The modelling of future energy scenarios for Denmark

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The modelling of future energy scenarios for Denmark

PhD Dissertation

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This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Abstract

The contributions of this PhD dissertation are in three main areas. In the first main area, existing energy scenarios - The Danish Society of Engineer's IDA 2050, the large research project CEESA, and the Danish Climate Commission's CC2050 are compared. Second, energy system analyses for the important but uncertain areas biomass and flexible demand are performed. Thirdly, modelling-related issues are investigated with a focus on the effect of future forecasting assumption and differences between a predefined priority order and order determined by given efficiencies and constraints.

Transformation from a conventional fossil-fueled energy system to a 100% renewable energy system is not an easy task, however, it is a necessary goal to be attained. Academic and governmental bodies in Denmark have released several projects on future scenarios free from fossil fuel by year 2050.

Three existing energy scenarios commonly conclude that a 100% renewable energy system in 2050 is feasible both technologically and economically. The three scenarios assume similar technology options, but different rates of usage. For example, the IDA 2050 scenario establishes an energy system dependent on more biomass than the other scenarios but also a system more self-reliant in terms of electricity with the least international interconnection capacity. The CC2050 scenario builds a more electrified energy system through producing weather dependent, thus intermittent RES rather than biomass and integrating more closely with neighboring countries with the largest interconnection capacity among the three. The CEESA scenario is located between the two scenarios in that sense.

Two scenarios, CEESA and IDA 2050, are compared by methodologies and results. Compared to IDA 2050, CEESA adopts three models external from the overall energy system model for analyzing three subjects which are important but uncertain areas in the future. The first model is a consequential LCA analysis for biomass potential. The second model targets transport demand due to uncertain technology development in the future transport sector. The third model addresses grid stability with a high time resolution. As a result of the consequential LCA, the potential of biomass is less than that of IDA2050. The reduced biomass potential in turn requires larger non-biomass RES capacity, which necessitates a larger capacity of flexible means as a chain effect. Especially, CEESA assumes a new technology more prevalent than IDA 2050 as a mean of reducing biomass in transport sector.

The potential of biomass is regarded as one of the most influential factor in future energy system as explained. However the availability of biomass is uncertain since there might be limits on the environmental capacity and opposition against biomass usage for societal and political reasons in the future. For clarifying better usage of biomass in a 100% renewable energy system, biomass usage for either heat production or electricity generation is compared in this thesis by assuming a decrease of biomass availability for the electricity and heat sectors respectively. The base line scenario for reducing biomass is set to be IDA 2050. The results show that reduction of biomass use in the heat sector could reduce biomass consumption with less electricity exported than the reduction of biomass use in the electricity sector. The less cost solution is achieved through reducing biomass for heat production compared to reducing biomass for electricity production.

Among the technologies supplying flexibility to the system in the future, this PhD dissertation focuses on flexible demand since this subject is less studied in a coherent energy system level than the other flexible means. The potential of flexible demand is assessed in two approaches. The first approach is a technical and bottom-up approach decomposing the electricity consumption into several processes and assesses the potential of flexibility within individual processes. The second approach is a top-down approach to find the

level of flexible demand that makes a significant impact on the energy system. For the bottom-up approach the processes are categorized with three criteria; storability, controllability and whether process is interlocked with other processes or independent. The first two criteria are used for assessing flexible demand in residential and commercial sector, and the last criterion is added for the assessment for the industry processes. The results show that 24% of the electricity demand can be moved within a time frame of two hours and approx. 7% of the electricity demand can be moved within a time frame of 24 hours. The system benefit at the assessed amount of flexible demand is limited however. Results from the other analysis indicate that in order to have a significant impact on the energy system performance, more than a quarter of the classic electricity demand would need to be flexible within a month, which is highly unlikely to happen.

For the investigation of the energy system model, EnergyPLAN, which is used for two scenario analyses, two questions are asked; "what is the value of future forecasting assumption in the model?", and "what is the difference between descriptive and prescriptive model?" For answering these questions, a linear optimization model is created with the ambition to emulate the EnergyPLAN model. The IDA 2050 scenario is used for common scenario for the emulation. Two of the main differences between EnergyPLAN and the created linear optimization model are a) that EnergyPLAN uses an endogen priority of technologies while priority in the linear model is given by efficiencies and b) the linear model could make use of the full set of exogenously given future hourly production and demand values if permitted by user.

Regarding the comparison results of these two models, total fuel consumption for dispatchable plants in the linear optimization model is less than that of EnergyPLAN by 11%. Most of the difference comes from the difference in condensing mode power plants. Except in the condensing mode power plants, the fuel consumptions of CHPs and boilers, irrespective of which district heating grid, are similar in both models.

Despite of the differences in the dispatch order for heat production of CHPs between two models, the overall results are similar since the electricity dispatch order override the heat generation dispatch order, and the electricity dispatch order is similar in the two models due to the chosen efficiencies.

The linear optimization model assumes perfect knowledge about the future in any given situation, and the demands can hence to a greater extent be meet by efficient plants compared with non-perfect knowledge, which results in a reduced fuel consumption. EnergyPLAN bases its production on the specific conditions in each hour, and only uses a limited knowledge about future situations. When the time frame of future forecasting is reduced to a week from a year, the fuel consumption is increased from the one year time frame but less than the case of no future forecasting assumption.

Dansk Resumé

Bidragene fra denne Ph.d. afhandling kan inddeles i tre hovedområder. I det første hovedområde sammenlignes eksisterende energiscenarier – Ingeniørforeningens Klimaplan 2050 (IDA2050), forskningsprojektet CEESA og Klimakommissionens (CC2050). I andet udføres energisystemanalyser af biomasse og fleksibelt forbrug, som er både vigtige men usikre områder. I tredje undersøges modelleringsrelaterede spørgsmål med fokus på effekten af antagelser om fremtiden og forskelle mellem en forudbestemt prioriteringsrækkefølge og en rækkefølge bestemt af virkningsgrader og begrænsninger.

Omdannelsen fra et konventionelt energisystem baseret på fossile brændsler til et 100 % vedvarende energisystem er ikke en nem opgave, men det er nødvendigt at nå dette mål. Akademiske institutioner og regeringsinstanser i Danmark har udarbejdet flere forskellige projekter omhandlende fossilfri fremtidsscenarier for år 2050.

Tre eksisterende energiscenarier konkluderer, at et 100 % vedvarende energisystem i 2050 er både teknisk og økonomisk mulig. De tre scenarier antager lignende teknologiske løsninger, dog med en forskellig fordeling af de enkelte teknologier. For eksempel anvender IDA2050 scenariet et energisystem, der er mere baseret på biomasse end de andre scenarier, men også et system, der er mere selvforsynende med elektricitet og med lavest kapacitet af udenlandsforbindelser. CC2050 scenariet er det mest elektrificeret energisystem, der dels anvender mere fluktuerende vedvarende energi, og er mere integreret med nabolandende igennem større kapacitet af udenlandsforbindelser end de andre to scenarier. CEESA scenariet kan, målt på disse parametre, placeres imellem de to andre scenarier.

To scenarier, CEESA og IDA2050, sammenlignes ift. metoder og resultater. Sammenlignet med IDA2050 anvender CEESA tre modeller eksterne fra den overordnede energisystemmodel til at analyser tre forskellige emner, som er vigtige i fremtiden. Den første model er en livscyklusanalyse af biomassepotentialet. Den anden model adresserer transportbehovet ift. usikkerheder i teknologiudviklingen inden for fremtidens transportsektor. Den tredje model ser på stabilisering af elnettet med en høj tidsopløsning. Som et resultat af livscyklusanalysen findes der frem til, at biomassepotentialet er mindre end i IDA2050. Dette reducerede biomassepotentiale øger behovet for andre typer vedvarende energi, hvilket nødvendiggør en større mængde fleksible løsninger. CEESA antager derfor en større udbredelse af syntetiske brændsler som et middel til at reducere biomasseforbruget i transportsektoren.

Som forklaret, betragtes biomassepotentialet som en af de vigtigste faktorer i et fremtidigt vedvarende energisystem. Tilgængeligheden af biomasse er dog usikker, da der er både naturlige begrænsninger og stor modstand mod anvendelsen af biomasse ud fra samfundsmæssige og politiske begrundelser. For at klarlægge en bedre anvendelse af biomasse i et 100 % vedvarende energisystem, sammenlignes biomasseanvendelsen inden for varme- og elektricitetsproduktion i denne Ph.d. afhandling ved at antage et fald i biomassetilgængeligheden for disse sektorer. Referencescenariet for reduceringen er IDA2050 scenariet. Resultatet viser, at en reduktion af biomasseforbruget i varmesektoren vil reducere elektricitetseksporten mere end en reduktion af biomasseforbruget i elektricitetssektoren. Der opnås færre omkostninger ved at reducere biomasseforbruget i varmesektoren end ved reduktion af biomasse i elektricitetssektoren.

Blandt teknologier, der kan levere fleksibilitet til fremtidens system, fokuserer afhandlingen på fleksible elektricitetsbehov, da dette emne kun er undersøgt i mindre grad på energisystemsniveau end andre fleksible teknologier. Potentialet for fleksibelt elforbrug er vurderet ud fra to fremgangsmåder. Den første er en teknisk bottom-up tilgang, som opdeler elektricitetsforbruget i flere processer, og bedømmer potentialet for fleksibilitet inden for hver proces. Den anden tilgang er en top-down tilgang, der har til hensigt at finde, ved

hvilket niveau fleksibelt behov har signifikant betydning for energisystemet. For bottom-up tilgangen er processerne kategoriseret efter tre kriterier; lagringsevne, kontrollerbarhed og om processen er forbundet med andre processer. De første to kriterier anvendes til at finde det fleksible behov inden for beboelse og kommercielle sektorer, og det sidste kriterie tilføjes for at finde det fleksible behov i industrielle processer. Resultaterne viser, at 24 % af elektricitetsforbruget kan flyttes indenfor en tidsramme på 2 timer, og ca. 7 % af elektricitetsforbruget kan flyttes indenfor en tidsramme på 24 timer. Systemfordelen af de fleksible behov er dog begrænsede. Resultatet fra den anden analyse indikerer, at for at opnå en signifikant virkning på energisystemets ydelse, skal mere end en fjerdedel af det klassiske elektricitetsforbrug være fleksibelt inden for en måned, hvilket anses for meget usandsynligt at ville ske.

To spørgsmål stilles i forbindelse med undersøgelsen af energisystemmodellen EnergyPLAN, der anvendes til de to scenarieanalyser; ”hvilken betydning har modellens antagelser om fremtiden?” og ”hvad er forskellen mellem en deskriptiv og præskriptiv model?”. For at besvare disse spørgsmål bliver en lineær optimeringsmodel lavet for at emulere EnergyPLAN modellen. To af de vigtigste forskelle mellem EnergyPLAN og optimeringsmodellen er, at a) EnergyPLAN benytter en endogen prioritering af teknologier, mens prioriteringen i den lineære optimeringsmodel er givet af produktionsenhedernes virkningsgrader, og b) den lineære optimeringsmodel kan gøre brug af det fulde set af eksogent givne fremtidige timebaserede produktions- og forbrugsværdier, såfremt det tillades af brugeren.

Ift. resultaterne af sammenligningen af de to modeller er det samlede brændselsforbrug for værker 15 % lavere i den lineære optimeringsmodel end i EnergyPLAN. Dette skyldes primært en forskel i driften af de kondenserede kraftværker, da kraftvarmeværker og kedler producerer stort set ens i begge modeller.

På trods af forskellene i prioriteringsrækkefølgen for varmeproduktion for kraftvarmeværker i de to modeller, findes et lignende overordnet resultat, da prioriteringsrækkefølgen for elektricitetsproduktion tilsidesætter prioriteringsrækkefølgen for varmeproduktion, og prioriteringsrækkefølgen for elektricitetsproduktion er ens i de to modeller, grundet de valgte virkningsgrader.

I den lineære optimeringsmodel antages fuld viden om fremtiden i alle situationer. Behovene kan således i højere grad leveres af effektive værker ift. ikke fuld viden, hvilket resulterer i et reduceret brændselsforbrug. EnergyPLAN baserer produktionen på forholdene i den specifikke produktionstime, og medtager kun en begrænset viden om fremtidige situationer. Ved at reducere tidsrammen for forudsigelser af fremtiden fra et år til en uge i den lineære optimeringsmodel øges brændselsforbruget, men dog mindre end i tilfældet uden forudsigelse.

Nomenclature

RES	Renewable Energy Source
IDA 2050	The IDA Climate Plan 2050
CEESA	Coherent Energy and Environmental System Analysis
CC2050	Green energy – the road to a Danish energy system without fossil fuel, The Danish Climate Commission
HP	Heat Pump
CHP	Combined Heat and Power
DH	District Heating

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1. Introduction

The aim of this dissertation is to make a contribution to Danish future energy system by doing variant scenario analyses and focusing on the models used for scenarios. In this chapter, the research subject is introduced by defining scenarios for the future Danish energy system, energy system structure, and importance of models for the scenario design and analysis.

1.1. The Danish energy system

Since the 1990s, the international community has on the one hand endeavored to firmly establish the science behind enhanced greenhouse effect and on the other hand tried to make a commitment to reduce Green House Gas (GHG) emissions. As the examples for such endeavors, there have been five iterations of Intergovernmental Panel on Climate Change (IPCC) reports to assess climate change [1], and there has been a series of 19 annual United Nations Climate Change Conferences (Conference of the Parties – COP). Only a few of these conferences have produced actual tools to reduce GHG emissions with COP3 in Kyoto 1997 being one of the exceptions with the implementation of reduction targets, Clean Development Mechanism (CDM) and Joint Implementation (JI), Unfortunately they have not been successful to reduce carbon emission significantly.

65% of carbon dioxide emissions origin from the use of carbon-based fossil fuels in the energy production and use [2], so the most important goal is to find an alternative for the conventional energy system based on fossil fuel. One such alternative is the energy system based on renewable energy sources (RES) where any carbon emitted is captured again through photosynthesis within a relative short time frame or no carbon emission emitted. The renewable energy system has merits not only in reducing carbon emission but also for the security of supply which is attributed to the geographically asymmetrical distribution of fossil fuel reserves around the globe. Taking an example of crude oil, approximately 62 % of reserves are located in the Middle East, 13% in North and South America [3]. Natural gas is also unevenly distributed resource with two thirds of the reserve in North America and CIS (Commonwealth of Independent States) countries [3]. Due to the benefits of RES, RES are attracting attention as future energy resources. The European Union (EU) has emphasized the importance of RES by setting a target of 20% of renewable energy in each country's energy mix by 2020 [4]. The Obama administration in the US also announced to have 20% of RES energy share by 2020 [5], and China also has a plan to increase the RES share of its energy portfolios [6].

In this global trend, in terms of RES penetration, the Danish energy system is as one of the most advanced energy system in the world. Denmark was the only energy self-sufficient EU country in 2011 [7], and has one of the highest share of wind power in electricity consumption in the world – if not the highest.

According to Danish energy statistics [8], Denmark produced energy from RES to cover 24.3% of the national consumption in 2011. As to domestic electricity supply, electricity from RES accounted for 43.1% of Danish electricity supply in 2012 [8]. Most of this renewable electricity comes from wind power (69%) and biomass (27.4%) [8]. Due to high average wind speeds over the land territory and offshore areas, there is high potential of wind power in Denmark – but in contrast, solar resources are not as favorable but a strong policy drove high investment of PV in households in recent years resulting in a fast growing capacity i.e. negligible capacity (3kW) before 2011 to over 57MW in 2014 [9] .

Looking at its long term development, the Danish energy system has evolved from being a highly oil dependent system in the 1970s to a system based on diverse fuels at present. This evolution originated from the first energy crisis in 1972-73. At that time Denmark was the most dependent country on imported oil [10]. Since then, it has diversified its energy sources to reduce the dependency of imported oil as shown in Figure 1.

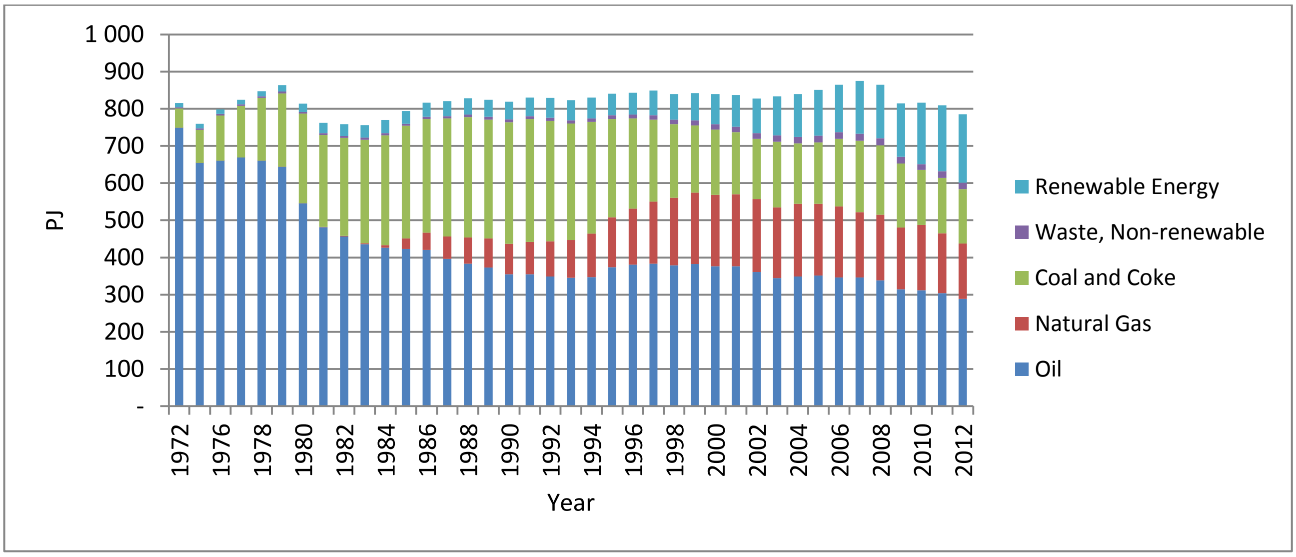

Figure 1. Danish Primary Energy Supply (PES) by fuels from 1972 to 2012 (Note: Adjusted for fuels used for net exports of electricity)[11]

As illustrated in Figure 1, total fuel consumption has maintained more or less the same level from 1972 to 2012 in spite of a parallel expansion of the Danish economy. During the same period, the Danish Gross Domestic Product (GDP) doubled in terms of constant local currency [12]. This has been possible through energy conservation and an endeavor for establishing a more efficient energy conversion system.

This historical development from the onset of the first oil crisis until present can be divided into three phases in terms of fuel shifts. The first phase was to shift the main fuel of electricity generation from oil to coal which took place until the 1980s. In 1972, 78% of Danish electricity generation was fueled by oil and the share was reduced to less than 5% in 1990 [11]. The oil was replaced by coal, which increased its share from 22% to its peak value of 96% in 1985[11]. The second phase was to replace coal with natural gas. The shift from coal to natural gas happened partly because Denmark found oil and natural gas reserves in the North Sea in 1984[13] thereby enabling the supply of domestic natural gas and partly because the Danish government set another goal of decreasing GHG emissions following the 1988 Toronto Conference on the Changing Atmosphere. The natural gas consumption peaked in 2002, and stabilized or decreased little bit until 2012[10]. The third phase was to expand RES in the Danish fuel mix. The share of RES steadily increased for four decades, but accelerated especially in 1996 and finally reached to the level of supplying a quarter of total PES in 2012.

Not only the fuel shifts mentioned above, but also changing structure of energy system from centralized to decentralized production is an interesting point for Danish energy system development. The Danish energy system has a high proportion of cogeneration of heat and power (CHP) and a large share of district heating. The share of district heating in the Danish heat sector was 53 % in 2012 [8], and 73% of electricity and 72% of heat produced by thermal heat plants came from CHP plants [8] in the same year.

Figure 2 presents the transformation from centralized to decentralized energy system by comparison of power infrastructure maps in 1985 and 2013. In the 1980s the Danish energy system was a centralized energy system which was dependent on a small number of central power generators in its electricity supply. The number of decentralized CHPs was not significant at that time. In order to exploit the synergy effects of cogeneration, it was necessary to locate more CHPs near the places where heat demands were. The regions where there was a large heat demand were preferentially converted into cogeneration and the conversion has been expanded gradually into small heat demand region. Therefore, the locations of CHPs could be dispersed geographically.

Centralized and decentralized CHPs are categorized by the original purpose they had when they built and the city size where the CHPs belong to. The centralized CHP is originated from the plants to generate electricity and the decentralized CHP used to be district heating plants. Normally, centralized CHPs are located in large cities, while decentralized energy CHPs are located in mid or small sized cities.

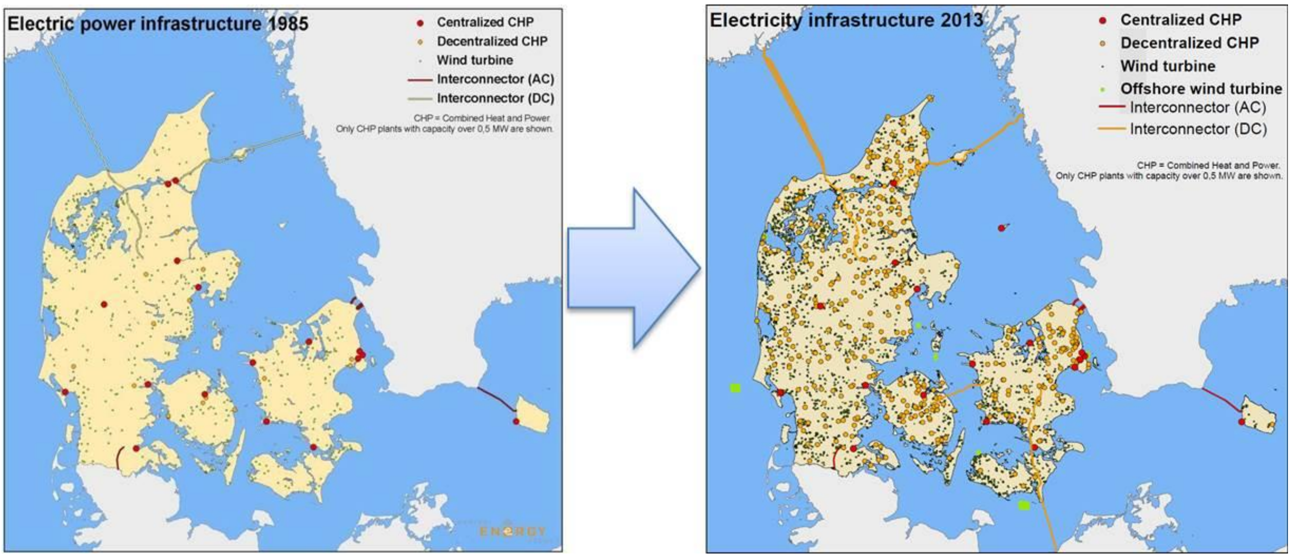

Figure 2. Infrastructure change from centralized system to decentralized energy system from 1985 to 2013. [14]

There has been a change in fuel for heating purpose as shown in Figure 3. The significant increase is observed in the share of biomass in total fuel consumption for heating purposes.

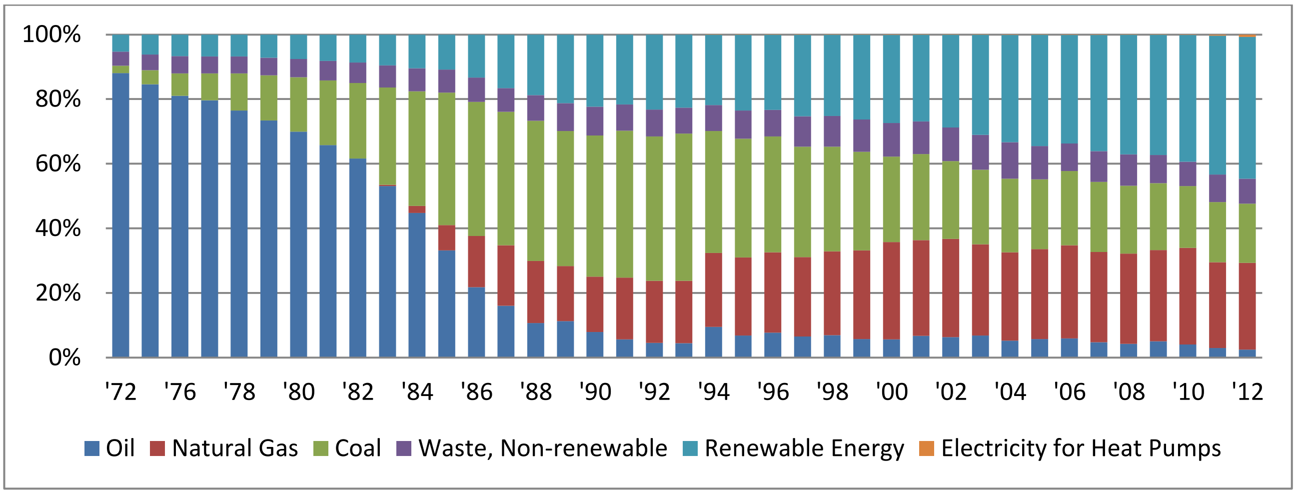

Figure 3. Fuel for heating purpose in Denmark from 1972 to 2012[8]

Similarly, the historical change of fuel for electricity production is presented in Figure 4. In both heat and power generation, the RES increase in the fuel mix is obvious. The biomass is another important pillar of RES in Denmark, with around 42% heat productions and 20.5% of electricity generation coming from this source in 2012[8].

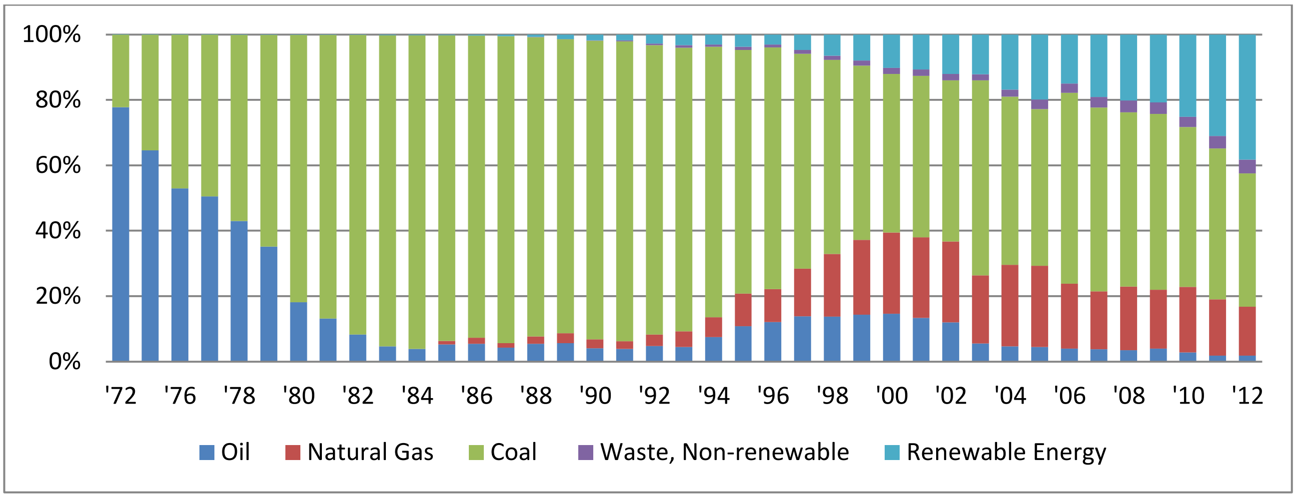

Figure 4. Fuel for electricity generation in Denmark from 1972 to 2012[8]

There are several benefits of biomass as a fuel source. Biomass is a carbon neutral resource while sharing the merits fossil fuels has such as storability and dispatchability. However, biomass import has increased significantly over the last decade and a half - from 233 TJ in 1995 to 48,181TJ in 2012[8], which is detrimental for self-sufficiency and possibly straining an energy resource thus limiting other countries' access to it . In the future, the potential for domestic biomass will bring into a question whether the potential could fulfill the demand thus a careful approach to biomass is required.

1.2. Future Danish energy system

In 2011, the Danish government announced its long term goal to make Denmark a country to be solely fueled by RES by the year of 2050 [15]. This is including transportation – a sector often considered hard to address. A variety of ways to attain such a goal can be suggested, based on research into 100% RES Danish futures [16-18] and it is generally agreed that the following measures would be essential for attaining the goal:

- More RES must be exploited
- More flexible technologies to cope with the intermittency from RES
- Biomass utilization for various purposes
- More integration among electricity, heat, and transport
- Energy conservation

The question remains however to what extent each measure should be applied, and more clear and plausible pictures could be drawn for the future energy system. A more detailed discussion of future energy plans is addressed in Chapter 3.

1.3. Scenario analyses

The transformation of the energy system and the impacts brought from the change needs to be assessed and prepared for beforehand. Therefore, it is imperative to endeavor having a choice of plausible scenarios and modelling these for dealing with the complexity.

Kahn[19] has defined a scenario as *"a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points"* while scenario analysis is a methodology to analyze future events by assuming one or more scenarios. Scenario analysis is used for diverse areas like business strategy [20,21], environment and energy system[22-24].

There are several merits to do scenario analysis for the future. First, scenarios provide a visualization of uncertainty. The future is uncertain and it is difficult to predict what will happen exactly. Therefore scenarios are formulated based on relatively uncertain factors. In dealing with the uncertainty, scenarios can be used for setting a boundary of uncertainty. Setting boundary for the uncertainty provides a framework for contemplating the future and appropriate future path ways. Second, while formulating scenarios, documentation of assumptions is done and thereby communicating with a variety of experts is facilitated.

Since energy is an essential element of modern human life, and since there are diverse interfaces of the energy system, the scenarios on energy system would rather be viewed from various perspectives. The energy issue is deeply related to economic growth, technology development, human behavior, and environmental issues. Thus the design of energy system encompasses a variety of academia from engineering to sociology.

Due to the interdisciplinary characteristic of energy systems, this communication among the various scholars seems to be crucial. The communication as an interdisciplinary approach enables a diversity of perspectives toward the future to be internalized and reflected into the scenarios. Not only communicating among the experts, but also involving the public and media as the audience for scenarios is necessary since they are the most important stakeholder for the future. This trial is a merit of formulating scenarios besides the accuracy of future scenario.

The two scenario methods, backcasting and forecasting, are frequently used and compared since they are contrasting each other. Backcasting is defined as a planning methodology that starts with a desirable future and finds paths that lead to this target. On the contrary forecasting is defined as a methodology to view likely futures based on the present trend. The difference of perspective can be described as in Figure 5.

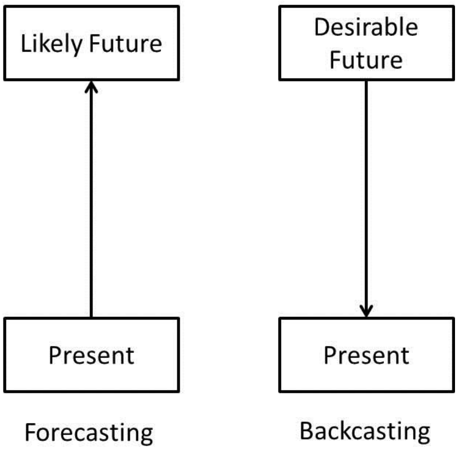

Figure 5. Illustration of the concepts of forecasting and backcasting

According to Robinson et al.[25], the backcasting method was suggested as an alternative to the forecasting method as it is difficult to forecast changes into the far future. Forecasting is applied to find the likely future, while backcasting does not focus on the likelihood but rather intends to specify the relative implications of various policy goals [25].

