20 Trillion Green Watts

A data-driven systematic analysis of global and national sustainable energy transition paths

PhD Research Proposal

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sustainable energy transition, renewable energy, system dynamics, EROEI, food-energy nexus, data visualization

1. OVERVIEW

We propose a thorough investigation of the dynamics of a sustainable transition from a fossil-fuel dominated society towards renewable energy. This research will survey the requirements, implications and impacts on society of a sustainable energy transition (SET) including feedback from climate and resources (especially food and water). Using a data-driven, net-energy based approach towards fossil fuel phase-out rather than the conventional exponential economic growth based considerations, we construct global and individual national sustainable energy transitions pathways under a range of greenhouse gas emissions budgets and technology scenarios leading to an exact capacity requirement to be deployed yearly to assure an undisrupted energy access of the society countries. This will help nations plan their energy transitions well ahead. Further on, we also investigate the potential transitions' implications on the food-energy nexus, global and national food and agriculture systems in particular. Using advanced data mining and data visualization techniques, we make all of the research publicly available online and easily trackable and browsable – to dub as a useful data exploration tool for both researchers and the general public.

2. BACKGROUND

Sustainable Energy Transition

Currently, fossil resources are not regenerating in any timeframe meaningful for human societies (Princen, Manno, and Martin 2013). Since fossil energy is a limited resource, a substantial uptake of renewable energy is required so that society maintains the available energy needed for its operation and concomitantly, mitigate emission of greenhouse gases. This, albeit with a substantial delay, is expected to lead to a slow-down and subsequent stop or turn-around of global warming sparing the worst negative climate effects on society. The resultant energy gap needs to be addressed through new energy-generating techniques which preferably are emissions-free or they have limited emissions or replacement of the energy consuming stock – both of which require a substantial energy investment. Moreover, the deployment rate of these installations must be in sync or higher than the fossil phase-out rate (Figure 4), so that the global energy demand is met at all times (S. Sgouridis et al. 2013). In (S. P. Sgouridis and Csala 2014) and (S. Sgouridis, U. Bardi, and D. Csala 2015) we have formalized these 4 criteria to yield the definition of a sustainable energy transition:

1. The impacts of energy production during SET do not exceed the long-run ecosystem carrying and assimilation capacity.
2. Per capita net available energy remains above the minimum level required to satisfy societal needs at any point during SET and without disruptive discontinuities in its rate of change.
3. The investment rate for the installation of renewable generation and consumption capital stock is sufficient to create a sustainable energy supply basis before the non-renewable safely recoverable resources are exhausted.
4. Debt as a form of commitment of future consumption is coupled to and limited by future energy availability.

Emissions budget

The Intergovernmental Panel on Climate Change (IPCC) in its latest report set the total safely emitable greenhouses gases to stay below 2 degrees Celsius of atmospheric temperature warming compared to pre-industrial levels with a 66% chance at 990 [510-1505] gigatons of carbon-dioxide equivalent, coming from fossil fuels and associated industrial processes (IPCC 2014). At the current consumption patterns, this would mean that the globe would exhaust its fossil greenhouse gas budget by 2032 [2020-2045]. Most of the emissions would come from coal-fired energy generation (EIA 2014), followed by oil consumption for transportation and natural gas for energy and heating purposes.

Energy demand

The 20 trillion green watts in the title breaks down to supplying 2000 W of sustainably generated renewable electric power for the roughly 10 billion people on Earth in the year 2100.

Currently, global per capita energy consumption hovers around 2400 W/capita (EIA 2014) when accounted in primary energy terms. However, this is by far not distributed equally among nations, ranging from about 100 to more than 10000 Watts. There is a strong correlation between GDP and per capita energy consumption, a trend which has been steady over the past few decades (Figure 1).

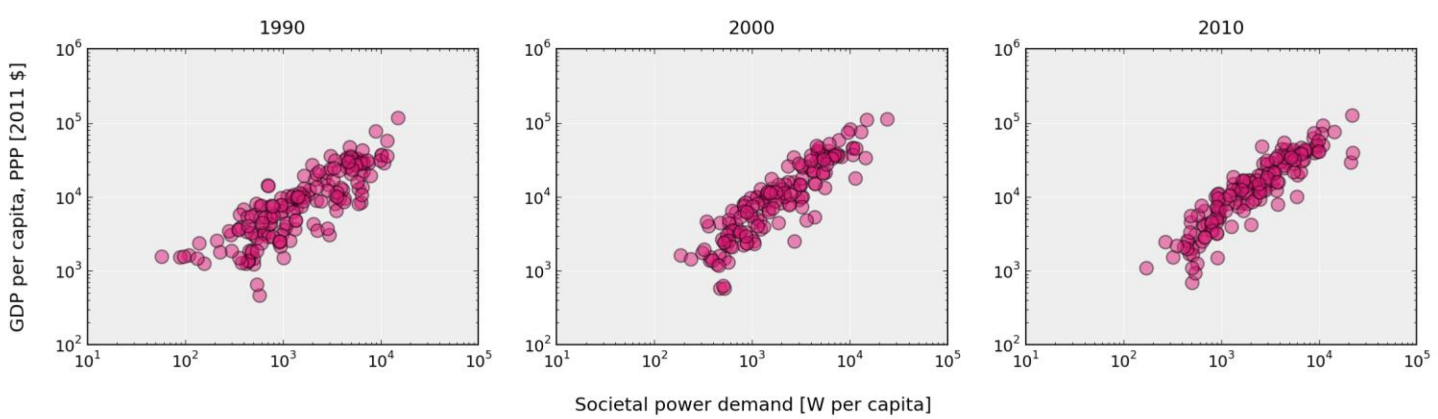

Figure 1 – Societal power demand vs GDP / capita

By the end of the century, however, the 2400W/capita power demand is expected to change. There are many mechanisms driving the change: Developing nations are expected to get wealthier, therefore increasing their per capita power demand. Advanced economies are expected to reduce their net power demand as a result of increase in efficiency in household appliances, as well as well as shift in social behavior towards energy consumption. Furthermore, primary energy demand is expected to decrease as more energy efficient - at the conversion stage - carriers are introduced, such as electricity directly – at the expense of less efficient traditional sources, such as internal combustion engines. These phenomena altogether lead to a wide interval estimates for per capita power demand by the end of the century, ranging from 1400W/capita (Jacobson and Delucchi 2011; Jacobson and Delucchi 2009), through 4000W (Spreng 2005) and up to more than 6000W (Pickard, Hansing, and Shen 2009). However, scientists at EPFL in the mid 2000s have defined 2000W as the lower feasible limit of average primary power per capita for maintaining an acceptable quality of life in a technical society (Marechal, Favrat, and Jochem 2005; Schulz et al. 2008; Pfeiffer, Koschenz, and Wokaun 2005). Therefore, based on this we have created a range of possible demand profiles to be studied in further in our analysis, and we will consider the 2000W/capita scenario as the base case (Figure 2). Using this information and the population projection of the UN (UNSD 2012), we can construct distinct demand profiles for the rest of the century.

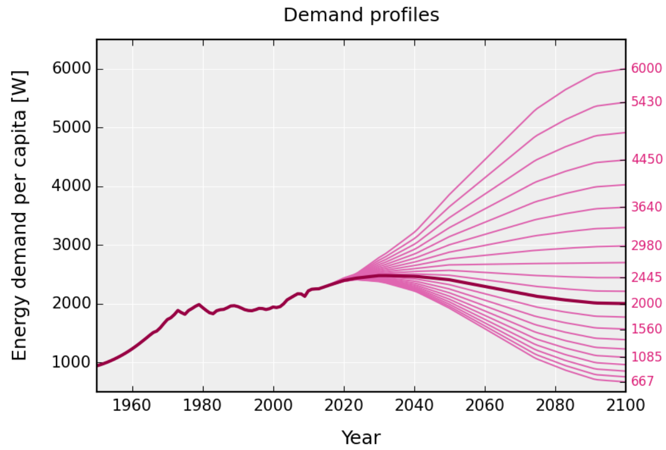

Figure 2 – Expected demand profiles

Energy economics

Fossil fuel extraction is currently affordable, due to the maturity of the industry. However, the effects of reaching the limit of resources has been encountered already, as shown by the increases in real fossil fuel prices, especially that of oil. This is due to the fact that fossil resources are increasingly harder to detect and extract, leading to an increase in the energy investment and subsequent financial investment in the process.

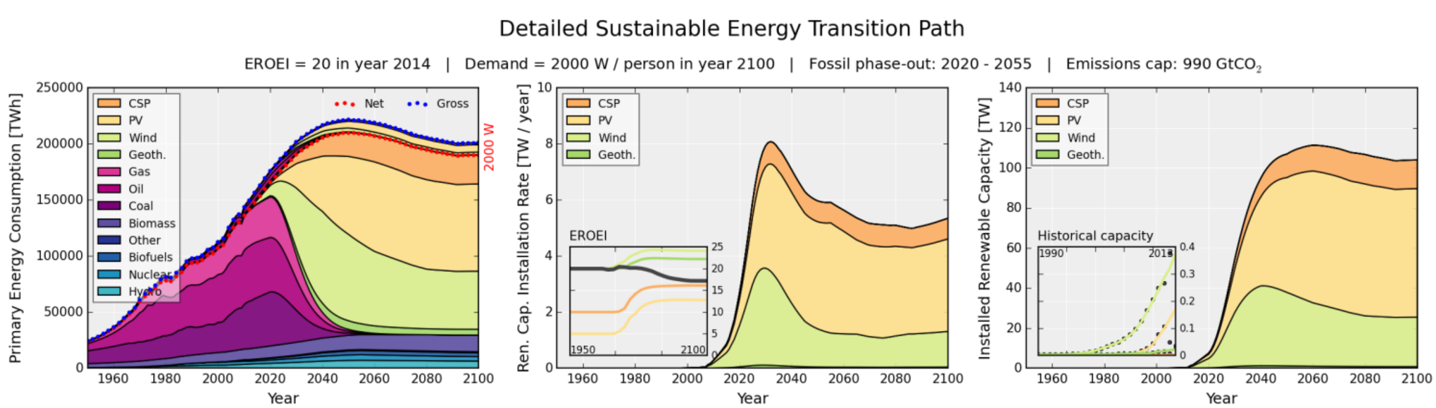

Figure 3 – Example of a sustainable energy transition

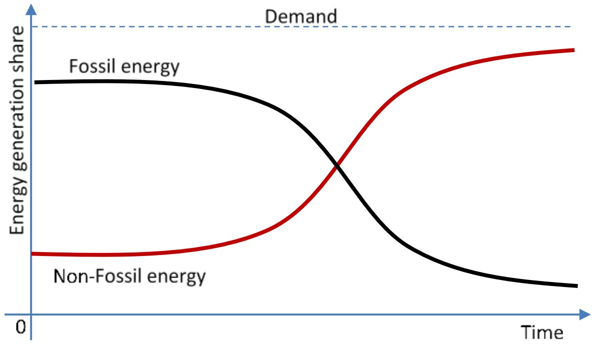

Figure 4 – Energy transition inflexion point

This can be formulated by stating that non-renewable fossil reserves have a decreasing energy return on energy invested (EROEI). Technological efficiency is increasing with increased research and development, which is increasing also proportionally with the scale of deployment but also the potential benefits the technology offers. Hence, as more renewable generation is deployed, its EROEI can rise until scaling limits are reached. In order to be adopted in a market economy, renewable energy technologies must be financially competitive against fossil technologies. Dale et al. (2011) suggest that EROEI (referred to by them as "EROI") can be represented as a function of two components (Figure 5), each depending on the cumulative production:

