Analysis and comparison of open source energy system models for the derivation of political recommendations for action

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1 Introduction

The transition of the energy system towards a low carbon system leads to an increased complexity in the system and consequently, to more complex energy system models. Due to this high complexity, the demand for transparency rises to ensure the comprehensibility of political decision making as well as the reproducibility of insights gained. Further, more complex energy system models have a greater time demand in developing them, and consequently lead to higher costs. Because of this, open source models are entering the market more and more. Since they are being developed based on certain research questions and for specific purposes there is a high diversity between these models. (Pfenninger, et al., 2014, p. 75; Pfenninger, et al., 2016, p. 211; Behn & Byfield, 2016, p. 5ff)

To systemise and group the models, so that the most relevant models for analysing the German energy system in 2050 can be identified, is the first objective of this work. Afterwards, the models identified are applied in two case studies, reproducing highly relevant scenarios. In the course of these studies it is determined which input data is needed and to what extent open source databases can provide this data. Finally, the last objective is to conclude if these models are capable of providing high level insights into the energy system, so that political recommendations for actions can be derived, based on their capability of reproducing the scenarios.

In the course of this thesis, after the motivation and objectives of the work are discussed, the placement of this work in the field of energy system analysis is clarified. Therefore, an overview of current challenges and situations in the energy field with a focus on the EU and Germany is given. Afterwards a deeper look into energy system modelling is provided by first explaining some basics in system analysis, then giving an overview of the energy system and finally providing insights into the different ways of classifying energy system models. After giving a brief historical discourse on the development of energy system modelling, which ends in the reason for the appearance of open source energy system models, the current status of the open source movement with some definitions is explained.

In the next step, an overview of the existing open source models is provided and these models are typified according to their level of openness. Based on this typification the models are arranged with regards to different criteria such as level of detail or spatial and temporal coverage and the most relevant ones are selected for deeper analysis.

Afterwards, the two most relevant open source models are used to reproduce two highly relevant energy scenarios, which are the "EU reference scenario 2016" (Capros, et al., 2016) based on the commercial model PRIMES and the reference scenario of the leading German study for the transition of the energy system “Langfrist- und Klimaszenarien” (Pfluger, et al., 2017) (long-term- and climate scenarios) analysed by Fraunhofer ISI et al.. At the end of this part, the scenario results of the open source models are compared with the original scenarios and the capability of open source models to create relevant insights is discussed. The outcomes of the study are summed up and analysed in the conclusion, a critical reflection of the methodologies applied is given and an outlook is provided.

2 Analysis, Comparison and Evaluation of Open Source Models

In the beginning, 40 open source models are compared and analysed in more detail. Therefore, first the models are typified according to their level of openness as Figure 1 illustrates.

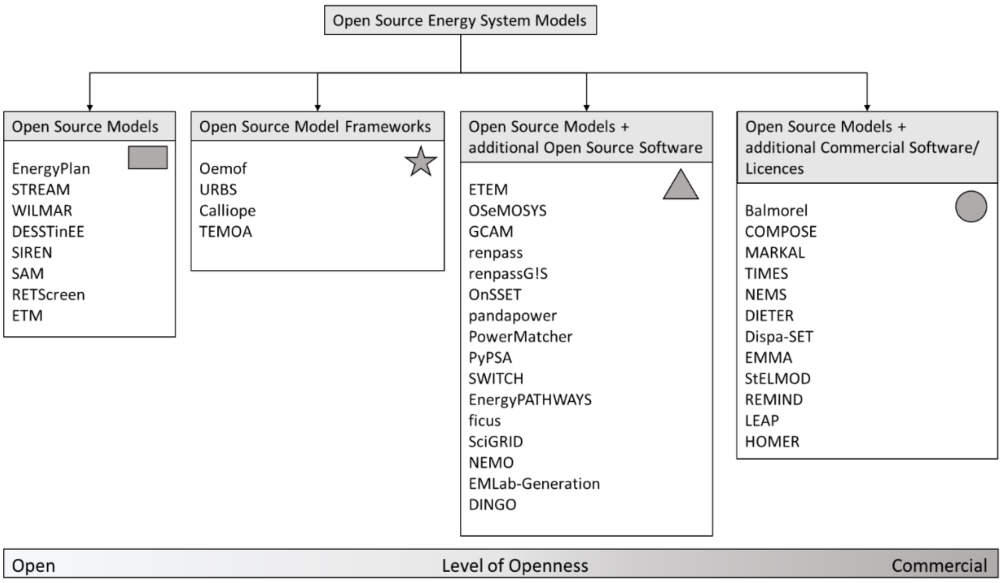

Figure 1: Typification of Open Source Models analysed (Own illustration)

