy-Water-Food nexus and Welsch et al. (2012) show the practical possibility of including CLEWs in national policy development for the island state of Mauritius.

The effect of the energy sector on regional and global climate is virtually undisputed (IPCC, 2012). An example of how climate change and related water availability can affect the energy sector could be seen in the drought affecting large parts of the USA in 2012. As reported by National Geographic, power plants had to decrease their load or shut down due to cooling water that was too warm (Eaton, 2012). If such changes were to become permanent some plant locations would likely no longer be operable and investment decisions would change.

Despite their substantive interactions there are few experts in all four CLEW areas. Models provide an opportunity for an integrated and systematic planning approach consolidating input from various collaborators (Sieber, Zander, Verburg, & Van Ittersum, 2010). Comprehensive resource integration is often only carried out within one sector. Energy models, for example, usually take resource processes into account only as input or output factors on an aggregate level and without reconciling short-term, long-term and global objectives (Hermann et al., 2011; Hoff, 2011). Similar can be said of the land or agricultural sector. While climate change, energy and water use may be included as separate manual inputs they are rarely included in an overarching model (Edwards, Mulligan, & Marelli, 2010; Rosegrant, Msangi, Ringler, & Sulser, 2012). Models that include CLEWs and other, typically economic, indicators are often extremely complex, involve expensive software use and require specific training (Edwards et al., 2010; PBL, 2012).

MATERIALS

The original concept of CLEWs did not include any materials production. As Allwood and Cullen (2012) nicely elaborate, modern materials' life cycles have a large influence on the CLEWs sectors. The same publication also describes the main materials concerns as being resource shortages, land and water stress, by-products and large emission contributions. It makes sense to add demand changes through materials innovation (Gielen, Newman, & Patel, 2011), non-energy carbon (Weiss, Neelis, Zuidberg, & Patel, 2008) and the sector's economic importance (Değer, 2012) to the arguments for an inclusion of materials in a global CLEWs model. Up to date there was little work done on large scale and international materials analysis. A lot of the work by the International Energy Agency (IEA), the United States Environmental Protection Agency (US EPA) and others focused on collecting country level data on industry emissions, innovation or efficiency improvement and economic prospects (J. M. Allwood, Cullen, & Milford, 2010; Dittrich, Giljum, Lutter, & Polzin, 2012; IEA, 2007; US EPA, 2008). With the finished resource model it will still take grand efforts to collect reliable data for global projections on materials production and the related effects in other sectors. The benefit of such work is expected to bring great added value to related resource modelling work.

INTERCONNECTIONS BETWEEN SECTORS

The interconnections between CLEWs are manifold and indicators are often subject to several if not all sectors as was nicely illustrated for the case of land by Rogner (2010). Connections were also analysed by the Stockholm Environment Institute (Hoff, 2011) and described in a collaborative input note to a Hot-Topic-Session on CLEW strategies (Howells & Hermann, 2011).

The main interdependencies described in these sources are shown in Table 1. An extensive listing can be found in a report by the Pacific Northwest National Laboratory (Skaggs, Hibbard, Janetos, & Rice, 2012). For a sustainable development discussion many additional aspects of resources need to be considered. Examples for such are food prices and security, access to clean energy and drinking water, sanitation, ecosystem services, biodiversity and many others. A comprehensive analysis and review of scenarios for sustainable development was prepared by UNDESA for the Rio+20 conference (UNDESA, 2013). It describes the influence of assumptions and shows questions that should be asked when developing scenarios, considering the environmental, social and economic pillars of sustainability.

Table 1: Matrix of main CLEWs and materials interconnections selected from Rogner (2010), Hoff (2011), Howells & Hermann (2011)

	Climate	Land/Food	Energy	Water	Materials
Climate		Climatic changes and extreme weather affecting crop productivity and increasing water demand	Changes in energy needs for cooling & heating and effects on hydropower potential	Changes in water availability and drought or flood frequency	Changing material choices due to GHG regulation and other decision parameters
Land/Food	Emissions from land use change (vegetation and "soil carbon") and fertiliser production		Energy for water pumping, fertiliser, pesticides, machinery and transport	Increased water demand due to volatile climatic conditions and intensification of agriculture, effects on N/P cycles	Land use regulation, prices and other uses of land competing with extraction of resources
Energy	GHG emissions and air pollution from fuel combustion	Land use for biofuels and renewable energy tech. (solar, wind, hydro, ocean), crop/oil price correlation		Changes in river flow, evaporation in hydropower dams, biofuels crop irrigation, fossil fuel extraction (esp. unconventional)	Materials used in energy sector for construction, operation, transmission and distribution
Water	Changes in hydrological cycles affect local climates	Changes in water availability for agriculture and growing competition for it affect food production	Water availability for biofuels, energy use for desalination but also storage of renewable energy as fresh water		Materials needed for water sector (extraction, desalination, purification, pumping etc.)
Materials	Emissions from materials fabrication and resource extraction	Land degradation due to extraction of resources and pollution and yield increases due to fertiliser/pesticide availability	Material-embedded energy and high energy intensity of new materials	Water consumption and pollution in mining, refining and production processes	

SCOPE

The presented work describes the development of a global CLEWs model using OSeMOSYS. The model is to represent the CLEWs categories and main materials industries and allow the integration of additional, single resource categories. The interconnections are to be represented in a simple manner that nonetheless accommodates the known challenges global policy-making in these sectors faces today. As an information basis, several national and regional case studies are used. The global model should allow for the visualisation of single decision's effects not only on one sector's global market but also on the CLEWs nexus as a whole.

The results from the global model will provide comprehensive, transparent information to modellers and policy makers as it does not exist to date (Hoff, 2011). As a generic construction it is to be easily adaptable to users' specific needs. Additional data entry should be simple and the model is to be applicable to varying degrees of depth and system boundaries definitions. It should therefore improve policy decisions and be a first step towards including synergies and trade-offs of targets for sustainable development. This could mark a first step towards global sustainable development goals, taking into account "food, water and energy security, maintenance of biodiversity and ecosystem services, sustainable urbanisation, social inclusion and livelihoods, protection of seas and oceans, and sustainable consumption and production", as deemed urgently necessary in the State of the Planet Declaration in 2012 (Brito & Stafford Smith). It could also be the first step towards a new class of models that are both comprehensive in the included full range of relevant interactions and effects (Skaggs et al., 2012) and fulfil requirements in terms of transparency and accessibility.

METHODOLOGY

OSEMOSYS TOOL

The OSeMOSYS tool was chosen for its advantages in simplicity, accessibility, affordability and flexibility, making the model and its results transparent and repeatable (Howells et al., 2011). Such properties are key to the usefulness of the model, be that within the scientific community or for application in policy making (Hermann et al., 2011; Howells et al., 2011; Welsch et al., 2012). OSeMOSYS is based on a cost optimisation-principle, allowing for direct economic comparison between policy options and their environmental consequences and giving a relatively clear picture of the social implications those might have. However, cost data was difficult to obtain and aggregate at the global level. The costs were therefore not expected to be accurate or strictly representative. They should be seen merely as a tool for the optimisation of the model system and as an indication of the order of magnitude of investments for the model sections where reliable data was found. More information on the modelling system can be found on the OSeMOSYS websites (KTH, SEI, UNIDO, & IAEA, 2013; SEI & KTH, 2013) and in related publications (Howells et al., 2011; Welsch, Howells, et al., 2012).

For the initial global version three OSeMOSYS models were set up for the energy, land and materials sectors. While the energy module was taken from current work at the division for Energy Systems Analysis at KTH Stockholm (Taliotis & Howells, 2013), the land and materials modules were newly developed. The development of the two modules is discussed in detail below. An illustration of the initial CLEWs model resource system that was to be developed is shown in Figure 2. Some sections of it were later expanded as described in the designated paragraphs.
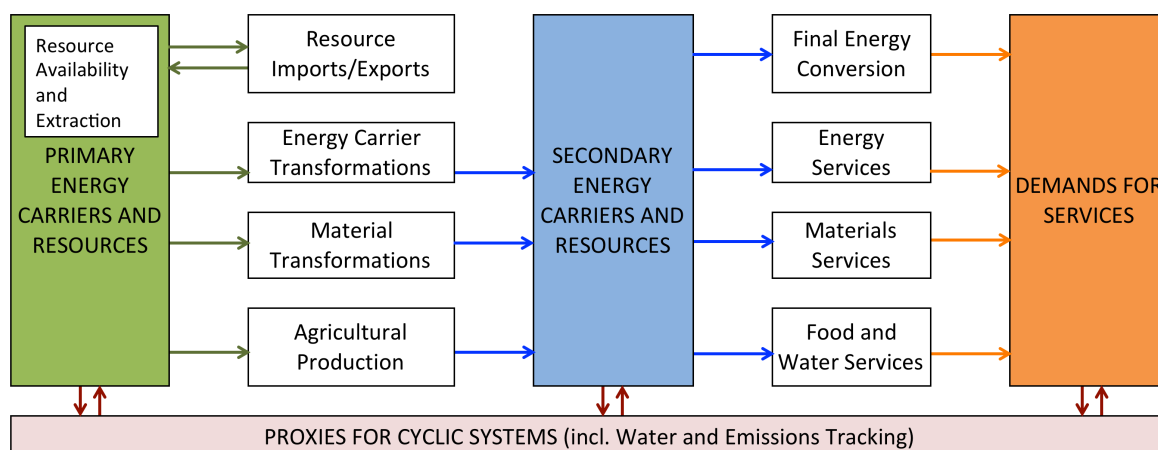

Figure 2: Simplified reference resource system for the global CLEWs model

APPROACH TO MODEL BUILDING

OSeMOSYS was developed with the aim of creating a tool for energy systems analysis that is easily understandable and expandable to other sectors (Howells et al., 2011). In the user interface currently used at KTH dESA, however, there were some restrictions as to the way constraints could be implemented. In the current version of the model land restrictions were modelled as emissions, and substitution between materials was not included. The land intensity of energy technology and materials extraction was likewise omitted. This helped concentrating the efforts on providing a base model version that can be developed according to future needs. Another measure of simplification was the inclusion of climate and water variables only as emissions. A feedback in the model from these two sectors was therefore only possible by applying emission constraints. Those represent a limited availability in the case of water and a maximum of allowed total GHG emissions. Greenhouse gas emissions could either be traced at the extraction or import stage, meaning that all fossil fuel extracted would be counted as full contribution to emissions. The second option was to add emission ratios to each conversion technology, allowing for emission ratio reductions where embodied carbon is created. For the present project the first method was chosen. Although it is less precise in tracking emissions its advantage in complexity was considered more significant. Corrections could be made at a later stage to account for embodied carbon by adding a negative emission ratio to the respective technologies.