- A technology component: more efficient technology leading to a net increase in EROEI
- A physical component: lesser resources leading to a net decrease in EROEI

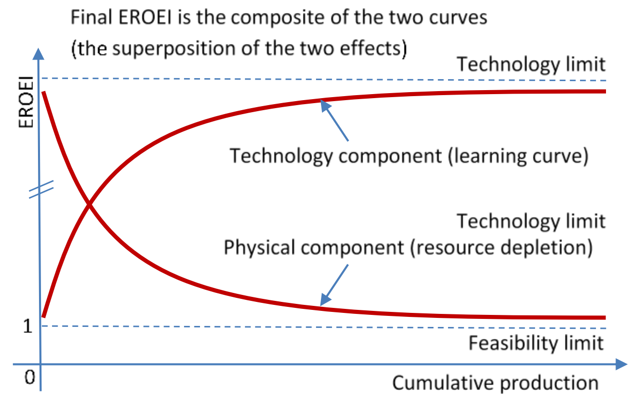

Figure 5 – EROEI = *f* (cumulative production)

Energy transition

For a sustainable energy consumption-generation parity it is desirable to have all global energy provided by technologies with an increasing or stable EROEI for the scale of deployment. Likewise an energy mix dominated by renewable energy technologies and a fossil energy generation rate which requires a lower extraction rate than the regeneration rate of fossil resources is desirable.

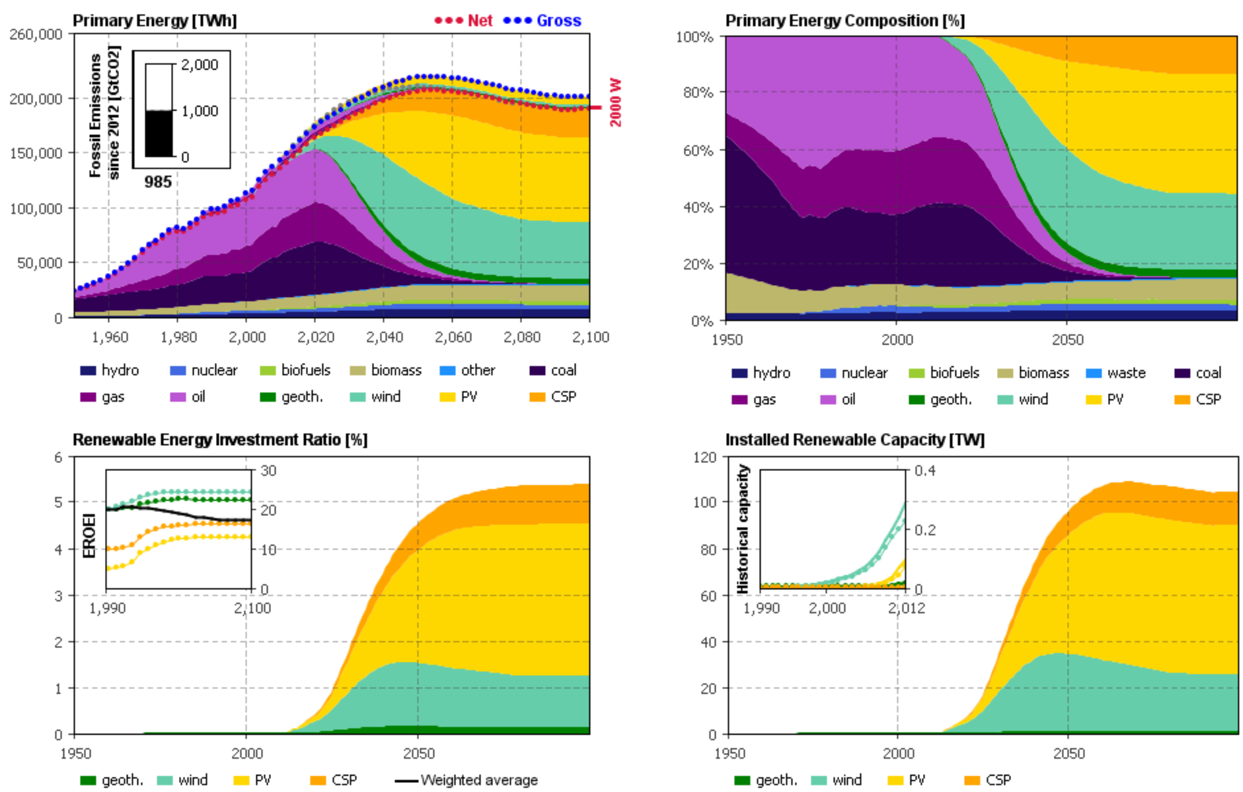

Figure 6 – Emissions constrained sustainable energy transition path

The global and national energy systems will have a transition point when the renewable resources overtake the fossil ones due to the emissions constraints, decreasing EROEI and increasing cost of fossil technologies and the increasing EROE~~EO~~I and decreasing cost of renewable energy technologies. In this study, we will investigate the timing and dynamics of such transitions. An energetically and economically successful transition that meets the above criteria, from a fossil energy based energy society to a renewable energy based one is what we will call a sustainable energy transition (Figure 3, Figure 6).

Connections to the food system

Food and agriculture form an essential component of the energy metabolism of human societies that is invariably missing in reviews of global primary and final energy supply. When the caloric energy content of food is included it is it comparable to more than 5% (14.6% including biofuels and biomass from agriculture) of the total primary energy supply in 2010. In the decades since the Green Revolution, the rate of increase in food production significantly exceeded population growth despite reductions in agricultural land (Godfray et al. 2010). Such intensification was the result of mechanization, irrigation, artificial fertilization, and pesticide protection along with selective breeding and more recently genetic modification all of which depend on high energy (and material) intensity inputs – such as maize or soybean or palm oil. While the crop yields have been significantly rising in emerging economies and developing countries as a result of increased wealth, the energy invested into the agricultural and food systems increased as well. In fact, for the past 50 years, it has increased at a faster rate than the net energy gains in crop energy content as a result of the increased yields (Figure 7, Figure 8). This increased energy input has been mostly enabled by the increased consumption of fossil fuels and fertilizers, granted by the rising economic potential of these countries over time. However, putting this in the context of global and national sustainable energy transitions and an imminent need to reduce fossil fuel consumption due to effects of greenhouse gas emissions, as well as depletion, with a prospect of an increasing population, we underline need of integrating the agricultural and food systems into future energy-economy decisions. (“Food Energy Flows” 2014).