The highest level of openness includes models which can be downloaded directly and used without needing additional software. In another group the open source frameworks are included, acting as toolboxes out of which single code parts can be selected and implemented creating a model, so that afterwards a system can be analysed. This leads to a greater time demand before the analysis can start. The next group are open source models needing additional open source software, such as open source solvers or programming languages, so that a certain amount of time is needed to download this software and check its compatibility. Finally, the last and least open group includes models needing additional commercial software. Often these models are only published with their source code and additional programming environments need to be bought, such as GAMS (GAMS, n.d.). Also included in this group are models needing a licence, as is the case for LEAP (Heaps, 2016), offering free access to the licence for some users, like universities and developing countries, but not all users, so that the accessibility is limited.

Comparing the methodologies used within the model types showed a tendency for the fully open models to be simulation models, whereas all open source frameworks use the optimisation methodology. For models of the type with less openness, a tendency towards the optimisation methodology can also be seen.

In a next step, based on the typification, the models are systemised and compared according to certain criteria. Comparing the criteria of time slices and whether transformation paths are included, showed a tendency that models from the highest level of openness analyse one year and not a transformation path including a couple of years. The comparison of the geographical and sectoral coverage demonstrates a high diversity even within the different types of openness. Further, focusing on the level of technological detail and the level of endogenisation the models settle around the medium level of both criteria, showing a tendency that the highest open models have a rather medium to low technological detail as well as level of endogenisation. This insight leads to the assumption that current models, grouped in the highest level of openness, implement a rather low level of complexity. Finally, the models are systemised according to their time resolution and spatial granularity, illustrating that the highly open models tend to have a rather low spatial resolution but high time resolution.

According to this systematisation, the most relevant models to analyse the German energy system in 2050 are selected. Therefore, the focus is on the highest level of open models, in which eight models are included. According to a procedure of exclusion focusing on certain features the models should have, such as high geographical and sectoral coverage, DESSTinEE (Staffell & Green, 2015) and EnergyPlan (Aalborg University, 2015) are identified as most relevant.

Both models have been used to analyse the German energy system as well as having a high sectoral and geographical coverage. Further, EnergyPlan implements the Smart Grid approach focusing on sector coupling and DESSTinEE is based on the Super Grid vision including 40 countries from Europe and North Africa.

3 Case Studies

To investigate the question of how capable open source models are of providing highly relevant insights for the derivation of political recommendations for action, two case studies are conducted. In these case studies the selected open source models are used to reproduce highly relevant energy scenarios, hence DESSTinEE is used to reproduce the EU reference scenario 2016 and EnergyPlan is applied for the reproduction of the reference scenario from the German long-term and climate scenarios.

3.1 DESSTinEE and the EU reference scenario

As one of the European Commission's key analysis tools for energy, transport and climate, the EU reference scenario provides important insights into where current policies and market developments will lead (Directorate-General for Energy, 2017). To create such important insights a set of models is applied, in which the central role, to create a price-induced market equilibrium, is played by the model PRIMES. (E3MLab/ ICCS, 2014, p. 7-17)

PRIMES is a hybrid model calculating a price-driven partial equilibrium across 35 countries in 5 year time steps from 2010 until 2050 (E3MLab/ ICCS, 2014, p. 25), whereas DESSTinEE is a bottom-up model simulating an equilibrium across 40 countries based on a multiregional merit-order stack in hourly time steps from 2010 and 2050. Both models are very different in the methodology integrated, influencing the accuracy with which DESSTinEE can reproduce the reference scenario.

Updating the DESSTinEE input data is a quite difficult and time-consuming procedure, even though the data basis is the EU reference scenario. Due to a lack of documentation, it is not clear what unit or currency is used for some of the parameters. This is, for example, the case for the currency of the GDP. Furthermore, some data is needed in quite a high level of detail, such as the energy mix 2010 of each sector, which is not provided in as much detail in the reference scenario, nor by an open source database, so that a commercial database must be used. Moreover, the conversion of the data so that it matches the conventions of the open source model is very time consuming, such as is the case for the GDP growth development index or the efficiency improvement index. The convention of the power plants considered for the definition of the installed capacity also does not match the convention of the reference scenario, so that splitting according to initial shares is necessary.