These two methods are chosen according to different time frames and purposes of scenarios. The forecasting method is used in the short term future with optimization models in order to find the most efficient scenario, while backcasting is applied to long term future in order to find the paths for a normative goal, for example, a renewable based energy system.

These two methods are so discerning that the situations and conditions each method is applied under varies. According to Höjer et al. [26] backcasting is necessary when the following conditions apply:

- *When the problem to be studied is complex, affecting many sector and levels of society*
- *When there is a need for major change, i.e., when marginal changes within the prevailing order will not be sufficient*
- *When the problem to a great extent is a matter of externalities, which the market cannot treat satisfactorily*
- *When the time horizon is long enough to allow considerable scope for deliberate choice*

Danish energy planning has long term objectives and involves major changes and fundamental impacts on various sectors and overall society. In this sense, a backcasting technique seems to be more appropriate than a forecasting technique. However, in order for the planner to know when backcasting is necessary, the forecasting is used for grasping the consequence of the current trend, therefore the relation between the two is complementary [26].

Beside the scenario techniques explained before, there are diverse scenario typologies defined by a variety of researchers. There being no consensus on the scenario typologies among the researchers, however, the typologies seem to be differentiated mainly by naming but the core concepts remain similar.

Borjeson et al. [27] distinguish scenarios by what questions are asked about the future; *What will happen? (Predictive), What can happen? (Explorative), and How can a specific target be reached? (Normative)*

Additionally, the predictive scenarios are further disaggregated into two detailed questions under the main question of "*what will happen*"; "*what will happen on the condition that the likely development unfolds?* (forecast)" and "*what will happen, on the condition of some specified events*? (What-if)". The explorative scenarios are divided into two types under the main question of "*What can happen*" ; "*What can happen to the development of external factors*? (External scenarios)", and "*What can happen if we act in a certain way?* (Strategic scenarios)". The normative scenarios are divided into two sub-scenarios types; "How can the target be reached, by adjustments to current *situation*? (Preserving scenarios)", and "How can the target be reached, when the prevailing structure blocks necessary *changes*? (Transforming Scenarios)".

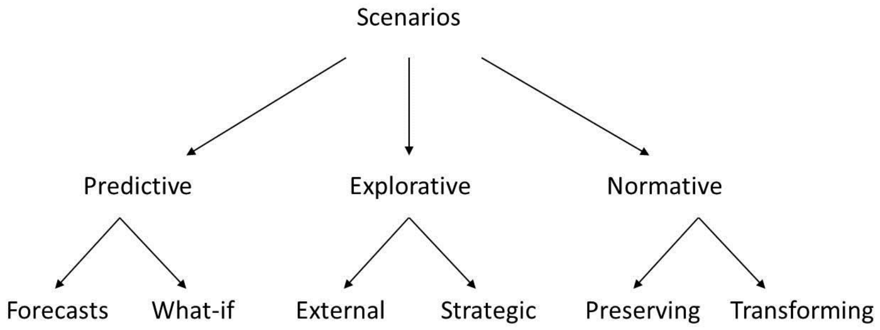

Figure 6. Scenario typology defined by Borjeson et al. [27]

Classifying the national Danish energy planning with the typologies introduced above, the Danish national energy plan is defined as a normative scenario to envision a discerning goal to become 100% renewable by 2050. However, in a normative scenario, there can be other perspectives for the future. For instance in estimating the demand, one can assume to follow the present path without a big change in the future, at the same time, in estimating future technology one could assume an innovation to deviate from the present path. Even within the same goal there could be a variety of scenarios. Likewise, it is important to have a number of explorative scenarios (what can happen?) by including external factor (*What can happen to the development of external factors?*) and strategic decisions(*What can happen if we act in a certain way?*) in order to reflect diverse futures. Having alternative normative scenarios for the pursuit of a main goal would be preferable since it could support decision by enabling the choice from more options rather than having very few decisions or "do it or never"[28]. It should be noted that the number should not be too large. If so, the significance of scenario analysis would be deteriorated.

Another aspect of Danish energy planning is the extent of change assumed in the scenario. Although the extent of transformation is different in the different energy sectors i.e. heat, electricity, and transport, the end-goal is the same – i.e. a 100% renewable energy system. This may be denoted as a transforming scenario in contrast to the counter-concept of a preserving scenario. The criterion to decide on either a transforming or a preserving scenario is subjective, differentiated by the context. A preserving scenario to one could be a transforming scenario to others. Therefore, the criterion is quite relative, not absolute.

In terms of a time scale, the Danish energy objective is a long-term energy objective. Generally, long-term plans have time horizons of more than 10 years [29]. From a geographical perspective, the Danish energy plan has a national scope, as the goal of becoming a 100% renewable energy system is restricted to the Danish territory. However, due to the broad impact of energy, the international perspective should be considered for the scenario. Not only direct impacts from the international exchange of energy resources or electricity interconnection to and from neighboring countries, but also indirect impacts like technology development could be considered as an international perspective.

1.4. Energy system components

In the future, energy supply is going to be transformed from conventional resources which are diverse in types of fuels but share same characteristic of supplying whenever it is necessary (dispatchability), to renewable energy sources which to a large extent follow natural cycles beyond the control of humans (intermittency).

Different parts of the energy system have different characteristics in terms of balancing requirements, and while fuel and heat infrastructures supply an inherent buffer or storage capability, electricity systems need to balance production and demand on a continuous basis. Therefore focus is often on the particular needs of the electricity system, though integration with the other sectors may in fact provide means for improving the balancing of the electricity system.

The way to integrate RES electricity into the electricity system is more complex than conventional fuel-based power generation. For this situation, flexible technologies are introduced in the electricity system for balancing supply and demand and thus enabling a more efficient and agile system. The flexible technologies include in general technologies that may convert energy carriers, storage systems and systems that may defer loads. Focusing on electricity systems, they are broadly categorized into three categories. The first category is the conversion of electricity to other demands like heat and transportation. It includes HPs and electric vehicles. The second category of technologies is to store electricity using e.g. potential energy (pumped hydro), elastic energy (a compressed gas), thermal energy (steam), chemical energy (batteries, hydrogen or a synthetic fuel). The electrolysis to produce hydrogen or synthetic fuel is an example. The last type of flexible technologies is loads that might be deferred – i.e. electricity demands that might be moved according to temporary system requirements.

Going beyond the electricity system, flexible technologies also include heat storages. Combined with CHP plants, this offers the plants the possibility to dispatch power production without regard to heat demands, but they may also provide flexibility to pure heat systems – e.g. solar thermal when production exceeds demand.

Looking strictly at the fuel efficiency – thus without considering other perspectives such imbalance between supply and demand - the significance of flexible technologies would be insignificant in a conventional fuel-based energy system. Here the efficiency is attributed to the fact that conversion from one form of energy to other forms is accompanied by efficiency loss, and flexibility itself cannot help avoiding these energy losses.

Therefore, the development of flexible technologies is mainly motivated by the use of intermittent RES and coping with the intermittency brought from the exploitation of RES. This fact is the reasoning behind the diagram in Figure 7 and Figure 8.

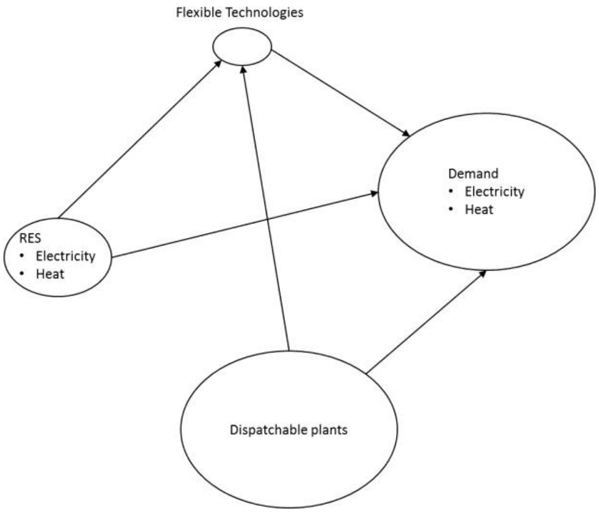

Figure 7. Schematic diagram to describe the present energy system from an electricity perspective

A diagram depicting the present energy system is drawn as Figure 7. The various energy system components may be categorized by how they are related to the electricity system. Figure 7 categorizes the energy components into four segments; Demand, Dispatchable plants (CHP, condensing mode power plants and boilers), RES production, and flexible technologies as deliberated above.

In the conventional energy system, the system structure it is simply required to have enough capacity of dispatchable production to cover the demand. Therefore, in Figure 7, most of the energy supply is done by dispatchable plants while only a small fraction comes from RES as indicated by the size of the ovals. The balancing is done by controlling dispatchable plants. The present Danish energy system is more complex with a more prevailing presence of CHP than in other countries. Still, the development of flexible technologies is premature in terms of installed capacity (electric boilers (306MW) and HP(3.94MW) in district heating[30]), and in terms of technological level – e.g. premature level of electrical vehicle (EV) development. Therefore, the oval indicating flexible technologies is negligibly small in Figure 7.

In a future energy system, balancing supply and demand will become more complex than in the present situation. The significance of intermittent RES and flexible technologies is thus increased, and accordingly the interaction among the system components would be more active. Using flexible technologies, electricity produced from RES is utilized not only for electricity end-use but also for heating and even transportation. Also, the storage function is included for fulfilling the demands in three sectors. The operation of such different technologies would become more multifaceted.

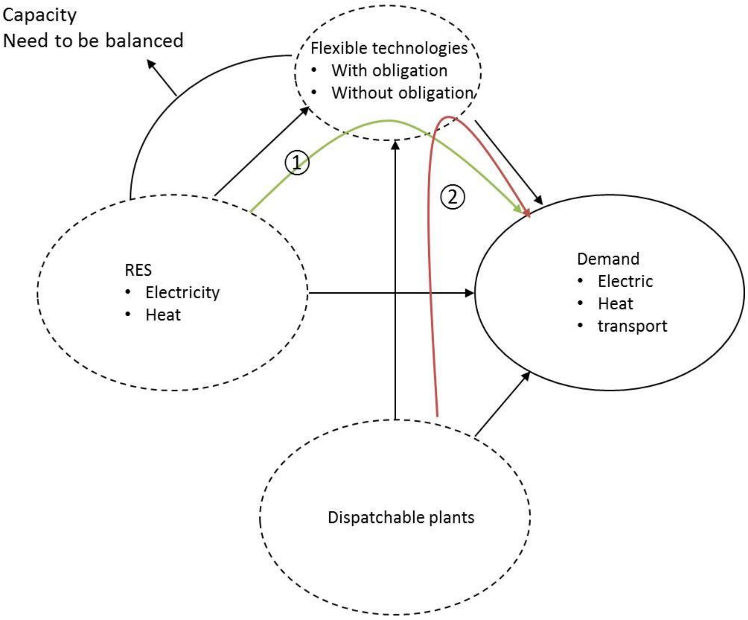

Figure 8. Schematic diagram to describe future energy system from an electricity perspective

The complexity does not only lie on the operation of the system but also in the design phase. For the determination of the installed capacity of RES, flexible technologies, and dispatchable plants fueled by biomass resource, several factors are to be considered. These factors are distinguished into two; internal factors to be brought from the interaction between the individual technologies and external factors indicate the inherent characters of individual technologies which are irreverent of the interaction between individual technologies. The external factors include the potential of RES to recognize how much exploitation of the RES will be available for the future, technology development to identify whether the technology will be possible in the future, and investment costs to identify whether the technology is economically attractive compared to alternatives. Also, the external factors encompass societal acceptance, employment effects, and whether technology is domestic or import. These factors are inherent characters of individual technology.

In Figure 8, which describes a possible future energy system, another aspect of relation between RES and flexible technologies is illustrated as follows. Two loops to use flexible technologies are observed in Figure 8. In the first loop (green), energy produced from RES, processed in flexible technologies ends to fulfill demands. This loop satisfies the original purpose of flexible technologies which is to absorb surplus energy brought from the intermittency of RES. The second loop presents a wrong way to use flexible technologies. In this loop (red) energy from dispatchable plants is converted by flexible technologies before covering a demand. This is not a desirable way to use flexible technologies, however it cannot be avoided completely. Some flexible technologies being obligated to fulfill the demand in transport sector may require electricity when it is necessary - not only when there is excess electricity in the system – in which case they are of course not fully flexible. For instance, once the transport demand is integrated into the electricity system via electric vehicles, the transport demand should be fulfilled by electricity. If low RES production is sustained for long time, the electricity for transport demand must be fulfilled by the operation of dispatchable plants. The frequency of having the second loop can be reduced if perfect forecasting for RES supply and demand is possible. However, in reality, accuracy of such forecasting is not perfect.

The capacity of dispatchable plants is also needed to be established within a systems context. As the main fuel for dispatchable plants will be biomass in 100% renewable energy systems, the potential biomass resource is an important factor which influences the operation and capacity of dispatchable generators. It also impacts RES and flexible technologies, therefore the availability of biomass in the future makes a coherent impact on the future energy system configuration. The biomass availability and usage of the biomass should be considered in future energy scenarios.

1.5. Energy system modelling

In order to simulate the complexity of energy system, the use of a computerized model is necessary and thus the selection of model is also important. For significant changes or for long-term trends in the energy system, scenarios are typically established to aggregate a series of changes. Normally, a scenario is composed of narrative part which explains qualitative developments and a quantitative part which reflect the qualitative description in a series quantitative data. A good scenario should balance well between the qualitative and quantitative parts and not be biased on one side.

Energy system models try to make an artificial system to describe the operation of a real system by using formulations and algorithms. This is of course a simplified representation of the real world but if the model is appropriate, results will be plausible. According to [31], one can have benefits of using energy system modelling 1) as a tool to transform the complexity of the real energy system into simple, but representative and comprehensive form thereby enabling to analyze it, 2) as a vehicle for better understanding and leading to better policies, 3) as a forecasting tool, and 4) as a providence of a common and objective platform.

According to Wurbs [32], system analysis models can be categorized into either prescriptive models or descriptive models. Wurbs differentiates this way, *"Descriptive models demonstrate what will happen if a specified plan is adopted"* [32] and *"Prescriptive models automatically determine the plan that should be adopted to best satisfy the decision criteria"* [32]. Generally simulation models tend to be categorized as a descriptive model and optimization models are likely to be categorized as prescriptive models even though the categorization is not rigid [32].

The ultimate objective would typically be to have a fully prescriptive model but reality does not allow it. In reality, there are various factors which are uncontrollable and unpredictable. They could be often assumed to be controllable and predictable in the models such as demand and electricity production from RES and complexity happened within complex mutual relation between the players in system.

Among these factors, the future prediction ability for RES and demand is in focus here. As explained in section 1.4, the integration of intermittent energy resources into the electric grid would be accelerated. The storage and the technologies to integrate other sectors and electric sector will be enlarged correspondingly in the future energy system. For the operation of these storage and integration technologies, forecasting ability is getting more attention since the better operation of these technologies is enabled by having more precise forecasting ability. However, it is true that there is a certain limitation in enhancing forecasting ability even in the future.

1.6. Summary for introduction and Problem formulation

To sum up the discussions above, Denmark announced a future energy goal to have a 100% RES-based energy system by 2050. Scenario analysis seems an imperative tool for the proper implementation of such a far future plan. The scenario analysis plays a role not only for probable, plausible future visualization, but also as a framework for communication among experts and public. The Danish energy plan may be categorized as a normative one since it has a discerning goal to be attained however, more explorative future scenarios are recommendable to prepare for more diverse futures.

Prescriptive and descriptive models are different whether it has a defined operation strategy or it finds the best operation strategy for a criterion. For becoming a prescriptive model, there are several elements to bridge the differences between reality and the simulated world. One of elements is future forecasting ability which is easily assumed to be perfect in the model whereas it is impossible to forecast perfectly in reality.

This dissertation endeavors to contribute for this complexity with two approaches. The first approach is scenario analysis within the normative goal of designing 100% renewable energy systems, and the second approach is to view this complexity from a model perspective.

Firstly, it is imperative to review and compare existing future scenarios. The Danish energy plan announced in 2012 to be agreed on by Danish parliament is still ambiguous without a blue print composed of quantitative presentation. It is still the level of plan for providing a momentum for the investment and agreement to have a pure renewable energy society within political actors. For more concrete view of this plan, three projects for the future scenarios have been done so far and they present similar but different views. Therefore, the first research question is formulated as

- **What are the differences in results and perspectives of existing Danish future scenarios?**

Secondly, scenario analysis is done for uncertain and important factors. Among these two with a significant possible effect on the energy system are selected; biomass availability and development level of flexible technologies. Biomass is a useful but limited resource and it is difficult to assess with accuracy. Related to the flexible technologies, flexible demand is selected as subject since compared to other flexible technologies from supply side, the flexible demand is less studied and investigated as a subject for energy system analysis. Therefore, the following questions are asked for scenario analysis.

- **What is the best usage for biomass in the Danish future?**
- **What is the potential of flexible demand in the Danish future?**
- **What is level of flexible demand to make a significant impact for the Danish future?**

Lastly, the model perspective is added. The impact of future forecasting assumption in the model is assessed and difference between prescriptive and descriptive model are investigated.

- **What is the value of forecasting ability in the future energy system?**
- **What are the differences between prescriptive and descriptive models?**

1.7. Structure of PhD dissertation

For this PhD dissertation, three articles have been submitted for and published in journals and one manuscript is written for only this dissertation with a view to later submission. This dissertation is comprised of a summary and extension of these articles and the original documents are present in appendix. The summary of analysis not only includes contents of each analysis but also adds subsequent reflection found afterward while the other subjects are investigated.

Chapter 2 presents the methodological background of the dissertation including energy system model used for scenario analysis, analytical framework to compare existing energy scenarios on future Denmark, and a brief and general introduction of linear optimization.

Chapter 3 reviews three existing future national energy scenarios and compares these. The comparison comprises both quantitative and qualitative elements. The quantitative elements are system configuration, fuel consumption, and total societal economy accordingly. The qualitative comparison is done by a framework of radical technology development (See Chapter 2). The purpose of this chapter is to introduce the future scenarios for an approximated visualization for Danish future energy system. Another perspective is to investigate what methodologies are used for approximating the future system configuration.

Chapter 4 focuses on the biomass usage in the future and especially on presenting with quantification which energy sector - heat or electric generation – makes the optimal use of biomass. This comparison is necessary since the availability of biomass is uncertain while also very important not only for operation but also for system configuration for the future. This analysis compares the value of using biomass as a heat source and for electricity generation in a 100% renewable energy system context. The comparison is done by assuming an incremental decrease in the biomass available for the electricity and heat sector, respectively. The assumed scenarios for the decrease of biomass are made by use of an hourly energy system analysis model, EnergyPLAN.

Chapter 5 focuses on the flexible electricity demand potential in the future. The flexible demand has the same function to enable the system to absorb more RES as flexible technology on the supply side does. The analysis adopts two approaches for the assessment of the potential of flexible demand. The first approach is a bottom-up technical approach investigating the potential of flexible demand from individual processes. Secondly, the level of flexible demand which makes a significant impact on the future energy system is assessed with a view to investigating whether the two approaches will ever meet and thus whether flexible demand has a significant role to play in the future energy system.

Chapter 6 introduces a comparative study of two modelling approaches to compare simulation (descriptive model) exemplified with EnergyPLAN and linear optimization (prescriptive model) – exemplified by a model designed to emulated EnergyPLAN to the extent possible. Two focuses for this comparison are highlighted; future forecasting ability and predefined priority order of plants vs. efficiency-decided operation for minimizing fuel consumption. These two models have the same purpose to reduce fuel consumption and international exchange, however adopted in different ways.

2. Methodology

As discussed in Chapter 1, this dissertation starts with comparisons of existing Danish future scenarios. For the comparison of the future energy scenarios, evolutionary perspective and radical technological development framework is introduced in Section 2.2 which is based on the article of "Comparison of future energy scenarios for Denmark: IDA 2050, CEESA (Coherent Energy and Environmental System Analysis), and Climate Commission 2050 [33]".

The scenario analyses for biomass potential and flexible demand (Chapter3 and 4 respectively) are followed. For scenario analysis, EnergyPLAN is used as an energy system model. The description of EnergyPLAN in Section 2.1 is based on the article of "Priority order in using biomass resources – Energy systems analyses of future scenarios for Denmark [34]". Lastly, linear programming is briefly introduced.

2.1. EnergyPLAN

EnergyPLAN has been under continuous development at Aalborg University since 1999. It originated from the analysis of the effects of cogeneration of CHP on the electricity system, but since then, there have been additions of functions as various research on energy system has been done with EnergyPLAN.

Considerable research on energy systems has been carried out by applying the EnergyPLAN model to various energy subjects. The subjects of previous study include

- 100% renewable future energy plans for various countries and municipalities[16,35-38],
- RES integration into energy system in a large scale [37,39-43] ,
- flexible technologies including energy storage to facilitate RES integration[44-48],
- integration of transportation sectors via electric vehicles[49] and synthetic fuels[50]
- market structures to facilitate RES integration[51,52],
- And comparison analysis with other energy model for its validity [53,54]

EnergyPLAN is a deterministic input/output simulation model. The calculation is based on analytical programming contrary to linear optimization, dynamic programming, and stochastic programming. It focuses more on operational optimization of a group of given energy units unlike the other models that optimize investment in the system.

EnergyPLAN is capable of simulating one year with one hour time scale. The input parameters include demands such as aggregate annual heat, electricity, and transport, technical specifications like efficiency, and capacity, and hourly distribution of fluctuating RES. The outputs include fuel consumption, CO_2 emission, energy production, international exchange, operation of individual technologies, and overall energy balances. All of results can be presented as an annual summation and hourly presentation. The hourly presentation of results and hourly variation of demand and production are one of the merits for the analysis for the integration of RES since the fluctuation of RES and demand should be taken into account in the hourly domain. Otherwise results may lead to wrong direction since aggregation of hours would omit the hourly balance problems which would be more significant for high level of RES integration.

EnergyPLAN has a number of strategies in its simulation. The strategies are broadly divided into market and technical optimization strategies. The technical optimization in EnergyPLAN is a predefined procedure to utilize the plants with main purpose of limiting fuel consumption and international exchange. Basically technical regulation gives preference to use-it-or-lose-it technologies i.e., fluctuating RES and waste energy from industry. After these technologies come CHPs and lastly condensing-mode power production and heat production on boilers. The CHPs may also be modeled with a thermal storage capacity enabling them a temporal shift in the supply of heat and electricity. In the market optimization strategy, the merit order is given to the plant according to lowest short term marginal cost which is comprised of fuel, and operation and maintenance costs.

The operation of flexible technologies such as HPs and electric boiler occurs in two situations. The first situation is when the heat demand is larger than the capacity of CHPs and available potential output from storage facilities on top of solar thermal heat and industrial waste heat. Here HPs operate first and if this is insufficient, electric boilers are dispatched. The other situation is when it is required to prevent Critical Excess Electricity Production (CEEP) from occurring. The user may stipulate a CEEP prevention strategy, which includes successive steps which may include the use of HPs and/or electric boilers to convert electricity to heat energy until the capacity of heat storage is saturated.

Another type of technology which can make the energy system more flexible is electrolyser. In EnergyPLAN, the electrolyser is set to store electricity by producing synthetic fuel when the electricity supply is over the capacity of the aforementioned flexible technologies. If there is excess electricity in the system even after consuming the electricity amount via flexible means, the CHPs would stop operating. The sequence of priority is set inherently in the model.

It is noted that each energy unit in EnergyPLAN does not mean an individual producer, but an aggregation of similar units. The EnergyPLAN model is an aggregate model with one unit representing all units of a given type.

Among the technical optimization strategies, there is difference in operating strategies according to the various regulation strategies listed before. In this PhD thesis, technical Regulation Strategy 3 is selected as optimization strategy, so the model seeks to reduce energy exchange to and from the system as much as possible. This may be denoted connected island mode [55]. For additional information, see the model documentation for EnergyPLAN[56]. In this PhD dissertation, EnergyPLAN is used as a scenario configuration and system analysis tool for the subjects of biomass (Chapter 4) and flexible demand (Chapter 5).

2.2. Evolutionary and Radical technological change perspective

In Chapter 3, which is on comparison of three Danish future scenarios, evolutionary perspective is used for comparing the methodologies applied in those scenarios. The term evolutionary perspective is used by Evans [57], however Evans' application of the concept evolutionary perspective is based on theory of evolution which includes the concepts of adaptation, variation, and decision. Here, the term "Evolutionary Perspective" is defined as temporal gradual refinement of energy scenarios through the inclusion of methodologies to reflect the reality better and thereby consequently enhancing the realism of scenarios through a refinement in the portrayal of the systems. In determining the "quality" of the future scenarios it is more important to have an objective conception for the future made in today than to predict the future accurately, as stipulated by Grunwald [58]. Identifying the most accurate scenario in the present is impossible, however one may assess scenarios based on methodologies of inclusion and application. Therefore it is necessary to assess the different methodologies and characteristics rather than the ability to predict the future. Hence the evolutionary perspective is suggested as the yardstick.

Future scenarios can be judged as quoted from [59], "*One may judge a forecast successful if it (a) helps energy planners, (b) influences the perceptions of the public or the energy policy community, (c) captures the* *current understating of underlying physical and economic principles, or (d) highlights key emerging social or economic trends.*"

Even though this quotation describes the criteria for judging forecasts, the same criteria can be applied to assist in evaluating the energy scenarios here. Especially, it may be proposed that a good scenario is able to influence the perceptions of the public or the energy community *(b)*. The change in perception will bring behavioral change for future. The behavioral change in the public is one of the most essential and foremost factor for future change. Therefore a good scenario is supposed to be amenable to the people of stakeholders and scenarios aimed at showing feasible pathways to people based on transparency and objectivity of assumptions and methodologies. Hence the degree of transparency and objectivity in methodologies is chosen as a component in the evolutionary perspective. Another component in the evolutionary perspective is chosen as the extent to which it analyzes the most relevant areas of uncertainty and importance. It means that the addition of them choose the right direction. Same criteria are used in [60] for evolving scenarios. To sum up, there can be at least two questions underlying this "Evolutionary Perspective";

- Are the given areas in the future uncertain but sufficiently important to require more advanced methodologies to analyze them?
- If so, do the methodologies become more transparent and systematic and can they analyze the subject in a more quantitative way?

Also, the results of these scenarios are also compared within the framework of Hvelplund's radical technological change. Hvelplund has done extensive research on technological change [61-63] and in this framework the five dimensions technique, organization, knowledge, product and profit are considered, and if more than one dimension are changed, Hvelplund labels it a "radical technological change" [64]. In [28], the theory of "radical technological change" is used to explain why radical technological changes necessitates the participation of local citizen and the public in the discourse of the energy future in order to break through some conventional concepts from the already existing institutions such as power companies and government councils because the existing participating players in the present energy sectors do not want "radical technological change". For the comparison among the scenarios, if a scenario has more number of dimensions to be changed than another scenario or the extent of change is more severe, it would be defined "more radical technological change" scenario. The more radical technological change means, on the one hand, the society will experience more burdens of change in the mentioned dimensions, hence it can be a subject avoided, on the other hand, it sends a normative message that more various stakeholders should participate in the decision process of future energy system in order to have better successful transformation.

2.3. Technical/technological analysis for radical change

According to radical technology development theory explained in Section2.2, normally a transition from fossil fuel to renewable energy is regarded as "radical technological change" since the transition should include more than one dimension [64,65]. For the simulation of radical change in energy system, a technical analysis to minimize fuel consumption and international exchange is selected for this thesis. There are several benefits to apply technical analysis over market analysis especially for a far future scenario. Technical analysis is free from market institutional change since it does not take account of fuel cost but thermodynamic coefficient like fuel efficiency. Future fuel cost is difficult to estimate and the accuracy of the estimate is not trustable [66]. The credibility of the cost estimation is worsened as time horizon is expanded. Forecasting for the investment cost of a certain energy technology in the future is also challenging. It is due to the complex function of technology innovation [67]. Technical analysis is not free from such uncertain technology innovation factor either. However, the estimation of thermodynamic coefficients like conversion efficiencies would deviate less than that of the future costs.

2.4. Linear optimization to find the least fuel consumption

For the assessment of the value of future forecasting assumption and difference between a descriptive and prescriptive model, in Chapter 6, a linear optimization model is built and scenario modelling with this model and EnergyPLAN is compared. As explained in Section 2.1, EnergyPLAN has predefined operation strategies and seeks to finds the optimal point with the given input parameters. In that sense, EnergyPLAN can be categorized as a descriptive model, to use Wurbs terms (see Section 1.5). Linear optimization (also known as Linear programming) is a kind of mathematical optimization to find the maximum/minimum point in terms of a certain criterion within a given a set of constraints. It resembles more prescriptive model in finding solutions by criteria without a fixed operation strategy. There are a number of models using linear programming for energy system models [68] - including MARKAL/TIMES, GTmax and Balmorel. These models have been used for finding the least cost investment decision based on given costs including investment, operation, fuel, and even externality costs. The optimization model presented in Chapter 6 has the same level of aggregation and the same functions as EnergyPLAN but uses a different approach from the analytical simulation model EnergyPLAN to find the least fuel consumption strategy. EnergyPLAN has a predefined algorithm for the order of plant operation, while the optimization model uses linear optimization solution subject to several constraints. The constraints applied to the model developed in Chapter 6 are formulated for the purpose of being similar to the EnergyPLAN functions. The GAMS (General Algebraic Modeling System) [69] is used for building the linear optimization model.

For the assessment of future forecasting assumption, two future forecasting horizons are used for the linear optimization model; one year and a week. For one year optimization model, the whole year information such as demands (heat, electricity, and transport), RES productions (wind, PV, wave, solar thermal) is known to the optimization solver and enables the solver to find the optimal operation for one year. For the case of weekly optimization, only one week’s information is given and the optimal operation for one week is found. The storage level at the end of each week is assumed to be a half of capacity except solar thermal storage. This process is repeated for 52 weeks (the last week includes the remaining two days), and weekly operation results are accumulated to form yearly results as shown in Figure 9. The aim of having two time frames for forecasting ability is to investigate the fuel consumption variance by varying the time frames.

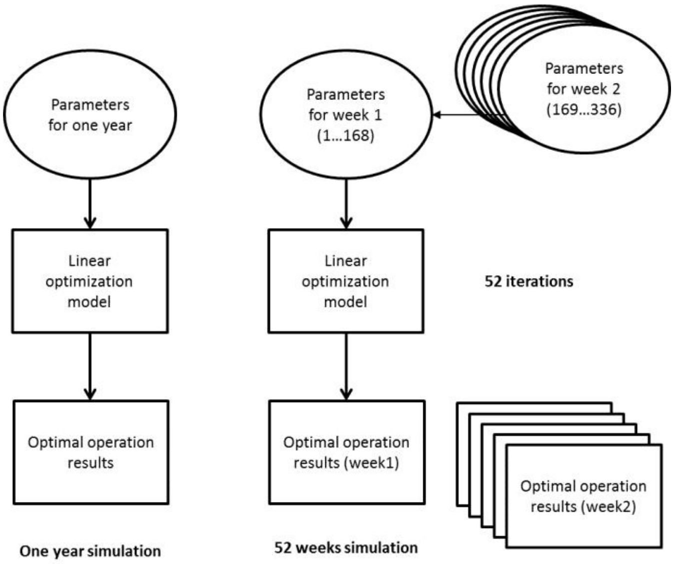

Figure 9. Two ways of linear optimization according to time frame of future forecasting

More detailed explanation on model development and assumptions are presented in Chapter 6.