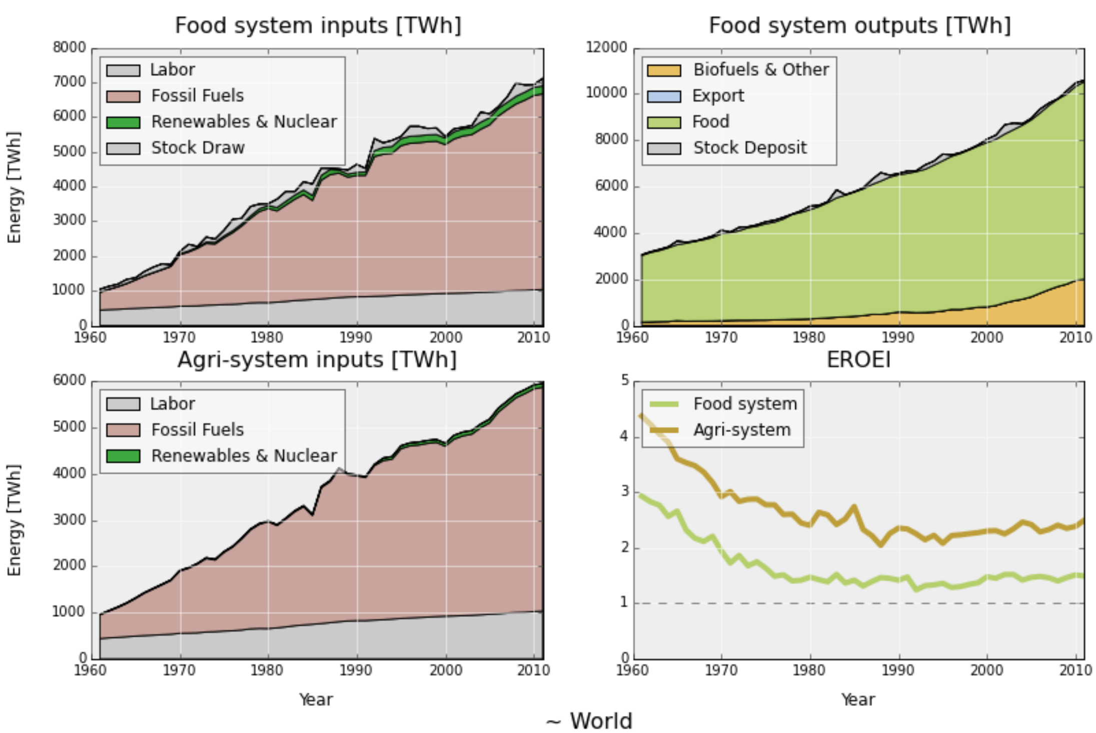

Figure 7 – Global agricultural and food system energy inputs and outputs

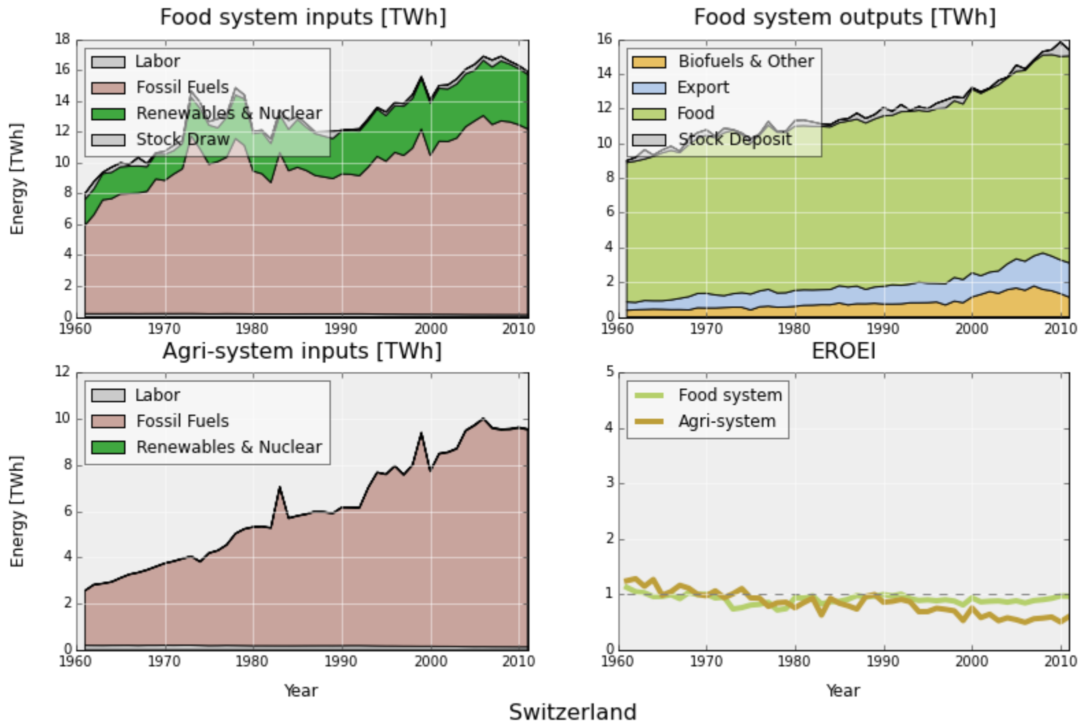

Figure 8 – Switzerland agricultural and food system energy inputs and outputs

3. RESEARCH QUESTIONS

In this study we will seek for a defining feasible pathways for a controlled global and regional sustainable energy transition. Because of the significant complexity of the problem, we will break it down into sub-problems and will seek answer to the following research questions:

A. Is a smooth sustainable energy transition feasible on a global scale?
   - If yes, what is the optimal time and rate of deployment of renewable energy technologies, as well as the optimal time and rate of phase-out of fossil-fuel technologies to achieve a sustainable transition of the global energy system?
   - What are the implications for the climate, economy and the society?
   - What are implications on the food-energy nexus?

   (In our 2014 and our upcoming 2015 paper and a June 2015 conference presentation, we have already addressed most of the A. questions. In an upcoming July 2015 conference presentation we will answer the remainder, connection to the food-energy nexus.)

B. Is a smooth sustainable energy transition feasible on a local (regional/country-level scale)?
   - If possible how is the national sustainable energy transition affected by:
     - Natural resources (water, food, energy)
     - Economic resources and trade

C. Does the best response of every country in order to achieve their local sustainable energy transition lead to a global energy transition?
   - Is there a transition pathway which is beneficial both on a local, as well as on a global scale.
   - What are its implications on the climate, economy and the society?
   - What are implications on the food-energy nexus?

D. Additional research objective
   - Present the results of the research in a visually appealing and intriguing way on an interactive interface that could be used as a policy planning and decision making aid by policy makers, as an open source database and visualization gallery for scientist and a source of inspiration and curiosity for the general public.

4. METHODOLOGY

Data model

The proposed work has a large data gathering component from public energy database APIs. So far, we have managed to set up access for the all databases needed to be worked with in the thesis, including:

- UNSD Population Statistics
- FAO FAOSTAT
- World Bank Development Indicators
- UN COMTRADE
- UNFCCC
- EIA
- BP

This totals 26500 lines of Python code. Figure 9 present a conceptual map of the data model components and their relative connections to each other.

Mathematical model

The sustainable energy transitions are guided by one recursive dynamic integral equation, as we have defined in (Sgouridis & Csala, 2014). It can be broken down into 3 major components:

- The demand component
- The fossil component
- The renewable component

I the introduction we have already seen how the demand component is constructed: based on a given population projection and an envelope of net societal demands. This demand then will have to met by a combination of fossil and renewable energy generation. In our model, we will consider the following energy types divided into the following categories:

Table 1 –Model energy types

Fossil Fuels	Renewables	Externals
Oil	Solar PV	Hydropower
Coal	Solar CSP	Nuclear power
Natural Gas	Wind	Biomass
	Geothermal	Others

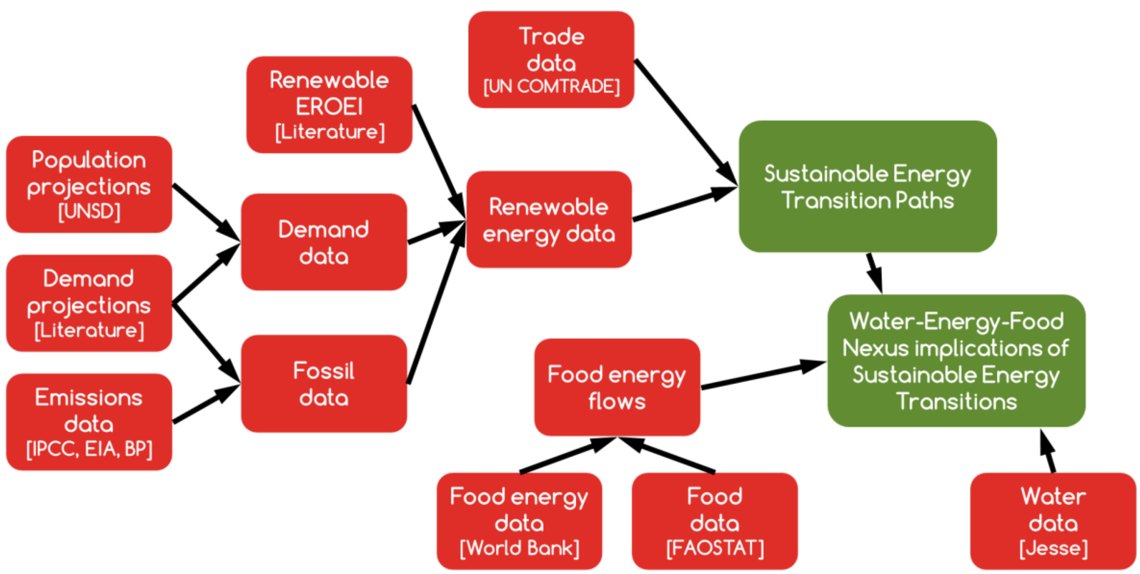

Figure 9 – Conceptual map of data model components

The fossil fuels will be considered following a natural depletion trajectory that follows a Hubbert curve (Maggio & Cacciola, 2009). Therefore, the equation governing the fossil part can be formulated as:

$$P = \sum^{i} \frac{2|P_{M_i}|}{1 + k_i \cdot cosh\left[b_i\left(t - t_{M_i}\right)\right]} \quad [1]$$

$$\text{Where: } b = \frac{4|P_M|}{U}$$

Equation [1] is the power P extracted form fossil reserve type i at any year t, given as a multi-variant of the Hubbert curve and has 3 key parameters:

- P_M, the peak power
- t_M, the time of this peak power
- U, the ultimately recoverable reserves
- k is a shape parameter

The greenhouse gas emissions cap is implemented by modifying the U (ultimately recoverable reserves) to S (safely recoverable reserves), keeping in mind the emissions intentions of the fossil fuels and the emissions cap.

Starting from the premise that all non-fossil (and non-external) energy has to be generated from renewable sources and that principles 1-4 of the sustainable energy transition must be fulfilled at all times, we can derive the equation for the renewables:

$$E_{renewable}\left(1-\frac{1}{R_{renewable}}\right)=D_{society}-E_{fossil}\ [2]$$

$$C_{renewable}=\frac{E_{renewable}}{8760\cdot CF_{renewable}}[3]$$

$$I_{renewable}=\frac{d}{dt}C_{ren}+\frac{1}{L}\int_{t-L}^{t}I_{renewable}\ [4]$$

Where:

- E is energy generated
- I is the renewable power installation rate
- C is the renewable capacity installed
- L is the renewable plant lifetime
- D is the net societal demand
- R is the energy return on energy invested
- CF is the capacity factor

The energy flows of the food system are calculated using a different model, to be presented in detail at a conference in July 2015, but the main energy input-output equation can be defined as:

$$EROEI=\frac{E_{out}}{E_{in}}\ [5]$$

$$E_{out}=\sum^{c}w_c\cdot i_c\ \ [6]$$

$$E_{in}=\sum^{f}\left[a_f\left(1+\sum^{z}b_z\cdot i_z\cdot\eta_{fz}\right)+e_f\cdot\eta_f+I\right]+P\cdot i_P[7]$$

$$I=\left(g\cdot\sum^{d}v_d\right)\cdot W\cdot(\alpha+\beta+\gamma) for\ countries;\quad =0\ \ for\ World\ [8]$$

Where:

c - crop c
i_c - energy content of c
w_c - weight of c
f – fossil f
z – fertilizer z
a_f – fossil energy
b_z – fertilizer amount
e – electric energy
η – conversion efficiency
P – people working in agriculture
v_c - value of c; $d \subseteq C$ – imported crop d
$\alpha,\ \beta,\ \gamma$ – energy mix shares of fossil, biomass, other
g – energy intensity of economy
W – country energy consumption

The reasoning behind equations 5-8 is to create a metric similar to energy systems for the global and national agriculture systems. This will be a rapport of the energy content of all agriculturally produced primary crops on the territory of a certain country/region over the energy that went into producing these crops – i.e. the sum of fossil fuels, electricity, fertilizer energy content and labor energy content. The resulting number, the argi-system energy return on energy invested – EROEI – will characterize the energetic efficiency of the entire system. Examining over time will give information about the energetic sustainability of the system as well.