In the initial phase the IEA's Energy Technology Perspectives (2012b) was used as a guideline to confirm realistic assumptions. The cross-sector demands were later adapted to the model values. This was of course only necessary for the separate sector modules when they were compared to the global CLEWs model.

DEVELOPMENT OF MATERIALS MODULE

Identifying Key Materials

The list of resources and materials that are critical for today's broad consumption patterns is long. While most nexus discussion has been about the four main topics of climate, energy, water and food (Hoff, 2011) recently there have been several publications underlining the importance of including other aspects of consumption and society in the discussion. The most prominent sectors among those were petrochemical products, forest products but also education, marine transport, buildings or textiles (Cullen & Allwood, 2010; IEA, 2007; US EPA, 2008). With their many applications in material production, minerals and metals are also expected to play a key role in the transition to a low carbon future (ICMM, 2012). In order to limit the model's scope six material sectors were selected for which there was reasonable assumptions of finding input data. These were aluminium, cement, iron & steel, pulp & paper, chemicals & petrochemicals and fertiliser. A simplified reference resource system for the materials module is shown in Figure B 2 in Annex B. Overall they were judged to give a good representation of structural materials, agricultural input and the largest energy consumers and GHG emitters (see previous references). Future efforts will likely want to include materials that have less weight in energy consumption but whose availability is crucial to today's demand for services. Interesting candidates are rare earths or precious metals.

To ensure that the used demand data for the materials module did not diverge strongly from industry-related energy use projections, the ETP 2012 was used (IEA, 2012b). Although the ETP data does not include non-energy feedstock, in some sectors it was challenging to consolidate different data sets. Therefore some adjustments were made that are described in more detail in the separate material sections below. In the module, all technology input and output was related to an activity of 1 Exajoule (EJ). This allows a good overview of the energy input mix from different fuel types. Consequently, the input and output ratios were not normalised to 1.

Aluminium

Data concerning the aluminium industry showed inconsistencies and contradictions in production volume and energy use. These were most likely attributable to variations in accounting of primary and secondary aluminium and to differing technical assumptions for the main production processes. A description of the bauxite mining process was found in a sustainability report by the International Aluminium Industry (IAI, 2008). An overview of the production processes was published by the IEA's Energy Technology Systems Analysis Programme (ETSAP) (IEA, 2012c), which was used for most of the cost and emissions data as well as to calibrate the aluminium production to input ratios.

The ratio of required bauxite ore per produced aluminium was taken from a study conducted by the European Commission's Joint Research Centre (Soria & Luo, 2007) as well as anode consumption data. For the energy demand the ETP 2012 projections were used, of which all coal was attributed to anode consumption. The water data was taken from a CSIRO metals review (Norgate & Iovel, 2004). The aluminium demand growth was kept at a low 0.5% annually plus the increase in energy use projected in the ETP. This resulted in values around 1% per annum and corresponded well with a consistent, moderate efficiency increase.

Cement

As for the aluminium production and demand, the cement technology was built using data from the ETP 2012 and an ETSAP fact sheet (IEA, 2010a). The direct emissions from calcination were taken from an IPCC report (Gibbs, Soyka, & Conneely, 2001) and the water consumption and energy intensity from a cement industry overview for the United Kingdom (UK EA, 2005).

Fertiliser

The production of fertiliser was to include several resources. Firstly, it was to include the energy intensive production of ammonia and its related emissions. Secondly, the use of mineral resources was to be included. For that reason, the ammonia production was singled out from other petrochemical products and represented as a separate technology. The ammonia was then used in a mixing technology that produced a standard fertiliser with an N:P:K ratio of [0.24:0.07:0.03](IEA, 2004). These values were converted into mixing values of $NH_3:P_2O_5:K_2O$, giving a ratio of [1:0.52:0.12]. The capital costs and global fertiliser consumption were taken from a Dutch industry study (Gerlagh & Van Dril, 1999) while water data was taken from a report on fertiliser production guidelines (IFC, 2007).

Ammonia production data was taken from Sukumaran Nair (2006) for the energy intensity, from the ETP 2012 for the energy consumption and from an ammonia report by the International Fertilizer Industry Association (IFA, 2009) for efficiency projections.

Iron and Steel

The iron and steel production required the consolidation of different products and processes in an aggregated global technology. Therefore the dominant technologies, namely blast furnace and basic oxygen furnace were used for production data. The main data sources were again the ETP 2012 and an ETSAP Technology Brief (IEA, 2010b). In addition, an efficiency improvement of 10% over the model period was assumed, corresponding to an annual 0.25%. While the emissions from fuel use were accounted for in the extraction technologies, the water consumption was taken from a CSIRO metals review (Norgate & Iovel, 2004).

Pulp and Paper

The pulp and paper sector posed several challenges in terms of data collection. Since many facilities operate their own combined heat and power stations they often only report external energy consumption. By-products of the manufacturing process can be used to cover part of the heat and power requirements of the plant, however. This creates a misrepresentation in terms of energy requirements and efficiency in

many cases and makes it difficult to separate wood feedstock from fuel wood use. For the current version of the module, most data was once more taken from the ETP 2012. For the demand projections FAO data was used (FAO, 2009).

To determine the right biomass feedstock ratio the ETP 2012 data was compared to the FORESTAT online database (FAO, 2013a) and to Ragauskas et al. (2005) and adjusted accordingly. As electricity was assumed not to be used for heat production it was accounted apart from the other fuels, resulting in similar values as reported by Gielen and Tam (2006). A significant environmental impact of the pulp and paper industry is water consumption and pollution (US EPA, 2008). Both have decreased significantly in developed countries. For the global aggregation of water use a high estimate from METSO (METSO Global, 2009) was used in the base year declining to half its value by 2050. This assumption was made while being aware of large differences between paper production regions, paper products and the considered production stages and will only give a general idea of the magnitude of the actual water consumption.

Petrochemicals

This sector brought forth the challenge of using energy sources as its only feedstock. It was to be expected that the global demand statistics would not match the ETP 2012 energy use since feedstock is generally not part of the ETP data. When the extra feedstock was added, however, the total fuel consumption exceeded data on fossil fuel consumption. As a consequence some of the feedstock fuel must be included in the ETP calculations. Even the lowest reasonable assumptions for feedstock use from Weiss et al. (2008), however, resulted in higher feedstock use than the oil-based energy use reported in the ETP. Finally, the total petrochemicals energy use including feedstock was taken from Saygin et al. (2009). The ETP energy use was subtracted from that value to give the feedstock required in addition to the ETP amounts. This resulted in an energy use in the petrochemicals sector that was slightly higher than the global IEA data but was seen as the best compromise for the current model version.

After subtracting the ammonium energy use and the just described issue, the main energy data for the petrochemicals sector was the ETP 2012. Water use data was taken from Visser & Appelmann (2009), assuming a similar water consumption in the industry sector as was reported for the refinery stage.

The chemicals and petrochemicals sector with its up to 60% feedstock use of energy input (CEFIC, 2012) represents a sector with high carbon and energy content of its products. For future model extensions it was therefore seen as important to distinguish between direct (combustion-related) and indirect (non-energy or incorporated) emissions for this sector. Similar could of course be said of other materials sectors where recycling is much less energy intensive than primary production (such as for aluminium).

DEVELOPMENT OF LAND MODULE

Including land use in the CLEWs discussion is essential not only due to its importance for humanity in terms of food production. Land use change related to agriculture is also responsible for more than 30% of GHG emissions (FAO, 2011) and has wide-ranging effects on biodiversity and surface water quality among other cross-sector connections (Giovanucci et al., 2012; Ramankutty, Evan, Monfreda, & Foley, 2008).

Choice of land categories

To aggregate the different land types with respective yields, water and current land use in the simplest sensible way the global available land was divided in several categories. The land categories were to be different mainly in climate condition. Additionally, it was decided to rate the current agricultural land according to how much yields would improve if the land were irrigated. Such categories would later allow the model to irrigate first those land areas that bring the highest yield increase. While the agricultural land was divided by country (FAO data) and each country data then assigned to a climate region, forests were aggregated as one single global region. This simplification was made mainly due to time constraints in the development of the model. A simplified version of the agricultural sector is shown in Figure B 1 of Annex B.

As agricultural land categories three climate regions were chosen according to a climate map from Peel et al. (2007); cold/arctic climate, temperate climate and subtropical/tropical climate. Within each climate type four yield-based categories were selected. Firstly, a category for rain-fed agriculture with the yield expected for its climate. Secondly, three irrigated agriculture types each representing a different yield improvement with irrigation. The distinction between irrigated land types was made to allow the allocation of new land to the category best representing it. A second distinction between the first and the other three (irrigated) land types was the agriculture intensity as described in the following section.