Additional studies and databases are only needed to a lesser degree in this case study, those being mainly Eurostat (Eurostat, 2017) and the World Bank (The World Bank Group, 2018). The fact that these sources are also used in the reference scenario reduces the danger of including deviations with the input data. Open source databases could not provide data which was needed but not included in the reference scenario.

The results of the first case study show that the data included, such as generating capacity (Figure 2) and final energy demand 2010 (Figure 3) match the original data quite well.

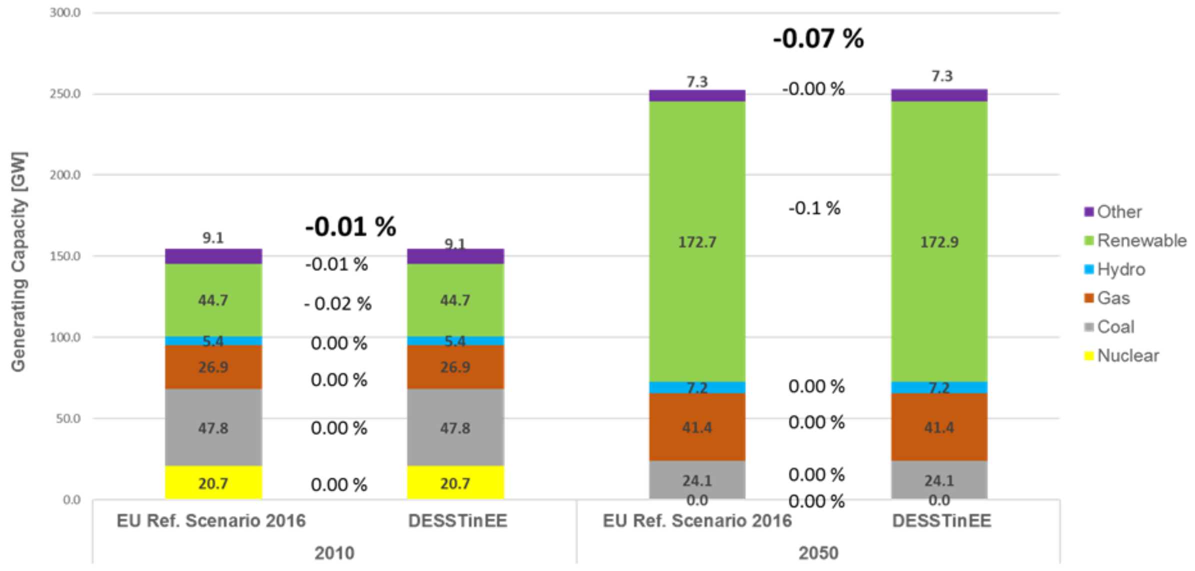

Figure 2: EU Reference Scenario - DESSTinEE; Generating Capacities (Own illustration based on Staffell & Green, 2015)

But the values defined by the model endogenously such as final energy demand 2050 (Figure 3) exhibit considerable differences.