When including secondary crop flows such as processed foods and meat, a similar process can be extended for the entire food system. For individual nations, here one has to account for the economic value of any imported products, as well the energy intensity if that particular country's economy to yield how much energy was expended for buying those food items. As expected, for most of the nations (except the large, net food importers with a lot of easily available energy such as the UAE and a harsh agricultural environment) the agri-system EOREI will be higher than the food system EROEI.

Due to the dynamic and complex nature of the described problem, with many types of interacting socio-technical and physical systems and the significant analytical complexity of the SET equations, it seems feasible to use a system dynamics modeling approach in order to account for the dynamic nature of the involved quantities.

Brief system dynamics modeling history

Forrester's originating *World* (1971) model Meadows' update to it *World3* (1972), revised (2004), were the first global system dynamics models to address the limitations of the exponential growth paradigm and forecast overshoot and collapse behavior of global attributes such as consumption and population. While comprehensive and innovative, resources were aggregated into one variable. Naill's natural gas model *GAS1* was the first to disaggregate (1971), but it was mainly focused on natural gas and was limited to the US. This work was also capable of capturing Hubbert "peak"theory (1956).

Starting with 1972, the Resource Policy Group at Darthmouth College and the System Dynamics Group at MIT have developed a series of national energy models for the US, after a winning a grant aimed at reducing dependence on domestic gas and oil: Nail and Meadows extended the natural gas model to include all major energy sources, but no specific renewables yet (*GAS2*) (1972). A major addition for the next iteration of the model (*COAL1*) (1974) was the endogenous incorporation of demand. Further development of this work yielded COAL2 (1977) and FOSSIL1 (1976), which showed that the energy problem of the US is not resolvable in the short term, neither demand nor regulatory policies alone are capable of handling it and demand needed to stabilize, along with the increase of alternatives. This work was one of the most comprehensive energy dynamics models up to date, but it was still limited to US and it was not too specific regarding alternative energies. Naill extended his work after moving to the Department of Energy, resulting the development of *FOSSIL2* and *IDEAS* models (1992), which represents the basis for today's national energy planning model (Roger F. Naill 1992), updating Forrester's *national model* (1976).

Sterman added economy to *FOSSIL1* which was the first model to capture energy-economy dynamics, as energy was being modeled in isolation from the economy in all previous models. He found that his model's major behaviors modes were remarkably robust (1982) – which he later used for his model in economy dynamics (1986), A more generic energy dynamics model was developed by Wang et al. (1983).

Also on energy-economy interactions, Richardson and Sterman extended Naill's natural gas model to account for endogenous technological change and created the *exploration-discovery-production* resource chain. Then, later, collaborating with Davidsen and using a synthetic data experimental technique, they have developed the petroleum lifecycle model (1990) which stood as one of the major supporting bases for the Hubbert theory.

Fiddaman (1995; 1998) extensively studied and added climate interactions to Sterman's model, inspired from Norhaus' *DICE* model (1992). His *FREE* model also endogenously accounted for technological change and bounded rational decision making. Fiddaman continued his work on climate-energy interactions, resulting in model updates focusing on global climate policy in (2002) and (2007).

The collaboration of Sterman, Fiddaman, Jones and others' at Climate Interactive lead to the development of the *C-ROADS* model (2012), which monitored the effect of national greenhouse gas emissions on climate and temperature. The very recent update of this, dubbed *En-ROADS* (2013) also accounts for the effects of changes in energy and public policy and economy on climate.

Modern renewable energy dynamics have been touched in several studies, for example the case of wind turbines in (Katherine L. Dykes and Sterman 2010). Also, in order to effectively answer the research questions, we will require extensive energy demand forecasting, in which the work of Sterman (1988) can serve as guideline.

For a successful energy transition model we will need to analyze both generic global energy transition dynamics as well as competitive and often conflicting dynamics of country-level energy transitions. For a sustainable transition, energy also needs to be secure, Shin et al. (2013) investigate energy security, combining system dynamics with quality function deployment and Mutingi (2013), Aslani et al. (2014) and Hu et al. (2013) study renewable energy adoption dynamics, using system dynamics.

FELIX (IIASA, 2014) is a more recent system dynamics model that includes social, economic, and environmental earth systems and their interdependencies, implemented in Vensim.

Modeling progress

To answer questions *A* & *B*, we intended to create a system dynamics model based on previous global models, and we will configure it to handle the global case of question *A* as well as local case of question *B* – i.e. countries. Let us call this model Sustainable Energy Transition (*SET*) model (Figure 10).

Question *C* requires the depiction of decisions as discrete events, a feature of which system dynamics modeling alone is not capable of. Likewise we will support it with agent-based part, creating an environment inhabited by a group of agents, each of which employs the logic of *SET*. Let us call this Sustainable Energy Transition Hybrid Dynamics (*SET-HD*) model (Figure 10).

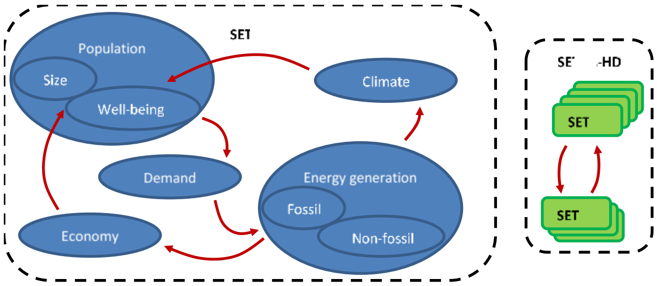

Figure 10 –SET and SET-HD model structure

This dynamic agent-based system model uses system dynamics replicated for individual agents to remove the structural rigidity of the method. In the problem's complex sociotechnical system, most of the time the individual decision-making entities (countries) are autonomous on the micro level and thus can be most accurately modeled using an agent-based approach. However, after a certain time period, a collective behavior of the system starts to emerge. A system dynamics-based global model (*governor*) could identify this behavior, feeding back the information to the individuals – then these might change their behavior, based on this new collective information learned. This way a very accurate structure can be created for sociotechnical systems modeling that combines elements from system dynamics, agent-based and discrete event modeling.

From a systems modeling perspective, the *SET-HD* model would represent the path towards the creation of a new modeling technique, which we will call *adaptive, intelligent* and *dynamic* system dynamics (*AID-SD*) modeling. An *AID-SD* model will have the characteristics of regular system dynamics model, plus:

- Adaptive: It will be adaptive in structure, making it possible for the model structure to change if required by its components or other (interacting) models, agents
- Intelligent: It can deduce what is the optimal transfer function and equation for links between certain variables and (interacting) models, agents
- Dynamic: It will dynamic in structure, making it possible for the model structure to change over the time of the simulation

So far, three versions of the SET have been developed and published (SET1 published in Sgouridis & Csala, 2014; SET1b, unpublished, formed the basis of SET2 and SET2 published in Sgourids, Bardi, Csala, 2015, in preparation).

- http://set.csaladen.es/set.html (Figures 11, 12)
- http://set.csaladen.es/set2.html (Figures 13, 14, 15)

The main difference between SET1 and SET1b and SET2 is that while SET1 is a laissez-faire model, the other two are regulated models driven by set demand curves and emissions caps.

All of these have been developed in JAVA as publicly available online simulators, hosted on AnyLogic's runtehmodel.com platform.

- The SET1, made public in May 2014, has clocked 1866 runs to date with 20 likes and 7 dislikes and in July 2014 it has been chosen the model of the month on the platform.
- The SET2, published in March 2015 has been run 92 times so far with 2 likes and 0 dislikes. SET2 includes a sensitivity analysis module and a Monte Carlo demand simulation module as well.

A project website has also been developed.