3. Comparison of three existing Danish energy future scenarios

This chapter is based on the article “Comparison of future energy scenarios for Denmark: IDA 2050, CEESA (Coherent Energy and Environmental System Analysis), and Climate Commission 2050 [33]” which is included in Appendix I.

3.1. Introduction

As mentioned in Chapter1, for the aim of becoming 100% renewable energy planning in 2050 Denmark, there have been three projects in Denmark; IDA2050, CEESA, and CC2050. The objective of this chapter is to compare these three scenarios in order to obtain main ideas on the future energy system in preexisting scenarios. It starts with overall comparisons such as authors, institutions, and motivation (Section 3.2), then compares these three projects with quantitative results such as fuel consumption, and system configuration (Section3.3). Some qualitative comparisons are followed later. First, the models used in each scenario are investigated (Section 3.4). Second, the model usages among the scenarios are compared with evolutionary approach and radical technology development.

3.2. Overview of the energy scenarios

These three scenarios are written by various research groups and initiated by different organizations. In order of date, IDA 2050 was prepared in Aug. 2009, CC 2050 in Nov. 2010, and CEESA was finished in 2012 (but is not fully published yet). IDA 2050, as name implies, was initiated by the Danish Society Engineers (IDA). It involved hundreds of engineers and specialists from Danish industry through holding many conferences and seminars. The CC 2050 was established by Commission on Climate Change which was appointed and financed by the Danish government. The commission was composed of ten scientists from fields such as climate, agriculture, transportation and economics. CEESA was funded by the Danish St7rategic Research Council and participating parties. More than twenty researchers from seven research departments at Danish universities participated in CEESA, and in addition, CEESA has an international advisory panel as a supporting group.

All of these scenarios have the same message that Danish future energy system without fossil fuel will be technologically and economically feasible. All these scenarios commonly suggest four measures; expansion of wind power, increased utilization of biomass resources, development of transportation technologies such as electrification and synthetic fuels, and more cohesive integration between energy sectors. For now these measures are going to be a main direction for the future despite varying degrees of dependence on the four measures.

These three scenarios are composed of sub-scenarios. The sub-scenarios are distinguished by several assumptions for the future. Their assumptions are different respectively. IDA 2050 scenario has a simple approach to divide into reference and alternative scenario which is called as IDA scenario in the document. The reference scenario is based on forecast without having a normative goal while the alternative is a normative scenario. CEESA formulated three explorative sub-scenarios according to different assumptions on technology development level; Conservative, Ideal, and Realistic/Recommended. The technology refers to renewable energy technologies, fuel cell, electrolysis, and battery technology. CC2050 presents four sub-scenarios according to international situation and biomass availability. The international situation is categorized into ambitious (Low oil price, High CO2 price, and high biomass price) and unambitious (High oil price, Low CO2 price, and Low biomass price) conditions. Biomass availability is divided into whether the future potential of biomass will be limited within 230PJ or not. CC2050 selected “ambitious and limited biomass availability” situation as the recommended scenario. For the analysis of this thesis, only recommended sub-scenarios in respective scenarios are used.

3.3. Quantitative Results

First comparison is done in terms of primary energy. All of three scenarios remove the fossil fuel in their energy portfolio thus all primary energy comes from RES. In Figure 10, the RES is categorized into biomass, thermal related RES(Solar thermal, and Geothermal) and intermittent RES (wind, PV, and wave).Even though there are various kinds of biomass resources in the future, they are presented as an aggregated biomass in the Figure 10. Total fuel consumption levels in three scenarios are ranged from 420 PJ to 503PJ. The largest primary energy consumption is observed in CC2050 but the biomass consumption is the smallest. On the contrary, IDA 2050 estimates the smallest primary energy consumption however biomass consumption is the largest among the three.

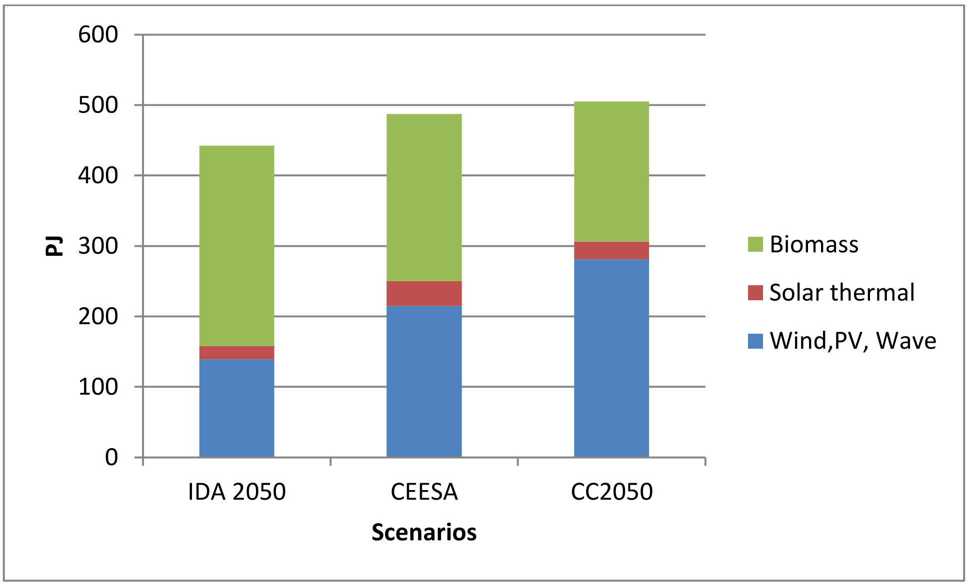

Figure 10. Primary energy consumption in three scenarios for Denmark [70-72]

Along with the differences in the fuel consumption above, the system configurations also present variances among the scenarios as shown in Table 1. Installed capacity of offshore wind is the most discerning one. CC2050 assumes the largest offshore wind capacity and IDA 2050 assumes the smallest one. This corresponds with the amount of primary energy consumption illustrated above in Figure 10. As to flexible technologies, the capacity of HP in CC2050 is distinguishing to be 4504MW. It implies that heat production is more electrified than other scenarios. As to the capacity of electrolysers, CEESA assumes considerably higher capacity than IDA2050. CC2050 does not specify the capacity of electrolysers but the electricity consumption for the electrolysers is presented to be significant (10.6% of total electricity consumption). Generally, a trend from three scenarios is observed that larger capacity of RES the larger capacity of flexible technologies as mentioned in section 1.4.

	IDA2050 (MW)	CEESA(MW)	CC2050(MW)
RES			
✓ Offshore wind	4,625	9710	14,600
✓ Onshore wind	4,454	4454	4,000
✓ PV	3,415	5000	3,250
✓ Wave	700	300	450
Flexible technologies			
✓ HPs	450	600	4,504
✓ Electrolysers	1,164	5395	Unspecified
International Connection	2500	5000	12,000

Table 1. Installed capacity assumed in the three scenarios

3.4. Comparison of usage of models in three scenarios

From a model perspective, IDA 2050, CC2050, and CEESA share in having energy system model at the center of the analyses and locating several models for analyzing other dimensions than energy system as supplementary roles. AS explained in Section1.3, as energy issue is related to various dimensions like economy, environment and society, the facilitation of models is necessary. This section discusses on how each energy scenario has dealt with such issue through investigating on the model usage.

IDA 2050 has a simple structure of quantitative models. The structure is composed of a macro economic model/emission model, ADAM/EMMA[73] and an energy system model, EnergyPLAN (introduced in Section2.1).

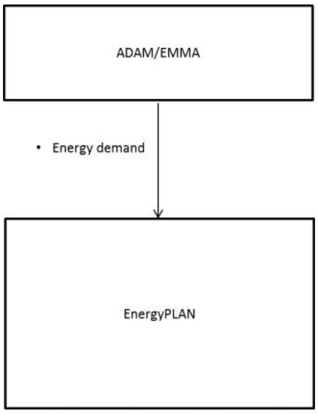

Figure 11. Usage of models in IDA 2050

Regarding the energy demand forecast, ADAM was used for assessing aggregated future demand in this project. Specifically there are various satellite models under ADAM. Among them, EMMA (Energy and eMission Models for ADAM) was developed for environmental assessment of economic measures. EMMA represents the detailed energy use by disaggregating the total energy use from ADAM. EMMA separates energy use into seven types; electricity, natural gas, district heating, solid fuels, fuels for transport, other fluid fuels and bio-fuels. ADAM has been used to evaluate greenhouse gas (GHG) emission in the agricultural sector in Denmark [74]. The agriculture sector is the second biggest GHG emitting sector after the energy sector. In the future, the role of biomass will become even more important than now, and according to [8] biomass already took 20% of share in electricity production in 2020, and is expected to increase its share in 2050. It means there will be a closer relation between energy sector and agriculture sector in the future. Therefore it is another reason that the analyses need to be done with an integrated model such as ADAM. In IDA 2050, however, ADAM/EMMA model is used in forecasting reference scenario.

In CEESA, a variety of models are employed for the purpose of analyzing the other domains such as environment, economy, and transportation.

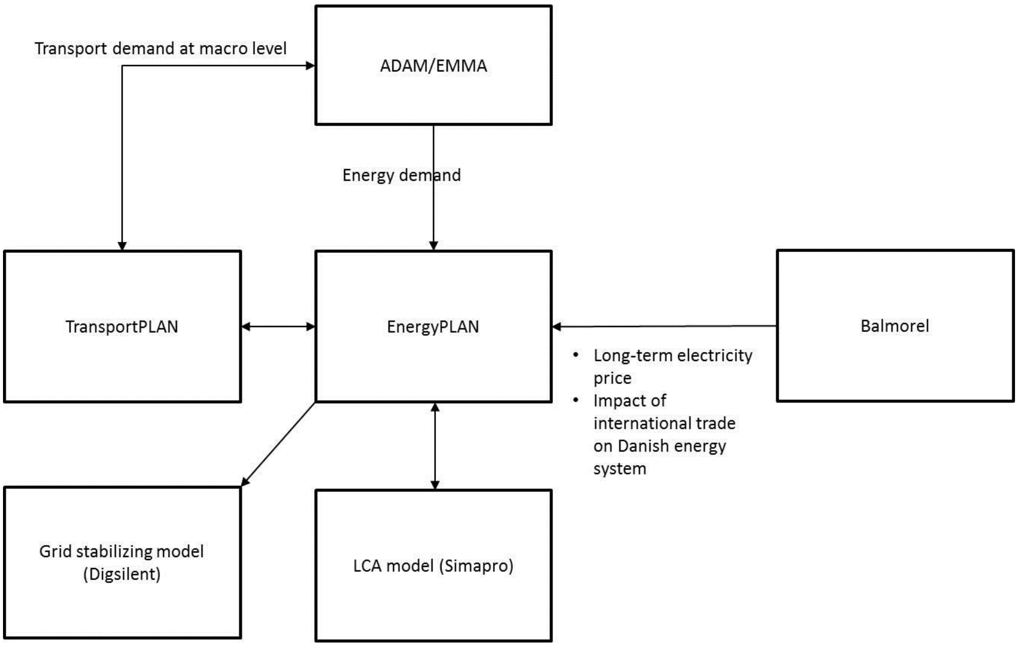

Figure 12. Usage of models in CEESA based on [70]

CEESA uses EnergyPLAN as a main energy system model, and gets help from Balmorel to estimate long term electricity prices. Like IDA 2050 ADAM/EMMA forecasts energy demand in the reference scenario.

Balmorel is a deterministic energy system model which is intended for finding the optimal investment strategy according to a set of assumptions. The input data are, for example, electricity and heat demand, fuel prices, CO_2 costs, technology data on generators, and efficiency in the conversion of energy. Originally it was designed to cover Denmark and electrically connected countries, but it has extended its regional application to have simulated for New Brunswick in Canada with a subject of large integration of wind power [75] Balmorel has been used in assessing possible flexible technologies for the integration of electricity and transportation [76,77]. Basically the Balmorel model is an endogenous investment model to represent which technology mix is more economical. At the same time Balmorel is able to analyze the hourly balance of energy demand and supply – though not for a whole year. Therefore Balmorel can examine the technical capability of a flexible technology to accommodate the intermittency of renewable power generation in the grid and it can assess the economic feasibility of a flexible technology as well.

For the analysis on transport, environment, and electric grid from perspective of electrical engineering, analyzing tools for each subject are applied. More detailed explanation on this is presented later sections (3.6~3.8).

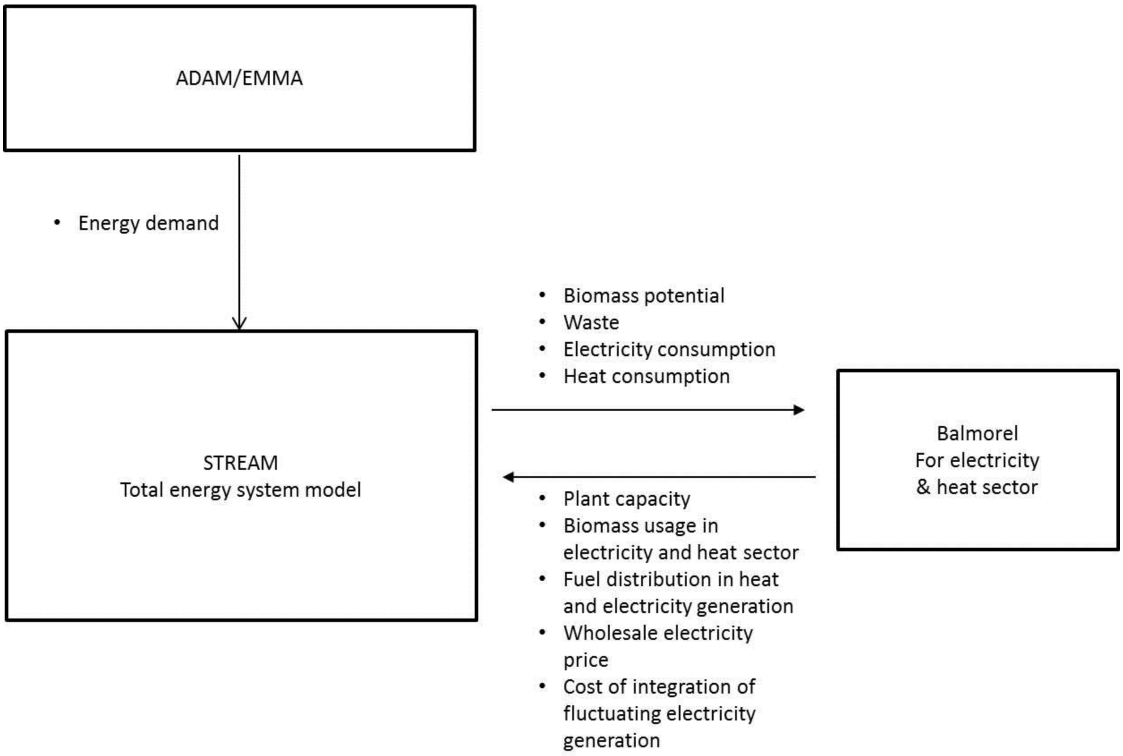

Figure 13. Usage of models in CC2050 [78]

CC2050 uses three models for the analysis; STREAM for energy system analysis, Balmorel for more detailed analysis for heat and power sectors, and ADAM/EMMA for analysis of macro economy.

STREAM (Sustainable Technology Research and Energy Analysis Model) model is composed of three spread sheet models; Energy saving model, Duration curve model, and Energy flow model. Energy saving model can deal with demand forecast by considering growth rate and energy intensity, and the energy intensity can be achieved through energy conservation by assuming better efficiency [79,80] . The Energy saving model overlaps partly with the function of ADAM/EMMA in estimating energy demand for whole energy sectors and partly corresponds to the function of transportation model in CEESA scenario since it has a function of estimating transport demand. The aim of the Duration curve model is to analyze hourly activity of plants and thereby supplying input to Energy flow and Energy saving models. The plants consist of several aggregated types of plants; CHP, heat storage, HP, heat boiler and various kinds of RES. Two groups of inputs from Energy saving and Duration curve model are gathered to Energy flow model and the model presents the overall results of the energy system i.e. emission, fuel consumption, and energy conversion.

There are several differences in using Balmorel model between CEESA and CC2050. In CEESA, Balmorel is used for a simple task to supply input parameters such as long term electricity price, while in CC2050, Balmorel model is involved in determining the installed capacity in individual plant, calculating biomass usage, wholesale electricity prices, and the cost of integration of fluctuating electricity generation. Also, CEESA uses an external transportation demand model while CC2050 analyzes transport sector with the integration of transportation demand forecast function in STREAM.

3.5. Scenario comparison

Among the three scenarios, IDA 2050 and CEESA have the same origin and are mutually more similar than to CC2050. They share the same energy system model, EnergyPLAN, but compared to IDA 2050, CEESA, a more recent scenario, uses more external methodologies other than EnergyPLAN such as life-cycle assessment (LCA) of biomass, a detailed transport model, and an application of power engineering methods to validate future power grid stability as illustrated in section 3.4. Within several areas, the CEESA scenario has different assumptions, and adopts more detailed methods for the analysis of a number of areas where it needs more investigation. If summarized the main differences, they can be presented as follow.

- Biomass
- Transport model
- Future power grid

In the following sections, the details of these three issues will be introduced and assessed from an evolutionary perspective as described in Section 2.2. Also, the results related with these methods will be presented and discussed in the framework of radical technology development (which is also explained in Section 2.2) to determine which scenario assumes more radical technological changes.

3.6. Future biomass potential

Assessing the biomass potential for energy purpose use in such a far future as 2050 is a difficult task. There are many factors that may have an impact on the future biomass availability like potential climate change and weather, land fertility, land-use change, cultivation method change, population dietary changes and demographics.

In assessing the potential biomass availability in the year 2050, CEESA considers more dimensions, and uses a quantitative methodology whereas the IDA 2050 assessed the future available biomass by literature review and simple calculation of necessary land area to cultivate energy crops. Furthermore, CEESA considers further environmental impacts through LCA methodology. Table 2 outlines the difference in methodologies adopted by two projects.

	IDA 2050/CC 2050	CEESA project
Method	Relatively simple estimation by literature review	Literature review and each future scenario is evaluated by • Direct land use changes • Indirect land use changes • Marginal mineral fertilizer Then compromise the results with the evaluations

Table 2. Comparison of methodologies to assess future biomass potential in IDA 2050 and CEESA

A consequential LCA analysis is adopted in the CEESA project. The consequential LCA has three main considerations; direct land use changes, indirect land use changes, and marginal mineral fertilizer. These considerations are used as criteria to assess environmental impacts of the future biomass scenarios constructed in the EnergyPLAN model. Direct land use change refers to the change in allocation of land area to cultivate energy crops, while indirect land use change indicates absolute expansion of cropland size, especially referring to the conversion of new land to agricultural land due to using biomass as energy resources. Besides, more fertilizer will be used in order to cultivate energy crops. Using more fertilizer has some environmental effects. Therefore there must be taken account of applying more fertilizer during the cultivation of energy purposed biomass. So CEESA defines the increase in fertilizer use as marginal fertilizer,

and tries to quantify it. For the quantification of the environmental impacts from them, four environmental categories are selected i.e. global warming, acidification, aquatic eutrophication and land use.
Thus, CEESA uses a consequential LCA which has an improved quantitative assessment of the output compared to the other scenarios, and seeks to prevent long term environmental consequences of excessive biomass usage. Such environmental consequences would not appear in the short term period, and as it is beyond the energy system model boundary, it is easily overlooked in the view of energy planners. Biomass is expected to be one of the major pillars together with wind power in two scenarios [70,71]. Utilizing biomass resources in the future will bring more issues in various reasons beside the environmental impacts such as ethical issues, i.e. using a potential food resource for energy purpose even though there are still starving populations in counties with poverty. So it can be an uncertain area to need to keep investigating with its significant importance.
Having a quantitative model to assess the future biomass potential is a more advanced way than the method of literature review in terms of systematic method and transparency in assumptions. There are a variety of opinions in the literature on the assessment of the future biomass potential. The research purposes of the various sources could deviate from that of the energy system modeling, and could not fit with it exactly i.e., different geographical scope, different time frame. Thus, the direct relation between the design of analysis and purpose of research in CEESA can enhance the results from the method of literature review in IDA 2050. Therefore, the added methodology in CEESA can be determined as a development in the evolutionary perspective.

Regarding the results, such a consequential LCA analysis renders the gross potential amount of future biomass in 2050 to be smaller by around 20% in CEESA than in IDA 2050. In numbers, this compares to a reduction from 307 PJ to 240 PJ. The discrepancy of 67 PJ may be compared to an annual Danish biomass production of 86.1 PJ in 2012 [8], and the more sophisticated modeling in CEESA hence reduces the available amount by more than three quarters of the present use. CC 2050 estimates 250 PJ as a potential future biomass comparable to the level in CEESA.
The reduction in biomass potential in CEESA leads to a different energy system as IDA 2050. The total year 2050 demands in the two scenarios converge at around 500PJ. The reduction of biomass usage should be replaced by other means such as changes in transport fuel and more electrification. More electrification can be found in Table 1 in Section 3.3 as the comparison of installed capacity of renewable electricity generating units assumed in each scenario.

The major difference is found in offshore wind. CEESA assumes twice the capacity of offshore wind compared to IDA 2050. Also PV has a larger installed capacity in CEESA. This is too a large part in order to make up for the lower biomass availability.

In terms of the rate of change in the installed capacity, it can be determined that CEESA adopts a more radical change than IDA 2050 since CEESA has larger installed capacity of renewable energy resources. The larger installed capacity implies that the better technological development level is prerequisite, and it is followed by change in knowledge. Since basically IDA 2050 and CEESA assume 100% renewable energy system, both scenarios change more than one dimension mentioned in Section 2.2, therefore they can be regarded as including “radical technological change”.

In the case of CEESA, the extent of change is larger as more renewable energy sources other than biomass are assumed to be installed as represented in Table 3. The way of using biomass is more similar to that of fossil fuel than the other renewable resources. Less use of biomass and larger capacity of other renewable technologies can be determined as more “radical technological change” in CEESA. The restriction of biomass also may bring more changes in the dimensions such as organization, knowledge, and technique in CEESA.

Dimensions	IDA 2050	CEESA	Comparison
Technique	✓ Renewable energy technologies ✓ Transport technologies ✓ Flexible technologies	✓ Renewable energy technologies ✓ More enhanced Transport technologies[1] ✓ More advanced flexible technologies	Same kinds of technologies but higher level of technologies are necessary in CEESA
Organization	✓ Subsidy on renewable energy technologies ✓ Demand side management via smart grid ✓ Installation of flexible means in a distributed way	✓ Subsidy on renewable energy technologies ✓ Demand side management via smart grid ✓ Installation of flexible means in a distributed way	Same types of changes but more significant level is applied in CEESA
Knowledge	✓ Research on renewable technologies ✓ Education for workers on renewable energy ✓ Public awareness of renewable energy for the political mood change	✓ Research on renewable technologies ✓ Education for workers on renewable energy ✓ Public awareness of renewable energy for the political mood change	Same types of changes but more significant level is applied in CEESA
Product	✓ Energy services such as electricity, transportation, heating, etc.	✓ Energy services such as electricity, transportation, heating, etc.	Same
Profit	✓ Shared by more market player in energy	✓ Shared by more market player in energy	Same

Table 3. Comparison of installed capacity in IDA 2050 and CEESA within the framework of “Radical technological change”

3.7. Transport

The transport sector is a significant challenge for achieving a renewable energy society since it has always been deeply reliant on fossil fuel with a fossil fuel share of 96% in Denmark in 2012[8] and with a technological development level of alternatives that is not mature yet. For independence from fossil fuel in this sector, therefore, are not only technological solutions suggested, but behavioral changes such as modal shifts are also proposed in CEESA and IDA 2050. In order to assess the proportion of the transport demand that can be replaced by alternative technologies, and which fraction that may be relieved by behavioral changes, future transport demands should be estimated concretely. (However CC 2050 does not take into account the behavioral change in assessing transport demand since it estimates that modal shifts will not be effective in reducing transport energy demand.) Here there is a difference in methodology for the estimation for future transport demand in IDA 2050 and CEESA.

In IDA 2050, there seems to be no separate tool to assess future transport demand. The IDA 2050 100% renewable energy transport sector is designed by starting from the present (2006) transport demand data and a certain share of the present demand of certain transportation will change into other means of transport in a

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[1] More detailed information is represented in Section 3.7

modal shift. Another fraction is reduced through technological development. For example, road transport demand is sorted out in terms of traveling distance to find out which fraction of the demand that can be replaced by EVs which have shorter driving range, biomass or synthetic fuel vehicles which have relatively long driving range, and for even longer distance the transport demand could be treated by modal shifts to electric trains. However, all the steps were based on the authors' assumption. In CEESA, on the other hand, a more advanced, detailed and transparent methodology is adopted for the assessment of transport energy demand. The methodology, TransportPLAN, considers more dimensions to use future demands, modal shifts, efficiency improvements, and different technologies as in Figure 14.

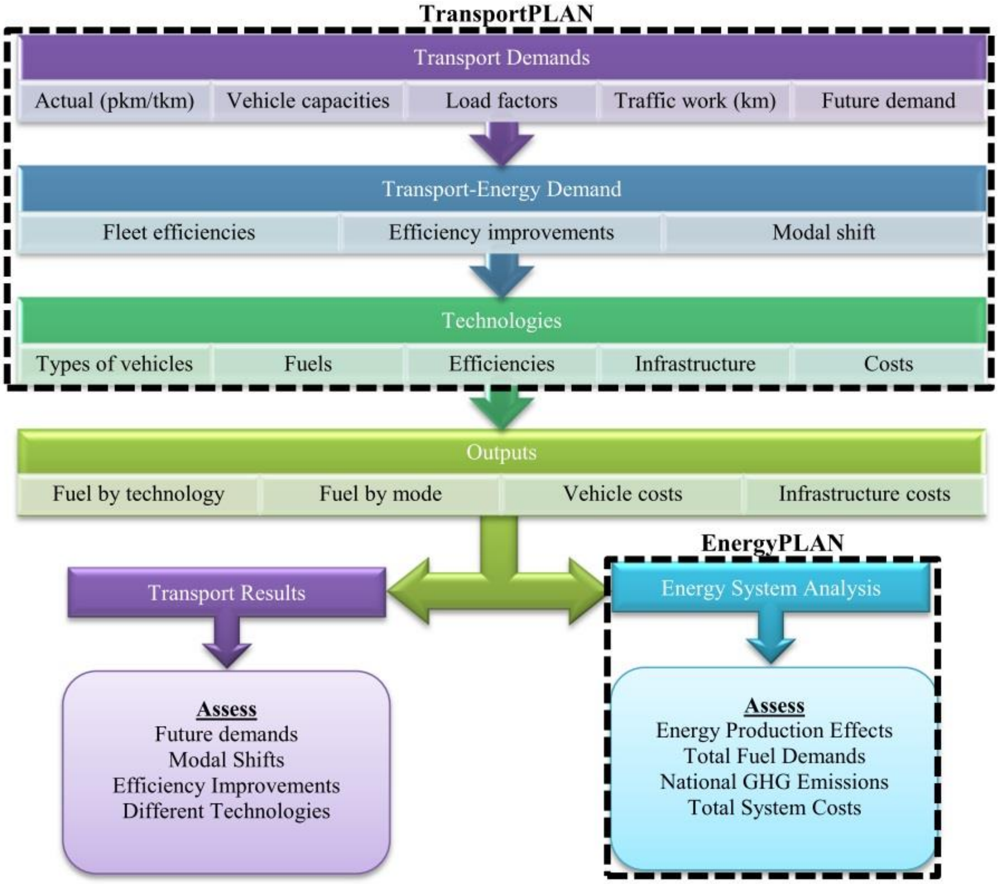

Figure 14. Schematic diagram of TransportPLAN in CEESA[70]

Having a separate and more advanced model for assessment of transport demand can be regarded as an evolution in CEESA compared to the IDA 2050. As mentioned before, the transport sector is one of the most difficult areas to become independent from fossil fuel, but also an important sector since the ascending trend for transport demand will keep going on in the future. At the same time, it is uncertain to reach a level of technology development to replace liquid fossil fuel in the future.

As shown in Figure 14, the TransportPLAN model itself, the way of calculating data, can be operated with transparency and objectivity; however, it still relies on data construction which can be subjective from the researcher's judgment. Compared with the methodology of literature review, the methodology in CEESA represents a higher level of transparency as it at least can show the underlying logics to audiences, and enable them to simulate it with their own assumed data. So the methodology in CEESA about transport demand assessment is determined to be a development in evolutionary perspective.

Regarding results, IDA 2050 reduces the gross transport energy demand from 269.3 PJ to 123.4 PJ, and CEESA reduces it from 280 PJ to 140 PJ, while the CC 2050 estimates 130PJ for transport energy demand in the future. However it is inappropriate to compare the transport energy demand directly by numbers since each scenario has a different scope about international trade or unspecified about the scope.

Even with the different methodology used, CEESA and IDA 2050 have in common a significant reduction in the overall transport demand compared to the BAU (Business As Usual) case. None of the scenarios consider increasing transport demands. If the future transport demands were as high as in the BAU case, the objective of 100% renewable society could not be met without either using too many biomass resources or too much electrolysis. Neither case is desirable since the former is restricted by limitation of biomass, and the latter would be too expensive. Therefore both scenarios assume that such a significant reduction in energy consumption can be reached through improvement in energy efficiency, modal shifts, and new infrastructure investment. They have more or less the same estimates in future transport energy demand.

However, if compared the two scenarios in a transport technology development perspective, (because CC 2050 does not explain as much as the other scenarios it is omitted), CEESA uses more synthetic fuel for transportation than IDA 2050. Biomass fueled vehicles, on the other hand, outnumber in IDA 2050 since the biomass potential is reduced in CEESA as in Table 3. Since the technology of synthetic dimethyl ether (Syn-DME) is not developed yet, and CEESA assumes more penetration of Syn-DME technology in the future, it can be determined that CEESA is more optimistic in terms of technological development. This is also a consequence of the reduced biomass availability in the CEESA scenario.

	IDA 2050	CEESA
Direct electricity	35%	22%
Bio-DME/Methanol	55%	44%
Syn-DME/Methanol	10%	34%

Table 4. Transportation fuel mixes in IDA 2050 and CEESA

All of these scenarios assume “radical technological change” in the transport sector in terms of technological transformation and transport energy demand. Determining which scenario has the most “radical technological change”, CEESA can be an answer. However, the difference is only for a dimension of technique, which is within limited scope e.g., Syn-DME as in Table 5. In fact, the difference of assumption in transport technology between the two scenarios may be brought from the difference of biomass potential explained in the section 3.6.