Fertiliser, irrigation and used land area

Temperature regimes as well as nutrient and water availability are the main external factors affecting crop yield. Less easily quantified ones are pollinator dependence, biodiversity or crop improvements (FAO, 2011). In addition to the first-mentioned climate criteria nutrient availability and irrigation were included as agriculture intensity distinction. An example for high-intensity agriculture was found in Nebraska corn production in the USA (Grassini & Cassman, 2012), giving the energy and fertiliser use per hectare. Since the energy mix used in agriculture in the USA differs significantly from global values the single fuel uses were adapted to the global agriculture fuel mix reported by the OECD iLibrary. These energy inputs include pumping for irrigation and the water requirements were adjusted for each land type. For low-intensity agriculture without irrigation only one tenth of the fertiliser and machinery use were assumed and no other fuel inputs. The yield or biomass output ratio for land was assumed to rise by 1% annually. This assumption was made expecting lower yield growth than were seen in the last decades. For comparison, the FAO has reported an annual yield growth of 1.3% for the world for the years 1997-2007 (FAO, 2011). The water use of rain-fed agriculture (green water) was not included in the current model. For the estimation of irrigation water requirements

several case studies for climatic regions were used (AgriInfo, 2011; Schreier et al., 2008; Wriedt, Van der Velde, Aloe, & Bouraoui, 2009).

Land representation and data

The Global Agro-Ecological Zones (GAEZ) database version 3.0 was used to obtain land cover, productivity and irrigation potential data (IIASA & FAO, 2010). Countries were first assigned to their respective climate category. In a second step, their current rain-fed agricultural Net Primary Productivity (NPP) was compared to the irrigated NPP of the same land. The difference between the rain-fed and irrigated NPP determined whether the country was considered as having a low, medium or high irrigation potential. Low irrigation potential meant increases of 0-25%, while medium and high meant improvements of 26-100% and >100%, respectively. A list showing the classification of the FAO country data can be seen in Appendix A. The current rain-fed agricultural land in each country was counted as low-intensity agriculture. Current irrigated land was counted as high-intensity agriculture and assigned to the country's respective yield category. The expected yield for low-intensity land was assumed as the low yield estimate from a biofuels report by the Worldwatch Institute (2007). High-intensity yields were assumed to be 110%, 175% and 200% of the low-intensity yield for low, medium and high irrigation potential, respectively as indicated by the abovementioned NPP improvements. Table 2 shows an overview of the land categories.

Table 2: Land categorisation overview including 2010 output ratio (yield) and water requirements for irrigation

Technology name	Climate category	Irrigation potential category	Yield 2010 (EJ/mio ha)	Irrigation requirement (Gt/mio ha)
L1	Cold/Arctic	-	0.067	0
L121	Cold/Arctic	Low	0.073	0.5
L122	Cold/Arctic	Medium	0.116	0.75
L123	Cold/Arctic	High	0.133	1
L2	Temperate	-	0.152	0
L221	Temperate	Low	0.167	1.5
L222	Temperate	Medium	0.266	5
L223	Temperate	High	0.304	10
L3	Hot/Tropical	-	0.228	0
L321	Hot/Tropical	Low	0.251	2
L322	Hot/Tropical	Medium	0.399	5
L333	Hot/Tropical	High	0.456	11
L4	Forests	-	0.106	0

For forest products a separate land category was created. The forest production was assumed to be without any fertiliser or irrigation input. Mechanical work required for harvesting was already included in the motion demand in the energy sector.

All land used in the base year was assumed to linearly decline by 20% to the year 2050 due to land degradation and build-up. Current used land was treated as residual capacity. For the minimum annual activity of each category an annual decrease of 4% from the 2010 residual capacity was found reasonable with regard to historical World Bank data. This value is double the historically reported land use

increases, representing an upper limit estimate (World Bank, 2013). The maximum new land area was assumed as the lost area through degradation plus the capacity to replace all historical capacity by 2050 (linearly adding up to 100% by 2050). An additional capacity constraint was the historical capacity plus all current grass- and woodland. This available new capacity was distributed evenly among the four land types in each climate zone. The forest category was not given any new capacity, representing current forest conservation efforts. This may have to be changed in a later version to follow evident reforestation trends (Rautiainen, Wernick, Waggoner, Ausubel, & Kauppi, 2011).

Biomass conversion

The GAEZ unit for Net Primary Production was not clearly stated in its Model Documentation (IIASA/FAO, 2012). Therefore, the biomass yield estimated from Worldwatch Institute report data (2007) was 3.5-24 dry t/ha at a related energy content of 19GJ/dry ton. This resulted in an energy yield given per area for each land type. The output biomass then needed converting to useful fuels. As food categories, vegetarian food (VFOO) and meat/animal product foods (MFOO) were used. The conversion ratio from biomass to VFOO was assumed as 6.568 and for MFOO as ten times that, 65.68. These ratios were deducted from the assumption that all agricultural product is used for food production and from UN population and caloric food production data (FAO, 2013b; UNDESA, 2011).

In addition to food production the model was to include biofuels, fuel wood and paper feedstock. All these uses were combined in one fuel called BIOW. Biomass from forests was only used as BIOW while the BIOW demand that was not met by forests was assumed to come from agriculture. The BIOW output ratios from VFOO and MFOO conversion were assumed to be 0.461 and 4.61, respectively representing by-products, animal waste and food waste used for some combustion technologies.

COMBINATION OF THE THREE MODULES

After completing the separate sectors, the modules were combined and evaluated as a global CLEWs model. In this first stage the interconnections implemented were few. Dummy technologies that imitated another resource sector were removed and exogenous demands were only kept where they represented final service or material demands. The interconnections represented dynamically in the global model are:

- Heat and electricity use of all sectors (met by energy module)
- Biomass and food demands (met by land module)
- Water use (represented as a global constraint)
- Greenhouse gas emissions (represented as a global constraint)
- Fertiliser demand (met by energy and materials modules)

As mentioned earlier the focus of the global CLEWs model was the development of a compact and easily understandable tool. As every new interconnection or externality has consequences on the complexity and the computing power required the selection was done carefully. However, post ex evaluation of results for further analysis should be possible to look at additional effects.

SCENARIO BUILDING

The scenarios were used to illustrate the usefulness of the model and show its responses to additional constraints and altered conditions. The additional parameters from the CO_2 tax and land cost scenario were added to the land use limitation scenario as well. Combining the scenario parameters was done to start developing model conditions that would move in the direction of sustainable development options, climate change mitigation and the Planetary Boundaries discussion (Howells & Roehrl, 2012; Rockström et al., 2009).

CO_2 tax and land cost scenario

Emission trading schemes and taxes exist in many parts of the world and are an integral part of international agreements such as the Kyoto Protocol (Bodansky, 2011; Klepper, 2011; Leung, Yung, Ng, Leung, & Chan, 2009). As a first additional constraint to test the base model response a tax on CO_2 emissions was added since all emissions are represented in CO_2-equivalents. This tax was assumed to enter into force in 2016 and to linearly increase from an initial price of 1 US\$/tCO_{2EQ} to 15 US\$/tCO_{2EQ} in 2030 and 25 US\$/tCO_{2EQ} in 2050. For land use change a compromise had to be made since the model interface used did not allow area-dependent emissions accounting. The operational life of agricultural land was therefore estimated at five years and the emissions tax was converted into a capital cost. The emissions from land use change were estimated according to Hermann et al. (2012) and then divided by five to account for the increased operational life. The resulting values are not expected to accurately represent land use change emissions but are more likely to reflect a cost dimension in land use in general.

Water cost scenario

Freshwater demand is a sensitive issue especially in many arid developing countries and future water availability is estimated to become more uncertain with climate change (UNEP, 2012). To model growing costs of water provision for industrial, agricultural and energy-related uses a water price was introduced to the model. Break-even price for thermal electric power plants in the USA was reported at 0.137US$/t of freshwater by Walker (2012). A sensitivity analysis showed that significant changes only occurred if this value was doubled. It should be kept in mind that little impact was expected in the land and materials sectors due to their low production flexibility. The sensitivity analysis was therefore concentrating on the energy sector's water use.

Land use limitation scenario

Nearly 40% of the world's ice-free land is already used for agriculture and pasture resulting in immense environmental challenges (Ramankutty et al., 2008). Rockström et al. (2009) suggest the planetary boundary for agricultural land to be between 15-20% of that. It was therefore seen as a good scenario condition to impose an absolute restriction on land use by not allowing any new land to be dedicated to agriculture. Although degraded land capacity could be replaced this would likely require significant intensification efforts.

To allow limiting the used land area an additional emission called "AREA" was added to the land technologies of each climate zone. These emissions (AREA1, AREA2, AREA3) would represent the used land and be constrained by an emission cap. The cap was determined using the climate zone split of today's agricultural land that was described in the section "Land representation and data" of this report.

RESULTS AND DISCUSSION

LESSONS FROM DATA COLLECTION

The nexus sectors have been analysed in many models and most data was found relatively easily. While it was considered important to first define the model type and then specifically look for the required data, this was made virtually impossible by the rapidly changing requirements as the model evolved. In some cases the model could not be implemented as desired because of a lack of the required data. This was especially the case in the least explored sector on materials industries. Databases on material energy intensity exist but are often quite expensive. The materials sector was also the most difficult in terms of aggregation of data. A wide variety of products and production techniques should be taken into account while only partial demand and technical data was found. The extensive literature and large number of data sources also created the problem of conflicting information. In the land and energy sectors it was possible to largely concentrate on one data source, namely the IEA and FAO. For the interconnections and the materials sector, however, a comprehensive review including technical, production and demand data on a global level was not found. MacKay (2009) and Allwood & Cullen (2012) likely show the most comprehensive analyses but had to be supplemented with less reliable data from industry sources or from single country case studies.

LESSONS FROM MODEL DEVELOPMENT

Using the OSeMOSYS tool proved a good choice in terms of allowing the base model version room for future adaptation. The help of a user interface was much appreciated although it caused limitations on sector interconnections that will need to be dealt with in coming versions. Much of the preparation for better integration of the sectors was done but could not be included in the current model version due to time constraints. In the case of water it became clear that its representation in the base model was not sufficient. To be able to include the technical parameters that connect the water sector to land use and energy it would need treating in more detail. In its current version the base model is an ideal educational tool to investigate resource relations and its simplicity allows for quick learning of the involved parameters.

Some of the limitations of the base model were a direct consequence of using relatively slow open source software. Although the OSeMOSYS code was updated during the course of the project it remains an open discussion as to which compilers should be used for larger versions in the future.