- http://set.csaladen.es

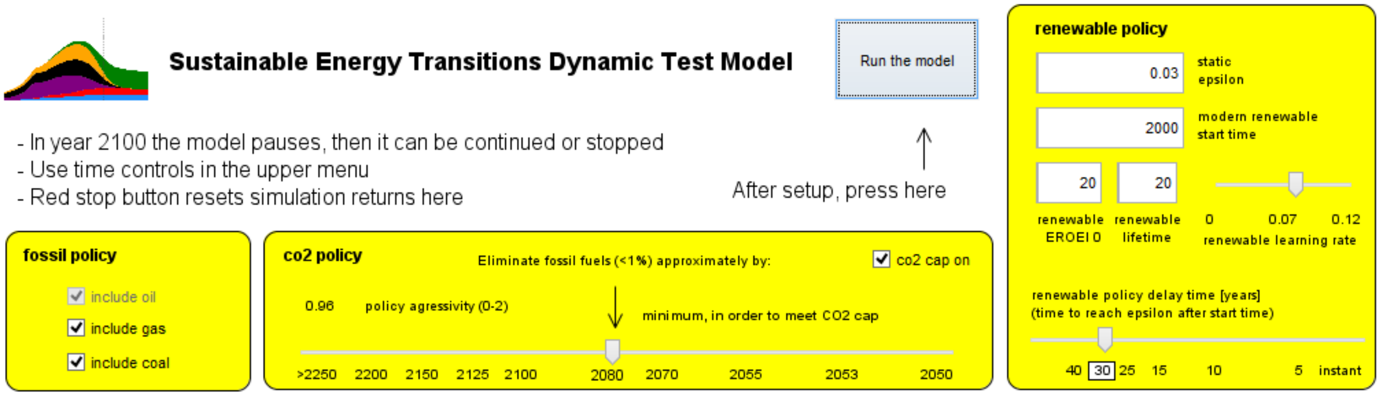

Figure 11 –SET1 parameter setup screen

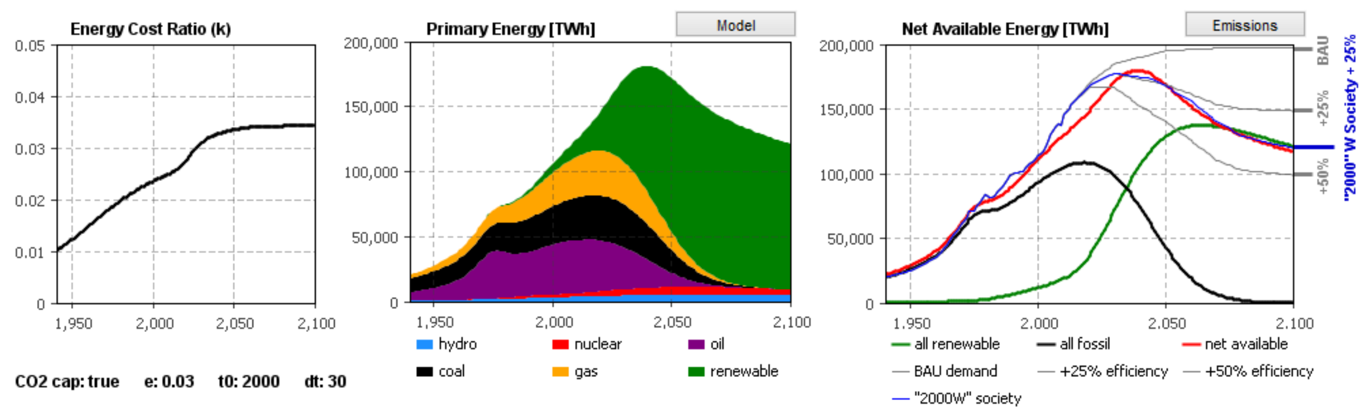

Figure 12 –SET1 results screen

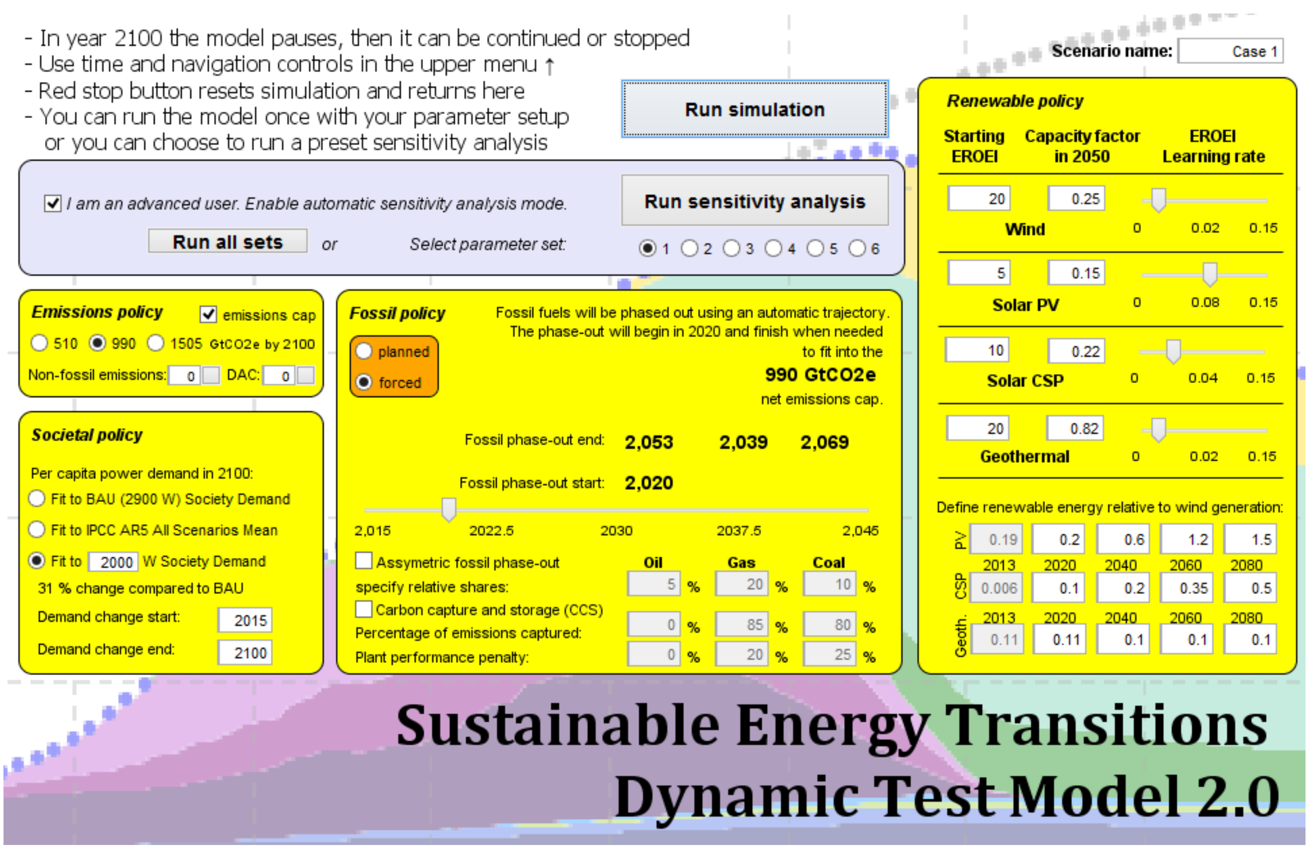

Figure 13 –SET2 parameter setup screen

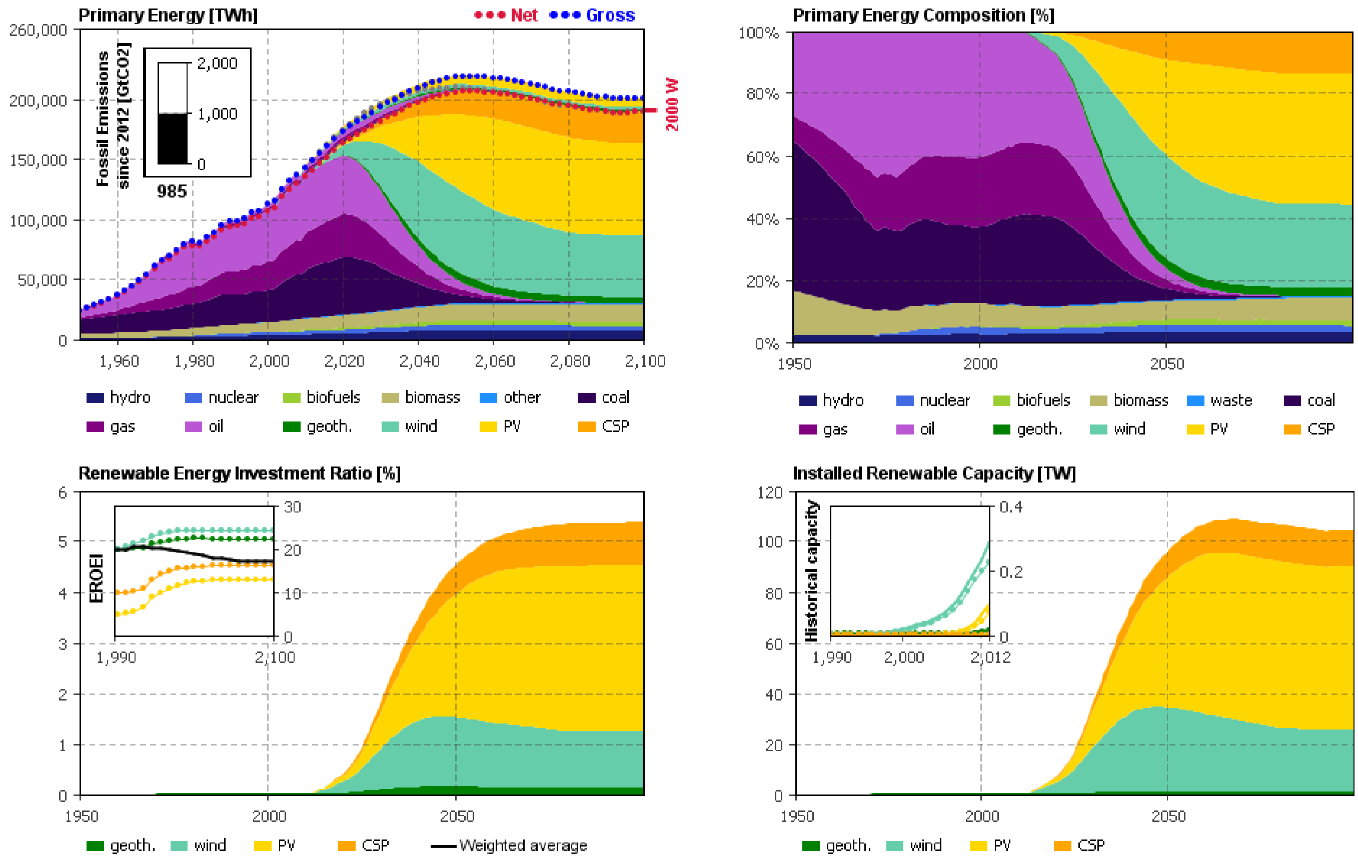

Figure 14 –SET2 simulation results screen

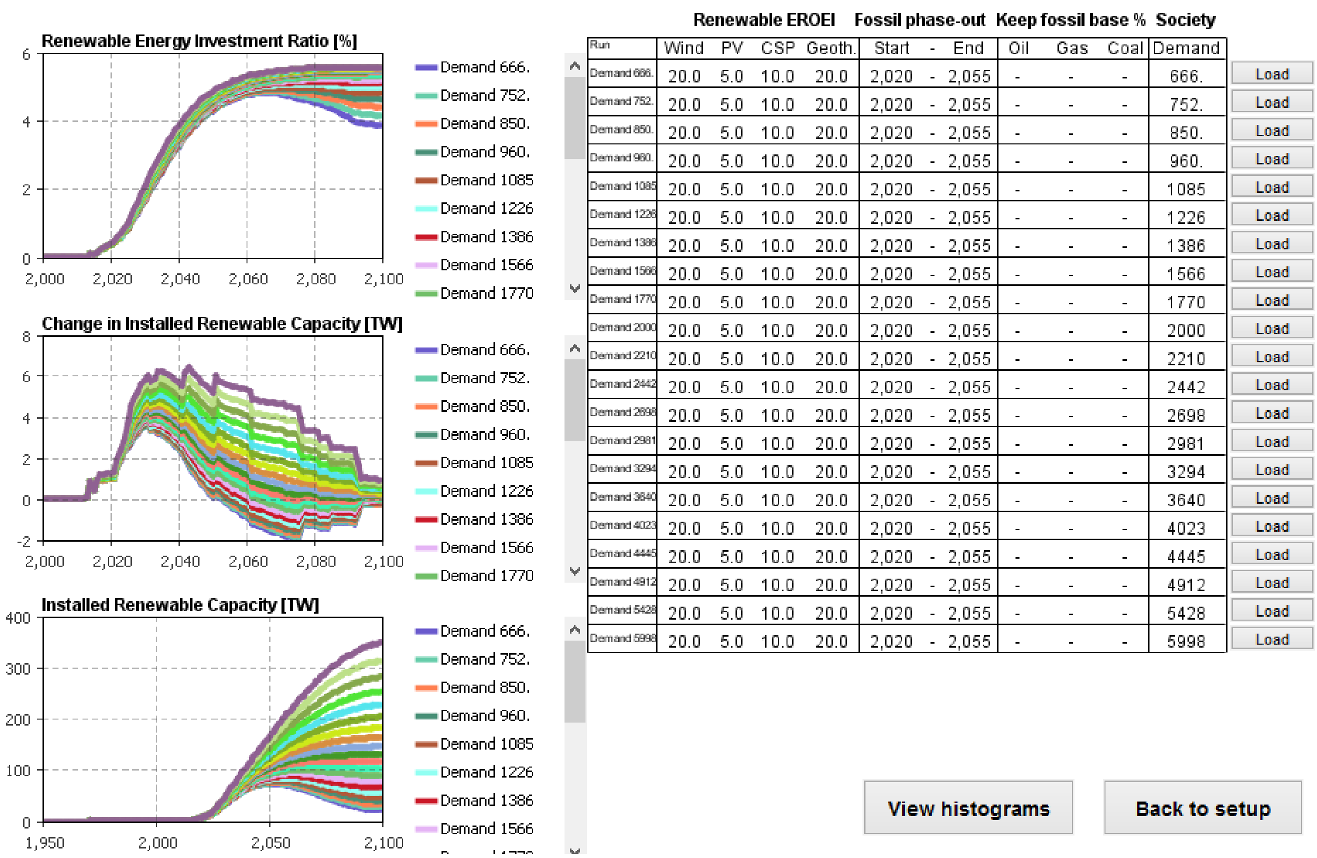

Figure 15 –SET2 sensitivity analysis screen

5. S PRELIMINARY RESULTS

Energy transitions

Using the SET2 model, we conducted a range of experiments for (Sgouridis, Bardi, Csala, 2015, in preparation).

For the global case, we have simulated the transition pathways for 3 different greenhouse gas emissions caps:

- IPCC RCP2.6 median: 990 $GtCO_2$ equivalent budget
- IPCC RCP2.6 low: 510 $GtCO_2$ equivalent budget
- IPCC RCP2.6 high: 1505 $GtCO_2$ equivalent budget

For the global case, we have simulated the transition pathways for 3 different greenhouse gas emissions caps:

- IPCC RCP2.6 median: 990 $GtCO_2$ equivalent budget
- IPCC RCP2.6 low: 510 $GtCO_2$ equivalent budget
- IPCC RCP2.6 high: 1505 $GtCO_2$ equivalent budget

For a median demand of 2000W/capita in year 2100, we have taken a logarithmic scale of 10 step below the value (down to 667) and 10 step above the value (up to 6000).

For an average renewable energy technology EROEI median values of 20 we have taken a similar approach to that of the demand, taking a logarithmically distributed 10 values below, until 6.67, and 10 above, until 60.

Using this sensitivity envelope, we have generated the sustainable energy transition morphology of the world under different greenhouse gas emissions budget constraints, different demands and different renewable technology EROEIs, all of which have some uncertainty attached to them in the literature. The results that we found were quite surprising!

Figure 16 presents the varying fossil fuel phase-out profiles under the 3 different carbon cap scenarios.

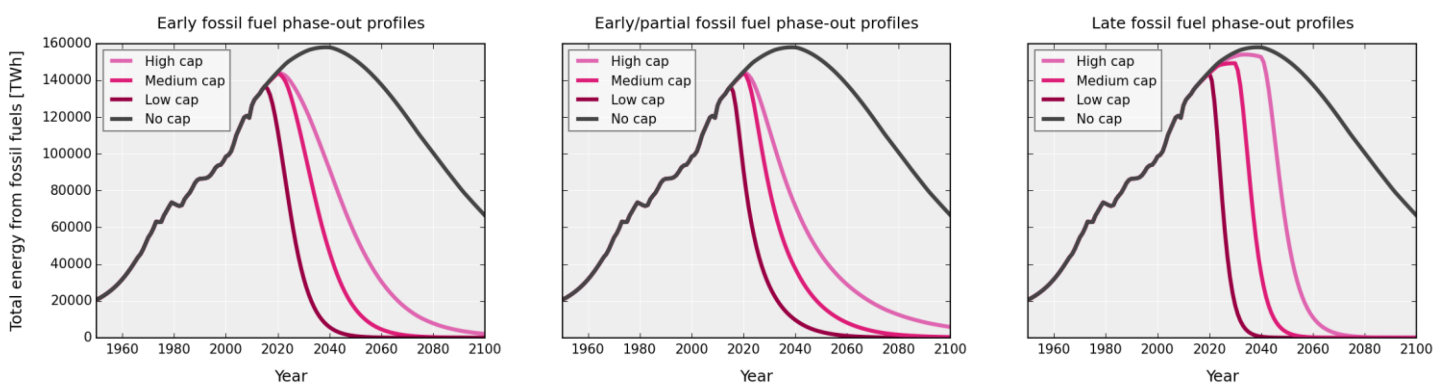

Figure 16 –Fossil fuel phase-out profiles

We can observe that even under the most lenient emissions cap, all fossil fuels must be effectively eliminated by the end of the century. There is an obvious trade-off between delaying the start of the transition and the transition speed – the slope of the phase-out curve. This becomes important when all this fossil energy generation capacity need to be replaced by renewable energy![1]