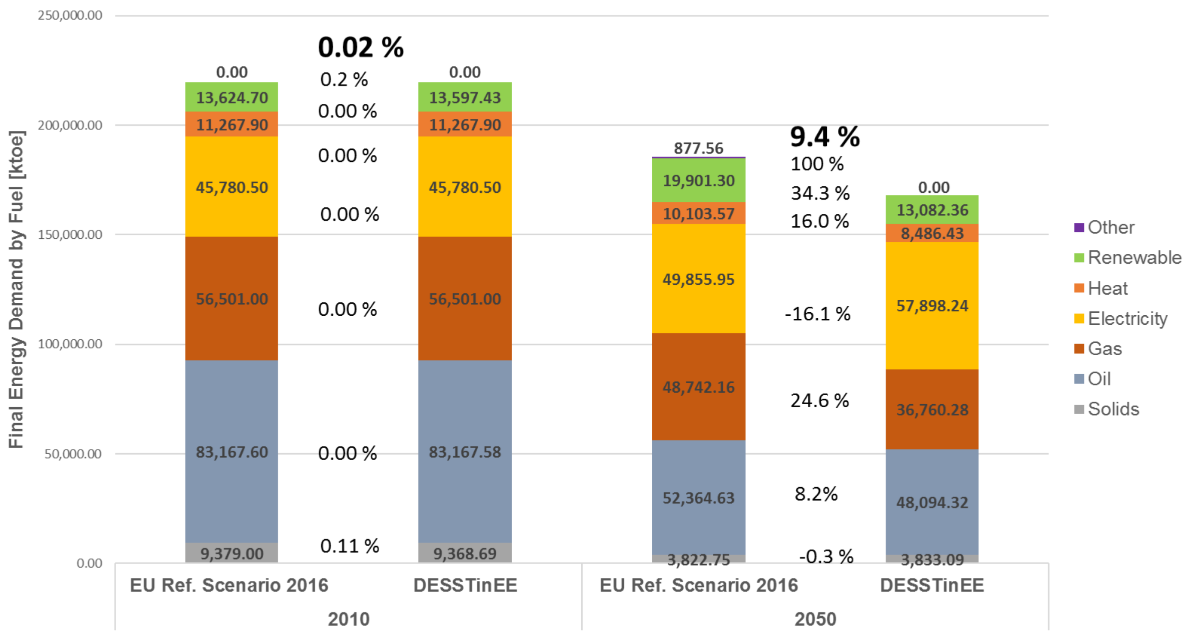

Figure 3: EU Reference Scenario - DESSTinEE; Final Energy Consumption by Fuel (Own illustration based on Staffell & Green, 2015)

The deviations are mainly caused by assumptions in the model, such as development of sectoral GDP share, as well as the lack of documentation, causing possible mishandling of the model and errors in including the input data.

Further, the electricity generation (Figure 4) calculated by DESSTinEE varies in a great deal from the original scenario results.

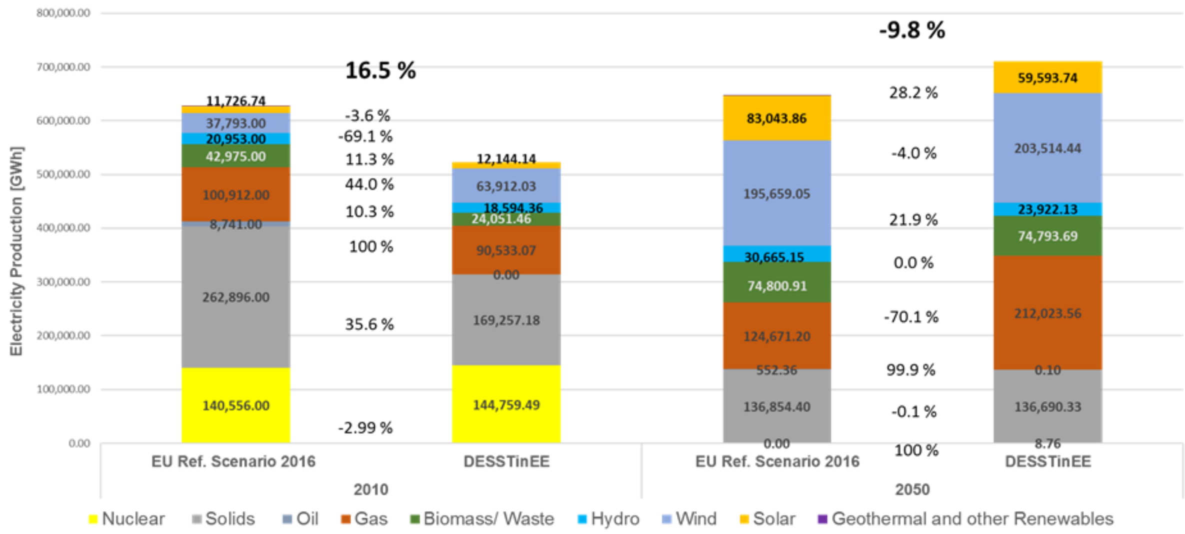

Figure 4: EU Reference Scenario - DESSTinEE; Electricity Production (Own illustration based on Staffell & Green, 2015)

Because the reference scenario and DESSTinEE are based on different methodologies, geographical coverage and level of detail of transmission restrictions considered, the high degree of variation occurs between the electricity productions that are determined, leading to deviations in the share of renewable energy in gross power generation, primary energy consumption and CO_2-Emissions.