For the development of the model a comprehensive energy sector module developed simultaneously at KTH dESA by Constantinos Taliotis was used. Its simplified reference resource system is displayed in Figure B 3 in Annex B. Thanks to Constantinos Taliotis' experience from previous projects and energy modelling the resulting energy module became reliable and more detailed than the other sectors.

Separating the tasks in this way made sure that problems could be discussed as they appeared and that connections were implemented correctly.

BASE MODEL DESCRIPTION

In this section a selection of results from the base model are shown. They give an insight into the completed work and provide indicative results on the usefulness of the CLEWs approach. These results should not be seen as detailed projections but rather as a first, coarse model run's output. Nonetheless they show the considerable potential of the model. In the subsequent scenario discussion this is made even clearer as additional constraints impact the entire CLEWs nexus.

As an illustration of the materials sector Figure 3 shows the energy consumption in the materials sectors included in the model. The included materials represent around 60% of global industrial energy use (Değer, 2012). Projections from different sources foresee a growth in industrial energy consumption from 90EJ to around 130EJ in 2050. As of now the model does not include substitution options between the material demands. This means that there are no shifts in production and the demands follow the ETP 2012. A potential substitution between steel and aluminium was investigated but no literature was found that gives estimations for it.
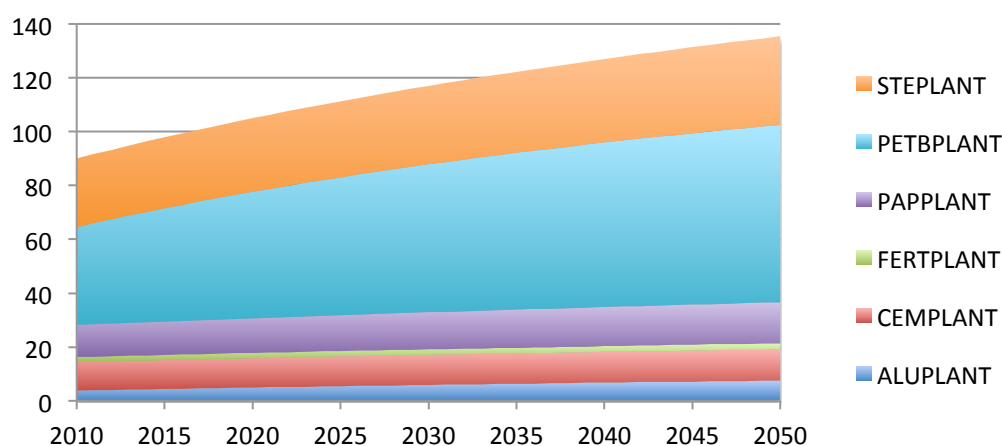

Figure 3: Materials BASE module; Energy consumption in the six included materials industries in ExaJoule (EJ)

Agriculture represents around 70% of global freshwater withdrawal (FAO, 2010) while municipal and industrial uses account for around 10% and 20%, respectively. Figure 4 shows the water use for the represented energy and materials technologies and "other industry", assuming that the represented industry sectors (materials plus non-hydro energy) make up roughly a third of total industrial water demand when compared to data from AQUASTAT (FAO, 2010). As displayed in Figure 4 water losses in hydropower shows the largest contribution due to evaporation in storage basins. The industrial sectors with the largest contributions are coal plants and iron and steel fabrication.
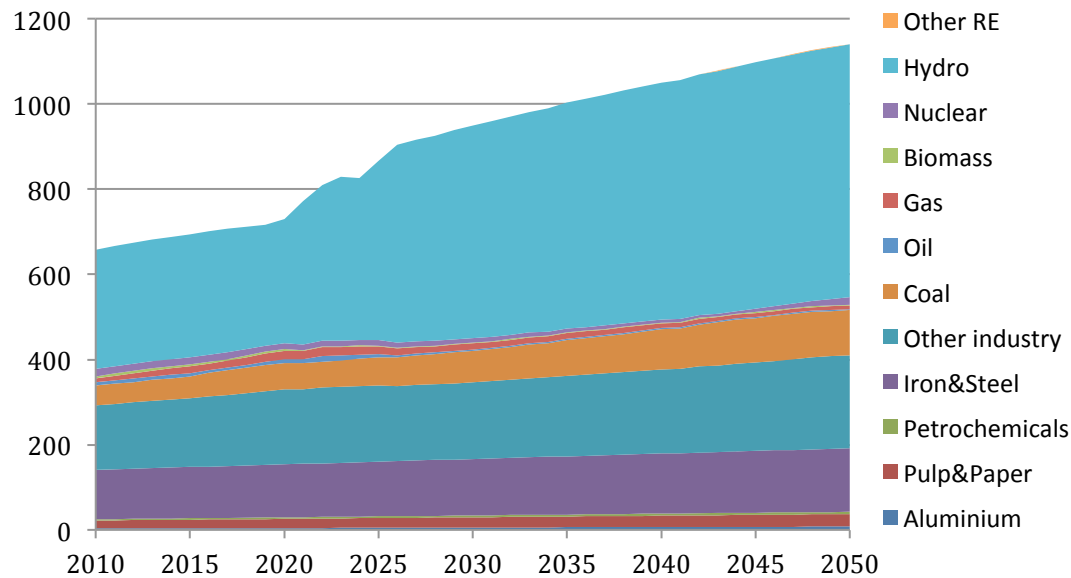
Figure 4: Global CLEWS BASE model: Water demand of the energy and materials sectors in Gt or km^3

In the base model there are very few restrictions in the land sector. The total land used cannot exceed the areas described in the methodology section and the expansion rate is kept at a maximum 4% annually. Although the biomass demands for non-food uses such as paper fabrication and biofuels were taken from the respective modules there is a distinct difference between the land sector module and the CLEWs model. Results for both for the different land categories are shown in Figure 5. The comparison shows that when considering the CLEWs interconnections, even at as simplified a level as in the present model, resource decisions vary. Similar can be said of the primary energy demand shown in Figure 6. Including the land sector allows for more continuous biomass use in the CLEWs model than the separate energy module calculates. This is in part because of biomass capacity being relatively stable and the availability of by-products from food production – which come at no additional resource input cost.
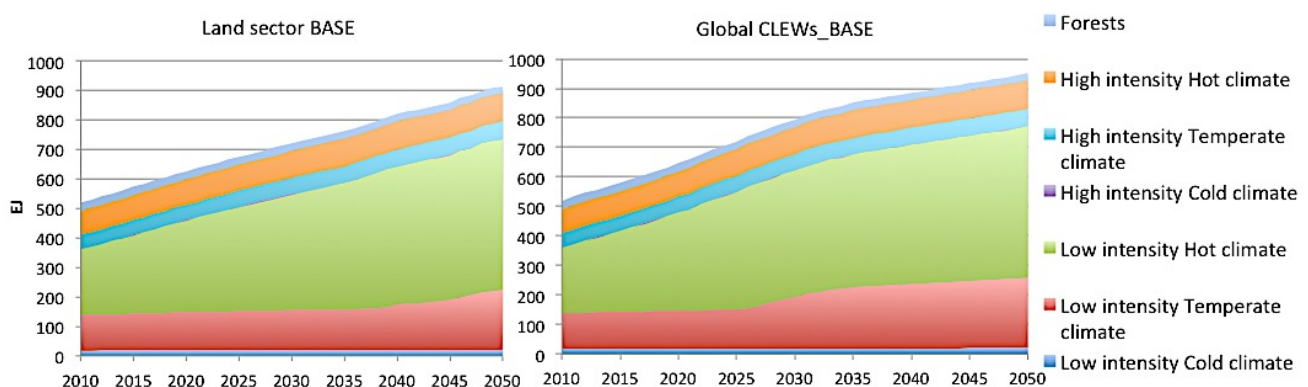

Figure 5: Biomass production from different climate and agriculture intensity land types. The left shows the output from the separate land module while the right shows the global CLEWs model output for the BASE model
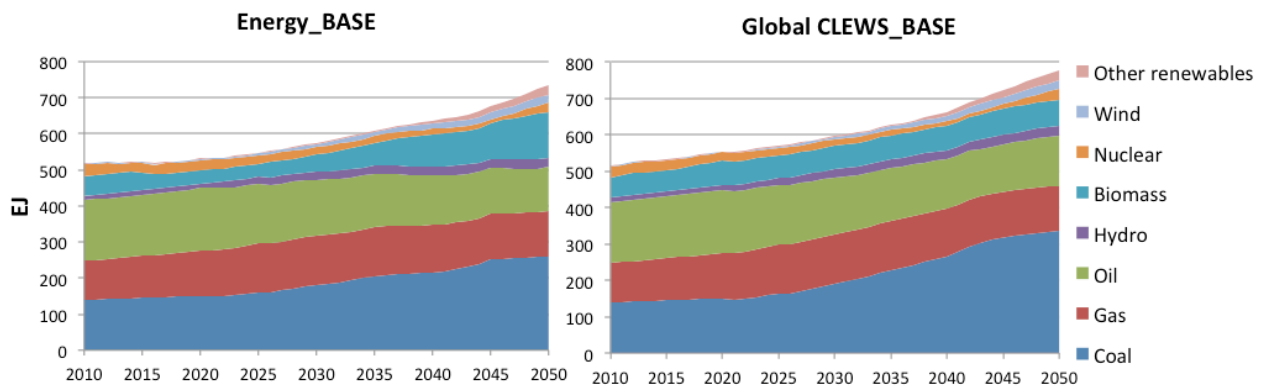
Figure 6: Primary Energy Supply for the separate energy module on the left and for the global CLEWs model on the right, both BASE model outputs

On the other hand this also means that when the nexus is considered, future biomass for non-food uses might be more limited. In the CLEWs case, biomass contribution to primary energy supply does not increase strongly, which is compensated by more investment especially in coal.