Dimensions	IDA 2050	CEESA	Comparison
Technique	✓ Enhanced battery technologies ✓ Biomass fueled vehicle technology ✓ Syn-DME technology	✓ Enhanced battery technologies ✓ Biomass fueled vehicle technology ✓ Syn-DME technology	Higher level of Syn-DME technology in CEESA
Organization	✓ Smart grid for EVs ✓ Chargers/Dischargers installed ✓ Public acceptance for modal shift	✓ Smart grid for EVs ✓ Chargers/Dischargers installed ✓ Public acceptance for modal shift	Same
Knowledge	✓ R&D on battery technology ✓ Education for workers on EVs, charging infrastructure, and smart grid ✓ R&D on biomass fuel, syn DME	✓ R&D on battery technology ✓ Education for workers on EVs, charging infrastructure, and smart grid ✓ R&D on biomass fuel, syn DME	Same, but emphasize on Syn DME in CEESA
Product	✓ Mobility	✓ Mobility	Same
Profit	✓ Replacing gas station with other organizations such as DSO (Distribution System Operator) of power and gas grid	✓ Replacing gas station with other organizations such as DSO (Distribution System Operator) of power and gas grid	Same

Table 5. Comparison of transport scenarios in CEESA and IDA 2050 within the framework of radical technological change

3.8. Future power grid

This subject is only treated in the CEESA project, and therefore, this section summarizes the background, methodologies, and results in the CEESA project briefly without comparison. Inherently, EnergyPLAN just can balance electricity consumption and production on an hourly basis, though with some restrictions imposed on the operation of the different units with a view to address grid stability [81,82]. However, from a grid stability point of view, the analyses need a higher time resolution for the balance issue. This will become more important and a critical issue in the future energy system with a higher renewable energy penetration. The technical feasibility of e.g. EVs to regulate power also from a short-term perspective is therefore an important issue. Many future scenarios including IDA 2050 and CEESA, suggest the integration among energy sectors such as heat, electricity, and transport as a path toward 100% renewable energy system. In the case of the integration of heat and electricity, the Danish energy system has a history of operating CHP [40], and has proven its feasibility through historical and empirical performance. However, the integration of the transport sector with the other energy sectors remains still a concept just to be assumed in a future. Vehicle technologies such as Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicle (FCEV) will enable integrating the transport sector with other sectors.

However, these technologies do not have much empirical data to support their adaptability to power grids since EVs are still in a demonstration phase or at the most in an early introduction phase. As EnergyPLAN is not sufficiently detailed to represent the dynamic performance of the power grid, it is necessary to simulate the integration of electricity and transport using a dynamic power analyzing tool. In analyzing this issue, not only EVs' role but also storage facilities such as fuel cell were taken into consideration.

For the dynamic analyses, the power analyzing tool, DigSILENT powerFactory [83] was used. For the validation of the EnergyPLAN model, the output of simulation of DigSILENT was compared with that of EnergyPLAN. The Danish island Bornholm was selected as an object of simulation, because this island has many similarities with the 2050 future Denmark in having isolated power system, and a high penetration of wind power. This works is also detailed in [53].

The results of the analysis can be summarized as follow.

- Regarding the role of V2G regulation by EVs, it asserts its technical ability to stabilize a power system with a quick response time. The analyses also shows a higher possible penetration of wind power with V2G than without in both PowerFactory and EnergyPLAN.
- The results of comparison between two models shows that less wind power can be integrated into the power grid in the case of dynamic power simulation than EnergyPLAN since EnergyPLAN does not capture the intra-hour variation in the power grid.
- However, the fluctuation level in the intra-hour has a tendency to be smaller than hourly fluctuation level.

3.9. Conclusion

All of the scenarios investigated in this analysis have a positive view on the feasibility of converting the Danish energy system into a fossil fuel free energy system by 2050. The scenarios are compared in two phases. The first phase is to compare three scenarios in a holistic and qualitative way. These scenarios suggest almost identical technological solutions for the given object with the only difference being in the extent of utilization of the solutions. For example, IDA 2050 is more dependent on biomass than the two other scenarios, while CC2050 uses intermittent RES such as wind, PV, and wave as a primary fuel rather than biomass and assumes the largest international capacity among the three scenarios. From a modelling perspective the three scenarios differ in their use. The models do not only include energy system model but also other models for the analysis of interfaced areas with energy system.

The second phase is mainly to compare the two scenarios, IDA 2050 and CEESA. Comparing IDA 2050 and CEESA, main differences are found in methodologies in three areas; biomass, transport, and power grid. These differences are described from the backgrounds, compared to each other, and the comparisons are assessed in terms of evolutionary perspective. Viewing the differences from the evolutionary perspective indicates the methodologies in CEESA can reflect the reality better than IDA 2050. Finally, the results are assessed within the framework of "radical technological change" in order to compare which scenario assumes more radical change for the future. The results show that CEESA adopts a more advanced and deeper investigation, consequential LCA for assessing future biomass potential, and which results in reduced biomass potential in the future than IDA 2050. The consequential LCA can be regarded as a development in "evolutionary perspective". Regarding the implications of the choice of methodology of CEESA, the reduction in biomass potential results in a need for more renewable installed capacity in CEESA. Therefore, in CEESA, not only the larger renewable installed capacity, but also the reduction of available biomass amount brings a more radical technological change than the IDA 2050 scenario in the dimension of organization, technique, and knowledge. Also, for CEESA an exogenous transport model was developed. This model considers more dimensions than IDA 2050 with a systematic method to quantify future transport energy demands, so it also can be regarded as an evolution in evolutionary perspective. However the results of the transport model are approximately the same as the other scenarios therefore future visions of the transport sector among the scenarios are similar. In CEESA a relatively new technology, Syn-DME, is assumed to be more prevalent but this only makes a small effect on technique dimension within the framework of radical technological change. Finally, the future power grid is examined by a power system analysis tool in parallel with hourly energy systems analyses conducted with the EnergyPLAN model in CEESA in order to refine the analyses.

Investigating the preexisting Danish future scenarios provide overview of future drawing of energy system. Therefore, it is meaningful as a starting point for the PhD dissertation. The way to use the model and model development would present what factor is important and uncertain for the future and what area should be investigated for more. Also, the way of having sub-scenarios would imply which areas are expected to be uncertain but regarded as important by the authors of the scenarios. Except the simple structure of scenario analysis in IDA 2050, CEESA and CC2050 commonly focused on the biomass potential in the future either in having a separate methodology or in using as a criterion for discerning sub-scenarios. From the detailed comparison of two academic scenarios; IDA 2050 and CEESA, one can see that biomass makes an effect on the capacity of RES and accordingly the capacity of flexible technologies like a chain effect also brings more radical technology change.

4. Optimal use of biomass in the future; heat vs electricity generation

This chapter is based on the article “Priority order in using biomass resources - Energy systems analyses of future scenarios for Denmark [34]” which is attached as Appendix II.

4.1. Introduction

As described in Chapter 1 and 3, biomass is regarded as an important primary energy resource to complement wind power. The significance of biomass resources is going to be larger as the integration of intermittent RES is larger in the future especially while looking at electric grid. The presently high and thus also growing penetration of wind power into the energy system can bring uncertainty in electricity generation. Inherently, wind power is intermittent in its output and the electricity demand too is fluctuating on a diurnal and seasonal basis, thereby creating balancing issues in demand and production of electricity. Biomass on the other hand can be utilized almost in an identical way as fossil fuel, that is to say, power from biomass can be dispatchable as long as the fuel can be supplied. In order to achieve grid balance, there are additional technological solutions such as heat pumps (HPs), electrolysers, electric vehicles (EVs), electricity storage, and reinforcement of electric interconnectors to neighboring TSO systems [84-86]. However, these solutions are better in the situation of excess electricity than in the lack of electricity in the system, although curbing demand on some of these units in effect corresponds to an upward regulation. Among the relevant renewable energy resources with a potential in Denmark, there are no options to dispatch electricity especially in a large scale except from biomass. Therefore biomass should play a significant role in coping with the grid balancing issue.

The high usage of CHP in the Danish energy system also increases the significance of biomass as a primary energy resource. As mentioned in Chapter 1, the Danish CHPs play a major role in heat and electricity sectors. The significance of CHPs is also found in the future plans and scenarios. Even though the technology is changed from thermodynamic machines into fuel cell, the concept of cogeneration is retained [87-89]. The future plans and scenarios include an important role of biomass to be used as a main fuel for the fuel cell CHPs to replace fossil fuels. Hydrogen or other synthetic fuels from electrolysis could substitute biomass for CHP fuels, however, using hydrogen and synthetic fuels are faced with a lower efficiency due to the additional energy conversion steps. The lower efficiency would in turn necessitate additional power production to meet the same demand, so besides the actual cost of electrolysis itself, the investment of larger capacity of RES to fill up the electricity that is lost from the low efficiency will be required. Therefore, biomass will be a more economical fuel for the operation of CHPs as long as the biomass is available.

Besides the balancing function and high usage in CHPs of biomass resources, the usage of biomass is anticipated to be more diverse in the future renewable energy system in Denmark compared to the present situation. IDA 2050 advocates that biomass should be used for various purposes; 26% for transport, 30% for industry, and 25% for larger or decentralized CHPs.

As such, biomass will be a versatile energy source in three main energy sectors; electricity, heat, and transportation. Besides the energy purposes mentioned above, biomass should replace fossil fuel as feed stock in the chemical industry since there is no alternative. Hence, biomass will have an important role to play throughout the society, so availability is an important issue.

The availability of biomass, however, is a potential barrier for such a fossil fuel-free future. The extensive use of biomass, however, will meet environmental limitations and is also likely to meet opposition in the population. The environmental limitation includes biodiversity issues [90], lack of land, land use conflicts, soil fertility degradation, erosion, and greenhouse gas emissions from deforestation due to more cultivating land as well as from increased humus degradation dues to tilling the soil. Several studies investigate the environmental effects of extensive use of biomass for energy production including the CEESA project. In the CEESA project [70], environmental issues were taken into account quantitatively by doing Life Cycle Analysis (LCA) while designing future energy scenarios.

The opposition among population against the extensive use of biomass is mainly due to the results of the mentioned environmental issues, and they are related to people's perception on bioenergy. The political opposition includes NIMBY (Not In My Back Yard) due to potential odors from manure, and ethical issues of using food material for energy or agricultural land for energy crops. They often derive from miscommunication between the public and policy implementer or the inertia of the conventional fuel system [91]. Unlike the barriers associated with environmental impacts, these obstacles are relatively unpredictable, and once occurring, it takes much effort to solve them in a democratic society. Consequently, the future use of biomass in the energy sector is likely to meet various barriers.

Considering the potential threats to biomass usage and the usefulness of biomass resources in the future energy sector which will bring about a high demand, the politically feasible biomass availability is likely to be less than the physically available biomass potential estimated in CEESA. Therefore, an evaluation of the biomass usage in the energy sectors is the subject of this analysis where it is analyzed which energy sector among electricity, and heat will be the most valuable choice for future Danish energy system in using the limited biomass resources.

In order to evaluate the value of biomass for each energy sector, in this analysis, a certain amount of biomass in each energy sector is artificially reduced from reference scenario. The reference scenario is set to be the so-called IDA 2050 scenario. There is another future scenario, CEESA, the most recent scenario, and it assesses future biomass availability with LCA (Life Cycle Analysis) considering various factors. Compared to IDA 2050, CEESA scenario assesses less biomass potential by 67PJ from 307 PJ to 240 PJ, and less usage of biomass resources by 47PJ from 284PJ to 237PJ. Hence, CEESA scenario conserves more biomass resources than IDA 2050 scenario.

In the CEESA plan, saving of biomass resources is occurred in transport sector by using more synthetic DME vehicles to replace biomass vehicles. The proportion of biomass in transportation is 55% in IDA 2050 and 44% in CEESA. It is noted that the amount of energy for transportation is not been compared between two scenarios because the different scope used for defining international transportation. Since the endeavor to reduce biomass resources in transport sector in CEESA and the reduction is highly dependent on the assumption of technology development of synthetic DME, the reduction in transportation sector is not considered in this chapter. Instead, the biomass resource is reduced in electricity and heat sector from IDA 2050, which is start point.

In order to evaluate the system benefit of biomass for the heating and electricity sector, respectively, a certain amount of biomass in each energy sector is artificially reduced compared to a reference scenario.

The two alternative scenarios analyzed are as follows:

- Biomass fuel is reduced in the **heat** sector by incrementally decreasing 2 TWh from the total biomass amount used in the IDA 2050 scenario
- Biomass fuel is reduced in the **electricity** sector by incrementally decreasing 2 TWh from the total biomass amount used in the IDA 2050 scenario

The 2 TWh reduction of biomass in the scenarios in the heat and electricity sector, respectively, is attained by an iterative analysis made in the hourly input/output energy system model, EnergyPLAN. In this analysis, the system impacts as well as the required installed capacities are assessed. Then these scenarios are compared to each other and to a reference scenario in terms of the biomass efficiency (output from biomass using technologies/biomass input), total costs, and the electricity export increase compared to the biomass decrease.

4.2. Alternatives to reduce the biomass share in the electricity and heat sectors

This section discusses the selection of alternatives to substitute biomass resources in electricity and heat generation and several assumptions for the analysis. All the alternatives are already used in IDA 2050. Table 6 lists the possible technologies and summarizes their characteristics.

Sectors	Alternatives to the production from biomass	Remarks
Electricity	1) Increase of RES	✓ Increase of magnitude of fluctuation of electricity output ✓ Necessary to increase flexible technologies in the energy system
	2) Synthetic fuel for CHPs or Condensing power plants	✓ Synthetic DME from electrolysis ✓ Energy losses due to additional conversions ✓ Dependent on adequate electricity in the system, so linked to increase of RES
Heat	1) Increase of HP use	✓ Highest efficiency among the conversion technologies from electricity to heat. However, supplementary heat sources may be needed in order to maintain a high coefficient of performance (COP) when a lower-value heat source is used [92].
	2) Increase of electric boilers	✓ Less efficient than HPs, nonetheless it can operate with a constant efficiency without supplementary heat source
	3) Synthetic fuel for CHPs and heat boilers	✓ Low efficiency due to additional stages of energy conversions

Table 6. Alternatives to biomass-based technologies in the electricity and heat sectors, and their characteristics

As seen in Table 6, there are two alternatives which can reduce the biomass use in electricity generation. The first alternative is to increase the share of RES in the system; however, this requires flexible means to cope with the variability of RES. The second alternative is the use of synthetic fuel from electrolysers, which is in fact not an application of a standalone energy generator but rather an energy carrier. This technology has a relatively low efficiency due to the loss from a series of conversions. In terms of investment, it does not only require electrolysers but also extra electricity generators to supply the electrolysers. In conclusion, the increase of RES is an unavoidable alternative when the aim is to reduce biomass use in the Danish electricity sector.

In the case of biomass reduction in the heat production, a greater variety of options can be applied than in the case of electricity. The first option is to employ more HPs. From a systems perspective, the second option - increasing the use of electric boilers – has some of the same characteristics; however, HPs show a better efficiency than electric boilers. The last option is to use synthetic fuel in CHPs and boilers, which has the drawbacks introduced above.

In order to replace biomass, it is necessary to increase the installed capacity of technologies exploiting other RES than biomass and thus the electricity generated from the RES. The problem is which particular RES should be increased. There are a number of RES candidates; Onshore wind, Offshore wind, Photo Voltaic (PV), wave, and tidal power. Each of the RES candidates has merits and weaknesses. In Denmark, onshore wind is limited by access to appropriate land, whereas offshore wind has a larger potential helped by shallow coastal waters [93]. Regarding PV, it is not desirable to expand its capacity beyond a certain point. Not only because the Danish geographical latitude is not optimal, but also because the production profile is not synchronized with the demand pattern. In the case of ocean energy like tidal and wave, even though it is less intermittent than other RES technologies, the technologies are still premature and the production is not synchronized with the demands neither on a diurnal nor an annual basis. In this analysis, only offshore wind power is considered to meet the reduction of biomass for each energy sector. Offshore wind power is already a proven technology and meets less public opposition. Furthermore, Denmark has the capability to produce wind turbines domestically making this technology socioeconomically more attractive.

In addition to the heat supply technologies in Table 6, there might be discussion on the way of providing heat in the future heat sector. One way is district heating systems, which at 46 % of the heat demand is prevalent in Denmark [94], while the remainder is supplied by a variety of individual heating technologies.

However, individual heating with the combination of flexible means which can absorb electricity while there is ample production on the fluctuating RES-based units in the system such as individual HPs and electricity boilers can be alternative options for the district heating. District heating is usually considered being more efficient than individual heating, though some results point in the other direction. Sørensen et al.[95] found ambient air HPs being the most economical option for individual heating, that it even showed similar economic performance as district heating. This is done by comparing the heating efficiency of single family house or apartment building without considering the interaction within the energy system. On the other hand, if almost the same comparison is done within an energy system framework, it shows another result. Lund et al. [94] compares district heating and individual heating based on HPs, fuel cell, electric boiler and Micro CHP. Here it is concluded that district heating shows better performance than individual heating in terms of fuel consumption, cost, and CO2 emission in a 100% renewable energy year 2060 system. The only comparable alternative among individual heating technologies is the individual HP. The district heating system is there assumed to be a suitable combination of electric heating, HPs and CHP units. According to [96] the district heating system can reduce biomass usage and make the energy system better for future Denmark in terms of cost effectiveness since the district heating system has a merit of cooperating with other renewable energy sources such as a large scale solar thermal, geothermal heat, and other heat sources such as industrial surplus heat and waste incineration.

In conclusion, district heating and individual HPs are comparable in performance. So, in order to compare between individual heating with flexible means and district heating, one needs more dimensions i.e., building density, and the distance to district heating grid. Perhaps the Danish future energy system will also be composed of a combination of district and individual heating instead of having only one way dominating the heating market. Therefore it is necessary to investigate the optimum ratio of district heating to individual heating. However this discourse is beyond the scope of this PhD dissertation. So here the fraction of district heating and individual heating is not a strategy to be changed from IDA 2050, but to be kept the same.

In IDA 2050 the fraction of district heating is increased from the present 49% to 63-70% in 2050. In individual heating in the IDA 2050 scenario, biomass covers only 10% of heating demand while 90% of the heat demand is generated by HPs. Meanwhile, in the district heating supplied from large and small CHPs, 55% of the heat is produced by biomass with the remainder being produced by HPs.

As mentioned before, HPs show the best performance in terms of efficiency and cost among the flexible technologies. Therefore, in this analysis, HPs are used as a main flexible technology and a conversion unit from electricity to heat energy since the biomass reduction scenario implies more electricity from renewable energy sources. However, before assuming that HPs simply are added on the district heating system, it is noted that HPs can decrease the cogeneration function of CHP somehow. According to Blarke et al. [97] a capacity of a HP associated with a CHP unit of 50-60% of the thermal capacity of the CHP unit offers good economic performance. However, this result is found under year 2020 market conditions for a system still using fossil fuels. A main issue when using large scale HPs integrated with CHP is that the combined system then operates not solely as a generator but also as a consumer of electricity thereby affecting the electricity market price. Therefore such a suggested ratio between capacity of HP and heat capacity of CHP might be disregarded in the situation of adequate electricity due to high penetration of wind power as assumed in this case.

To summarize all discussions, in this analysis, the biomass reduction scenarios for each energy sector are designed to meet the requirement of high efficiency and least change in the energy system to the extent possible. Therefore, two options are selected as means of reducing biomass; HP for the heat sector and the increase of RES for the electricity sector. The RES and HP should be paired, since the augmentation of one technology has an effect on the operation of the other. Consequently, it brings the adaption of the capacity of the other technology in order to keep the same level of flexibility in the whole system. The other conditions, such as the efficiency of conversion, the shares of district and individual heating, and other system configurations are assumed to be the same as in the reference scenario.

4.3 The reference scenario (IDA2050)

As mentioned in section 4.1, the reference scenario is the IDA 2050 scenario. From this scenario, biomass is incrementally reduced by 2 TWh from the electricity and heat sectors. The biomass resource usage in IDA 2050 is categorized into three sectors as in Table 7.

	Biomass amount (TWh)	Proportion (%)
District heating	1.81	2.11%
Decentralized CHPs	5.18	6.04%
Larger CHPs	6.34	7.39%
Central power plants	6.80	7.93%
Boilers in decentralized CHPs	3.88	4.52%
Boilers in larger CHPs	5.37	6.26%
Industrial	23.61	27.52%
Transportation	20.84	24.29%
Waste	11.09	12.93%
Household	0.87	1.01%
Sum	85.79	100%

Table 7. Biomass usage in IDA 2050[98].

Table 7 describes the fractions of biomass usages in IDA 2050, whose input file can be downloaded from the EnergyPLAN site [98] The results can also be simulated with the EnergyPLAN version 7.20 which can also be downloaded from the same site. Focusing solely on district heat and electricity generation – and disregarding biomass usage in industry, transportation, households (biomass boilers, wood stoves) and the biomass fraction of waste used in waste incineration CHP plants, biomass use is distributed as shown in Table 8.

For the CHP case, biomass consumed for dual purposes. There is a dilemma on how to define biomass amount for CHP facilities. In this analysis, the amount of biomass for CHP would be taken into account in both electricity and heat purposes.

This is hence the distribution of biomass in these sectors in the reference situation on which alternative scenarios are based.

	Heat [TWh]	Electricity [TWh]
Decentralized CHPs	5.18	5.18
Larger CHPs	6.34	6.34
Condensing power plant	-	6.8
Boilers in Decentralized CHPs	3.88	-
Boilers in Larger CHPs	5.37	-
Sum	20.77	18.32

Table 8. The biomass usage to be reduced for electricity or heat generation [98]

Total biomass use for each sector is 20.77 TWh for heat and 18.32 TWh for electricity in the starting point as shown in Table 8. There is thus a slightly larger room to reduce biomass usage in the heat sector. In the heat sector, the boilers at CHP plants are used only for heat purposes, while condensing heat power plants are used for only electricity generation in the electricity sector. The reducing biomass use in boilers and condensing power plants is given first priority in the electricity and heat sector respectively as they are the plants that do not exploit the synergy of co-producing heat and power and thus have the lowest overall efficiency. As mentioned before, the biomass used in CHPs is attributed to both the heat and electricity sectors therefore the CHPs perform at higher efficiency. Hence, the amount of biomass in CHPs is the second priority in both sectors.

4.4. Formulation of biomass reduction scenarios for each sector

The methodology applied to reduce biomass in each sector in sequential 2 TWh steps is as follows.

In the reference scenario, IDA 2050, electricity is generated from fluctuating RES, and biomass fueled production such as larger CHPs, decentralized CHPs, and condensing power plants. For reducing biomass use in the electricity sector, as mentioned before, the biomass in the condensing power plant is given first priority. For the reduction, there are no options to increase electricity generation but from fluctuating RES. Among the fluctuating RES, as explained in section 4.2., only offshore wind power is assumed to be increased. However more wind power will not only influence the operation of condensing mode power plants; due to its non-dispatchable nature and weather dependency, the increased production will also occur when condensing mode power plants are not operated thus also affecting the operation of CHP plants. This in turn can influence the operation of heat boilers. The capacity of HPs is therefore adjusted to prevent from influencing the operation of heat boilers. The addition of HPs also increases electricity demand, which necessitates larger RES consequently. This is a kind of feedback mechanism, which is to be avoided as much as possible in the simulation through an iterative process.

To summarize the steps in the modelling;

- Increase renewable energy sources (RES) to reduce biomass into CHP and condensing power plants
- If there is an increase in boiler production by decreasing CHP operation, the capacity of HPs is adjusted to maintain the same level of biomass boiler use
- Iterate until the targeted amount of biomass reduced (i.e., 2TWh, 4TWh and so on) is attained.

As mentioned in section 4.2, the share of district heating and individual heating for heating demand is assumed to be the same as in the reference scenario, IDA 2050. Mainly HP replaces electric boiler and CHP in heat generation. However, it is noted that there is an assumption for the operation of HPs in the reference. HPs are assumed to cover until a half of the maximum heat demand. The rest of the maximum heat demand should be covered by other heat sources such as CHPs, boilers, and electricity heating. This assumption is necessary to keep a relatively high level of COP of 3.5, which is assumed in IDA2050.

The process applied for reducing biomass use in the heating sector is as follows:

- Increasing HPs for reducing boilers burning biomass as well as CHP heat production
- Increasing RES as otherwise electricity will be insufficient in the system causing condensing power plant to be operated more, which is not intended case (the reason is also the increased biomass use of the condensing mode plants).
- Iterate until the targeted amount of biomass reduced in heat sector (i.e., 2TWh, 4TWh and so on) is attained.

4.5. System configuration and behavior with reduced biomass for electricity generation

Table 9 shows the configuration of each scenario for biomass reduction in the electricity generation through the application of the methodology outlined in Section 4.4. The installed capacity of RES increases with the decreasing biomass use in the electricity generation. The largest increase is thus found in the interval between 12 and 14 TWh. This is due to the fact that the reduction of the condensing power plant operation reaches a point of saturation, because there are simply hours in which the wind is not strong enough to generate any significant electricity. In 2012, for instance, during 2 h in Western Denmark and 138 h in Eastern Denmark, the wind production was ≤ 2 MW compared to average productions in the two areas of 865.5 MW and 298.7 MW, respectively (Based on hourly production data from [97]).

After reducing the biomass use for condensing mode power generation, the biomass use in CHP is the next target to reduce. However, this is difficult. The amount of biomass in CHPs is not reduced by increasing RES linearly, since the CHP basically follows heat demand and is regulated as the last means to prevent the CEEP.

The capacity of HPs is also adjusted in order not to have an effect on the biomass boilers for the reason mentioned in Section 4.4. Up to 8 TWh of reduction of biomass for electricity, the capacity of HPs is increased. However, when exceeding 10 TWh, the HP capacity decreases. Up to 8TWh of reduction, the capacity of the HP must be increased in order to fill up the heat reduction from the decrease of CHP operation by HP and not biomass boilers. Meanwhile, the decrease of HPs from the reduction above 10 TWh is attributed to the characteristics of the HP as a flexible technology, which tends to expand the number of operating hours when the supply of electricity from the RES exceeds the electricity demand. The expanded operation of HPs decreases the operation of the biomass boiler.

Biomass	Offshore wind(MW)	HP capacity in decentralized CHP(MW$_e$)	HP capacity in centralized CHP(MW$_e$)
Reference	4,625	150	300
-2 TWh	5,330	153	300
-4 TWh	5,994	156	301
-6 TWh	6,670	159	301
-8 TWh	7,265	161	301
-10 TWh	8,015	157	295
-12 TWh	10,520	135	270
-14 TWh	15,350	105	235

Table 9. System configuration while decreasing biomass amount in electricity sector

Figure 15 shows how the heat demand is covered. Until the case of 8 TWh reduction, HPs substitute the reduced heat production by CHPs. EH (Electric Heating) and Synthetic fuel from electrolysers starts to substitute the reduction of heat production from CHPs from 10 TWh of biomass reduction. The synthetic fuel used in CHPs and boilers increase from 0.62 TWh in the reference to 2.09 TWh with a 14 TWh reduction of biomass for electricity generation. EH also increases significantly from nil in the reference to 2.83 TWh with a 14TWh reduction of biomass for electricity generation. So even though the ambition is only to reduce biomass use in electricity generation, the heating sector is also inevitably affected due to the links between the two sectors.

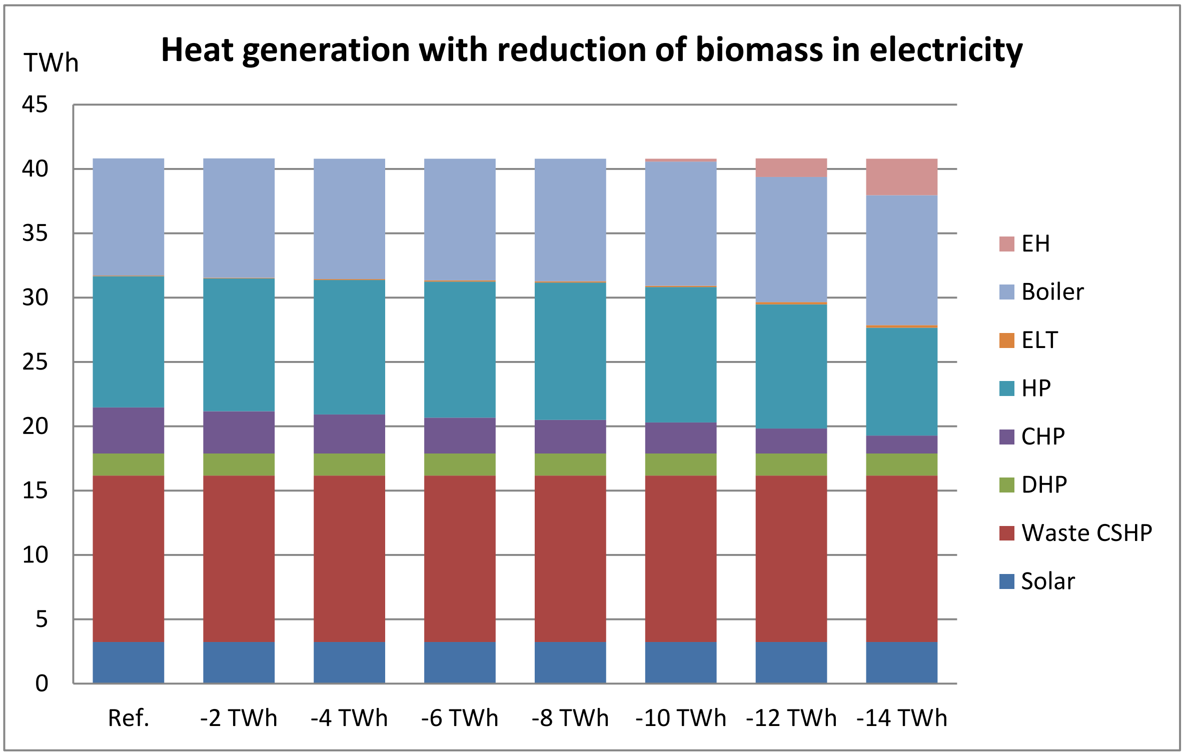

Figure 15. Changes in heat production with decreasing biomass use in electricity sector

The higher the biomass reduction in electricity generation, the more wind power, and hence the more electricity export as in Figure 16. The upward trend of having more electricity and export is accelerated when biomass use is reduced by 12 TWh and 14 TWh.