Overall DESSTinEE has a high potential to provide interesting insights into the energy system. However, further development is necessary, especially in the detail of the documentation, but also in the complexity of the model itself. The high level of detail of the input data needed by the model leads to a high time demand in applying the model. Finally, the large deviations between the results from DESSTinEE and the reference scenario lead to the conclusion that the model is not able to reproduce the scenario with a certain level of accuracy. Consequently, there are doubts to what extent DESSTinEE is capable of providing highly relevant insights into the energy system for the derivation of political recommendations for action.

3.2 EnergyPlan and the German reference scenario

In the course of the projects "long-term and climate scenarios" scenarios are being developed to investigate transformation paths towards a GHG neutral energy system in Germany by 2050 (BMWi, 2017, p. 2f). The reference scenario of these projects is the only one that does not include the energy and climate targets for 2020 and consequently will not fulfil them, representing the fictive case that Germany phases out the energy transition. This scenario provides insights into how much the energy system would still cost without political actions towards decarbonisation. A set of models creates the highly relevant insights and the model Enertile, a cost-driven optimisation model, is at the centre of this model set. (Pfluger, et al., 2017, p. 21f)

EnergyPlan and Enertile implement both the bottom-up approach and cost-driven optimisation of the energy system with sector-coupling focusing on integrating fluctuating renewable energy. Both models exogenously integrate the hourly demand values, but Enertile determines the solar and wind power outputs endogenously, which are defined exogenously for EnergyPlan. While Enertile determines endogenously if heat demand is solely satisfied or combined with electricity demand through CHP units, EnergyPlan needs an exogenously defined simulation strategy. Lastly, the geographical level of Enertile is far bigger than that of EnergyPlan. Enertile focuses on Germany but also considers the energy systems of Europe, North Africa and the Middle East. Furthermore, the downstream models implemented in the model set of the reference scenario include a high resolution for grid connection between and within the different countries, whereas EnergyPlan considers interconnections with other energy systems solely by defining one transmission line capacity to limit trading. (Fraunhofer ISI, 2018)

With respect to the input data, the exogenous hourly distributions for demand, supply and price cannot be integrated based on the reference scenario nor from an open source database. Therefore, the reference dataset of EnergyPlan is used and adjusted to the annual values. Further, the high aggregation level of conventional technologies in the open source model leads to the need to integrate average values, for example for the marginal costs of the different power plants, resulting in deviations particularly in the electricity production mix reproduced (Figure 5).

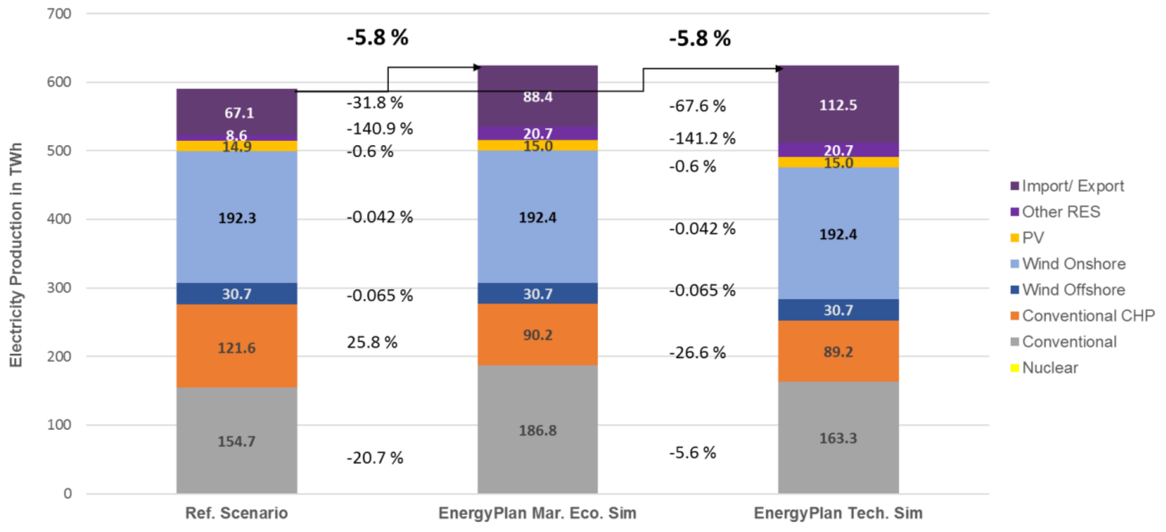

Figure 5: German Reference Scenario - EnergyPlan; Electricity Production in 2050 (Own illustration based on Aalborg University, 2015)

With a deviation of -5.8%, the total annual electricity production is quite close to the original reference scenario values. A more detailed look into the different power plants reveals some larger deviations between export/ import as well as conventional CHP and conventional power plants, mainly caused by the exogenously implemented hourly price distribution, hourly wind and solar power outputs as well as average marginal costs.