OUTPUT FROM SCENARIOS

CO$_2$ tax and land cost scenario

An example for output data from the Base model and the CO$_2$ tax scenario is given in Figure 7, displaying the power generated for the two cases. As is to be expected when emission costs are introduced the most CO2 intensive generation technology produces less, in this case power from coal. In the earlier model years up until around 2030 this lower coal production is balanced by larger investments in hydro and especially gas power. After 2030 significantly higher generation from biomass, nuclear and wind resulted in relation to the Base model output. The results are an indication that for most technologies the emissions tax only reaches a significant cost when it surpasses 15US$/tCO$_{2EQ}$.
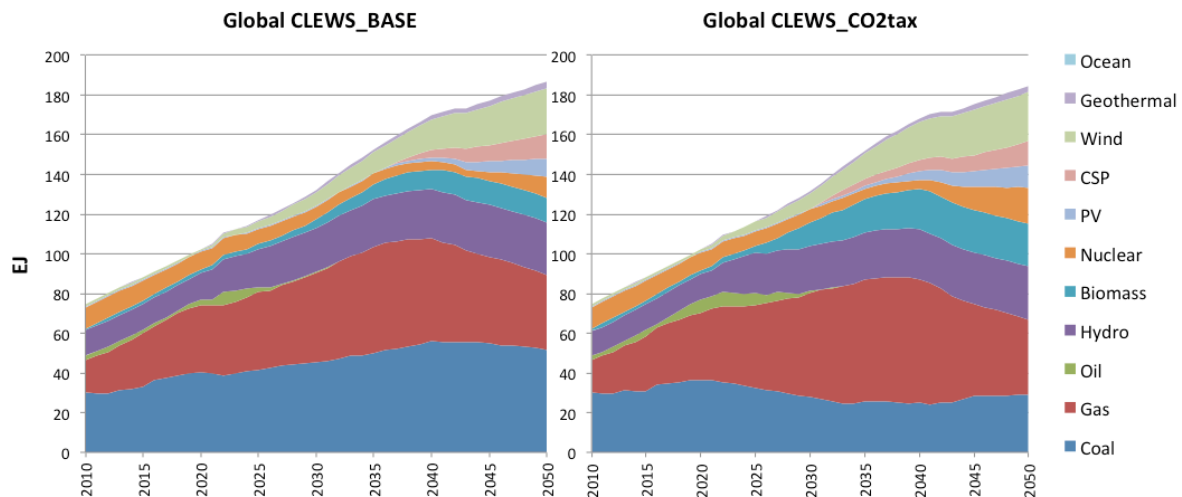
Figure 7: Power Generation for the BASE model and the CO2 tax scenario. Generated power is given in EJ.

These model outputs do not accurately reflect a systems response since many parameters, such as land use for wind and solar power, are not included yet. These factors likely play a game-changing role in the support especially for renewable energy technologies and an investigation into these factors is planned for the near future. Even more interesting, however, are the differences seen between the energy sector module and the CLEWs model. The separate energy module predicted a continuous decrease of coal and more nuclear power while the CLEWs model calculated a larger share of biomass power and even a slight increase in coal power after 2040. Such large differences in predicted power generation may be due to a better feedback of inter-sector demand changes in the CLEWs model.
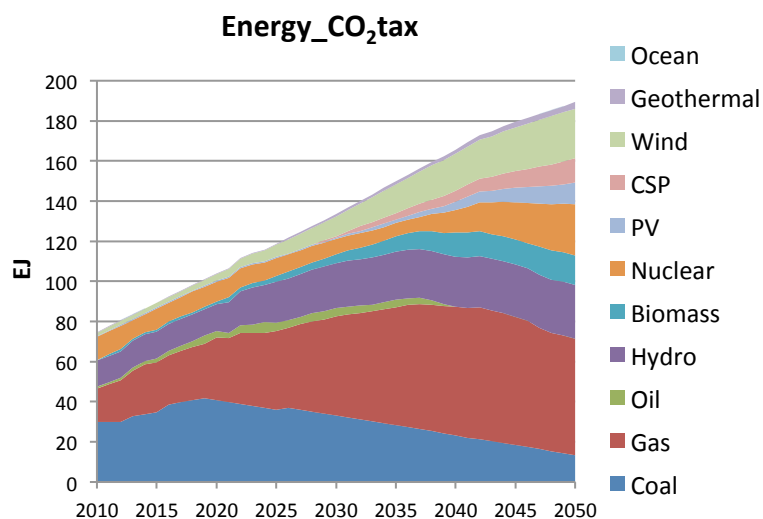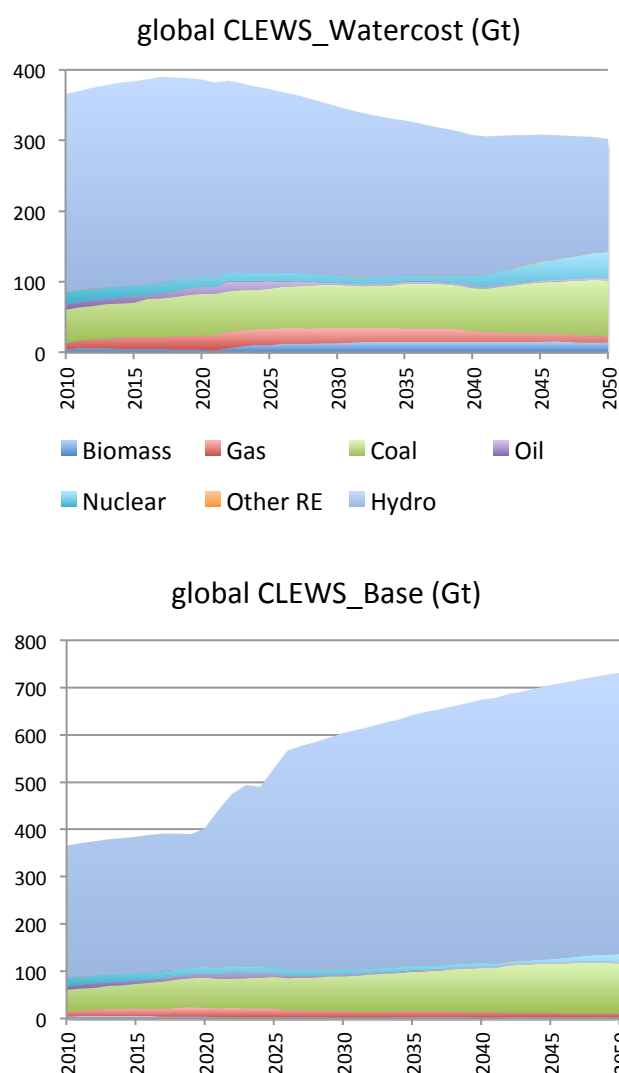

Figure 8: Power Generation mix from the separate Energy module with the same parameters as the CO$_2$ tax and land cost scenario

Water costs scenario

Cost assumptions for freshwater use of 0.274US$/t were predicted as double the break-even costs for using recycled water in thermal power plants (Walker, 2012). This value surpassed the sensitivity threshold of hydropower production as is illustrated in the water consumption change from the Base to the Water Cost scenario in Figure 9. The remainder of the power production was only slightly affected. Water losses by evaporation in storage dams, industrial and municipal water uses and irrigation requirements are subject to fundamentally different value systems. Using one single cost value was evidently not ideal. The approach of an overall water cost value might still find applications where processes are more similar. The results from the water cost scenario made it clear that for a useful representation of the water sector more detail would be required. The different types of water use would need to be looked at separately, answering the question of what sustainable water allocation to different users is among others (Johansson, Tsur, Roe, Doukkali, & Dinar, 2002).

global CLEWS_Watercost (Gt)

Legend: Biomass, Gas, Coal, Oil, Nuclear, Other RE, Hydro

global CLEWS_Base (Gt)

Figure 9: Water consumption in the energy sector for the global CLEWs Base model (bottom) and the Water Costs scenario (top). Water consumption is given in Gt.

Land use limitation scenario

Ausubel et al. (2012) suggest that peaks will be reached for other resources than fossil fuels and that the expansion of land for agriculture has already halted. This means higher yields from crop improvement and the intensification of land use in addition to slowing population growth. In the land limitation scenario the additional demands for food, energy and materials needed to be met by just these means. Since yield increases were assumed at 1% annually they could not meet them entirely. In the base module and CO_2 scenario all new production capacity was created in the tropical and temperate low-intensity land type. Given that the maximum land used in those scenarios included all current pasture and grasslands

and there were no land costs included this result was to be expected. The land use limitation scenario, on the other hand, included land costs (related to estimated CO_2 emissions from land use change) and no new land capacity was allowed. When the power generation results shown in Figure 10 are compared to the CO_2 tax scenario results in Figure 7 these conditions are immediately apparent. Biomass power production is strongly reduced and entirely replaced by nuclear power. The incentives for a greater use of biofuels from emissions taxes were entirely eradicated by the costs for agricultural input in the form of fertiliser, fuels and electricity. Instead, nuclear power takes over its role as a lo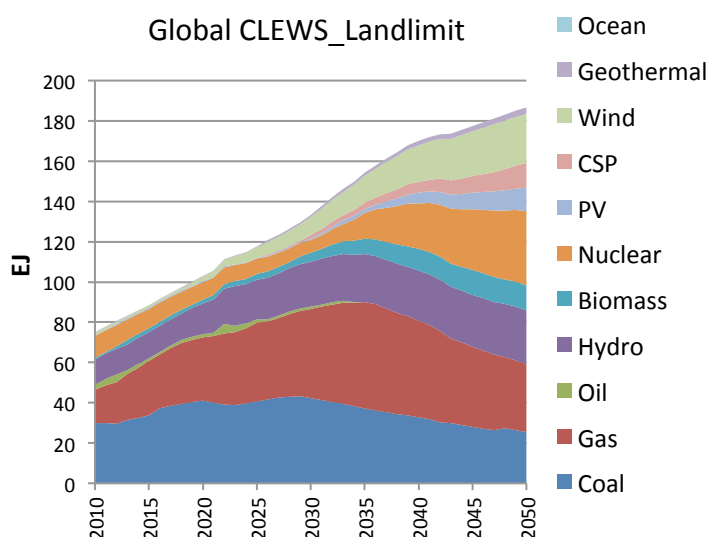w-carbon generation technology. Of course the actual resource systems concerning land use limitations are much more complex. Changes in yield increase, the potential of genetically modified crops, wood fuel availability due to reforestation, uranium mining and nuclear waste storage and many other aspects are not addressed in this model. It would be interesting to add such parameters step by step to observe changes in the model's optimisation in future work.