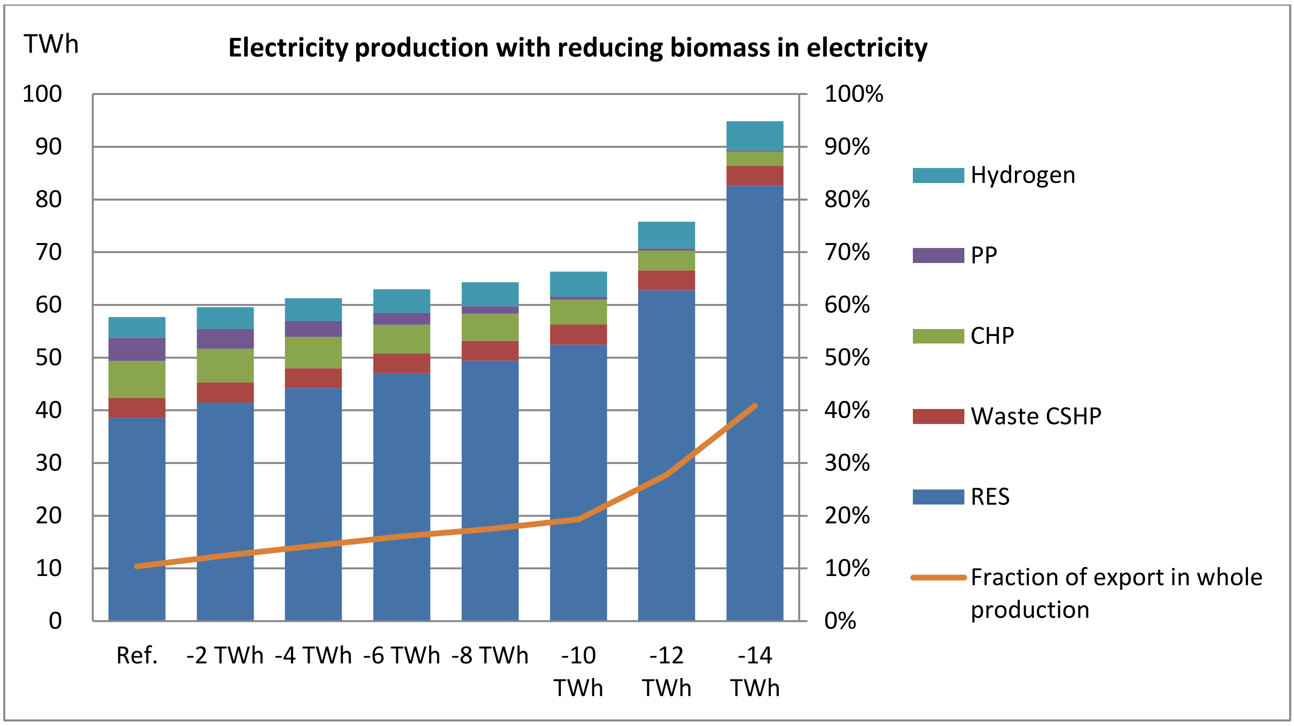

Figure 16. Electricity production with decreasing biomass use for electricity generation.

4.6. System configuration and behavior with reduced biomass for heat production

Table 10 presents the configuration of each scenario for biomass reduction in the heat sector. The biomass reduction for heat generation requires that the system has a larger capacity of HPs and a minor increase in the offshore wind capacity. Compared to the scenarios in Section 4.5, the rate of increase in offshore wind capacity is not as steep as the scenarios for biomass reduction in the electricity sector. On the other hand, the capacity of HP in the reduction of biomass for heat production shows a steeper increase than the biomass reduction in the electricity sector.

Up to the 8 TWh reduction of biomass, the expansion of HPs can reduce the biomass use in a boiler from 9.1 TWh (ref.) to 1.46TWh (8TWh reduction). However, the biomass usage in CHP stays the same. This is attributed to the higher priority order of CHP in heat generation in EnergyPLAN, as explained in Section 2.1.

Thus, in order to reduce the biomass use by 10, 12 and 14 TWh in the heat sector, it is necessary to reduce the CHP operation. Therefore, the installed capacity of CHPs is reduced exogenously to ensure less CHP usage.

In terms of energy conservation, it is not an optimal option to replace the CHP-based heat with electric heating; however, it is the only possibility.

Biomass	Offshore wind (MW)	HP capacity in decentralized CHP(MW) (MW)	HP capacity in centralized CHP(MW)	Installed capacity of decentralized CHP (MW)	Installed capacity of centralized CHP (MW)
Reference	4,625	150	300		
-2 TWh	4,800	186	369		
-4 TWh	4,950	230	460		
-6 TWh	5,070	335	530		
-8 TWh	5,200	450	750		
-10 TWh	5,690	600	900	1,300	1,950
-12 TWh	6,455	600	900	1,015	1,365
-14 TWh	7,100	800	1,050	650	1,000

Table 10. System configuration while decreasing biomass amount in heat sector

Figure 17 illustrates how the heat demand is covered, while the biomass resource for heat production is decreased. While decreasing the biomass available for the heat sector, the heat from biomass boilers and CHPs is decreased, and the heat from HPs is increased most significantly. Up to the 8TWh of reduction, most of the biomass reduction comes from the biomass boilers. From the 10TWh of reduction, at which the installed capacity of CHPs starts to decrease, the biomass amount in CHPs is decreased.

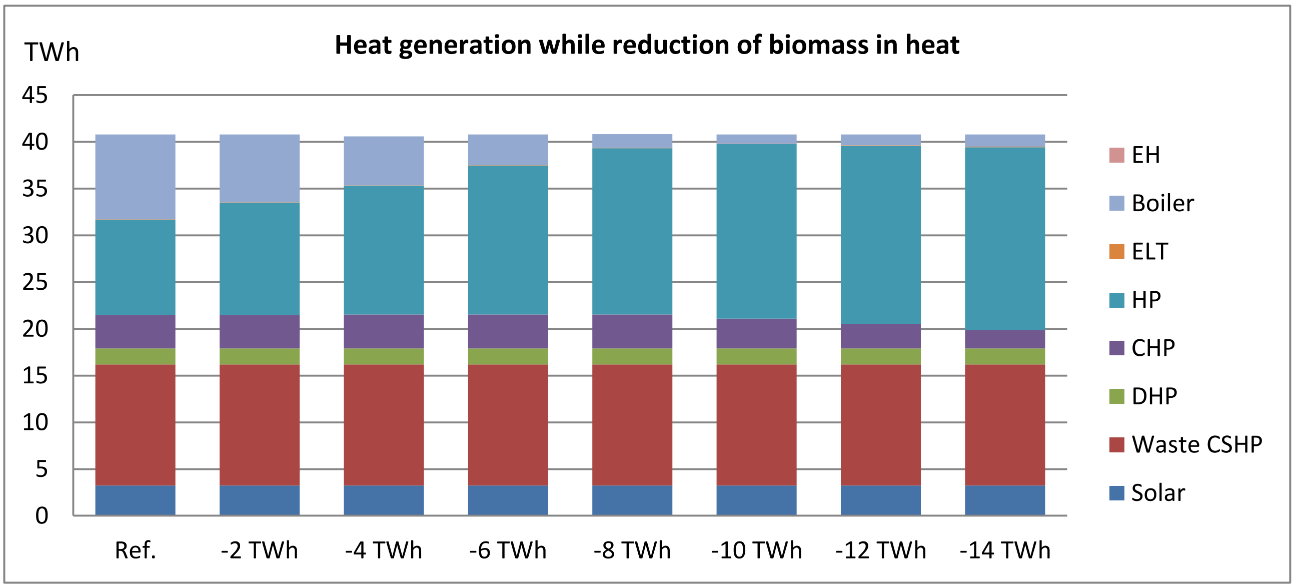

Figure 17. Heat production with decreasing biomass availability for the heat sector

As shown in Figure 18, compared to the biomass reduction scenario in the electricity sector, the biomass reduction scenarios in the heat sector do not tend to increase the electricity generation significantly. This is because the expansion of offshore wind power is low in the biomass reduction scenarios within heating. Another major difference between these two scenarios is the ratio of exported electricity compared to the total electricity production, which is related to the difference in the installed wind power capacity. With more condensing mode power and less wind power present in the heat scenarios, the system simply has a better load-following capability.

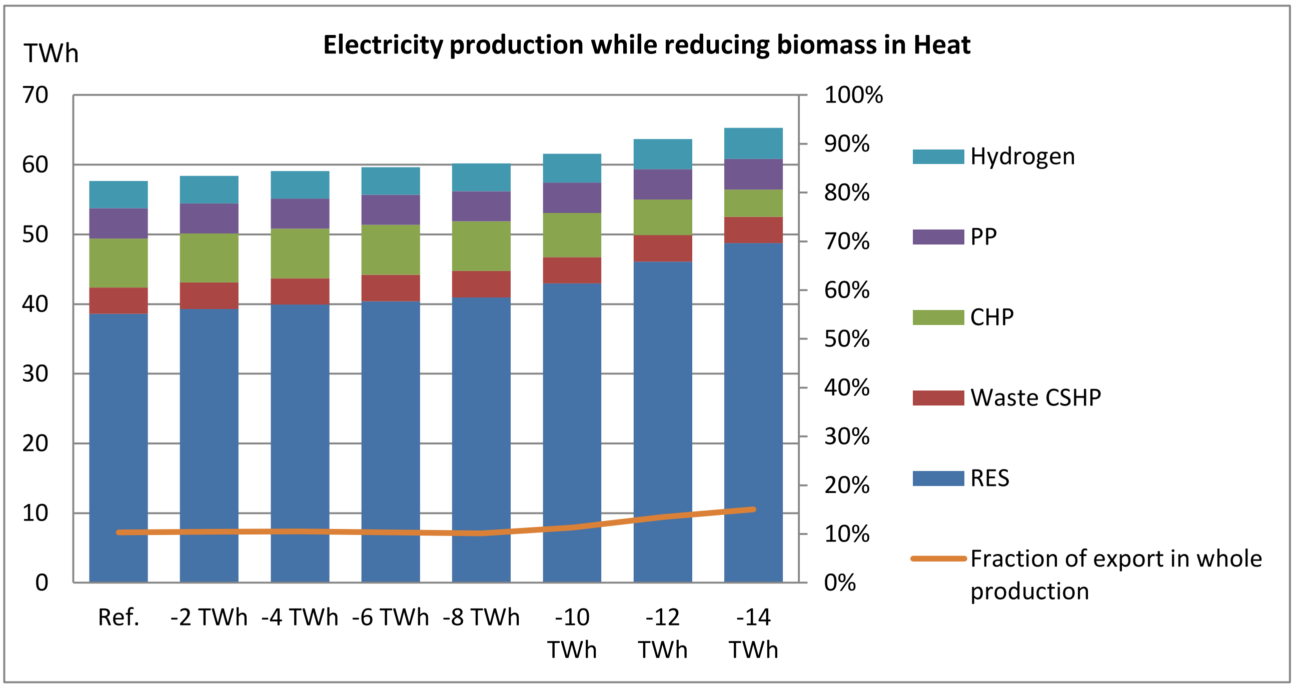

Figure 18. Electricity generation with decreasing biomass availability for the heat sector

4.7 Scenario comparison (Efficiency)

For a comprehensive comparison of the biomass reductions in the electricity and heat sectors, the efficiency of biomass fueled plants is calculated and presented as in Equation 1. The efficiency is defined as:

Eq. 1) $Biomass\ system\ Efficiency = \frac{Output\ of\ all\ plants\ fueled\ by\ biomass - Output\ from\ synthetic\ fuel}{Input\ biomass\ amount - biomass\ used\ for\ transporation}$

As shown in Table 7 in Section 4.3., CHPs, boilers, condensing power plants, waste incineration, district heating, and industry are mainly fueled by biomass, and synthetic fuel on a small scale. However, the amount of synthetic fuel used in these units increases in the high biomass reduction scenarios (i.e., 12TWh and 14TWh) in the electricity sector. Therefore it cannot be disregarded when calculating the efficiency. The amount of biomass used for the transportation sector is excluded, because there is no connection between bio-fueled vehicles and the other energy sectors. Even though the transportation sector is integrated with other sectors the link between the sectors is limited to the interface between the electric grid and the EVs. The proportion of EVs in IDA 2050 in terms of energy consumption is small (19.9%) compared to the other fuels (biofuel, synthetic DME). This analysis assumes smart charging like IDA 2050, in which EVs charge whenever excess electricity is produced [56]. Hence, the electricity charged into EVs might include the electricity from biomass even though the amount is small. However, this effect is ignored here, partly because it seems to be trivial due to the synchronization of excess electricity production and high wind hours, and partly because it is too complicated to calculate the efficiency if this is considered. In Figure 19, the efficiency of biomass fueled units is decreasing as the amount of biomass is reduced in both the electricity and heat sectors. The reduction of biomass in the electricity sector shows a better efficiency than the efficiency in the heat sector. This is due to the reduction of biomass use related to the decreased operation of condensing power plants, which have a lower total efficiency than other units.

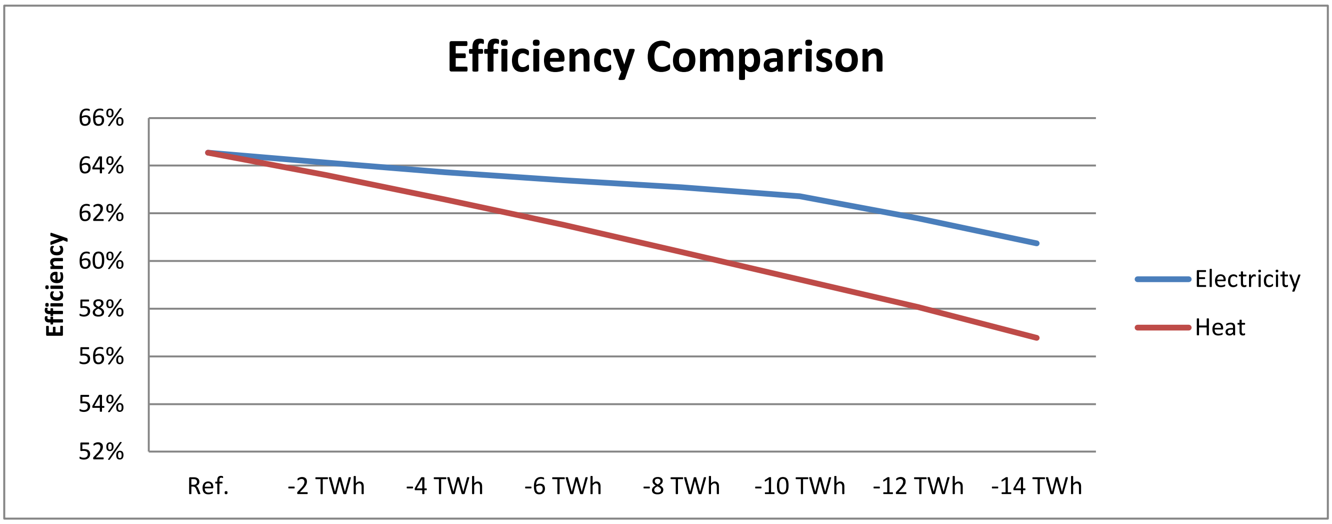

Figure 19. The efficiency trends while decreasing biomass amount in electricity and heat sector

4.8. Scenario comparison (Cost)

The calculation of the system cost is based on the assumed cost data in IDA 2050. The investment costs of the facilities used are reflected as annualized investment cost by taking into account a discount rate of 3% and technology specific lifetimes. Fixed and variable operation costs are also included in the calculation on annual basis (fixed) and by usage amount (variable). The fuel costs consider only biomass and synthetic fuel since a 100% renewable energy system is assumed. As seen in Figure 20, the system costs in the two scenarios diverge from the point when biomass is reduced by 12TWh. In the heat sector, the installed capacity of CHPs with 10, 12 and 14TWh reduction of biomass is reduced as listed in Table 10 and the investment costs for CHPs is correspondingly reduced. The reduced CHP investment cost can offset the increased investment cost of additional wind power capacity, while biomass costs are also reduced. Combined, the cost level is even lower than the reference case. On the one hand, when reducing biomass use in the electricity sector, the cost level surges when 12TWh of biomass in heat sector is reduced - mainly because of high installed capacity of RES as in Table 9

Figure 20. The annual system cost with decreasing biomass availability in the heat and electricity sectors

4.9. Scenario comparison (Effects on Export)

In this analysis as well as in the IDA 2050 scenario, importing and exporting electricity is not counted as an optimal solution as it would affect neighboring regions possibilities of performing a similar transition [55]. As an indicator to express the effectiveness to reduce biomass in heat and electricity sector, the ratio of forced electricity export (also known as excess electricity production) to primary energy source reduction is suggested. If the export is too large compared to the reduced biomass use in a sector, it may be interpreted as an ineffective way of reducing biomass use and additionally as a less flexible energy system than a system not having this characteristic. As seen in Figure 21, biomass use reduction in the heat sector presents better performance than the counterpart according to this indicator. Among the biomass reduction in the heat sector scenarios, the electricity export stays at almost the same level as in the reference case while the biomass use is decreased in steps of 2TWh. This trend is kept until the biomass use in heat sector is decreased by 10 TWh. It means that the additional installed wind power capacity needed for reducing the biomass use in the heat sector is small enough that the energy system can absorb the electricity well without causing additional exports at times. It also agrees with the results that HPs expanded for heat generation and the capacity of CHPs is reduced, which implies that more electricity can be converted into thermal energy rather be exported to other countries.

Meanwhile, the indicator shows relatively high values for the biomass reduction in the electricity sector scenarios. With 12 TWh and 14 TWh of biomass reduction scenarios in the electricity sector, the ratio becomes bigger than 1, which means more electricity is exported than the reduced amount of biomass. It is attributed to a high share of RES in the energy system.

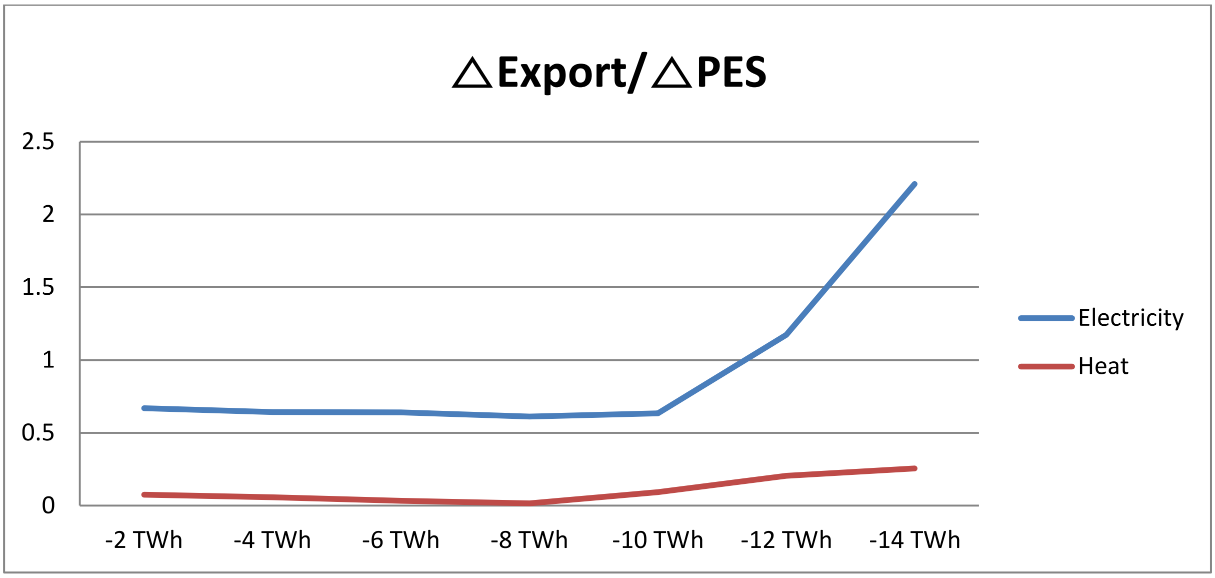

Figure 21. Ratio between exported electricity and biomass use reduction

4.10. Conclusion

Electricity is usually considered as a more valuable energy carrier than heat as the exergy of electricity corresponds to the energy contents whereas for heat – at the temperature levels appropriate for heating purposes – the exergy level is a fraction of this [100]. The high value of electricity compared to heat comes at a cost though, as electricity systems need to be balanced much better than heat systems and as electricity storages are considerably more complex than heat storages.

This analysis compares the value of using biomass for heat source and for electricity generation in a 100% renewable energy system context. The comparison is done by assuming a decrease of biomass availability for the electricity and heat sectors respectively. The results are shown in terms of system configuration, biomass fuel efficiency, and impacts on export. According to every single of these criteria, the reduction of biomass in the heat sector is better than the alternative reduction in the electricity sector. It is partly because that there are not many alternatives to replace the electricity generation from biomass even in the future, and partly due to because that there are the different characteristics of the both energy carriers.

Especially for the high biomass reduction scenarios in the electricity sector, it is highly expensive to have a sufficiently large capacity of offshore wind power capacity, and the export of electricity is increased in accordance with the larger wind power. Meanwhile the reduction of biomass is attained without the large increase of wind power and the accompanied export of electricity in the heat sector. The results coordinate well with the general choice mentioned above.

Methodologically, one kind of flexible technology (HP) and only one kind of RES (Offshore wind turbine) are used to reduce biomass in this analysis. The reason why these technologies are selected as biomass reduction means is that these technologies are the best in terms of efficiency or the fittest after consideration of potential RES and the Danish technology level. The other technical assumptions such as efficiency, insulation and the assumptions to necessitate changes in people’s behavior such as a decision between individual and district heating are to be the same in the reference scenario. It can be pointed out that these assumptions should be varied according to available level of biomass for the optimum use of biomass resources. This comment is valid, but the conditions for the optimum use of biomass cannot be attained in a short term. From a time perspective of time, the installation of more HPs and offshore wind turbine power does not happen in a day but it can be realized in a time frame where people can estimate a future change. Hence, this method has a validity to cope with the reduction of biomass in a relatively prompt way, thereby can handle small reduction of biomass. However, it is noted the biomass reduction scenarios are for fictitious cases where particularly the high biomass reduction cases are beyond what would be reasonable. At the very high biomass reduction cases, there are some flaws on the methods – and thus the results should only be seen as indicative – but for the more limited biomass reduction levels, results remain valid.

5. Potential of flexible demand in the Danish future energy system

This chapter is based on the article "Assessment and evaluation of flexible demand in a Danish future energy scenario [101]" which is included in Appendix III.

5.1. Introduction

For the purpose of balancing supply and demand in the electric grid, demand flexibility can provide the exact same service as the supply side as long as the same extent of controllability on both sides is assumed. Hence demand side flexibility is getting more attention as ICT (Information and Communication Technology), which enables consumers to monitor and control their demand automatically, develops. With this technology, electricity demand may react to real-time price signals [102] and real time energy system requirements.

In the future the significance of flexible demand is different from that of the present time since there are other flexible measures to buffer the intermittency of RES in exiting fuel-based energy systems. Thus, a future context is necessary. For the assessment of flexible demand in a future context, a Danish 100% RES scenario is used.

The Danish Climate Commission (See Chapter 3) suggested four scenarios according to two assumptions of international framework and limitation of biomass consumption [72]. Among the scenarios, the recommended 2050 scenario which assumes ambitious international framework and limited biomass consumption (referred to as CC2050 henceforth) is selected for the analyses of flexible demand. In the CC2050, the Climate Commission lists flexible demand as a necessary component in the future Danish energy system without, however, quantifying the potential available amounts nor the required amounts of flexibility in a 100% RES-based energy system [33,88].

In this chapter, the potential and system benefit of flexible demand in the far future is assessed from two approaches. In the first approach, which is a bottom up, the potential future flexible demand is assessed in the residential, commercial and industrial sectors in the context of a year 2050 100% RES scenario. Subsequently, this scenario is simulated using the energy systems analysis model EnergyPLAN (see section 2.1) in order to assess the system benefit of the potential flexible demands established. In the second approach, which starts from the systems level, the required system effects are first defined and then it is analyzed which level of flexible demand is adequate to realize these system effects.

5.2. Aggregated and decomposition methods

There have been a number of studies to assess the potential and value of flexible demand with different methodologies. The methodologies can broadly be categorized into two by whether the electricity demand is viewed at an aggregate level or individual level divided into specific electric services.

The aggregated approach relies on market mechanisms for assessing the demand change in accordance to electricity price change. For that, price elasticity is necessary for assessing the change as well as market data to present the normal price variation in the system. Both data sets can be empirical like market data, or particularly for the case of price elasticity it would be assumed numbers as short term empirical data, such as real-time elasticities, are rarely found [103]. Several studies use this approach to assess the potential and financial value of flexible demand. Zarnikau et al. [104] assess the aggregated industrial demand response to price change, based on a market-based analysis. The results confirm that the responsiveness of industrial loads is very small to wholesale electricity price levels and that there are factors contributing to the low responsiveness, including types of demand response service, and short notice period for price change. Sezgen et al. [105] estimate the value of demand response technologies such as load curtailment, load shifting, and fuel substitution by a financial methodology, real option analysis, finding that demand response can reduce electricity price fluctuations as well as the average electricity price level. Faria et al. [106] analyze demand responses in a simplified 33 node electrical system where each node is modeled to be a relevant player. When normalized tariffs and individual consumer tariffs are compared in this model, it concludes that consumers' benefit would be more or less the same – but system benefits are not considered.

The second approach puts more emphasis on the technical aspect in assessing the potential of flexible demand. It starts with decomposition of electricity consumption into several processes to assess whether the individual processes can be shifted temporally or not, and if so, the potential time shifts that can be realized. Several articles follow this second approach. Barker et al. [107] separate residential loads into interactive and background loads and use an algorithm to allocate background load for the hours of less demand in order to shave peak load or reduce gap between high and low load level. Stadler [108] assesses the potential of flexible demand by dividing candidates of flexible demand into several categories. These candidates include not only electric home appliances but also energy system components such as CHPs and HPs. Stötzer et al. [109] try to assess the potential of demand side management in Germany by breaking down electricity demand into load blocks for each sector based on limitations including shifting time, break after shifting, and usage thereby finding the optimal status of allocating the load blocks. Starke et al. [110] quantify the flexible industrial loads by segregating industrial demand by presenting the fraction of flexible demand and non-flexible demand. Boëda et al.[111] use a classification method to sort the electric demand according to its controllability and show how the load control can be a benefit for the intermittent production.

Among the two approaches explained above, a technical approach is used for the assessment of flexible demand for this chapter, as the technical approach sets the physical boundary and thus is independent of implementation and incentives. For its application, here, electric processes are categorized by several criteria. The criteria are different by each energy sectors. The residential and commercial electricity services are categorized by two criteria; storability and controllability of the service. These two criteria are used to determine which processes are easier to be flexible demand.

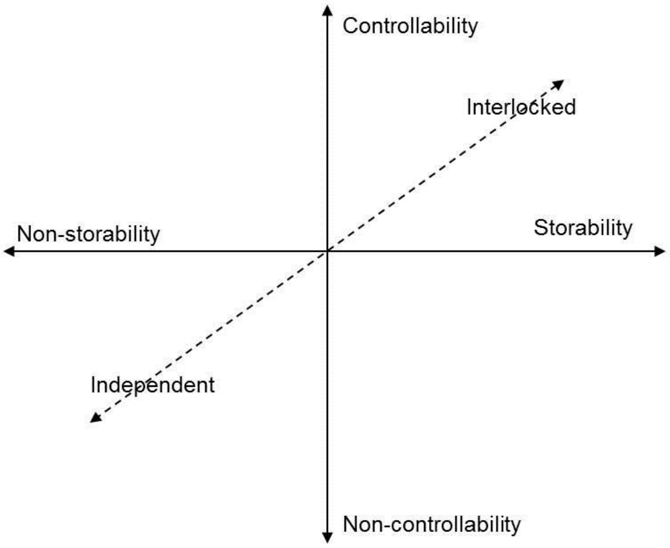

Figure 22. Three criteria for the assessment of flexible demand potential

The most accessible target is the automatically controllable and storable service, and the second easiest target has two candidates; storable but human factored and non-storable but automatically controlled while the least accessible target is the non-storable human factored demand.

For the industrial flexible demand, one more criterion is added on these two criteria. The criterion is whether the process is independent or interlocked. Processes that are interlocked with other processes are considered as a hampering factor for being flexible demand. The following section quantifies the potential of flexible demand in Denmark with these methods.

5.3. Residential sector

Analyzing the electricity consumption in Danish residential sector, Figure 23 indicates the share of electricity consumption by category. The largest share of electricity consumption in the residential sector is refrigerators and freezers with 18%. The second largest share of electricity consumption is washing equipment (washing machine, dryer, and dish washer). However, the electricity consumption is relatively evenly distributed to all the listed categories.

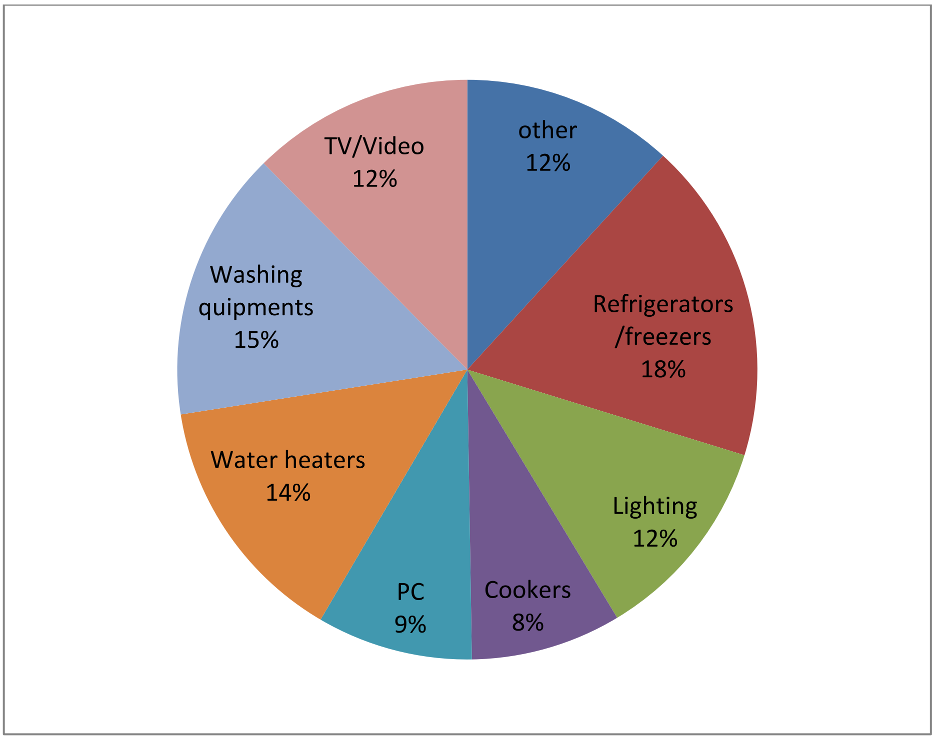

Figure 23. Electricity consumption by category in the Danish residential sector [23]

Table 11 lists how the residential processes from Figure 23. Electricity consumption by category in the Danish residential sector [23] are categorized according to the method introduced in section 5.2.

	Storable energy	Non-storable energy
Non-control	Water heaters for domestic hot water	Lighting PC Entertainment Cooker (oven)
Automatic control	Refrigerator/Freezer(18%)	Washing equipment (15%)

Table 11. Categorization of residential electric processes by potential for flexible demand

Refrigerator/Freezer demand would be the first target for flexible demand followed by washing equipment. Even though heating domestic hot water is located within the area of storable and non-control, which is categorized as a flexible demand by the criteria, this process is not regarded as having a potential in this analysis. This is attributed to the fact that electric boilers are not considered for future heating sources in the CC2050 scenario, and thereby the electricity consumption for water heaters will dwindle.

As for the potential time shift of these processes, Table 12 presents this feature of different electric demands including influencing factors and potential time shifts. The potential time shifts are referenced from a German study [109].