With respect to the hourly results of EnergyPlan larger deviations can be seen (Figure 6 and Figure 7).

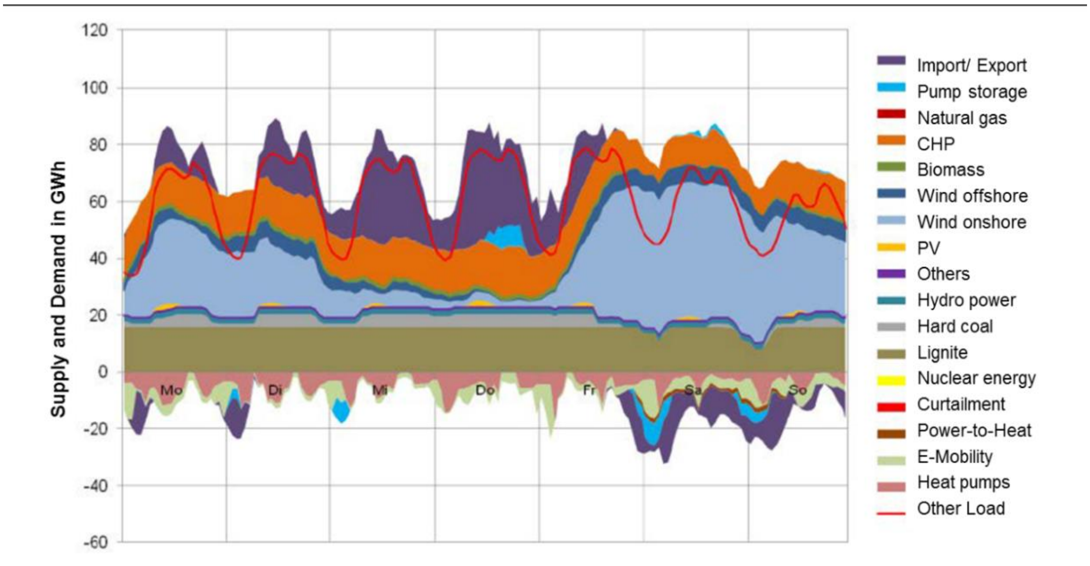

Figure 6: Hourly electricity production Germany week 2 in 2050 from German reference scenario (Pfluger, et al., 2017, p. 170)

A far more detailed analysis conducted in the reference scenario, with endogenously calculated hourly distributions for demand and supply, as well as integrated transmission restriction on a nodal level between and within countries lead to the differences. Nevertheless, some general similarities can be observed, such as high share of onshore wind and compensation of wind fluctuations with import.