[1] We must note that we are replacing primary fossil energy with electricity. With the current conversion ratios, this results in at least double-sizing the system. However, given the intermittency and power quality problems of renewables today, this has been judged feasible and plausible.

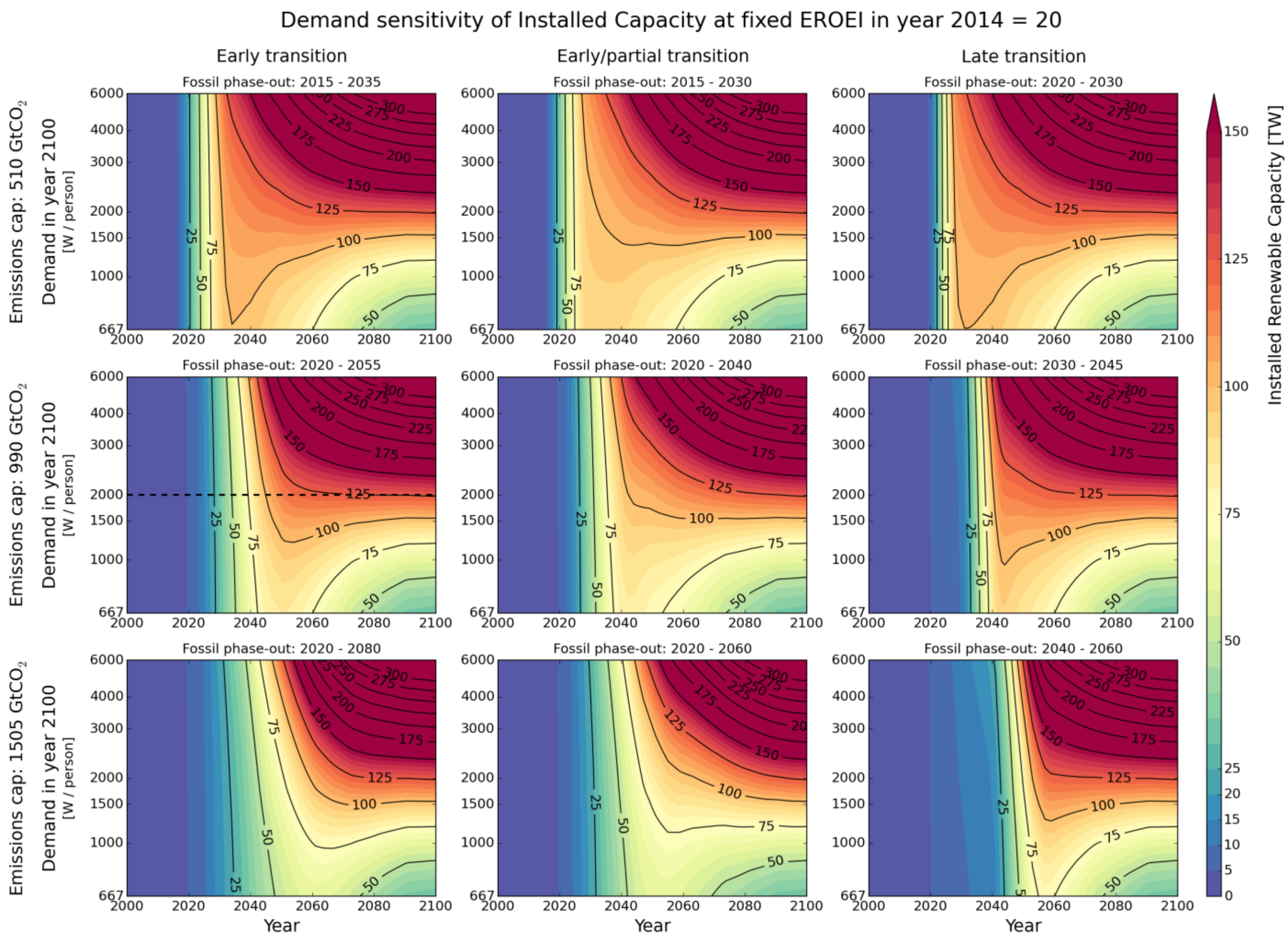

Figure 17 – Demand sensitivity of installed capacity

On Figure 17, we can see a sustainable energy transition morphology for the demand sensitivity (with a starting EROEI of 20) of the cumulative installed renewable capacity. What we can observe is that the contours are almost parallel lines meaning that in the critical initial acceleration phase – the next two decades or so – capacity additions are largely independent of the EROEI and the final demand but critically dependent on the aggressiveness of the required fossil phase-out with corresponding peaks at 5.2, 10.8, and 7.4 TW/year. For reference, in 2013, RE installations were only 0.2TW. Therefore, a successful SET requires a sustained acceleration in the rate of investment in renewable energy of more than one order of magnitude within the next three decades. A delay in the rise of investments cannot be compensated by subsequent additional acceleration because, if we wait too long, the decline in net energy produced by constrained fossil fuels would become insufficient to power the transition in accordance to the proposed guidelines. In addition, attaining SET rests on replacing a large part of the present capital infrastructure (from appliances to buildings and roads) to utilize the new energy resources. Given that there are significant lead times and many investment decisions taken today (road construction, buildings, aircraft) have useful lives of several decades, it is far from certain that their accelerated depreciation will be acceptable. To this the into light, in Figure 18 we have plotted the entire simulation envelope (all EROEIs, all Demands) of renewable installation rates under the different emissions caps. The 2000W lines are highlighted.