Electric appliances	Feature	Influencing factor/final energy	Shifting time (minutes) [109]
Refrigerators/freezers	Potential for load shifting/operated with intermittency	Temperature	15 ~ 120
Lighting	Cannot/should not be load shifted	Consumers' behavior	
Cookers	Cannot/should not be load shifted	Consumers' behavior	
PC	Cannot/should not be load shifted	Consumers' behavior	
Water heaters for domestic hot water	This demand can be postponed to other hours within limited range and without intermittency	Consumers' behavior	15~180
Washing equipment	This demand can be postponed to other hours within moderate range	Number of member in household, and Member's activity	150 (Dish washer) 180~540 (washing machine)
Entertainment (TV, Video)	Cannot/should not be load shifted	Consumers' behavior	

Table 12. Potential time shift of electric processes in the residential area

Refrigeration and freezing is normally used for conservation of products or provision of drinks and foods which should be served at lower than an ambient temperature level. Some products are more sensitive to temperature than other products, and even with the same purpose of maintaining a low temperature level, there is difference in temperature tolerance levels. Apart from temperature sensitive contents which have small temperature tolerance range, refrigerator/freezer can be operated flexibly. Saengprajak [112] analyzes the temperature variation of residential 140 liter refrigerator at an ambient temperature of 25°C. This temperature level is relatively high compared to ordinary Danish in-door conditions. The results are optimistic towards the potential of flexible demand in refrigerators. It takes 15h to 30h for the temperature inside a refrigerator to increase from 0 to 10°C depending on the weight of its contents where heavier contents result in a slower variation of temperature due to a higher internal heat capacity. This electricity demand can be controlled by automation and varied in accordance to the electricity demand and supply situation if only the temperature level is guaranteed. In this analysis, this demand is assumed to be flexible within a shorter time frame of two hours for a conservative view.

Washing equipment is defined here to include electric appliances like washing machines, dryers, and dish washers. As seen in Figure 23, the washing demand comprises 15%, which is the second largest proportion of the residential demand. Even though the washing demand is not a thermal demand, the timing of using washing equipment can be shifted in order to avoid the high demand and low supply hours, but the duration of shifting is limited [113].

This demand is mainly from the residential sector and any washing demands within commercial and industry may be considered inflexible. A German study has investigated the usage pattern of dish washers, washing machines and driers, finding that they are only used from 7 am to midnight [108]. It would typically be better if the usage hour can be shifted to the hours of less demand i.e. typically after midnight, however this would depend on the actual RES production of the time of the energy service need. In addition, noise and the acceptance of consumers for shifting to those hours are uncertain issues.

According to [114] which presents an analysis of the usage pattern of washing equipment in Denmark, washing machines are used 256 times per year, dish washers 249 times per year, and dryers 163 times per year. The market penetration of these appliances is 0.7 per household for dish washers, 0.51 for dryers, and 0.79 for washing machines. Combining the market penetration and usage pattern of these appliances, it is a moderate assumption that the washing equipment demand is a daily demand, which means that at least one of the appliances is used per day. Even with the limited duration of shifting for individual washing demand (from 2.5 hour to 7 hour) as seen in Table 12, the aggregation of washing demand enables it to be operated more flexibly than individual washing demand. Furthermore, if households have all washing equipment appliances, it would be possible to distribute the demand by using only one of the appliances at a time, which could make it another possibility of flexible operation. In this analysis, the washing demand is assumed to be a daily demand and flexible within a day.

5.4. Commercial sector

The same definition of flexible demand is used while assessing the potential of flexible demand in the commercial sector. For that, the commercial electricity demand is categorized into individual processes in [26], and the share of processes is shown in Figure 24.

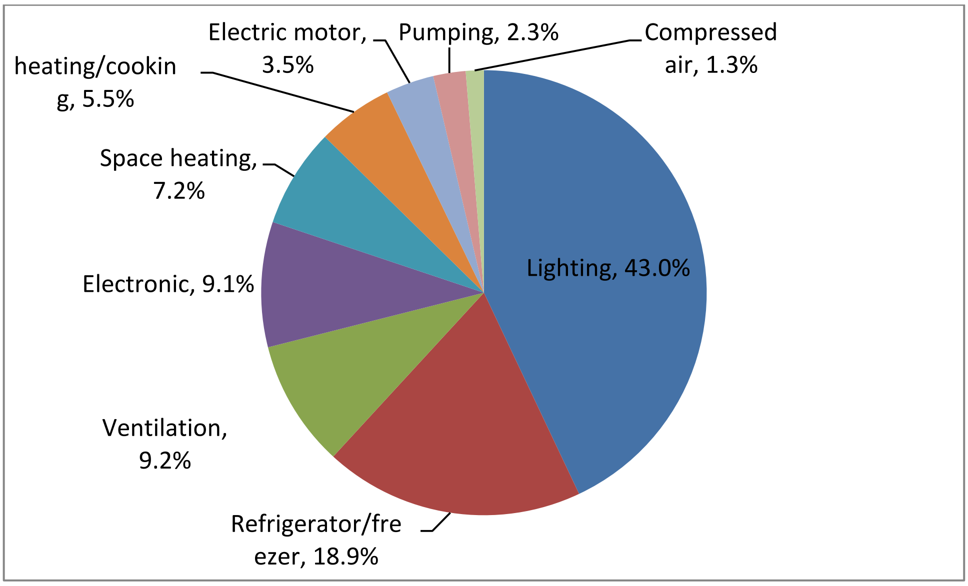

Figure 24. Electricity consumption by category in the Danish commercial sector [115]

It is seen that the largest share is lighting (43%) followed by demands of refrigerator/freezer (18.9%) and ventilation (9.2%). Like the residential case, these processes are categorized by the two criteria storability and controllability in Table 13. Storable and automatically controlled demand would be the most accessible flexible demand in commercial sector and this category is assumed to be flexible demand in this analysis.

	Storable energy	Non-storable energy
Consumers' behavior	• Compressed air	• Electronic • Heating/cooking • Electric Motor
Automatic control	• Refrigerator/Freezer (18.9%) • Ventilation (9.2%) • Space heating (7.2%) • Pumping (2.3%)	• Lighting

Table 13. Categorization of commercial electric processes by potential for flexible demand

Among the process demands in the storable and automatically controlled category, pumping demand has a precondition of installing adequate size of storage tank for flexible demand. In this analysis, sufficient storage tank and pumping capacity is assumed to be installed to give 24h flexibility - thus its time frame is assumed to be one day. The other three demands (refrigerator/Freezer, ventilation, and space heating) use other materials (cold mass, air, and hot water) as energy vehicles. Therefore, these demands are assumed to have a time frame of two hours like the residential case. According to [116], a part of lighting demand is possibly flexible demand which can be controlled by sensor to catch human movement and sense brightness of inside environment. However, the lighting demand is not considered for flexible demand in this analysis since it belongs to electricity saving, not load shifting.

5.5. Industrial sector

Normally, demand side management in industry is regarded as an easier task and has a longer history [106] than other demand sectors since the industrial sector already has human resource for energy management as well as typically significant electricity demands.

The composition of a country's industry determines the flexibility of overall industrial loads as some industrial branches have more potential than others depending on their characteristics in process and management.

	Electricity (GWh)	Share
Food, beverages and tobacco industry	2,105	27%
Plastic, glass and concrete	1,156	15%
Metal	775	10%
Chemical industry	723	9%
Wood and paper products and printing	650	8%
Mechanical industry	611	8%
Medicine industry	386	5%
Furniture and other manufacturing.	373	5%
Oil refineries, etc.	323	4%
Transport industry	181	2%
Textile and leather industry	140	2%
Electronics industry	123	2%
Manufacture of electrical equipment	113	1%
Sum of industry	7,659	100%

Table 14. Electricity consumption by Danish industrial branches in 2011. Data from [117]

Table 14 presents the 2011 electricity consumption in the Danish industry. Total electricity consumed in Danish industry was 7.66 TWh this year with the biggest fraction comprising food, beverages and tobacco industry, which was 27% of total electricity consumption. This is followed by plastic, glass, and concrete industry and metal industry. These largest three industrial sectors comprise over half of the overall electricity consumption in the Danish industry sector. According to a study by EPRI, although done in a California context, these three main industries have more than a "fair" level of potential demand response (cement industry is assessed "good" while food processing and metal industry are labeled as "fair"). Therefore, it is assessed that Danish industry, as a whole, has a large potential based on the industry composition.

Looking at the electricity consumption by process rather than branch, Table 15 presents the processes which consume electricity in industry and farming/fishery sector sorted by magnitude. It is noted that the data sums the demands of fishery/farming and industry. The consumption of fishery/farming is 2,028GWh thus the industry consumption is 9,949GWh[2].

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[2] The data is from 2006, therefore the industry demand was larger than the data in Table 14 which is from 2011. It is explained by the descending trend of Danish industrial demand shown in Figure 3 in Appendix III.

Electricity consuming processes	Electricity consumption (GWh)	Share(%)
Electric motors	2,624	21.9%
Ventilation and Fans	2,391	20.0%
Pumping	1,343	11.2%
Compressed air and process air	1,160	9.7%
Lighting	1,136	9.5%
Refrigerators / freezers	980	8.2%
Melting / Casting	683	5.7%
Reduction	478	4.0%
Second heating up to 150 °C	244	2.0%
Drying	208	1.7%
Stirring	197	1.6%
Heating / cooking	141	1.2%
Computer and electronics	138	1.2%
Space heating	119	1.0%
Other electricity use	102	0.9%
Second heating above 150 °C	26	0.2%
Roasting	7	0.1%
Total	11,976	100%

Table 15. Danish electricity consumption in industry (including farming/fishery) by processes in 2006 [115].

As explained in section 5.2, one additional criterion regarding whether a process is independent or interlocked is added for the assessment of potential of flexible demand. However, this criterion is difficult to apply.

Identical processes in two different plants can be used differently. Some processes are integrated with industrial processes while the same processes may be operated independently in other branches of industry. All relationships among the processes are different in every context and impossible to know without in-depth analysis of every single context, which is beyond the scope of this analysis.

Therefore, in an analysis of the flexibility in the industrial sector, one of the barriers is a lack of specific knowledge on processes making it difficult to assess the potential demand response or flexible demand – as also confirmed by McKane [118].

		Automatic	**User control**
Non storable	**Interlocked**		• Lighting • Computing • Drying • Stirring • Other electricity use • Reduction
	Independent		• Computing
Storable	**Interlocked**	• Ventilation/Fans (5%) • Refrigerator/Freezer (4.1%) • Pumping (5.6%)	• Melting/Casting • Second heating above 150 °C • Second heating up to 150 °C • Heating / cooking • Compressed air
	Independent	• Ventilation/Fans (15%) • Refrigerator/Freezer (4.1%) • Space heating (1%) • Pumping (5.6%)	

Table 16. Categorization of commercial electric processes by potential for flexible demand

Ventilation demand is a more complicated case than refrigeration/freezing demand in terms of having more factors impacting the demand. The ventilation demand is dependent on indoor air quality such as moisture and CO_2 level which in turn are affected by the number of people inside the house, their behavior as well as on the outside air quality [108]. According to [119], the CO_2 concentration level is highly dependent on the number of people inside and it concludes that saving electricity by reducing air flow rate without significant changes in air quality is possible. Ventilation demand can be used for the object of flexible demand [108].

However, in industrial areas, ventilation has other purposes like drying, and removing dust and is thus related to processes for producing products and services. Hence there is no potential flexibility in this case, as it would have an impact on the products and services and not just human comfort. This industrial ventilation demand is determined not by the working environment but by product requirements. Therefore, it is a hard task to draw a line between the normal ventilation and the necessary ventilation for products and services. In this analysis, half of the ventilation demand is assumed to operate for pure ventilation purpose, thereby being independent of other electric demand. The other half of the ventilation demand is assumed to be interlocked with other processes.

Like residential and commercial area, refrigerator/freezer demand is assumed to be a flexible demand, however, only a half of it is assumed to be flexible. It is attributed to the fact that much of the freezing demand may be used for fast freezing as a manufacturing process instead of simply preserving the contents. The characteristics of the pumping demand are also uncertain and half of the pumping demand is assumed associated to the storage tank whose size is large enough to cover one day demand. The compressed air process is a storable process but the duration is generally less than one hour (15 minutes [116]), therefore it is excluded from the flexible demand. Theoretically the compressed air process has no actual limit in storing so this 15minute limit is more a consequence of typical existing storage facilities rather than a theoretical potential. In addition it should be mentioned, that since the overall efficiency of compressed air systems is very low, the usage should be minimised in the future.

5.6. Future scenario in Climate Commission 2050

The Danish Climate Commission presented four scenarios for 2050 in their 2010 report - referred to as CC2050 henceforth. These four are based on a certain level of consumption as well as a certain production system configuration. Of these four, the so-called "recommended scenario" is selected for this study. A main characteristic of this scenario is the large-scale deployment of wind power capacity which makes wind the primary energy resource followed by biomass. The basic energy system configuration is abstracted from the main and background reports [120] and used for the simulation of EnergyPLAN. The parameters and conversion of data are detailed in Appendix III. This section briefly introduces how to assess future flexible demand potential based on the assumed share of flexible demand for each energy sectors introduced in the previous sections.

The future electricity consumption by sector is likely to deviate from the present pattern. The CC2050 forecast that the total electricity consumption increases significantly from the 2011 level of 31.47 (excl. grid losses) to 89.2TWh in 2050. However, the 89.2TWh includes grid loss (5TWh), electricity consumption in transportation sector (20TWh), for synthetic/bio fuel (9.4TWh) and for HP (9.8TWh). The electricity consumption associated to flexible demand is the "classic" electricity consumption, which mainly refers to electricity consumption for electric appliances excluding heat and transportation purposes. Therefore they are subtracted from the total electricity consumption. Hence the classic electricity consumption, which is 45TWh, is used as a pool for flexible demand in this analysis.

The proportion of electricity consumption in three energy sectors is specified into the three sectors; residential (10TWh), commercial (12TWh) and industrial demand (23TWh) [121]. The assessment of flexible demand by technical approach is presented in the Table 17. As mentioned before, it is noted that the electricity consumption share of each process is assumed to be the same as in the present situation.

Area	Time frame for flexible demand	Processes for flexible demand	Sectorial electricity consumption in CC2050	Flexible demand in CC2050 in a year
Residential	Short term (2 hours)	• Refrigerator/Freezer (18%)	10TWh	1.8TWh
	Long term (day)	• Washing demand (15%)		1.5TWh
Commercial	Short term (2 hours)	• Refrigerator/Freezer (18.9%) • Ventilation (9.2%) • Space heating (7.2%)	12TWh	4.5TWh
	Long term (day)	• Pumping (2.3%)		0.3TWh
Industrial (including farming and fishery)	Short term (2 hours)	• Refrigerator/Freezer (4.1%) • Ventilation (15%) • Space heating (1%)	23TWh	4.6TWh
	Long term (day)	• Pumping (5.6%)		1.3TWh

Table 17. Approximation of the flexible demand for CC2050

Combined with the approximation of flexible demand in CC2050 (Table 17), the input parameters for EnergyPLAN simulation are presented in Table 18. For the simulation of flexible demand, the maximum hourly capacity of flexible demand is necessary. For the assessment of these values there is not many ways to approximate them from the annual flexible demand since it is impossible to know the future capacity of each process. Hence, in this analysis, the maximum hourly capacity for flexible demand is assumed to follow its usage pattern. For example, a daily flexible demand is assumed to be used for 4 hours per day, therefore the annual amount for daily flexible amount is divided by 8784 and multiplied by a factor of 6 (for 4 hours).

Time frame	Hour	Flexible demand (TWh)	Maximum hourly capacity of flexible demand (MW)
Short term	2 hours	10.9	2,481
Long term	Daily (24hours)	3.1	2,117

Table 18. Input parameters for flexible demand in EnergyPLAN simulation

5.7. Effect of flexible demand

The effects of flexible demand are compared with respect to the three parameters mentioned above as shown in Table 19 where CC2050 is the reference scenario and the scenario assuming flexible demand is labelled FD2050.

A first observation is that the international exchange is decreased. Both import and export are decreased. The decrease in export is larger than that of import. It means that the produced electricity is more effectively utilized within the domestic system rather than relying on using neighbouring countries as buffers.

The condensing mode power plant operation is decreased slightly in FD2050. It is closely associated with the import amount, since these two are options that EnergyPLAN apply for providing electricity when RES, waste and industrial CHP are not sufficient. Of these two, condensing mode power plants are prioritized over import. Less operation of condensing power plants means that the flexible demand enables to adopt more from RES electricity and thereby can avoid import and the operation of condensing power plant eventually.

Parameters	CC 2050	FD2050	Difference
International exchange			
Import (TWh)	1.23	0.98	-0.25
Export (TWh)	14.83	14.02	-0.81
Condensing power plant operation			
Electricity production (TWh)	13.86	13.52	-0.34
Biomass consumption (TWh)	30.8	30.04	-0.76
Consumption			
Electricity consumption (heat and transport sectors included)	88.05	88.09	+0.04
Heat consumption	51.26	51.26	0

Table 19. Overall comparison of CC2050 and Flexible demand Scenario

Probing into the details of international exchange, the frequency of international exchange over 8 GW is presented in Figure 25. As shown, the frequency in FD2050 indicates that capacity above 11 GW is not used within the year. A smaller frequency is found for FD2050 in all exchange ranges in Figure 25.

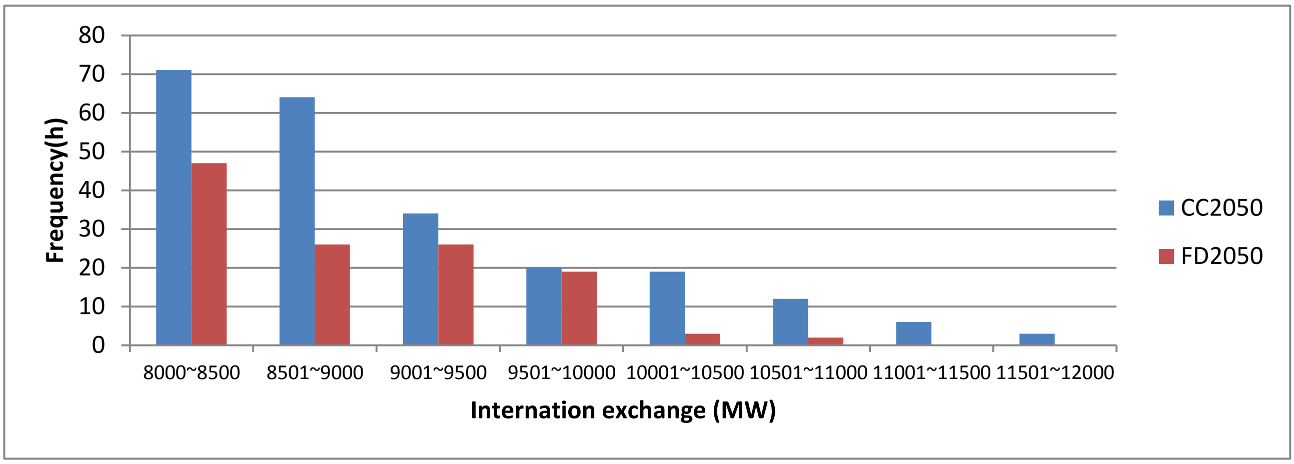

Figure 25. Frequency of hours of international exchange over 8 GW in CC2050 and FD2050 Scenario

One of the major benefits of the flexible demand is to avoid the investment of low utilized energy system components. In this sense, reducing the capacity of interconnection capacity would be a benefit from the exploitation of flexible demand. In Figure 25, the frequency of hours in high power international exchange such as above 10 GW is reduced in the case of FD2050 from the level of CC2050. It means there might be a chance to reduce the required interconnection capacity (mainly export in this simulation) by 1-2 GW through having adequate flexible demand. This corresponds to the largest capacity used in Denmark which is around 2 GW for a double 400 kV AC overhead system [122].

5.8. Size of flexible demand for system impact

Then from the other end, the question remains which size of flexible demand would it take to make a significant impact on the energy system. In this analysis, finding a level of flexible demand to reduce the international connection line from the present level is endeavoured. The present capacity of international link is 6,640 MW[123]. However, the capacity in CC2050 is assumed to be 12,000MW, which is about double the present capacity. If the flexible demand can prevent the installation of additional international connection then this is favourable. It can even decrease demand to below the current level, then this is even better. In these analyses, it is analysed whether it is feasible to reduce the international connection by half, which would be a significant change for the energy system, not only from the perspective of saving investment but also from the perspective of security of supply in reducing dependence from neighbouring countries. This is particularly relevant as Germany to the south of Denmark also is introducing high levels of fluctuating RES, and while both Norway and Sweden have significant shares of hydro power, this very flexible production technology cannot meet the regulating demand of all European countries opting for fluctuating RES.

In the analysis, flexible demand is increased in steps of 1 TWh from 0 till 20 TWh – and the remainder of the total of 45 TWh is thus modelled using the fixed hourly distribution curve. In each step, the international connection is subsequently decreased to the minimum level which permits sufficient exchange. This analysis is conducted for monthly, weekly, daily and 2h flexible demand.

The capacity of flexible demand per hour for weekly and monthly time frame is calculated by using a factor of 4, which is less than the factor of daily demand explained in the Section 5.6. Varying this factor does not have a large impact on the results.

The results of these analyses are presented in Figure 26 showing results for all four analysed time steps. From the Figure 26, it is evident that the longer time frames of flexible demand present larger reductions in the international connection capacity. For the very short term flexible demand - 2h - there is no relevant decrease of the international exchange capacity.

Neither daily nor weekly flexible demand can make the energy system feasible with 3,320 MW of international connection. It is found to be feasible only in the monthly flexible demand case when around 13TWh of flexible demand is assumed. In practice, it is difficult to find any possible case to be flexible within the monthly time frame. Even more, the amount of 13TWh is over a quarter (28.8%) of classic electric demand in CC2050, which means it is not plausible to assume this level of flexible demand even in terms of amount.

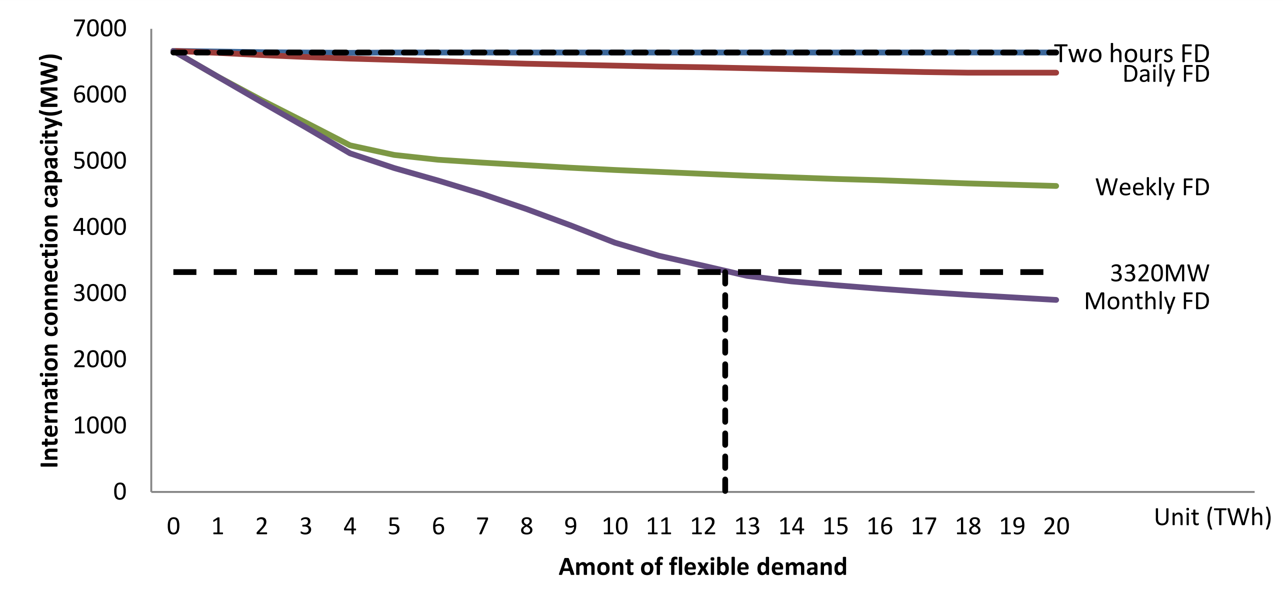

Figure 26. The minimum feasible international connection capacity according to amount and time frame of flexible demand. 20 TWh corresponds to approximately 44% of the total classic demand.

5.9. Conclusion

In order to answer the question of “what is potential of flexible demand in the future?” introduced in Section 1.6. this chapter assesses the potential of flexible demand through the technical perspective and estimates the system impact with the assessed potential flexible demand in a year 2050 scenario by the Danish Climate Commission (CC2050) in order to assess the usefulness of flexible demand in a future Danish energy system. The assessment of potential of flexible demand is done within three energy sectors; residential, commercial, and industrial sector. Among them, the potential of industrial flexible demand assessed in this analysis is uncertain due to the complexity in the relation of the individual industrial processes causing it most likely to be underestimated.

The potential of flexible demand is separated into two time frames; 2h for a short term and 24 h for a long term. Compared to the long term flexible demand, the short term flexible demand is assessed as a larger amount mainly due to thermal related processes i.e., refrigerator/freezer.

The system impact from the assessed amount of flexible demand is investigated with respect to two parameters; international exchange and the operation of condensing power plants. Regarding the international exchange, the import and export amount decreases 0.25 TWh and 0.81TWh respectively. The operation of condensing power plant is also reduced by 0.34 TWh. However, these results are not substantial enough to make an impact on the energy system. The most sensitive parameter in relation to flexible demand is international exchange, looking at the frequency of usage of transmission line, the flexible demand contributes to avoid the investment of 1~2GW of transmission line.

Looking at the system from a top down approach, it is assessed what level of flexible demand that makes a significant impact on future energy system. Here it is found that the level of flexible demand which can decrease international connection by half would need to be approximately 13TWh of flexible demand within a month. This is more than a quarter of the classic electricity demand and such long time frame of flexible demand is rarely found in practice. Flexible demand within the classic demand can thus not contribute sufficiently if this level of reduction in international exchanges is required.

6. Comparison of two energy system model methodologies

In order to determine the value of forecasting in the future energy system and the differences between prescriptive and descriptive models as explained in Section 1.6, this chapter presents a linear programming model and compares results from the model to results obtained with the simulation model EnergyPLAN.

6.1. Introduction

For comparison of EnergyPLAN and linear programming, the IDA 2050 scenario is selected. IDA 2050 is selected partly because it is a fully documented scenario and the input parameters of IDA2050 can be found in the EnergyPLAN homepage [98]. IDA 2050 was simulated with an earlier version of EnergyPLAN – version 7.20 - which has a simple structure compared to newer versions of EnergyPLAN but the core functions of EnergyPLAN like CHP operation and integration of transport, are still valid.

6.2. Optimisation criteria and objective function

In linear programming models, only one criterion may be applied – the so-called objective function. It is thus essential for building a linear programming model to establish this objective function. Normally, the criterion is to minimize monetary expenditures since it is commensurate to represent not only cost but also other dimensions i.e., resource use and environmental impacts by putting cost on environment effect. However, as mentioned in Section 2.3, it is difficult to estimate fuel cost and investment cost in the far future like 2050. In this case, cost is avoided as criterion and a criterion fitting the EnergyPLAN regulation strategies is established.

As explained in Section 2.1, there are several regulation strategies in EnergyPLAN which are grouped in economic and technical regulation strategies, where the technical regulation strategies are aimed for the optimal operation from a technical and resource perspective not from an economic perspective. Among the technical regulation strategies in EnergyPLAN, 'Regulation Strategy 3' is used for IDA2050 scenario. In RS3, EnergyPLAN seeks to minimize export of electricity mainly by the use of HPs at CHP plants and at the same time CHP plants are also participating in balancing partly instead of condensing mode power plants. This results in the lowest fuel consumption and international electricity exchange among the technical regulation strategies in EnergyPLAN. To match the technical regulation strategy in EnergyPLAN used for IDA 2050 with the criterion of linear programming, the criterion is set to minimize fuel consumption within the given constraints of energy supply technologies.

International exchange is difficult to control by the fuel consumption parameter since only domestic fuel consumption is included in calculation. In RS3 in EnergyPLAN, one of the goals is to minimize international exchange and only use it as a last resort for the balancing of electricity supply and demand. Therefore the fuel efficiency for the international exchange is set to be artificially low - 10% - to force the model to abstain from using import/export if at all possible. As a consequence, the fuel consumption for international exchange is an artificial number. The fuel consumption for international exchange is just used for the minimization of fuel consumption as a vehicle for linear programming.

For convenience of referring to the linear programming model built in this chapter, the term LP 2050 is used in contrast to the IDA 2050 which is simulated by EnergyPLAN.

6.3 Overall system structures

For the analysis and building the linear optimization model, the structure of EnergyPLAN is analyzed first. In EnergyPLAN v7.20, there are three district heating grids; 'small district heating grid', decentralized district heating grid and centralized district heating grid. Any heating demand other than these three district heating grids is defined as individual heating. The electricity system is assumed to be comprised of one electric grid without transmission constraint. Two of the district heating grids are connected to the electric grid via CHPs, HP, electric boilers, and electrolysers. The 'small district heating grid' is an independent system which does not have any linkage to other system component. It is solely for district heating purpose and the heating demand in the small district heating is fulfilled by its own biomass boilers and solar thermal. The integration of transportation into the electric grid is done via EVs and synthetic fuel from electrolysers.

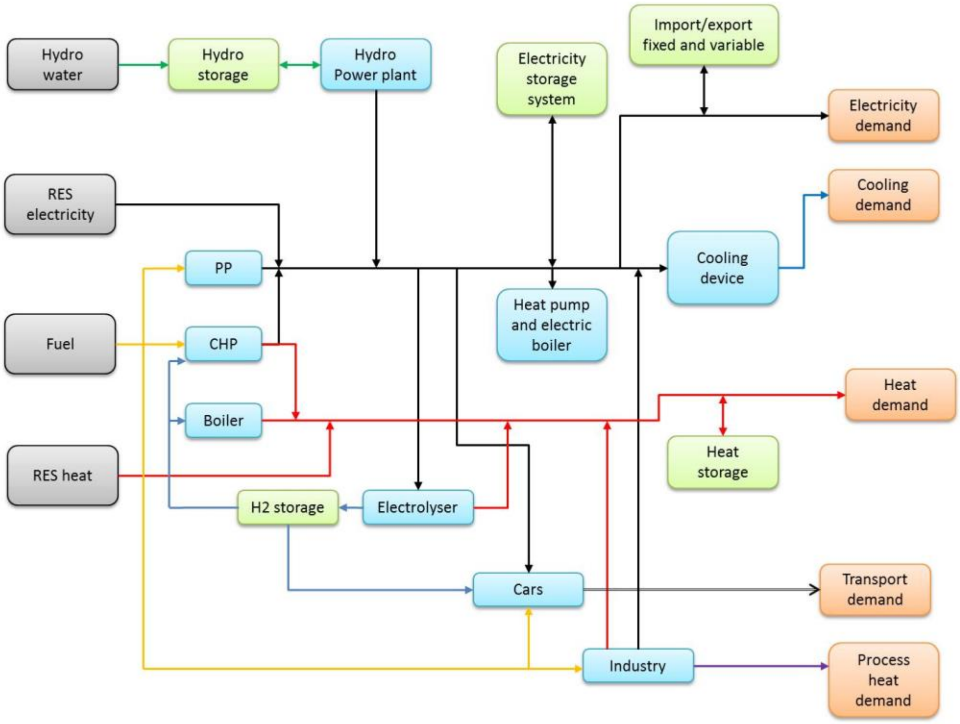

Figure 27. Schematic diagram of EnergyPLAN 7.20

For the analysis, the structure of EnergyPLAN is categorized into three levels as in Table 20 according to the extent of integration of those district heating grids and the electric grid. The first level is highly related to endogenous calculation of electric grid balance and district heating grid balance. This level is highly detailed described in LP 2050 almost the same as EnergyPLAN. The second level is defined as sectors whose linkages are weak, unidirectional and exogenously calculated. The second level is slightly simplified in LP2050. The third level is totally outside the endogenous calculation. It is calculated exogenously and later the calculation results are added. In LP 2050, the third level is excluded and also exogenously calculated and included afterward.