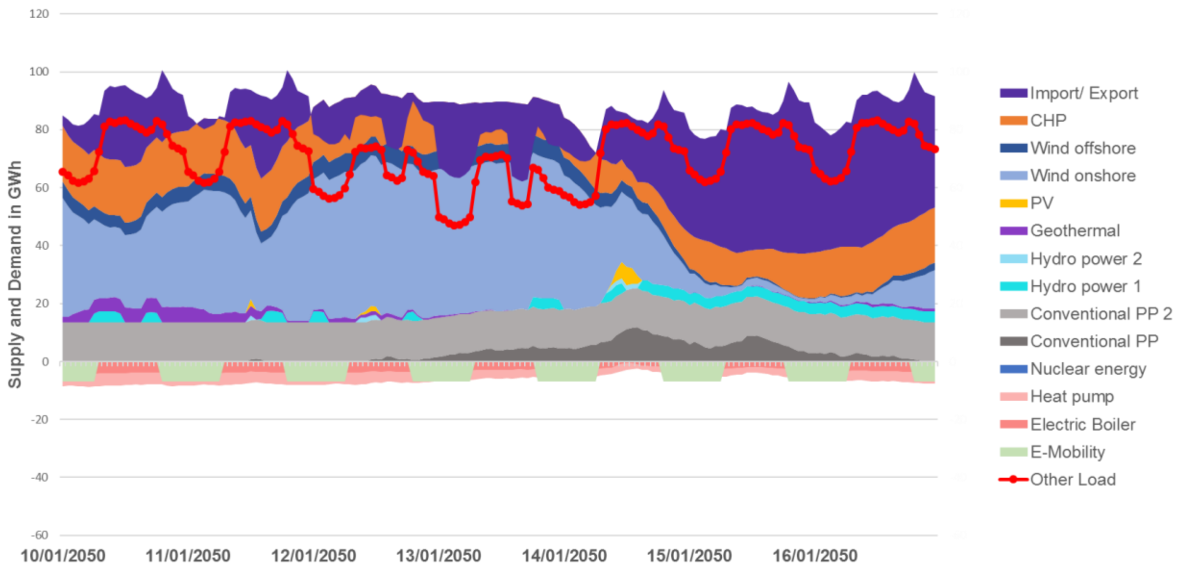

Figure 7: Hourly electricity production Germany week 2 in 2050 from EnergyPlan (Own illustration based on Aalborg University, 2015)

For the share of renewable energy in electricity production, GHG-Emissions, CO_2-Costs and annual investment costs the results reproduced almost match the original results.

Overall it can be concluded that EnergyPlan is capable of reproducing the annual values of the reference scenario well enough, so that it can be assumed that it could be able to provide highly relevant insights into the energy system on a lower time resolution for the derivation of political recommendations for actions with some limitations. It is limited by its fixed structure and lack of accessible source code.

4 Conclusions, critical appraisal and outlook

The analysis of the 40 open source models indicates that the models exhibited a high degree of diversity. Even after typifying the models according to their level of openness, conclusions for one type of model are not always possible.

Fully open source models still have the potential to be more endogenous and to implement a higher level of technology detail, meaning that the complexity of the models could still be increased, which could lead to a higher time demand in preparing documentation. Furthermore, the potential for implementing transformation paths and higher spatial resolution has not yet been fully exploited.

In the first case study the data search process for DESSTinEE implies that there is a considerable risk of including differences between the DESSTinEE values and the original scenario results due to the limited level of documentation and high level of detail needed for the exogenously included data.

Based on the comparison of results gained from DESSTinEE with the original scenario results, it can be concluded that DESSTinEE is an open source model with a considerable potential to provide interesting insights into a super grid energy system, but it needs further development. In the course of this work the lack of documentation increases the time needed to apply the model to any great degree as well as increasing the level of potential errors. Further, the large amount and detail of input data needed is another source of errors directly included in the model. This work shows that with the current status, DESSTinEE is not able to reproduce the EU reference scenario to a reliable level and consequently, there are doubts as to the extent to which the model is capable of providing high level insights for the derivation of political recommendations for action.

In the second case study, the model EnergyPlan is used to reproduce the results gained from Enertile. It is interesting to point out that even though the level of endogenisation is slightly higher for DESSTinEE, due to its determination of hourly values, the overall time needed to provide the input data in the right convention is far higher than for EnergyPlan. This is also due to the more aggregated technologies implemented in EnergyPlan.

Neither case study uses data from open source databases, even though such databases are increasingly accessible. Eurostat and the World Bank database are the main sources that can be used. Other databases simply could not provide the necessary data in a detailed enough manner.

Overall, EnergyPlan seems to reproduce the annual German reference scenario quite well, leading to the assumption that it could be capable of providing highly relevant insight on an annual level for the derivation of political recommendations for action albeit with some limitations. It is limited by a rather high amount of exogenous input data and its fixed structure of the energy system with its technologies, limiting the purpose for which the model can be used.

Reflecting on the methodology used in the course of this thesis, it can be seen that it would have been useful to include the availability of open source licences and the level of documentation in the selection process of the relevant open source models. If the licensing had been considered it would have been clear at an earlier stage that EnergyPlan is solely freeware and not really open source, and consequently its modification level is rather limited.

Furthermore, a selection including level of detail of documentation would have prevented the usage of DESSTinEE, leading to a lower time demand. The lack of documentation for DESSTinEE also limits the possibility of evaluating the capability of the model to generate high level insight into the energy system.

Based on this work, an open source model can be implemented taking into consideration the potentials identified by the systematisation of the different models. Furthermore, it could be interesting to analyse open source frameworks as well as the combination of different open source models in more detail.

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