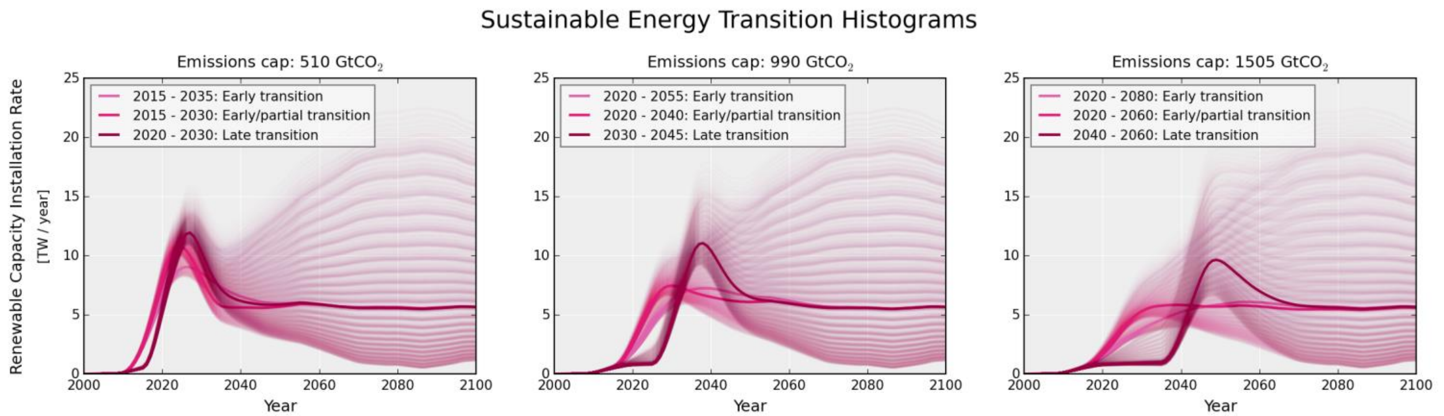

Figure 18 – Renewable capacity installation rates simulation envelope

Food-energy nexus

For this part of the study most of the work has been invested into setting up the database access, querying the database and producing the data visualization to be used a basis for the rest of the data analysis.

According to the International Renewable Energy Agency's (IRENA) 2015 report, renewable energy, coupled with sustainable investment, is the only enabler for keeping the water-energy-food nexus in balance. In contrast to this, the total energy input into the global food system in 2011 was 6929TWh, and the total energy content of the output was 10472 TWh, in the light of total primary fossil energy consumption of 129300TWh. However, the food system's fossil energy input share has hit 81% - up from 61% in 1961, 50 years ago. The Agri-system EROEI was 3.66 in 1961, and 2.35 in 2011. The food-system changed from 2.50 to 1.46: there has been a steady decline in the EROEI of both the food as well as the agri-system, and they number have stabilized on the beginning of the 90s.

So far, we have developed and open-sourced a Sankey diagram Javascript plug-in (Figure 20), which we later used to create aesthetically compelling and functionally effective visualizatios, to provide a visual basis for conducting data analyses of food energy flows by crop types, for all years and all countries.