Calculation level	Items	Remarks
Exogenous calculation	Biomass consumption for transportation	The amount of biomass fuel for transport is exogenously assumed by user. The assumed biomass amount does not influence neither electric nor district heating grids. It is different from the synthetic fuels which consume electricity from electric grid for the production.
	Biomass consumption for individual household	For supplying heat to the individual household which is aggregation of heat demand outside the district heating grids, HP and biomass boilers are used in IDA 2050. The heat demand in individual households is covered by the given amount of biomass first and the residual heat demand is supposed to be dealt with HP operation The electricity charging for individual HPs in EnergyPLAN follows a predefined order to decrease excess electricity and condensing power plant operation. This individual HP operation is included in the calculation of LP 2050.
	Biomass consumption for small district heating	Small district heating is rather simple since it does not have cogeneration. The heat demand is covered by solar thermal and heat storage first – the remainder by biomass boilers. However, the district heating grid is separated from the other energy system like electric grid and the other district heating grids. The simulation for the small district heating grid by linear optimization is omitted. The biomass amount used for this district heating system is assumed to be the same.
	Biomass amount for industry and industrial heat and electricity generation	The amount of biomass for industry is also fixed and provided from exogenous calculations in EnergyPLAN. The heat and electricity as by-product is supplied into district heating grids and electric grids with as much as user defined with an annual amount and hourly distribution profiles.
	Waste amount for electricity and heat through incineration	The amount of waste is also fixed and provided from exogenous calculations in EnergyPLAN. Like the industry case above, the heat and electricity from waste incineration are by-products from incinerating waste.
Weak linkage	Electricity and heat from industry and waste	The heat and electricity as by-product is supplied into district heating grids and electric grids with user defined annual amount and hourly distribution profiles. It is simplified in LP 2050 as explained in Section 6.3
Endogenous calculation	- CHPs in decentralized and centralized district heating grids - Boilers in decentralized and centralized district heating grids - Condensing mode power plants - HPs in decentralized and centralized district heating grids - Electrolysers in decentralized and centralized district heating grids - Electrolysers in transportation purpose	

	- Electric vehicles charging pattern

Table 20. Three levels for calculation in LP2050

6.4. Model formulation

This section explains the functions of EnergyPLAN briefly and presents the equations required to build the LP2050 to follow the assumptions and correlations from EnergyPLAN. The section furthermore presents which assumptions are different between LP2050 and EnergyPLAN.

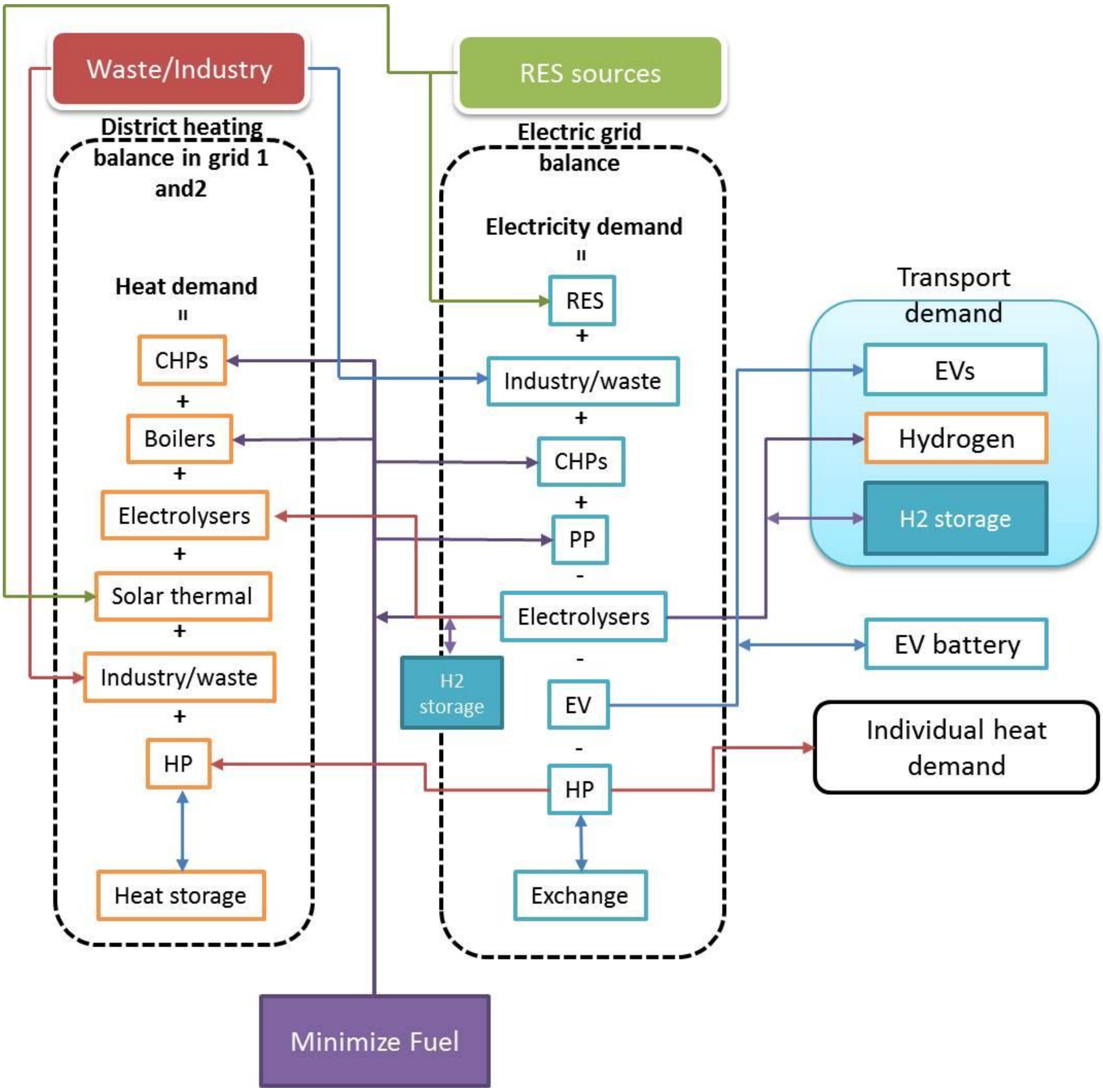

Figure 28. Schematic diagram for LP 2050 model

For formulating the linear programming model, there needs one single objective function as discussed in Section 6.2 and a number of constraints. The constraints include capacity constraints, storage constraints to define inter-temporal relation of storage levels between the adjacent hours, and balance constraints for electric grid to balance electricity balancing and district heating grids to balance heat.

Figure 28 describes the relations between the system components in LP2050. All the interactions are connected to two balance equations as shown graphically in Figure 28, one is district heating grid balance and the other is electric grid balance equation. The balance equation of district heating grid is applied into two different district heating grids in LP2050, but here is only shown one district heating grid to avoid redundancy as the district heating grids are similar to each other.

LP2050 uses the same hourly distribution profiles used for demand and renewable energy generation for IDA 2050.

The following subsections explain the equations used for constraints, correlations, and objective function.

Electricity grid balance equations

The electricity generation and electricity demand are balanced on an hourly basis as shown in Figure 28 and it can be presented as Eq.1.

$$\textbf{Eq. 1) } \mathbf{EL\_d}_{\boldsymbol{h}} \mp \boldsymbol{Wflex_h} \mp \boldsymbol{Dflex_h} = \mathbf{EX\_el}_{\boldsymbol{h}} + \boldsymbol{Ep_{chp,h}} + \boldsymbol{Ep_{pp,h}} - \boldsymbol{Elconsumption_h} \mp \boldsymbol{exchange_h}$$

The equation is composed of eight factors. These eight factors are categorized into five parts for the explanation as follow:

- Electricity demand
- Electricity supply from RES, Waste, and industry (Fixed electricity supply)
- Dispatchable electricity production
- Electricity consumption for flexible technologies
- Import/export

The explanations for each part are presented in following sections.

Electricity demand

In EnergyPLAN, the electricity demand is partly composed of what one may label the normal electric demand and partly flexible demand. The difference between these two demands is explained in Section 6.5.

Resembling the structure of electricity demand in EnergyPLAN, in LP2050, the normal electricity demand is given as a parameter (like $\mathrm{EL\_d}_h$ in Eq. 1) indicating hourly electricity demand over a year and flexible demand is given as a variable. The variable, flexible demand, is constrained by two parameters; the maximum hourly capacity of flexible demand, and the amount of flexible demand in a period. In IDA 2050, daily and weekly flexible demands are used therefore the linear programming only considers these two time frames. From these two parameters, two constraints to regulate flexible demand variables are provided. The first constraint is to set the boundary which is the hourly maximum capacity for the flexible demand. The second constraint is that the summation of flexible demand in a period, which is given such as a day, week, and month, should be equal to the given amount.

The flexible demand is controlled by following equations.

$$\textbf{Eq. 2) } \textstyle\sum_{week} |\boldsymbol{Wflex_h}| = \textbf{weekly flexible demand} * \mathbf{2},\ \textbf{week} \in \mathbf{1}, \dots, \mathbf{168}$$

$$\textbf{Eq. 3) } \textstyle\sum_{day} |\boldsymbol{Dflex_h}| = \textbf{daily flexible demand} * \mathbf{2},\ \textbf{day} \in \mathbf{1}, \dots, \mathbf{24}$$

When the order of week is 52,

$$\textbf{Eq. 4)}\ \sum_{week} |\boldsymbol{Wflex_h}| = \textbf{weekly flexible demand} * \textbf{2},\ \ \textbf{week} \in \textbf{1}, \dots, \textbf{216}$$

The summation of absolute value of weekly and daily flexible demand should be twice the amount of weekly and daily flexible demand set by user. The hourly flexible demands should be less than the capacity set by users.

$$\textbf{Eq. 5)}\ |\boldsymbol{Wflex_h}| \leq \boldsymbol{capacity\ of\ weekly\ flexible\ demand}$$

$$\textbf{Eq. 6)}\ |\boldsymbol{Dflex_h}| \leq \boldsymbol{capacity\ of\ daily\ flexible\ demand}$$

Within these constraints and the balancing constraint in Eq. 1, the flexible demands adjust the electricity demand for the objective of minimizing the fuel consumption.

However, for linear programming, the absolute function should be avoided since it introduces a nonlinearity which cannot be solved with linear optimization method. In order to avoid the nonlinearity, the daily and weekly flexible demand variables are separated into two variables; subtraction and addition. The ‘subtraction’ plays a role of decreasing electricity demand at certain hours and to the opposition, the variable of ‘addition’ plays a role of adding electricity demand at the other hours. These two variables are subject to constraints to limit maximum hourly values for setting boundaries and to make the daily and weekly summation of a pair of ‘subtraction’ and ‘addition’ equal. By doing this, the nonlinearity problem could be avoided.

$$\textbf{Eq. 7)}\ \sum_{week} \boldsymbol{Wflex\ addition_h} = \textbf{weekly flexible demand},\ \ \textbf{week} \in \textbf{1}, \dots, \textbf{168 or 216}$$

$$\textbf{Eq. 8)}\ \sum_{week} \boldsymbol{Wflex\ subtraction_h} = \textbf{weekly flexible demand},\ \ \textbf{week} \in \textbf{1}, \dots, \textbf{168 or 216}$$

$$\textbf{Eq. 9)}\ \sum_{day} \boldsymbol{Dflex\ addition_h} = \textbf{daily flexible demand},\ \ \textbf{day} \in \textbf{1}, \dots, \textbf{24}$$

$$\textbf{Eq. 10)}\ \sum_{day} \boldsymbol{Dflex\ substraction_h} = \textbf{daily flexible demand},\ \ \textbf{day} \in \textbf{1}, \dots, \textbf{24}$$

$$\textbf{Eq. 11)}\ \sum_{week} \boldsymbol{Wflex\ addition_h} = \sum_{week} \boldsymbol{Wflex\ subtraction_h}$$

$$\textbf{Eq. 12)}\ \sum_{day} \boldsymbol{Dflex\ addition_h} = \sum_{day} \boldsymbol{Dflex\ substraction_h}$$

Electricity supply from RES, waste/industry

There are several electricity supply units. These are grouped into two depending on whether it is dispatchable or not. In the LP2050, the electricity supply from waste incineration and industry is assumed to be constant and non-dispatchable, while in EnergyPLAN, the electricity supply from waste/industry is set as the highest priority among the biomass fueled productions thus it operates almost at a constant level all the time[3] except regulating downward when there is surplus electricity over the electricity demand. It is partly different from the EnergyPLAN.

For the emulation of EnergyPLAN in linear programming, the annual amount of biomass consumption for industry and the amount of waste for waste incineration is given. This given amount of fuel is consumed regardless of utilizing the energy (i.e. heat and power) from these sources.

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[3] In EnergyPLAN, the user can set the hourly operations of waste and industry by providing hourly distribution profiles for the operation. However, the operation of waste and industry is assumed to be constant all the year in IDA 2050.

In contrast, in LP 2050, the electricity production from industry and waste are basically exogenously calculated electricity productions without the downward regulation. The production from waste and industry is set to be constant over the year as a constant production was also assumed in the IDA 2050 scenario.

$$\textbf{Eq. 13) } \boldsymbol{Industry\_el_h = annual\ amountfrom\ industry/8784}$$

$$\textbf{Eq. 14) } \boldsymbol{waste\_el_h = annual\ amountfrom\ waste/8784}$$

In linear programming, this regulation function for reducing output when necessary cannot be simulated since the linear model needs a fuel consumption to regulate the output. For the industry and waste which consumes fuel but for other purposes than to generate electricity and heat; manufacturing and disposing waste, the fuel used for such purposes cannot be considered as the object of minimizing in this model. Therefore, in this model, electricity and heat supplied from industry and waste is assumed to be constant for the year. Due to the high priority of waste and industry production, there is slight difference in regulating power between two models.

In EnergyPLAN, the electricity supply from RES is assumed to follow given hourly distribution over the whole year. The hourly RES electricity production ($\boldsymbol{RES_h}$) is calculated in the same way as EnergyPLAN but the waste/industry is little bit different from the EnergyPLAN. The production from RES is given as a time-variant parameter

$$\textbf{Eq. 15) EX\_el}_h = \boldsymbol{RES_h + Industry\_el_h + waste\_el_h}$$

Dispatchable generation

Contrary to electricity generators with exogenously established production profiles, dispatchable plants are set as variables for the calculation of fuel consumption, which is the objective to minimize.

The dispatchable plants in the electricity balancing equation (Eq. 1) are CHPs and condensing mode power plants. The CHPs affect both the electric and district heating systems while the condensing power plants only affect electricity system. In order to reduce the fuel consumption, the operation of dispatchable plants should be minimized. The other factors in the balance equation just play a supplementary role for this purpose.

The equation of converting fuel to electricity makes a linkage between the balance equation and the objective function to minimize fuel consumption.

For electricity production in condensing mode power plants, the amount of fuel is converted according to the given efficiency.

$$\textbf{Eq. 16) } \boldsymbol{Ep_{pp,h} = eff_{chp} * F_{pp,h}}$$

For the electricity production in CHPs, besides biomass fuel, the hydrogen-based synthetic fuel to be produced from electrolysis could be used as fuel therefore,

$$\textbf{Eq. 17) } \boldsymbol{Ep_{chp,h} = eff_{chp} * (F_{h,chp} + \mathrm{H2dh1out}_h)}$$

OR (depending on which district heating grid)

$$\textbf{Eq. 18) } Ep_{chp,h} = eff_{chp} * (\mathrm{F}_{h,chp} + \mathbf{H2dh2out}_{h})$$

The electricity generation from the fuel consuming facilities are set as positive variables, controlled by fuel consumptions, and constrained by the installed capacities as follows:

$$\textbf{Eq. 19) } Ep_{chp,h} \leq Cap_{chp,h}$$

$$\textbf{Eq. 20) } Ep_{pp,h} \leq Cap_{pp,h}$$

Within the capacity constraints and under the balancing constraint, the dispatchable plants operate in order to minimize fuel consumption. Accompanied with flexible demand explained before and flexible technologies explained later, dispatchable plants should play an important role to meet the electricity balancing constraint (Eq. 1). In addition, there is another important constraint for the operation of CHPs which is the district heating balancing equations, which will be explained later.

Electricity consumption as a flexible means

Beside the conventional electricity demand there are other processes consuming electricity such as HPs, electrolysis, and electricity for EVs in the balance equation. This is grouped as in the following equation.

$$\textbf{Eq. 21) } Elconsumption_{h} = Ec_{ev,h} + Ec_{EL,h} + Ec_{hp,h}$$

Except for the consumption of EVs, which is assumed to be a fleet of EVs ($Ec_{ev,h}$), the other two entities in Eq. 21 are the aggregation of electrolysers ($Ec_{EL,h}$) in Eq. 23 and HPs ($Ec_{hp,h}$) in Eq. 22 which are distributed in district heating grids, transport or individual households.

$$\textbf{Eq. 22) } Ec_{hp,h} = Ec_{hp1,h} + Ec_{hp2,h} + Ec_{hpi,h}$$

$$\textbf{Eq. 23) } Ec_{EL,h} = Ec_{ELdh1,h} + Ec_{ELdh2,h} + Ec_{ELcar,h}$$

The electricity consumption of these flexible technologies is also linked to the district heating demands, and the demand for EVs and synthetic fuelled transportation. The dynamic between the demands and storage is explained in later sections.

Electrolysers

Electrolysis consumes electricity and produces hydrogen used for synthetic fuel as an output. During operation, heat is generated as a by-product. Electrolysers produce fuel for two purposes; for transportation and for CHP and boiler use. The former purpose has an obligation to satisfy the transportation demand while for the other purpose the electrolyser is operated without any obligation apart from the object of storing excess electricity for later use in order to minimize the fuel consumption and reducing export. The heat production from the electrolysis is constrained under the balancing equation of district heating grid which is explained later.

The electrolysers for CHPs and boiler grouped in centralized and decentralized district heating grids have different capacity of hydrogen production and storage capacity. The hourly electricity consumption of the electrolysers is constrained by these given capacities as follows:

$$\textbf{Eq. 24) } Ec_{ELdh1,h} \leq capacity_{ELdh1}$$

$$\textbf{Eq. 25) } Ec_{ELdh2,h} \leq capacity_{ELdh2}$$

$$\textbf{Eq. 26) } Ec_{ELcar,h} \leq capacity_{ELcar}$$

The amount of synthetic fuel is decided by the electricity consumption and efficiency as follows:

$$\textbf{Eq. 27) } H2dh1_{h} = Eff_{ELdh1} * Ec_{ELdh1,h}$$

$$\textbf{Eq. 28) } \mathrm{H2dh2_{h}} = \mathrm{Eff_{ELdh2}} * \mathrm{Ec_{ELdh2,h}}$$

$$\textbf{Eq. 29) } \mathrm{H2car_{h}} = \mathrm{Eff_{ELcar}} * \mathrm{Ec_{ELcar,h}}$$

Converting from electricity to hydrogen and again to final energy uses is a less efficient conversion than the other conversion technologies, thus giving this technology the last priority. However, as the electrolysis for transport use has an obligation to supply fuel for the transport demand, the optimization solver finds the best hours of producing hydrogen by avoiding the electricity from the CHPs and condensing power plants and exploiting RES electricity as much as possible. The synthetic fuel storage is also charged or discharged for the same purpose.

The storage is controlled by the following equations:

$$\textbf{Eq. 30) } H2strdh1_{h+1} = H2strdh1_{h} + H2dh1_{h} - H2dh1out_{h,chp} - H2dh1out_{h,boiler}$$

$$\textbf{Eq. 31) } H2strdh2_{h+1} = H2strdh2_{h} + H2dh2_{h} - H2dh2out_{h,chp} - H2dh2out_{h,boiler}$$

$$\textbf{Eq. 32) } H2strdh1_{h} \leq capacity_{ELdh1}$$

$$\textbf{Eq. 33) } H2strdh2_{h} \leq capacity_{ELdh2}$$

The synthetic fuel produced is stored and any needs for CHPs and boilers is subtracted. The amount of fuel in the storage is limited up by the installed capacity of the storage. The reason why there are two storages associated with two DH grids is that the storages are associated with the electrolysers that supply waste heat to the DH systems.

In IDA2050, two fuels are used for transportation; electricity and synthetic fuel. The common thing is that both fuels comes from electricity however, the efficiency is different according to the number of conversions and conversion efficiency of battery and electrolysis. Even though the cycle efficiency of a battery is higher than the conversion efficiency of hydrogen systems, some transportation still needs liquid fuel for high demands where energy storage and power output from a battery would be insufficient. The electrolysers for transport produces hydrogen according to Eq. 34 and the storage amount of hydrogen for transport is regulated as in Eq. 35. The synthetic fuel is stored with the production of synthetic fuel from the electrolysers for transportation and discharged with the transportation demand. The transport demand of synthetic fuel is an exogenously given time-variant parameter. In IDA2050, the same hourly distribution is used for EV transportation and transportation based on synthetic fuels.

$$\textbf{Eq. 34) } H2strcar_{h+1} = H2strcar_{h} + H2car_{h} - hydrogentransport_{h}$$

The hourly storage amount of synthetic fuel for transportation is constrained by the capacity of storage facility.

$$\textbf{Eq. 35)}\ \boldsymbol{H2strcar_h \leq capacity_{ELcar}}$$

EV

The batteries of a fleet of EVs are assumed to be aggregated and treated as one entity.

The battery of EVs is charged and discharged for the minimization of fuel consumption. The status of charge (SOC) in the batteries is determined by the SOC in the previous hour as well as the charging amount and transportation demand in previous hour. The SOC is restricted by the storage capacity of batteries.

The hourly transport demand for EVs ($Transport_h$) is given by the user. The charging hours and amount are decided by LP2050 to minimize fuel consumption, so the hours with more RES production share should be exploited in the case. An important constraint for charging EVs is the available capacity of battery for every hour. The charging capacity of a fleet of EVs is different by hours, and it is determined by the number of EVs parked. It is calculated from the share of cars parked, max share of available EVs for charging and hourly transport demand. The calculation is explained in the EnergyPLAN manual[124] and the same calculation is applied in LP2050.

The initial and final status of batteries is set to be the half of maximum storage capacity of batteries otherwise the storage would be depleted in the end due to the object to minimize fuel consumption. The charging of battery is constrained by two kinds of capacity constraints. The first constraint is that the charging amount for an hour should be less than ‘available capacity’. The second constraint is to limit the hourly charge less than maximum charging capacity. Normally, ‘available charge’ is less than ‘maximum charging capacity’.

$$\textbf{Eq. 36)}\ \boldsymbol{Ec_{h,EV} \leq available\_capacity_h}$$

$$\textbf{Eq. 37)}\ \boldsymbol{Ec_{h,EV} \leq Capacity_{EV}}$$

$$\textbf{Eq. 38)}\ \boldsymbol{Storage_{h+1,EV} = Storage_{h,EV} + Ec_{h,EV} * Eff_{EV} - Transport_h\ (except\ h = 1, 8784)}$$

$$\textbf{Eq. 39)}\ \boldsymbol{Storage_{h,EV} = 0.5 * Cap_{storgeEV}\ (when\ h = 1, 8784)}$$

$$\textbf{Eq. 40)}\ \boldsymbol{Storage_{h,EV} \leq Cap_{storgeEV}}$$

In IDA 2050, it is assumed that there is no discharge from battery of EVs to grid, so only charging battery is simulated here.

Electricity consumption for HP

In EnergyPLAN, electric HPs are used in district heating grids and for individual households. They are operated to minimize electricity consumption which is produced through the fuel consumption within the condition of heat storage status for the goal of meeting each heating demand. Waste incineration may have steam-driven absorption HPs in EnergyPLAN which do not consume electricity; these are regarded as constant for LP2050.

$$\textbf{Eq. 41)}\ Hp_{h,hp1} = Eff_{hp1} * Ec_{h,hp1}$$

$$\textbf{Eq. 42)}\ Hp_{h,hp2} = Eff_{hp2} * Ec_{h,hp2}$$

$$\textbf{Eq. 43)}\ Hp_{h,hpi} = Eff_{hpi} * Ec_{h,hpi}$$

$$\textbf{Eq. 44)}\ Ec_{h,hp1} \leq capacity_{hp1}$$

$$\textbf{Eq. 45)}\ Ec_{h,hp2} \leq capacity_{hp2}$$

$$\textbf{Eq. 46)}\ Ec_{h,hpi} \leq capacity_{hpi}$$

In the LP 2050 model, HPs in the two district heating grids are preferred ahead of boilers and CHP due to the high efficiency. This is not a dispatch priority as in EnergyPLAN but merely the mathematical consequence of the stipulated efficiencies. Since the objective function is to minimize fuel consumption, higher efficiency is a critical and the sole factor to decide priority of production. The coefficient of performance (COP) of HP is set as 3.5, and the fuel efficiency to generate electricity of centralized CHP and condensing power plant are 0.64, hence the final efficiency for generating heat through these conversions is over 200% which is higher than any other heat generation even when the electricity generation is based on fuel.

The HPs in district heating grids are not only constrained by the electricity balancing equation (Eq1) but also the district heating grid balancing equation which will be explained later.

HPs in individual households are influenced by the heat storage contents in individual households and the heat storage contents is also linked to the solar thermal production. The electricity consumption for individual HPs considers not only the fuel consumption of dispatchable power generation but also combined with the output of solar thermal and the storage status. Therefore, beside the heat demand covered by biomass in individual households, the rest of the heat demand is covered by HPs and solar thermal with supplementary role of heat storage. Only the heat demand supplied from HPs and storage combined with solar thermal production interacts with the electricity grid since the HPs are electric.

$$\textbf{Eq. 47)}\ IHd_h = SHI_h + Hp_{h,hpi} + IHout_h - IHin_h$$

$$\textbf{Eq. 48)}\ IHstr_{h+1} = IHstr_h - IHout_h + IHin_h$$

$$\textbf{Eq. 49)}\ IHstr_h \leq capacity\ of\ heat\ storage\ in\ individual\ household$$

For HP operation another constraint is introduced to ensure a high COP. There needs a certain range of heat sources for HPs in the low temperature seasons and therefore the user can limit HPs in EnergyPLAN not to overpass e.g. half of maximum heat demand in individual households. The same assumption is added to LP2050.

$$\textbf{Eq. 50)}\ Hp_{h,hpi} \leq 0.5 * maximum\ value\ of\ IHd_h$$

Every storage is assumed having the same storage contents in the initial and final hour like Eq.51. It is as attributed to a practical reason to leave some amount for fair initiation of the next period.

$$\textbf{Eq. 51)}\ IHstr_h = 0.5 * capacity\ of\ heat\ storage\ in\ individual\ household, when\ h = 1, 8784$$

International exchange

The international exchange is also controlled by fuel consumption otherwise it cannot be handled in a single objective linear programming model. However, as explained before, the efficiency of fuel for international exchange is set to be artificially lower than the other technologies since the objective of technical regulation strategy in EnergyPLAN is to operate the energy system in an island mode so the amount of international exchange should be minimized as much as possible. The efficiency for international exchange is set to be 10%.

$$\textbf{Eq. 52)}\ \boldsymbol{exchange_h = Eim_{\ h}}$$

$$\textbf{Eq. 53)}\ \boldsymbol{-exchange_h = Eex_h}$$

$$\textbf{Eq. 54)}\ \boldsymbol{Eim_{\ h} = 0.1 * F_{h,import}}$$

$$\textbf{Eq. 55)}\ \boldsymbol{Eex_h = 0.1 * F_{h,export}}$$

District heating grid

The balance equation of district heating grid is composed of seven factors and they are categorized into three like the electricity balancing equation; dispatchable heat generation, non-dispatchable heat generation, and storage. There are several heat generation technologies; CHPs, boilers which consume fuel, heat generators converting from electricity like HP, electric boiler and heat as a by-products of other activities like heat from electrolysis, industry, and waste incineration and lastly there is heat from renewable resources like solar thermal.

The dispatchable heat generation is composed of CHPs, HPs and boilers, but the CHPs and HPs are also constrained for the aim of balancing electric grid, solely dispatchable heat generating technology is boilers. The storage is separated into two according to which facility is associated to; storage in district heating grid, and storage associated to solar heating. The balancing equations of district heating grids are separated into two district heating grids however, only one district heating balance equation is described here in order to avoid redundancy.

$$\textbf{Eq. 56)}\ \boldsymbol{Hddh_h = nondispatchableheat_h + dispatchableheat_h \mp exchange_h}$$

The three factors in Eq. 56 are explained in the following sections.

Non-dispatchable heat sources

Like the electricity sector, there are heat sources as by-products from industry and waste. These heat sources are assumed to constant for every hour of the year in LP2050 as in the IDA 2050. There are two ways of supplying district heating from the waste incineration. The first way is through the direct combustion of waste and the other one is through an absorption HP which uses steam as high-temperature heat source and geothermal energy as low-temperature energy source. Using the absorption HP enables to system to increase heat production compared to when producing heat directly through combustion. Therefore when it is necessary to reduce heat production, less steam may be bled to the HP and production linearly shifts towards the productions of heat and electricity found with direct combustion. However these two heat sources are the last to adjust heat production since they are byproducts and thereby being set as prior productions.

$$\textbf{Eq. 57)}\ \boldsymbol{nondispatchableheat1_h = heat(waste)_h + heat(indusry)_h + SHout1_h}$$

Heat generation from industry and waste is calculated by dividing the annual heat production given by user by the number of hours in a leap year (8784).

$$\textbf{Eq. 58)}\ \boldsymbol{heat(waste)_h = annual\ heat\ from\ waste/8784}$$

$$\textbf{Eq. 59)}\ \boldsymbol{heat(indusry)_h = annual\ heat\ from\ industry/8784}$$

The other non dispatchable heat source is solar thermal. The hourly solar thermal pattern is given by user. Solar thermal is assumed to be associated to heat storage, which is separated from the heat storage in district heating grids. The heat storage of solar thermal is only operated for flexible use of solar thermal.

$$\textbf{Eq. 60)}\ \boldsymbol{SHin1_h = solarthermalproduction_h}$$

$$\textbf{Eq. 61)}\ \boldsymbol{SHstrdh1_{h+1} = SHstrdh1_h + SHin1_h - SHout1_h}$$

$$\textit{Eq. 62)}\ \boldsymbol{SHstrdh1_h \le Capacity}$$

Dispatchable heat sources

There are four dispatchable heat sources; heat from CHPs, HPs, boilers, and electrolysers as in the following equation.

$$\textbf{Eq. 63)}\ \boldsymbol{dispatchableheat_h = Hp_{chp1,h} + Hp_{boiler1,h} + Hp_{ELdh1,h} + Hp_{hp1,h}}$$

The hourly heat from CHP and boilers is calculated as the summation of hourly fuel (biomass) and hydrogen from electrolysis multiplied by the heat efficiency. With both electricity and heat production, operation is regulated through the electricity and heat balance equations at the same time. Heat from the HP is related to the electricity consumption amount which is also constrained by electricity balancing equation.