Figure 10: Power generated in the global CLEWs Land Limitation scenario that includes the CO_2 tax and land cost parameters from the first scenario

Implications of the results

The selected results presented here give an indicative view of climate-water-energy relations. Although still in an early stage of development the presented model can be a useful tool both in education and policy development. In the base model version the main resource sectors are mirrored accurately. Future studies on the model can evaluate the thresholds for policy effects as they appear in the overall CLEWs nexus. When comparing the single sector modules to the CLEWs model versions distinct differences were observed. Even though both input data and the applied constraints were at the highest aggregation level the CLEWs approach showed effects between the sectors that had not been anticipated by the separate modules.

CONCLUSIONS

In the current model version each sector module accurately describes the resource and demand projections until the year 2050 in comparison with mainly IEA and FAO projections. The global CLEWs model combined these sectors and provides a dynamic representation of resource activities from extraction to conversions and final services. The interconnections and global variable constraints allow for a first estimation of dependencies and trade-offs and can be further developed in the future. Some of the limitations to the model originate in the user interface that was used for this project. The expansion of its functions or a hybrid use of interface and text file format would be necessary to further improve the model.

The results from BASE model and scenario runs indicate that the CLEW strategies approach is useful both at a global scale and with strongly aggregated input data. Effects of emission taxes, land use limitations and water pricing were shown. All had a distinct effect on the resources concerned.

FUTURE WORK

While the current version of the global CLEWs model and its separate modules present a good starting point its usefulness is limited. The next steps, however, have already been prepared and will be implemented after the finalisation of this project. Immediately following steps include the addition of land use for solar and wind power facilities as well as large hydropower. Additionally material demands will be added to the construction of material and energy production sites.

After several climate change scenarios are run the work will need to focus on the developmental aspects of resource modelling. Using mostly post-ex calculations it will be attempted to give some indications on which CLEWs and materials interconnections are recommended for consideration.

Another potential application of the base model is a focus on regions. Splitting the world in regional entities would allow trade flows to be studied. Other factors like virtual water and emissions could also be investigated. A more localised database would make the model more representative for resources that are geographically distinct, such as water availability.

In the following weeks the entire database and the model itself will be published online in an energy assessment wiki that is currently under development by the World Bank. Using the wiki as a collaboration tool, experts from the different CLEWs sectors will be asked to contribute data and collaborate in further analyses. The open source collaboration will then be able to contribute to the discussion on sustainability, development and resilience in the broader scientific community.

REFERENCES

AgriInfo. (2011). Water Requirement and Irrigation Requirement. *My Agriculture Information Bank*. Retrieved June 17, 2013, from http://www.agriinfo.in/

Ahmed, S. a, Diffenbaugh, N. S., & Hertel, T. W. (2009). Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, *4*(3), 034004. doi:10.1088/1748-9326/4/3/034004

Allwood, J., & Cullen, J. (2012). *Sustainable Materials: With both eyes open* (C.). Cambridge, UK: UIT. Retrieved from http://publications.eng.cam.ac.uk/400536/

Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environmental science & technology*, *44*(6), 1888–94. doi:10.1021/es902909k

Ausubel, J. H., Wernick, I. K., & Waggoner, P. E. (2012). Peak Farmland and the Prospect for Land Sparing. *Population and Development Review 38 (Supplement)*, *8*, 221–242.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., et al. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, *39*(12), 7896–7906. doi:10.1016/j.enpol.2011.09.039

Bodansky, D. (2011). W[h]ither the Kyoto Protocol ? Durban and Beyond. *Harvard Project on Climate Agreements - Viewpoints* (Vol. 1, pp. 1–12). Belfer Center.

Brito, L., & Stafford Smith, M. (2012). State of the Planet Declaration. *Planet Under Pressure conference*. London, UK: Earth System Science Partnership.

CEFIC. (2012). *Facts and Figures 2012 - The European chemicals industry in a worldwide perspective*. Brussels, BE.

Chakravarty, S., Chikkatur, A., De Coninck, H., Pacala, S., Socolow, R., & Tavoni, M. (2009). Sharing global CO2 emission reductions among one billion high emitters. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(29), 11884–8. doi:10.1073/pnas.0905232106

Cullen, J. M., & Allwood, J. M. (2010). The efficient use of energy: Tracing the global flow of energy from fuel to service. *Energy Policy*, *38*(1), 75–81. doi:10.1016/j.enpol.2009.08.054

Değer, S. (2012). *Assessing industrial energy use and CO2 emissions - Opportunities for energy efficiency, biomass and CCS*. Utrecht University.

Dittrich, M., Giljum, S., Lutter, S., & Polzin, C. (2012). *Green economies around the world? Implications of resource use for development and the environment*. Vienna, Austria.

Downing, T. E., Butterfield, R. E., Hope, C., Hunt, A., Mathur, V., Matin, N., Taylor, R., et al. (2012). *Technical Policy Briefing Note 7: Extreme Outcomes*. Oxford, UK.

Eaton, J. (2012). Record Heat, Drought Pose Problems for U.S. Electric Power. *National Geographic News*. Retrieved January 29, 2013, from http://news.nationalgeographic.com/news/energy/2012/08/120817-record-heat-drought-pose-problems-for-electric-power-grid/

Edwards, R., Mulligan, D., & Marelli, L. (2010). Indirect land use change from increased biofuels demand. *JRC Scientific and Technica Reports*. doi:10.2788/54137

FAO. (2009). *State of the World's Forests* (pp. 62–96). Rome.

FAO. (2010). AQUASTAT. Rome. Retrieved from http://www.fao.org/nr/aquastat

FAO. (2011). *LOOKING AHEAD IN WORLD FOOD AND AGRICULTURE: Perspectives to 2050*. (P. Conforti, Ed.). Rome: Food and Agriculture Organization of the United Nations.

FAO. (2013a). FAOSTAT. *Food and Agriculture Statistics*. Retrieved June 17, 2013, from http://faostat.fao.org/

FAO. (2013b). Food Balance Sheets. *FAOSTAT*. Retrieved May 21, 2013, from http://faostat3.fao.org/

Gerlagh, T., & Van Dril, A. W. N. (1999). The fertiliser industry and its energy use: prospects for the Dutch Energy Intensive Industry. *ECN Policy Studies*. Amsterdam, NL.

Gibbs, M. J., Soyka, P., & Conneely, D. (2001). CO2 Emissions from Cement Production. Geneva, Switzerland.

Gielen, D., Newman, J., & Patel, M. K. (2011). Reducing Industrial Energy Use and CO2 Emissions: The Role of Materials Science. *MRS Bulletin*, *33*(04), 471–477. doi:10.1557/mrs2008.92

Gielen, D., & Tam, C. (2006). Energy Use, Technologies and CO2 Emissions in the the Pulp and Paper Industry. Paris, France.

Giovanucci, D., Scherr, S., Nierenberg, D., Hebebrand, C., Shapiro, J., Milder, J., & Wheeler, K. (2012). *Food and Agriculture: The future of sustainability. A strategic input to the Sustainable Development in the 21st Century (SD21) project*. New York, USA.

Grassini, P., & Cassman, K. G. (2012). High-yield maize with large net energy yield and small global warming intensity. *Proceedings of the National Academy of Sciences*, *109*(10), 4021–4021. doi:10.1073/pnas.1201296109

Hermann, S., Rogner, H.-H., Howells, M., Young, C., Fischer, G., & Welsch, M. (2011). In The CLEW Model – Developing an integrated tool for modelling the interrelated effects of Climate , Land use , Energy , and Water (CLEW). *6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems - Proceedings*. Stockholm, Sweden.

Hermann, S., Welsch, M., Segerstrom, R. E., Howells, M. I., Young, C., Alfstad, T., Rogner, H.-H., et al. (2012). Climate, land, energy and water (CLEW) interlinkages in Burkina Faso: An analysis of agricultural intensification and bioenergy production. *Natural Resources Forum*, *36*, 245–262. doi:10.1111/j.1477-8947.2012.01463.x

Hoff, H. (2011). Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm, Sweden: Stockholm Environment Institute.

Hope, C. W. (2006). The social cost of carbon : what does it actually depend on? *Climate Policy*, *6*(5), 37–41. doi:http://dx.doi.org/10.1080/14693062.2006.9685621

Howells, M., & Hermann, S. (2011). Hot-Topic-Session Background Paper Sustainable Energy for All - What does it mean for Water and Food Security. Stockholm, Sweden.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerstöm, R., Alfstad, T., Gielen, D., et al. (n.d.). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change, forthcoming*.

Howells, M., & Roehrl, R. A. (2012). *Perspectives on Sustainable Energy for the 21*. New York.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., et al. (2011). OSeMOSYS: The Open Source Energy Modeling System. *Energy Policy*, *39*(10), 5850–5870. doi:10.1016/j.enpol.2011.06.033

IAI. (2008). *Fourth Sustainable Bauxite Mining Report*. London, UK.

ICMM. (2012). *The role of minerals and metals in a low carbon economy - Mining's contribution to sustainable development* (pp. 1–8). London, UK. Retrieved from www.icmm.com

IEA. (2004). A review of greenhouse gas emission factors for fertiliser production. *IEA bioenergy task*. Paris, France.

IEA. (2007). *Tracking Industrial Energy Efficiency and CO2 Emissions*. Paris, France.