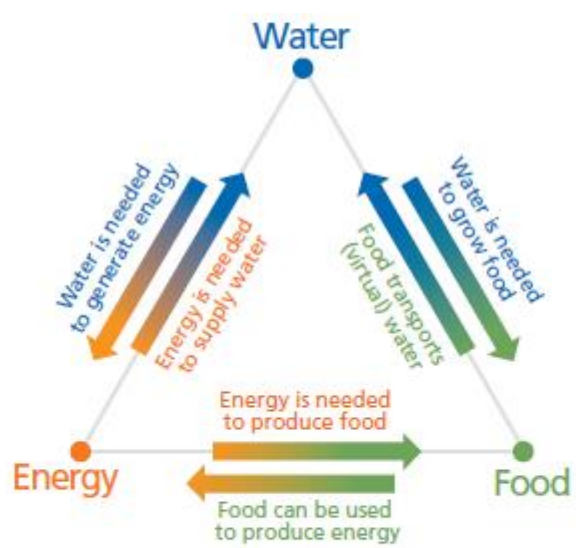

Figure 19 – Water-Energy-Food Nexus Definition by United Nations University

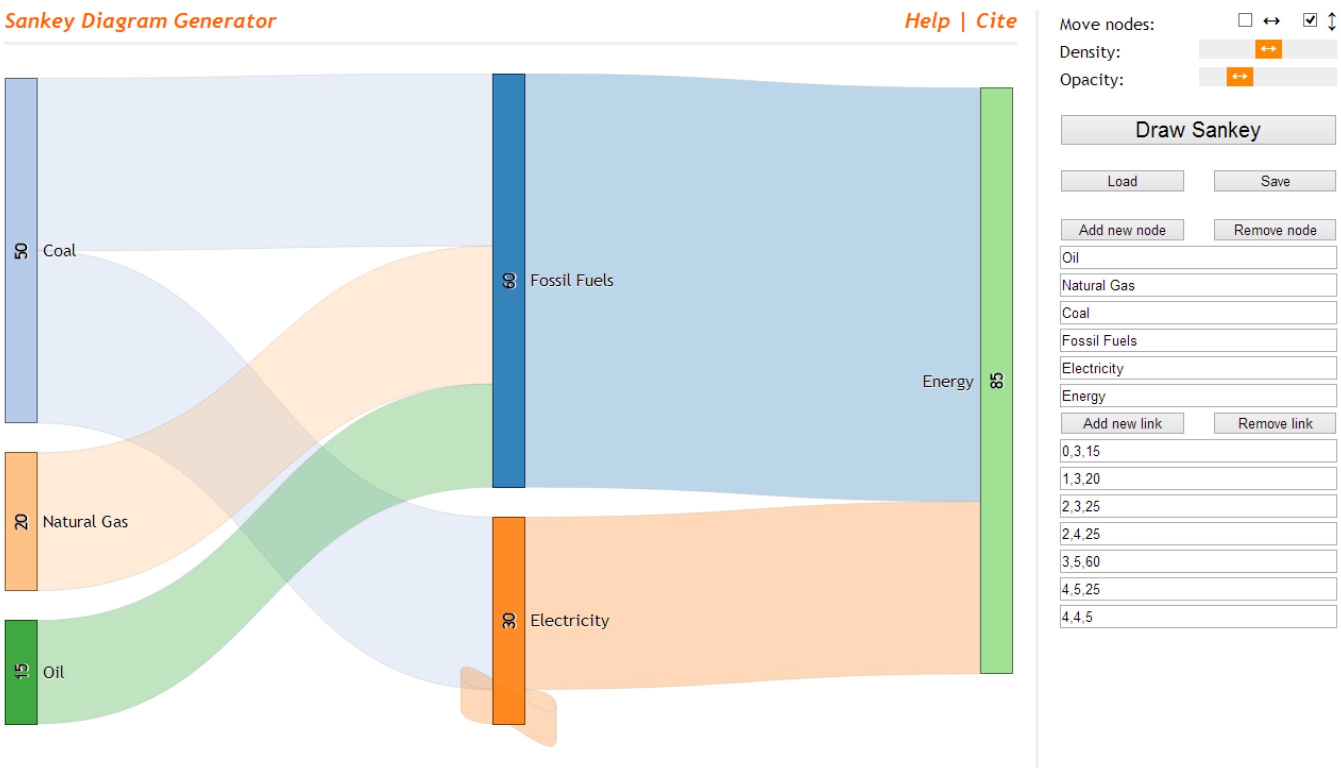

Figure 20 – Sankey Diagram Generator

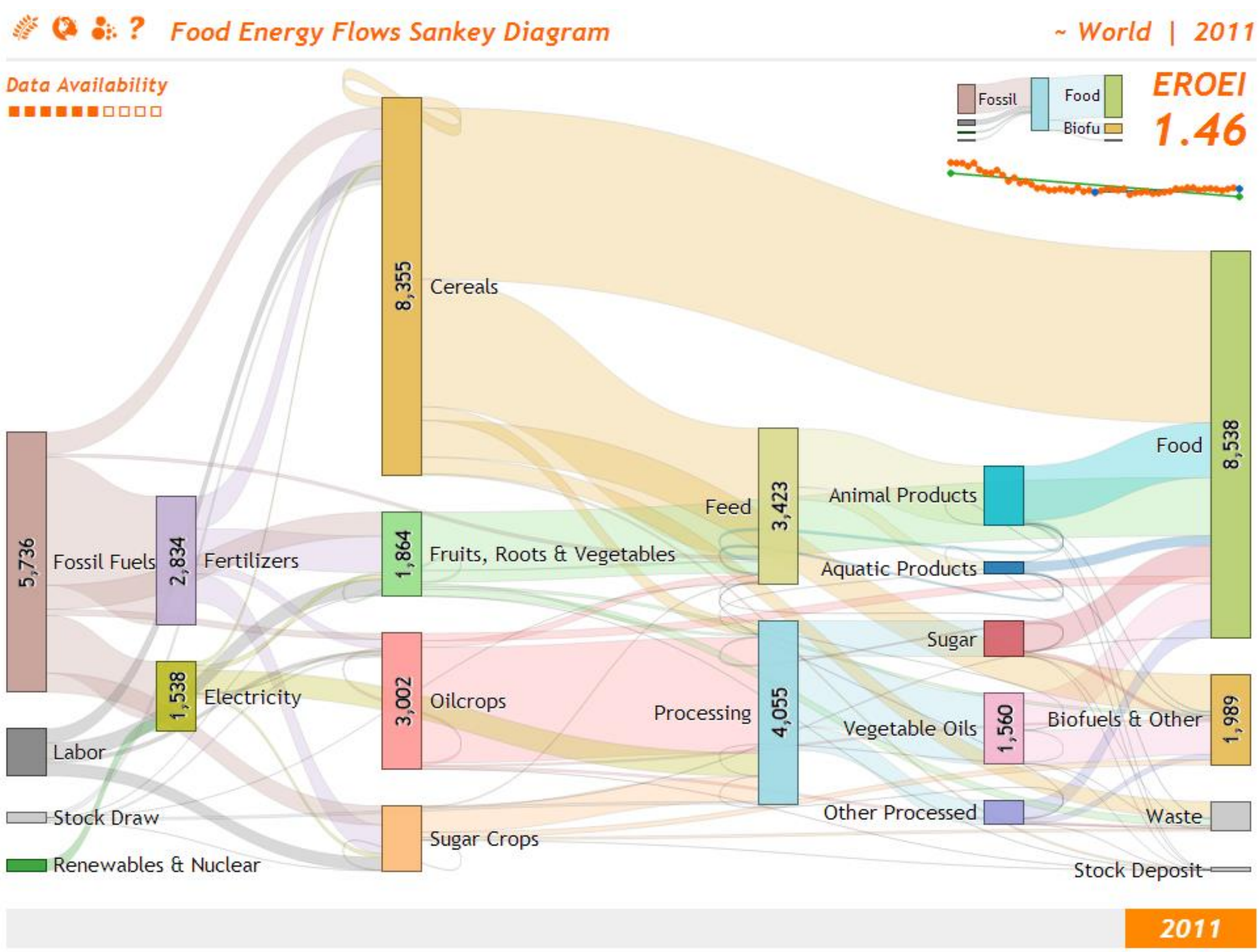

Figure 21 – Global Food Energy Flows 2011

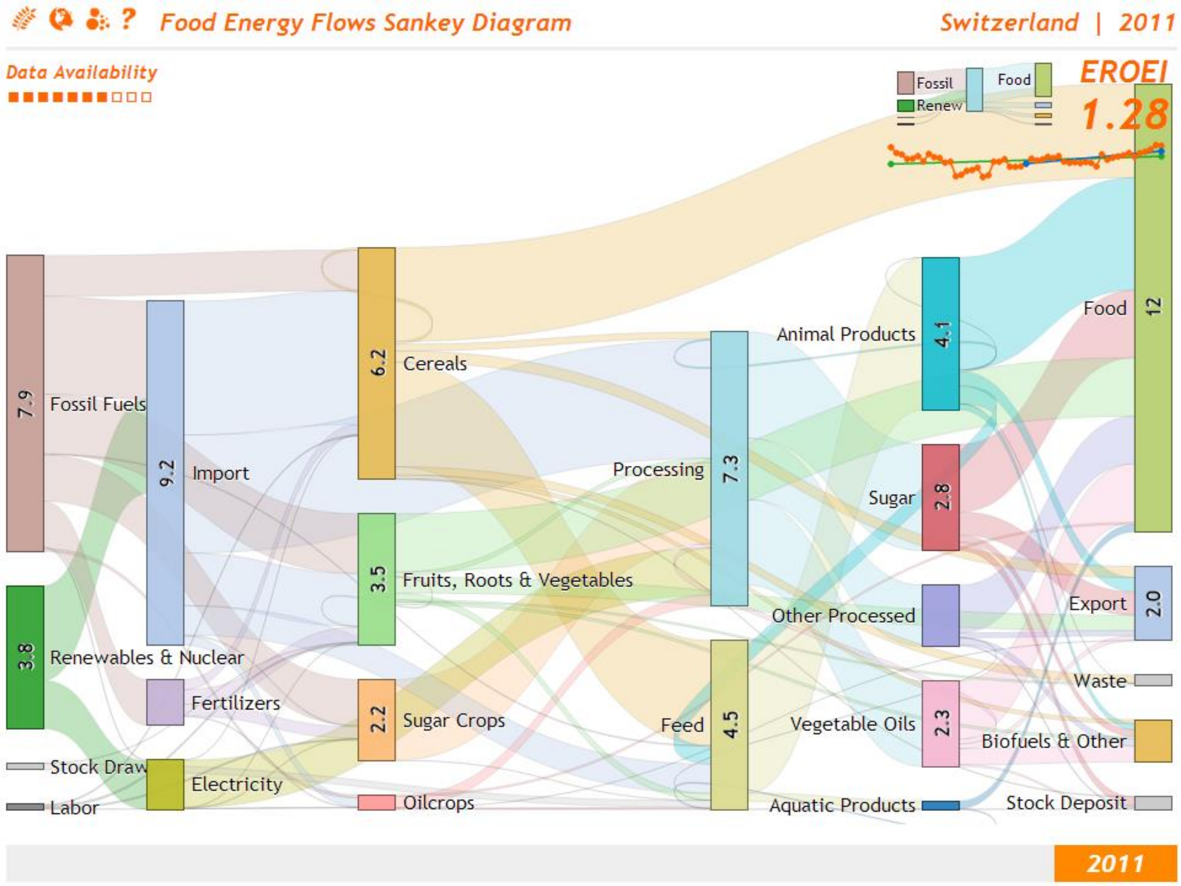

Figure 22 –Switzerland Food Energy Flows 2011

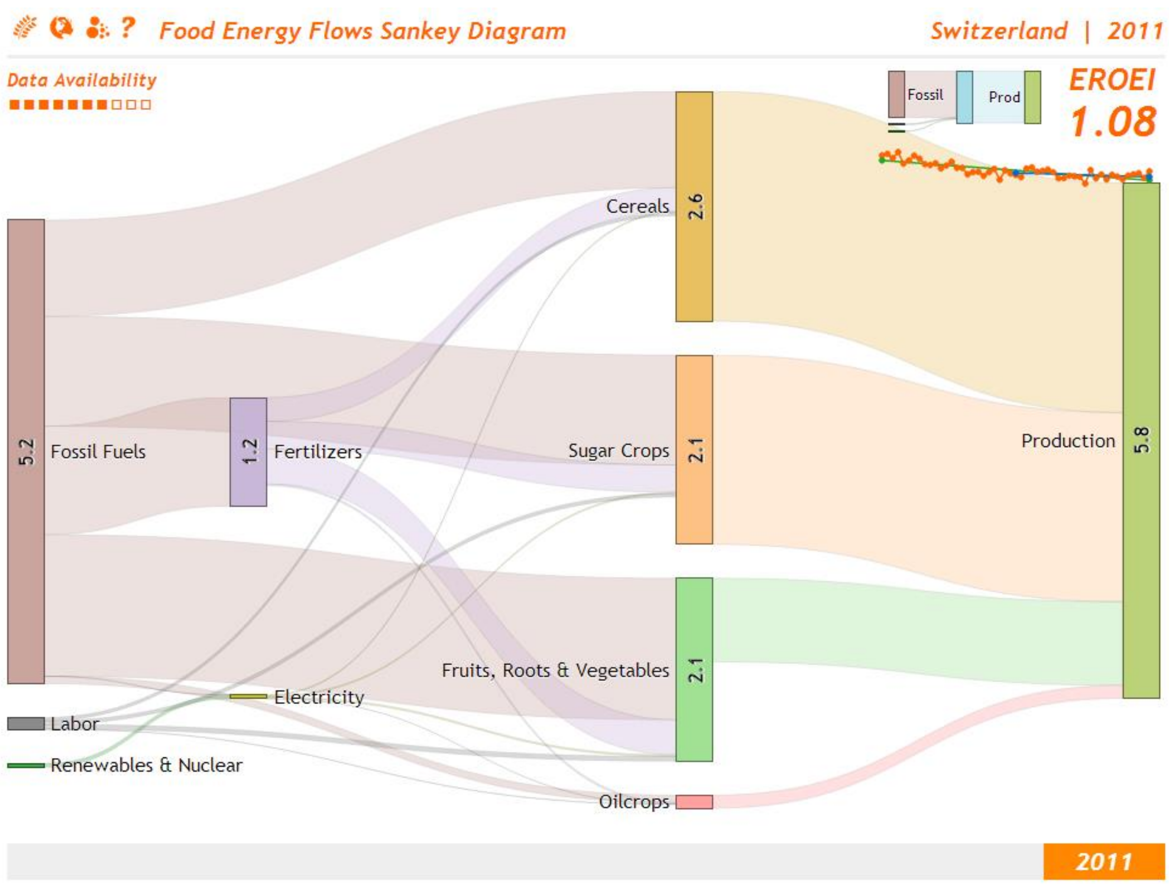

Figure 23 –Switzerland Agriculture Energy Flows 2011

In Figure 21, we have mapped all crop flows for the world, for the year 2011. We can see that most the energy input comes from fossil fuels: 2/3 is expended on fertilizers manufacture and 1/6 and 1/6 goes for electricity and direct use on the land. The largest crop group by energy content are cereals, followed by oil crops. The Processing and Feed stages are the seeds for secondary food products which include processed foods and liquids, animal and aquatic products. Looking at the same data for countries, such as Switzerland (Figure 22), we have to introduce a new category into the energy inputs: Imports.

Let us look at Switzerland as a good example of a mechanized, advanced agricultural system. In Figure 23, only the energy flows of the primary crops are depicted, yielding the picture of the agri-system. Here we can see that most of the energy input comes in the form of fossil energy. However, when switching to the food system view, we can see that as much as 32% if the energy input is, in fact provided by renewable nuclear energy. Then a country imports food, the equivalent monetary value is converted into energy units using the energy intensity of the particular country's economy. Then, that amount of energy is split evenly among the countries generation sources. This methodology ensures a fair accounting of energy use for cheap energy producer and large food importer countries.

6. PROSPECTS

My action plan for the rest of the duration of my PhD at Masdar Institute is to:

- Modify the existing global model (SET2.0) to include
  trade flows and **terrain limitations**
- Parse country-pair-energy-flows from UN COMTRADE/MIT OEC
- Create energy and products import cap mechanism, similar to emissions, using the experience from the food energy flows
- Automate reading of IRENA renewable energy potential maps
- Create renewable depletion mechanism, similar to fossils
- Automatically estimate sustainable energy transition paths for nations based on country terrains and trade flows
- Streamline nexus connections
- Investigate the role of biofuels
- Summarize and analyze per country food energy data
- Decide whether and how to include water data into the analysis
- Summarize results into major research article

Thank you for your consideration,

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