IEA. (2010a). *ETSAP Technology Brief I03 - Cement Production* (pp. 1–8). Paris, France. Retrieved from www.etsap.org

IEA. (2010b). *ETSAP Technology Brief I02 - Iron and Steel* (pp. 1–6). Paris, France. Retrieved from www.etsap.org

IEA. (2012a). *World Energy Outlook 2012*. Paris, France. doi:10.1787/weo-2012-en

IEA. (2012b). Energy Technology Perspectives. Retrieved May 8, 2013, from www.iea.org/etp

IEA. (2012c). *ETSAP Technology Brief I10 - Aluminium Production* (pp. 1–5). Paris, France. Retrieved from www.etsap.org

IFA. (2009). *Energy Efficiency and CO2 Emissions in Ammonia Production: 2008-2009 Summary Report* (pp. 1–4). Paris, France. Retrieved from www.fertilizer.org

IFC. (2007). Environmental, Health and Safety Guidelines for Phosphate Fertilizer Manufacturing. Washington DC, USA.

IIASA, & FAO. (2010). GAEZ v3.0, Global Agro-ecological Zones. Retrieved June 17, 2013, from http://www.gaez.iiasa.ac.at/

IIASA/FAO. (2012). *Global Agro-ecological Zones (GAEZ v3.0)*. Laxenburg, AT and Rome, IT.

IPCC. (2012). *Renewable Energy Sources and Climate Change Mitigation - Special Report of the Intergovernmental Panel on Climate Change*. (O. Edenhofer, R. Pichs-Madruga, Y. Sokon, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, et al., Eds.). Cambridge, UK and New York, USA: Cambridge University Press.

Johansson, R. C., Tsur, Y., Roe, T. L., Doukkali, R., & Dinar, A. (2002). Pricing irrigation water: a review of theory and practice. *Water Policy*, *4*, 173–199.

Klepper, G. (2011). The future of the European Emission Trading System and the Clean Development Mechanism in a post-Kyoto world. *Energy Economics*, *33*(4), 687–698. doi:10.1016/j.eneco.2010.12.014

KTH, SEI, UNIDO, & IAEA. (2013). OSeMOSYS - the Open Source Energy Modelling SYStem.

Leung, D. Y. C., Yung, D., Ng, A., Leung, M. K. H., & Chan, A. (2009). An overview of emissions trading and its prospects in Hong Kong. *Environmental Science & Policy*, *12*(1), 92–101. doi:10.1016/j.envsci.2008.09.002

MacKay, D. J. C. (2009). *Sustainable Energy — without the hot air* (Version 3., pp. 1–383). Cambridge, UK: UIT Cambridge Ltd. Retrieved from www.withouthotair.com

Martin-Nagle, R., Howard, E., Wiltse, A., & Duncan, D. (2012). The Water, Energy and Food Security Nexus - Solutions for the Green Economy. *Conference Synopsis (February 2012)*. Bonn, Germany: BMU, BMZ, OOSKAnews.Inc.

METSO Global. (2009). Paper industry consumes less water. *METSO articles*. Retrieved June 17, 2013, from http://www.metso.com/corporation/articles_eng.nsf/WebWID/WTB-060309-2256F-6A087?OpenDocument#.Ub8sy_ZpO5c

Nierenberg, D., Hebebrand, C., Shapiro, J., Milder, J., & Wheeler, K. (2012). *Food and Agriculture : The future of sustainability Food and Agriculture : The future of sustainability*. New York.

Norgate, T. E., & Iovel, R. (2004). Water Use in Metal Production : A Life Cycle Perspective. Clayton South, Australia. Retrieved from http://www.minerals.csiro.au/sd

PBL. (2012). The IMAGE model suite used for the OECD Environmental Outlook to 2050. The Hague, Netherlands.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, *11*, 1633–1644. doi:10.5194/hess-11-1633-2007

Ragauskas, A. J., Nagy, M., Kim, D. H., Eckert, C. A., Hallett, J. P., & Liotta, C. L. (2005). From wood to fuels - Integrating biofuels and pulp production. *Industrial Biotechnology*, *2*(1), 55–65.

Ramankutty, N., Evan, A. T., Monfreda, C., & Foley, J. a. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, *22*(1), 1–19. doi:10.1029/2007GB002952

Rautiainen, A., Wernick, I., Waggoner, P. E., Ausubel, J. H., & Kauppi, P. E. (2011). A national and international analysis of changing forest density. *PloS one*, *6*(5), e19577. doi:10.1371/journal.pone.0019577

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T. M., et al. (2009). Planetary Boundaries : Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2).

Rogner, H.-H. (2010). APPENDIX to CLEWS : Climate , Land , Energy , Water Strategies A pilot case study. Vienna, Austria.

Rosegrant, M., Msangi, S., Ringler, C., & Sulser, T. (2012). *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description*. Washington DC, USA.

Saygin, D., Patel, M., Tam, C., & Gielen, D. (2009). *Chemical and Petrochemical sector. Potential of best practice technology and other measures for improving*

energy efficiency. IEA Information Paper, OECD/IEA, September (pp. 1–60). Paris, France.

Schreier, H., Brown, S., Lavkulich, L., Wilson, J., Van der Gulik, T., Tam, S., Lee, S., et al. (2008). *Integrating Blue, Green and Virtual Water: Comparing Irrigation Water Requirements for Different Land Uses in the Driest Watershed in Canada* (pp. 1–61). Toronto, CA.

SEI, & KTH. (2013). COMMEND OSeMOSYS Forum. Retrieved from http://www.energycommunity.org/default.asp?action=10&fid=104

Sieber, S., Zander, P., Verburg, P. H., & Van Ittersum, M. (2010). Model-based systems to support impact assessment—Methods, tools and applications. *Ecological Modelling*, *221*(18), 2133–2135. doi:10.1016/j.ecolmodel.2010.07.002

Skaggs, R., Hibbard, K., Janetos, T., & Rice, J. (2012). *Climate and energy-water-land system interactions*. Richland, WA, USA.

Soria, A., & Luo, Z. (2007). *Prospective Study of the World Aluminium Industry*. *JRC Scientific and*. Luxembourg. doi:10.2791/36024

Steffen, W., Crutzen, J., & McNeill, J. R. (2007). The Anthropocene: are humans now overwhelming the great forces of Nature? *Ambio*, *36*(8), 614–21.

Sukumaran Nair, M. P. (2006). Ammonia industry - today and tomorrow. *Hydrocarbon Processing*, *Petrochemi*(April), 47–55.

Taliotis, C., & Howells, M. I. (2013). KTH Energy Systems Analysis. *CLEWs Nexus Model Development*. Retrieved from www.desa.kth.se

UK EA. (2005). *Measuring Environmental Performance* (pp. 1–25). Bristol, UK.

UNDESA. (2011). *World Population Prospects: The 2010 Revision* (pp. 1–7). New York.

UNDESA. (2013). *Sustainable Development Scenarios for Rio+20 - A Component of the SD21 project*. New York, USA.

UNEP. (2012). *The Fifth Global Environmental Outlook Report. Chapter 4: WATER*. Nairobi, Kenya. Retrieved from www.unep.org/geo

US EPA. (2008). *2008 Sector Performance Report*. Washington DC, USA.

Visser, A., & Appelmann, J. (2009). *Water and wastewater The petrochemical industry is organized in four sectors : exploration and*. Nijmegen, NL. Retrieved from http://www.royalhaskoning.com/en-GB/Publications/watwchd1033e3petrochemicalindustry.pdf

Walker, M. E. (2012). *Thermoelectric Power Systems and the Energy-Water Nexus*. Illinois Institute of Technology.

WEC. (2010). *World Energy Council: Water for Energy*. London, UK.

Weiss, M., Neelis, M. L., Zuidberg, M. C., & Patel, M. K. (2008). Applying bottom-up analysis to identify the system boundaries of non-energy use data in international energy statistics. *Energy*, *33*(11), 1609–1622. doi:10.1016/j.energy.2008.05.014

Welsch, M., Hermann, S., Howells, M., Ramma, I., & Rogner, H. (2012). Uncovering CLEWs - Modelling the Energy System and its Interdependencies for Mauritius. Stockholm, Sweden.

Welsch, M., Howells, M., Bazilian, M., Decarolis, J. F., Hermann, S., & Rogner, H. H. (2012). Modelling elements of Smart Grids e Enhancing the OSeMOSYS (Open Source Energy Modelling System) code. *Energy*, *46*, 337–350.

World Bank. (2013). Agricultural land. *World Bank Online Data*. Retrieved May 15, 2013, from http://data.worldbank.org/indicator/AG.LND.AGRI.ZS?page=2

Worldwatch Institute. (2007). *Biofuels for transport: Global potential and implications for sustainable energy and agriculture*. (Worldwatch Institute, Ed.). London, UK: Earthscan.

Wriedt, G., Van der Velde, M., Aloe, A., & Bouraoui, F. (2009). Estimating irrigation water requirements in Europe. *Journal of Hydrology*, *373*(3-4), 527–544. doi:10.1016/j.jhydrol.2009.05.018

APPENDIX

APPENDIX A

Table A 1: Climate zone classification of countries in GAEZ database including irrigation potential

Cold/arctic zone			
FAO n°	**Low irrigation potential**	**FAO n°**	**Medium irrigation potential**
2	Greenland	11	Russian Federation
17	Iceland	1	Canada
22	Svalbard and Jan Mayen Isl		**High irrigation potential**
169	Antarctica	161	Mongolia
Temperate zone			
FAO n°	**Low irrigation potential**	**FAO n°**	**Medium irrigation potential (cont'd)**
165	Kyrgyzstan	23	Sweden
70	New Zealand	34	Montenegro
18	Ireland	16	Finland
162	Korea Rep.	158	China
59	Chile	7	Hungary
31	Slovenia	56	Argentina
37	Belgium	3	United States of America
4	Belarus	25	Albania
40	Netherlands	35	Serbia
41	Switzerland	8	Moldova, Rep.
14	Denmark	29	Italy
19	Latvia	13	Ukraine
159	Korea DPR	5	Bulgaria
FAO n°	**Medium irrigation potential**	**FAO n°**	**High irrigation potential**
26	Bosnia and Herzegovina	33	Macedonia FYR
27	Croatia	28	Greece
21	Norway	125	Armenia
6	Czech Republic	30	Portugal
36	Austria	32	Spain
160	Japan	126	Azerbaijan
9	Poland	164	Kazakhstan
39	Germany	139	Turkey
128	Georgia	122	Morocco
20	Lithuania	166	Tajikistan
24	United Kingdom	127	Cyprus
10	Romania	168	Uzbekistan
12	Slovakia	163	Afghanistan
38	France	167	Turkmenistan
15	Estonia		

Subtropical/tropical zone			
FAO n°	**Low irrigation potential**	**FAO n°**	**Medium irrigation potential (cont'd)**
62	French Guiana	118	Sierra Leone
72	French Polynesia	119	Togo
74	Solomon Islands	65	Peru
75	Vanuatu	115	Guinea
88	Equatorial Guinea	144	Lao PDR
96	Swaziland	53	Mexico
101	Djibouti	57	Bolivia
133	Kuwait	78	Kenya
135	Oman	146	Myanmar
136	Qatar	50	El Salvador
137	Saudi Arabia	155	Nepal
140	United Arab Emirates	91	Lesotho
141	Yemen	150	Timor-Leste
145	Malaysia	77	Ethiopia
147	Papua New Guinea	46	Jamaica
153	Bhutan	82	Tanzania UR
66	Suriname	111	Benin
143	Indonesia	**FAO n°**	**High irrigation potential**
55	Panama	84	Cameroon
71	Fiji	92	Malawi
73	New Caledonia	114	Guinea-Bissau
79	Madagascar	156	Pakistan
148	Philippines	93	Mozambique
89	Gabon	110	South Sudan
116	Liberia	154	India
67	Uruguay	95	South Africa
44	Dominican Republic	97	Zambia
80	Rwanda	98	Zimbabwe
86	Congo, Rep.	103	Gambia
64	Paraguay	117	Nigeria
FAO n°	**Medium irrigation potential**	85	Central African Republic
81	Uganda	123	Tunisia
157	Sri Lanka	99	Burkina Faso
48	Belize	120	Algeria
60	Colombia	134	Lebanon
151	Viet Nam	83	Angola
87	Congo, Dem. Rep.	90	Botswana
42	Bahamas	104	Mali
47	Puerto Rico	69	Australia
63	Guyana	100	Chad
58	Brazil	129	Iran, Islamic Rep.
112	Cote d'Ivoire	131	Israel
43	Cuba	106	Niger

| FAO n°	Medium irrigation potential (cont'd)	FAO n°	High irrigation potential (cont'd)
61	Ecuador	138	Syrian Arab Republic
113	Ghana	107	Senegal
49	Costa Rica	130	Iraq
76	Burundi	94	Namibia
152	Bangladesh	109	Sudan
142	Cambodia	132	Jordan
54	Nicaragua	105	Mauritania
68	Venezuela	108	Somalia
51	Guatemala	102	Eritrea
149	Thailand	121	Libyan Arab Jamahiriya
52	Honduras	124	Egypt
45	Haiti		

APPENDIX B
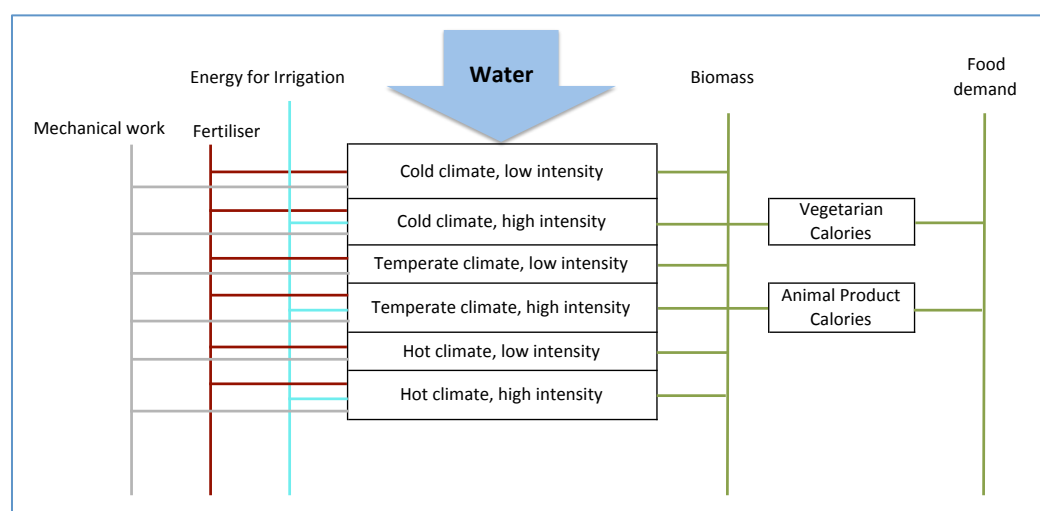
Figure B 1: Reference resource system for the land sector
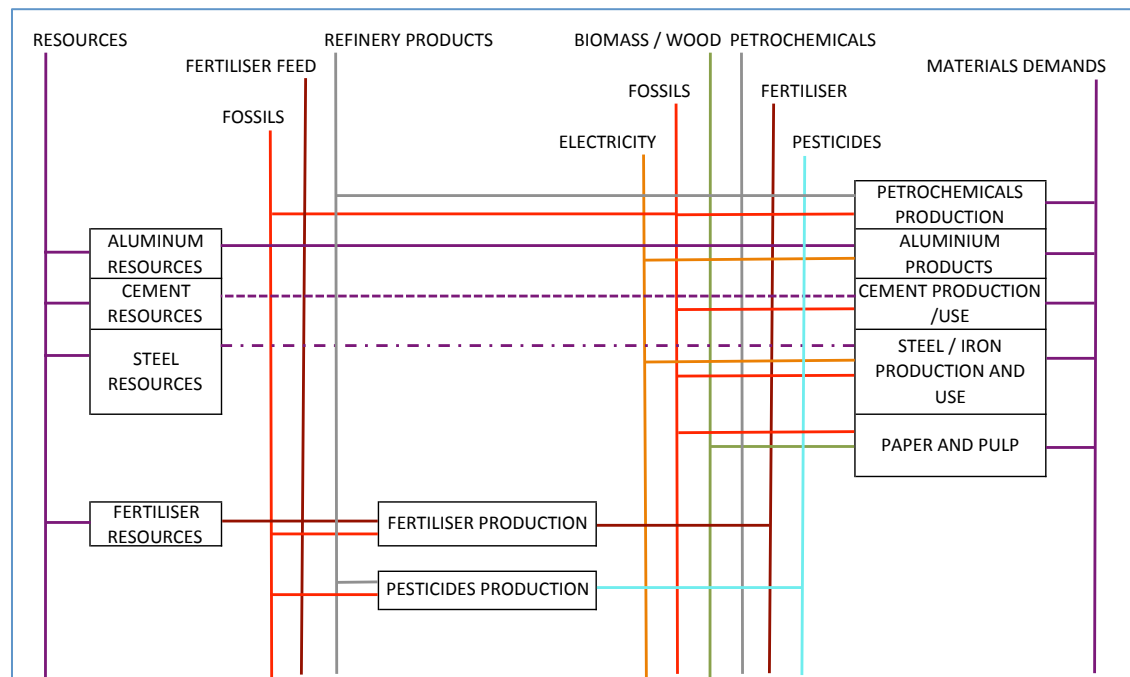
Figure B 2: Reference resource system for the materials module
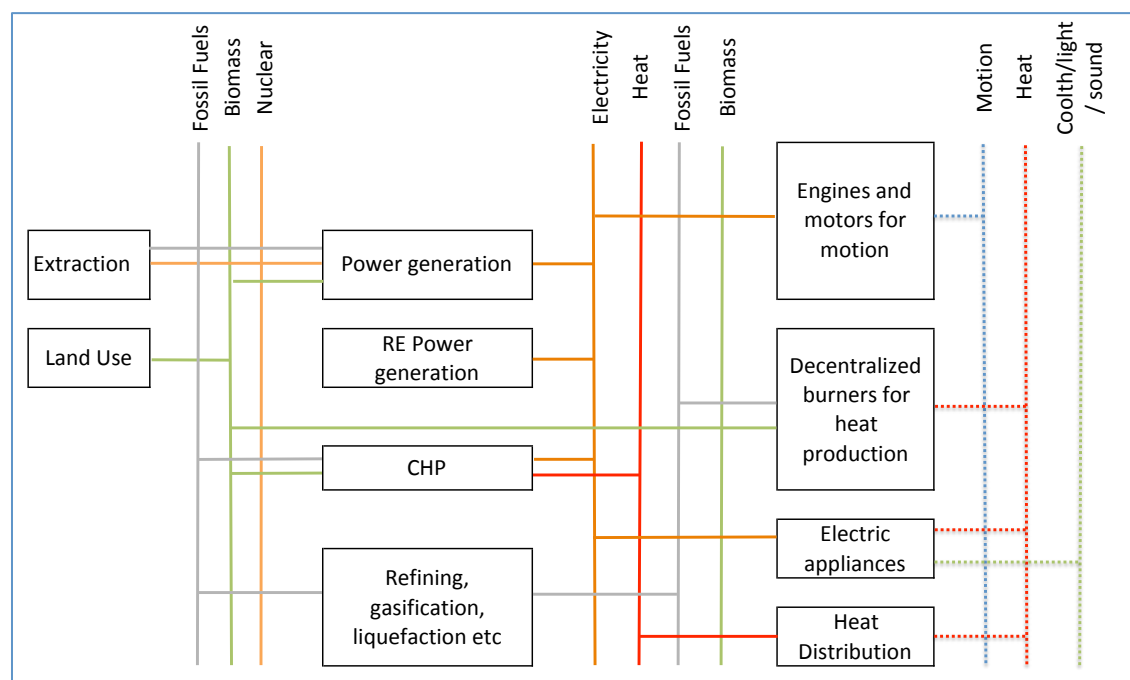

Figure B 3: Simplified reference resource system for the energy module developed by KTH dESA in 2013