In EnergyPLAN, the heat production from electrolysis is regulated with following priority order. 1) reduce boiler production 2) reduce CHP production 3) reduce HP production then the heat from electrolyser is wasted. While in LP 2050 heat from electrolysers is constrained not only by heat balance equation but also by electric balance equation.

$$\textit{Eq. 64)}\ \boldsymbol{Hp_{chp1,h} = eff_{chp1} * (F_{h,chp} + H2dh1out_{h,chp})}$$

$$\textit{Eq. 65)}\ \boldsymbol{Hp_{boiler1,h} = eff_{boiler1} * (F_{h,boiler1} + H2dh1out_{h,boiler})}$$

$$\textit{Eq. 66)}\ \boldsymbol{Hp_{h,hp1} = Eff_{hp1} * Ec_{h,hp1}}$$

The capacity of boiler and CHP constrains their heat productions. The HPs are already constrained by the electricity consumption constraint.

$$\textbf{Eq. 67)}\ \boldsymbol{Hp_{chp1,h} \le Capacity}$$

$$\textbf{Eq. 68)}\mathbf{Hp}_{\boldsymbol{boiler1,h}} \le \boldsymbol{Capacity}$$

Heat storage

The function of heat storage is to store heat, mostly produced from excess electricity and discharge heat when necessary. The heat amount stored is constrained by the storage capacity and stored amount in prior hour. The variable ‘exchange’ is defined as heat output from or input to heat storage according to whether it is negative or positive value

$$\textbf{Eq. 69)}\ \boldsymbol{exchange_h = Hout1_h}$$

$$\textbf{Eq. 70)}\boldsymbol{-exchange_h = Hin1_h}$$

The heat storage contents are defined as follows:

$$\textbf{Eq. 71)}\ \boldsymbol{Hstrdh1_{h+1} = Hstrdh1_h + Hin1_h - Hout1_h}$$

$$\textbf{Eq. 72)}\boldsymbol{Hstrdh1_h \leq capacity}$$

Individual heating

The heat demand beyond district heating areas is defined as individual heating. This heating demand is fulfilled by solar thermal, biomass boilers, and HPs and is largely isolated and only connected to the electric grid. The amount of biomass for individual heating is user-defined so the heat demand covered by biomass is also determined exogenously. The rest of the heat demand is fulfilled by interaction of HP and heat storage.

There is a little difference between EnergyPLAN simulation and LP2050 in interaction of HP and heat storage. It is attributed to the different feature of taking account of future happening which is described later.

Object function

As mentioned in Section 6.2, the object function LP2050 is to minimize fuel consumption. The objective function is summation of fuel consumed for dispatchable generations such as CHP, condensing mode power plants, boilers, and international exchange.

$$\textbf{Eq. 73) Object function} = \textbf{minimize}\ \boldsymbol{\sum_h F_{h,chp1} + F_{h,chp2} + F_{h,pp} + F_{h,boiler1} + F_{h,boiler2} + F_{h,export} + F_{h,import}}$$

Special regulations for reducing excess electricity production

In EnergyPLAN, seven regulations are prepared for preventing from excess electricity over the transmission line capacity.

1. Reducing RES1 and RES2
2. Reducing CHP in decentralized DH by replacing with boiler
3. Reducing CHP in centralized DH by replacing with boiler
4. Reducing boiler with electric heating in decentralized DH with maximum capacity
5. Reducing boiler with electric heating in centralized DH with maximum capacity
6. Reducing RES3
7. Reducing power plant in combination with RES1, 2, 3 and 4

These excess electricity regulation steps are applied according to a user-specified order. In IDA 2050, the Regulation Steps 2, 3, 4, and 5 are assumed in this order. The maximum capacity for electric boilers is set as 600MW for the regulation 4 and 5.

Regulation Steps 2 and 3 can be reflected in LP 2050 somehow, while Regulation Steps 4 and 5 are not reflected in LP2050. These regulation steps are hard to implement in LP 2050 since they require two sequences of solving the problem such as; finding the solution with one regulation and if there is additional excess then the regulations would be activated. Those two separate levels in calculation cannot be performed in linear optimization in exactly same way. In LP2050, for the Regulation Steps 2 and 3, let biomass boiler compete with other dispatchable plants in heat sector and satisfy the balance equation in electric grid and DH grids. The bigger challenges are Regulation Steps 4 and 5. These steps include adding capacity beyond the original system design for only the case of excess electricity after using all the measures including

Regulation Steps 2 and 3. These regulations are not implemented for LP2050. Therefore, there is no electric heating capacity in LP 2050. In IDA 2050, the number of operating hours of electric heating occurred is 745 hours in decentralized DH and 522 hours in centralized DH. The function of electric heating in IDA 2050 can be compatible to that of international exchange, especially for export, in LP 2050. Strictly speaking, IDA 2050 has more flexibility than LP 2050 with the extra capacity of electric heating by 1200MW. It is noted that there is no international connection capacity in IDA 2050 while there is 2500 MW for LP2050. Therefore the amount of electric heating can be regarded as international exchange in LP2050. However, such flexibility from the electric heating would become important if LP 2050 presents an infeasible solution even within the international connection capacity. To avoid the situation of infeasible solution, it would be better for LP 2050 to have the capacity of electric heating. Fortunately, there is no infeasible solution without the electric heating capacity in LP2050 in this analysis.

6.5. Input parameters for IDA 2050

The IDA 2050 recommended scenario is simulated for the comparison of the EnergyPLAN model and the model constructed as detailed in Section 6.3. The scenario assumes a 100% renewable energy system including the transportation sector. The main input parameters presented in Table 21 are used for both EnergyPLAN and LP 2050 simulation. Since LP 2050 is designed to minimize fuel consumption and international exchange by imposing an artificial (and unrealistic) penalty of 10 units of fuel for one unit of exchange, a closed energy system simulated by EnergyPLAN is comparable. LP 2050 sets its international exchange capacity as 2500MW in order to avoid infeasible solution.

LP2050 can be used either for finding optimal operation strategy with user-specified installed capacities or finding optimal capacities and operation strategy at the same time by setting installed capacities as decision variables. Later, the decision variable mode is used for deciding the capacities.

Electricity and heat production				Demand (TWh)	
	capacity	efficiency (electricity)	efficiency (Heat)		
Offshore wind	4654			Electricity demand	31.1
Onshore wind	4454			Flexible demand	2.7
PV	3415			Transport demand in EV	6.79
Wave	700			Transport demand by hydrogen vehicle	3.29
CHP (Decentralized)	1945	0.54	0.36	DH demand (Decentralized)	13.49
CHP (Centralized)	2500	0.64	0.26	DH demand (Centralized)	24.34
Condensing mode power plant	7833	0.64			
Boiler (Decentralized)	3484		0.9462		
Boiler (Centralized)	7574		0.9462		
Electricity consumption				Storage (GWh)	
EV	36000			Heat storage (Decentralized)	40
Electrolyser (Decentralized)	200	0.6935	0.075	Heat storage (Centralized)	10
Electrolyser (Centralized)	400	0.6935	0.075	EV battery storage	90[4]
Electrolyser (Transport)	564	0.676		Hydrogen storage (Decentralized)	33.6
HP (Decentralized)	150		3.5	Hydrogen storage (Centralized)	67.2
HP (Centralized)	300		3.5	Hydrogen storage for transport	63
Interconnection capacity	0(2500)[5]				

Table 21. Input parameters for IDA 2050

6.6 Comparison of results from IDA 2050 and LP 2050

This section compares the results of the LP 2050 model introduced in Sections 6.3, 6.4, and 6.5 with IDA 2050 modelled using the EnergyPLAN model. Firstly, the electricity production and consumption from these two models are presented in Table 22

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[4] According to the input parameter which is found in energyplan.eu website, the battery storage capacity is 200 TWh which must be wrongly assumed. Therefore, the value is changed into 90GWh based on the assumption that battery capacity is 50KWh per EV and the estimated number of EVs in IDA 2050 (1.8million)

[5] According to background report of IDA 2050[70], the transmission capacity is estimated to be 2500MW, however, for the simulation of closed energy system, the presented results is based on zero transmission capacity for simulation of ʻclosed’ energy system.

Unit(TWh)		IDA 2050		LP 2050		Difference	
Electricity Production							
CHP	CHP (decen)	7.14	2.84	6.99	1.17	-0.15	-1.67
	CHP (cen)		4.30		5.82		1.52
PP			2.30		0.58		-1.72
RES			38.58		38.58		0.00
Industry			1.19		1.19		0.00
Waste			2.61		2.61		0.00
Total electricity production			51.82		49.95		-1.87
Electricity Consumption							
HP	HP (decen)	4.54	1.02	4.26	1.09	-0.28	0.08
	HP (cen)		1.88		1.90		0.01
	HP ind		1.64		1.27		-0.37
Electrolyser	Electrolyser(decen)	7.47	0.76	6.48	0.55	-0.99	-0.21
	Electrolyser(cen)		1.84		1.06		-0.78
	Electrolyser trans		4.87		4.87		0.00
Electric heating			0.48		0.00		-0.48
EV			6.79		6.79		0
Import			0.00		0.00		0
Export			1.44		1.32		-0.12
Ordinary Demand			31.10		31.10		0
Total electricity consumption			51.82		49.95		-1.87

Table 22. Comparison of electricity production and consumption in LP2050 and IDA 2050

Total electricity production and consumption in LP 2050 is less than IDA 2050 by 1.87 TWh. The electricity production from waste, industry, and RES in LP2050 are identical to IDA 2050 as explained in Section 6.3 so the difference is only found in the dispatchable plants i.e. CHPs and condensing mode power plants. The largest difference is found in the production of condensing power plant which is 1.72 TWh less in LP 2050 while the difference in CHPs is not significant (0.15TWh). This difference might originate from the future forecasting assumption in the model. The difference between two models on future forecasting assumption is discussed in Section 6.8.

Looking at the CHPs production by DH area, a significant difference is observed. Compared to IDA 2050, centralized CHPs in LP2050 produce more electricity while decentralized CHPs produce less electricity in LP 2050 even though total electricity production from both decentralized and centralized CHPs is similar. The difference of productions in centralized and decentralized CHPs is attributed to the different efficiencies assumed for their cogeneration. The efficiencies of decentralized CHPs for heat and electricity are set as 0.54 (electricity) and 0.36 (heat) respectively. Meanwhile the efficiencies of centralized CHPs are higher in electricity generation (0.64) and lower in heat production (0.26) respectively. Thus, centralized CHPs are prioritized to decentralized CHPs in electricity production due to its higher efficiency in centralized CHPs in LP2050. EnergyPLAN operates dispatchable plants according to the built-in priority order which is not sensitive to stated efficiencies; therefore the difference of efficiency between centralized and decentralized CHPs is not reflected in the results of EnergyPLAN while it is reflected in the results of LP2050.

As to electricity consumption including export, the electricity consumption in LP 2050 is less than IDA 2050 by the same difference in electricity production. Ordinary demand and EV demand are identical, hence only flexible technologies and export differ. The largest difference is found in electricity consumption for electrolysis in centralized DH region. The electricity consumption for HPs is slightly less in LP2050. The export is lower in LP2050 compared to IDA 2050. As mentioned before, electric heating is only included in IDA 2050 and consumes 0.48TWh of electricity. Among the flexible means, the last option would be electrolysers since one more conversion is necessary to reach final energy usage; electricity, heat, and transport. Also the exportation of electricity is assumed to be artificially low for LP 2050. Therefore, it is reasonable to avoid these two options as much as possible when it is possible to use future parameters.

Unit(TWh)	Decentralized DH			Centralized DH		
	IDA 2050	LP 2050	Difference	IDA 2050	LP 2050	Difference
CHP	1.89	0.78	-1.11	1.75	2.37	0.62
Boiler	3.50	4.61	1.11	5.02	4.57	-0.45
HP	3.55	3.82	0.27	6.58	6.63	0.05
EH	0.26	0.00	-0.26	0.22	0.00	-0.22
Electrolyser	0.05	0.04	-0.01	0.09	0.08	-0.01
Solar thermal	1.39	1.39	0.00	0.61	0.61	0.00
Waste	2.85	2.85	0.00	7.43	7.43	0.00
Indusry	0.00	0.00	0.00	2.65	2.65	0.00
Sum	13.49	13.49	0.00	24.35	24.34	-0.01

Table 23. Comparison of heat production in LP2050 and IDA 2050

Table 23 presents heat productions by categorizing district heating grids in the two models. In decentralized DH area, less operation of CHPs in LP2050 is observed as noted also for electricity production. In LP 2050 the combination of biomass boilers and HP operation covers the reduced heat production from CHPs and electric heating, the latter which is only included in IDA2050. In centralized DH area, conversely, an increased operation of CHPs is observed. It results in reduction of heat production from biomass boilers in LP2050. The heat from electric boilers in centralized DH is also covered by the combination of HPs and CHPs.

The fuel consumption of dispatchable plants is presented in Table 24. As shown in Table 20, the fuel consumption of the other components i.e. industry, individual household, and waste is the same, therefore the comparisons are omitted instead only the dispatchable plants are highlighted.

Fuel consumption(TWh)		IDA 2050				LP2050			
		Biomass	Synthetic fuel	Total fuel	Total fuel by technologies	Biomass	Synthetic fuel	Total fuel	Total fuel by technologies
CHP	Decentralized CHP	5.07	0.19	5.26	11.98	2.00	0.16	2.16	11.26
	Centralized CHP	6.1	0.62	6.72		8.79	0.31	9.10	
Condensing mode power plants		3.59		3.59	3.59	0.90			0.9
Boiler	Boiler in Decentralized DH areas	3.37	0.34	3.71	9.01	4.65	0.22	4.87	9.7
	Boiler in Centralized DH areas	4.65	0.65	5.30		4.35	0.44	4.83	
Total		22.78	1.8		24.58	20.79	0.8		21.87

Table 24. Comparison of fuel consumption in LP2050 and IDA 2050

As shown in Table 24, the total fuel consumption (including synthetic fuel) from the dispatchable plants amounts to 24.58TWh (IDA2050) and 21.87 TWh (LP2050). The fuel consumptions by technology, irrespective of district heating grid, are similar in both models except the condensing mode power plant. The fuel consumption in condensing mode power plants is 3.59 TWh for IDA 2050, 0.9 TWh for LP 2050 respectively. This might be attributed to the different usage of given future parameters and the lowest efficiency of the condensing mode power plants, which is discussed in Section 6.8.

6.7. Predefined dispatch priority vs priority for the objective function

The predefined series of procedures in EnergyPLAN technical regulation strategy to describe reality is different from the order established according to the efficiency in the LP 2050 model. In this section, the main differences in results are addressed and contemplated.

One main difference is the boiler operation. EnergyPLAN gives the least priority for using boilers for the heat demand in its technical regulation irrespective of given efficiencies. This order is a description of reality to prioritize cogeneration over boiler for heat demand and it corresponds with a perspective of exergy as mentioned in section 4.10. Also cogeneration is typically more valuable judged from market perspective since electricity is more valuable than thermal energy in general. In fact the efficiency of fueled boilers is set higher (94.6%) than the combined efficiency of CHPs (90%), therefore the more energy units (heat and electricity) are converted from the same units by biomass boiler than CHPs. Hence, the boiler would be given a priority over CHPs for heat generation when compared between CHPs and boilers, if only considered in terms of fuel efficiency, but without differentiating the value of electricity and heat.

As shown in the results in Table 24, the boiler production in LP 2050 is not increased dominantly over CHPs for heat production. It is because LP 2050 reflects two contexts. First, there are more efficient alternatives for heat production such as HPs and storage facility[6] to give more flexibility for balancing supply and demand in the heat sector than electricity sector. HPs could enhance the fuel efficiency of CHPs over that of boilers if

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[6] In IDA plan, only batteries in EVs can store electricity with a loss of 10% of charging electricity. Meanwhile thermal storage has no energy loss.

the electricity produced by CHPs is used for HP whose COP is 3.5. Furthermore, storage facility raises the frequency of using HPs for heat generation. Second, in IDA2050, the efficiency of CHPs is set to be the same as condensing mode power plants (62% for centralized CHPs) or slightly lower (52% for decentralized CHPs) for electricity generation. Therefore CHPs are highly prioritized in electricity generation among the dispatchable electricity generators. Such system contexts would naturally emphasize the value of electricity over heat in the output of CHPs somehow thereby making the operation between the two models similar each other.

Another difference is found in the operation of HPs. Since the COP of HPs is set to be 3.5, one unit of electricity can be converted into 3.5 units of heat. It results in the HP being the most efficient technology among the heat production technologies. Even when the electricity produced from the least efficient power generator, decentralized CHPs, is used for HPs, the fuel efficiency of HPs is 189%. It is higher than those of boilers and CHPs. Hence, LP2050 puts the highest priority on HP whereby HPs would practically participate as a base load technology for the heat sector. According to Blarke and Lund on HP operation [123] with large wind power integration, the operation of HPs is more favored in an electricity market frame than CHP operation. However, in LP 2050, CHPs should replace HPs for 209 hours in decentralized DH and 585 hours in centralized DH when there is not enough RES electricity and at the same time there is electricity and heat demand to be fulfilled. The higher frequency to replace HP with CHPs in centralized DH than decentralized DH corresponds to the larger operation of CHPs in centralized DH for its high efficiency as explained before. At this time CHPs should supply electricity since these are the most efficient plants for generating electricity when there is also a heat demand. The heat supplied by CHP units push out HP operations. Eventually the constraint of balancing electric grid does make an effect on HP operation.

In EnergyPLAN, generally CHPs are set to operate before HPs. HPs are operated ahead of CHPs only when there is excess electricity. The inherently defined priority order in EnergyPLAN does not consider the high efficiency of the technology as does LP 2050. In spite of different dispatch mechanisms for HP thereby having different hourly operation pattern of HPs the annual aggregated operation is similar as presented in Table 22.

However, it is noted that the similar results would be coincidently brought from the high level of efficiency assumed for CHPs in IDA2050. If the efficiency of CHPs is low compared to that of condensing mode power plants and boilers, the results would deviate from each other. For the validation of this claim, a scenario which artificially lowers the efficiency of CHPs and the other parameters are the same as IDA 2050, is analyzed by the two models and the fuel consumption is compared in Table 25.

Fuel consumption(TWh)		EnergyPLAN CHP(η_{e}=0.42; η_h=0.32)				LP2050 CHP(η_{e}=0.42; η_h=0.32)			
		Biomass	Synthetic fuel	Total fuel	Total fuel by technologies	Biomass	Synthetic fuel	Total fuel	Total fuel by technologies
CHP	Decentralized CHP	6.96	0.19	7.15	16.09	0.00	0.09	0.22	0.28
	Centralized CHP	8.32	0.62	8.94		0.00	0.19	0.54	
Condensing mode power plants		3.95		3.95	3.95	11.80			11.80
Boiler	Boiler in Decentralized DH areas	3.08	0.33	3.41	7.89	5.21	0.31	5.52	12.52
	Boiler in Centralized DH areas	3.83	0.65	4.48		6.47	0.52	6.99	
Total		26.14	1.79		27.93	23.48	1.12		24.60

Table 25. Comparison of fuel consumption between the models with lowered CHPs efficiency

The efficiency of CHPs is set as 42% for electricity and 32% for heat which is decreased from IDA 2050 where the efficiency of CHPs are 64%(54%) for electricity and 26%(36%) for heat (value in bracket for decentralized CHPs). The overall efficiency (72%) of CHPs in the changed scenario is still higher than 64% of condensing mode power plants.

The results in Table 25 are significantly different from Table 24. The biomass consumption for CHPs in LP 2050 is totally removed while the biomass consumption for CHPs in EnergyPLAN becomes larger than IDA 2050. The lowered efficiency for CHPs results in a significant increase of fuel for condensing mode power plant in LP2050 while there is a minor increase in the result from EnergyPLAN.

The electricity production and consumption for this case is presented in Table 26. EnergyPLAN supplies electricity with a similar pattern to IDA 2050 even with lowered efficiency of CHPs. The electricity production of CHPs is decreased from 7.14TWh in IDA 2050 to 6.76TWh for this case. LP 2050 radically shifts electricity sources from CHPs to condensing mode power plants.

Unit(TWh)		EnergyPLAN CHP($\eta_{e=}0.42$; $\eta_h=0.32$)		LP 2050 CHP($\eta_{e=}0.42$; $\eta_h=0.32$)		Difference	
Electricity Production							
CHP	CHP (decen)	6.76	3.01	0.12	0.04	-6.64	-2.97
	CHP (cen)		3.75		0.08		-3.67
PP			2.53		7.35		5.05
RES			38.58		38.58		0.00
Industry			1.19		1.19		0.00
Waste			2.61		2.61		0.00
Total electricity production			51.67		50.05		-1.62
Electricity Consumption							
HP	HP (decen)	4.41	0.98	4.37	1.13	-0.04	0.08
	HP (cen)		3.75		1.97		0.01
	HP ind		2.53		1.27		-0.37
Electrolyser	Electrolyser(decen)	7.45	0.76	6.47	0.58	-0.98	-0.21
	Electrolyser(cen)		1.82		1.03		-0.78
	Electrolyser trans		4.87		4.87		0.00
Electric heating			0.47		0.00		-0.47
EV			6.79		6.79		0
Import			0.00		0.00		0
Export			1.43		1.32		-0.12
Ordinary Demand			31.10		31.10		0
Total electricity consumption			51.66		50.04		-1.62

Table 26. Comparison of electricity production and consumption in LP2050 and IDA 2050 with lowered efficiency of CHPs ($\eta_{e=}0.42$; $\eta_h=0.32$)

Through the examples of boilers and HPs, one can see that the electricity situation brought from RES overrides the efficiency-based order in LP2050 so that the results of both models converges somehow despite of different solution approaches the models have. However, it is a specific case and cannot be generalized as shown by modeling using relatively low efficiencies for CHPs combined with high efficiency for condensing mode power plants. The higher usage of CHP in EnergyPLAN under such circumstances is thus a model characteristics energy systems analysts have to be aware of.

6.8. Value of future forecasting

LP2050 and IDA 2050 are different in the way of using data for future hours. Especially the operation of storage facility is related to the future forecast capability. The flexibility brought from the storage facility help to result in the reduction of fuel consumption in dispatchable plants.

Even though EnergyPLAN is a deterministic model which has perfect foresight, it only makes limited and passive use of the foresight. LP 2050 on the other hand takes full advantage of foresight with a time frame of one year. For example, the charging of EVs in EnergyPLAN[7] considers future transport demand up to 24 hours for the future with a purpose of avoiding the situation of deficit storage amount against the driving demand. No forecast for RES production and electricity demand is considered in deciding the charging of EVs. This means that while determining the charging electricity amount of battery at a certain hour there is no coherent consideration for the balance of electricity supply and demand. However, it resembles reality where the accuracy of forecasting RES production in the future is not as perfect as the given distribution profiles used in EnergyPLAN. LP 2050 use all given information to decide the charging of EVs for the purpose of minimizing fuel consumption and also for reducing the exportation of electricity. This model uses the entire forecasting period of a full year.

The other storages in EnergyPLAN such as thermal storage do not consider data for future hours. Only the flexible demand in EnergyPLAN takes account of data for future hours for better system operation but in a limited time frame according to the time frame of flexible demand which is set by users e.g. day, week, and month. The difference in using the given parameters for the future is presented in Table 27

	EnergyPLAN	LP 2050
Flexible demand	The duration of future forecast is given	All known for the period (day, week, and month)
EVs	Only future transport demand up to 24hrs	All given information is used
Thermal storage (EnergyPLAN ver.7.20)	Two weeks of future knowledge is used mainly for making the storage amount the same for start and end of period	All given information is used
Electrolyser	No future information is used	All given information is used
Electrolyser_transportation	No future information is used	All given information is used

Table 27. Usage of given parameter for the future in two models

As an example, the following will address the different operation of dispatchable plants for charging EVs as a consequence of different forecasting strategies. The EV battery storage levels in the two models from hour 1 to hour 672 (four weeks) are presented in Figure 29.

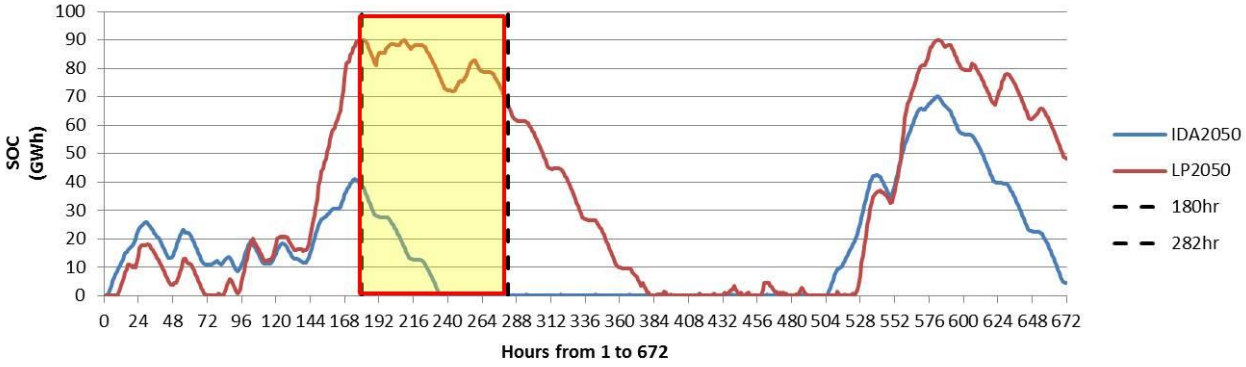

Figure 29. EV Battery storage level from hour 1 to 672 in both models

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[7] There are two ways of charging EVs in EnergyPLAN; Smart charging to fill up battery for the reduction of fuel consumption by avoiding the condensing mode power plant operation and reducing excess electricity in the system by charging EVs, and Dump charging to fill up battery when necessary. This example indicates the Smart charging.

There is significant different storage level observed from hour 180 to 282 which is highlighted in Figure 29. In LP 2050, more electricity is charged in EVs up to the maximum capacity level (90GWh) at hour 180. In IDA 2050, on the other hand, the SOC (State Of Charge)peaks at the same hour, but the level is less than half than in LP 2050. The decrease from hour 180 is faster in IDA2050 than in LP 2050. In order to investigate the dispatch strategy in this period, Figure 30 is presented, showing CHPs and condensing mode power plants (PP in the Figure).

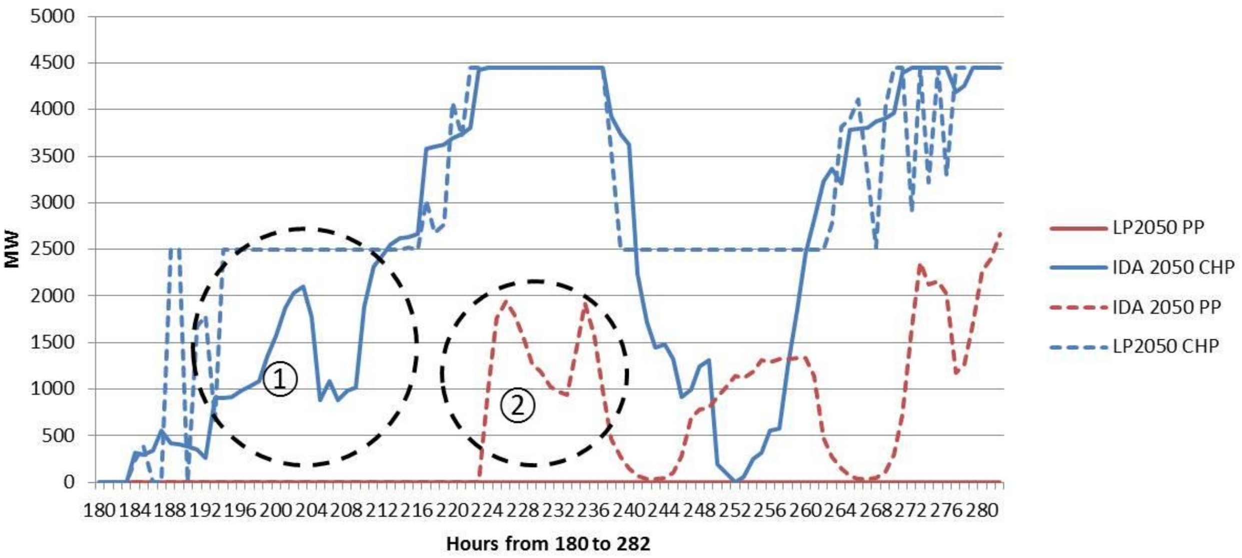

Figure 30. Operation of dispatchable power plants between the hour 180 and hour 282 (CHPs and condensing mode power plants (PP))

During the period from hour 196 to 220 (region ① in Figure 30), CHPs produce more electricity in LP 2050 than in IDA 2050. Meanwhile, the condensing mode power plants produce electricity in the region ② which only occurred in IDA 2050. This observation can be interpreted that the LP 2050 avoids producing electricity by condensing mode power plants in region ②, which is the least energy efficient means, through producing necessary electricity from CHPs beforehand (in region ①). It might be attributed to the forecasting assumption in LP 2050 model, which is not assumed in EnergyPLAN. The example in Figure 30 is a good case to present how future forecasting assumption can differentiate the operation of dispatchable power plants. However this comparison is just one of aspects in the energy system since there are other factors e.g. other storages and various flexible means to make an impact on the operation of dispatchable plants.

For a more general investigation of the value of forecasting assumption, as explained in Section 2.4, the forecasting period is shortened from a year to a week. The shortened forecasting period can give another implication of value of forecasting assumption with more general aspect. The shortened foresight assumption model is called as “LP2050 week” in order to differentiate from the LP2050.

Unit(TWh)		IDA 2050 (α)		LP 2050week(β)		LP 2050		Difference (β-α)	
Electricity Production									
CHP	CHP (decen)	7.14	2.84	7.77	1.51	6.99	1.17	0.63	-1.33
	CHP (cen)		4.3		6.25		5.82		1.95
PP			2.3		0.65		0.58		-1.65
RES			38.58		38.58		38.58		0
Industry			1.19		1.19		1.19		0
Waste			2.61		2.61		2.61		0
Total electricity production			51.82		50.79		49.95		-1.03
Electricity Consumption									
HP	HP (decen)	4.54	1.02	4.10	1.04	4.26	1.09	-0.44	0.08
	HP (cen)		1.88		1.84		1.9		0.01
	HP ind		1.64		1.22		1.27		-0.37
Electrolyser	Electrolyser(decen)	7.47	0.76	6.88	0.70	6.48	0.55	-0.59	-0.06
	Electrolyser(cen)		1.84		1.31		1.06		-0.53
	Electrolyser trans		4.87		4.87		4.87		0
Electric heating			0.48		0		0		-0.48
EV			6.79		6.79		6.79		0.00
Export			1.44		1.93		1.32		0.49
Ordinary Demand			31.1		31.1		31.1		0
Total electricity consumption			51.82		50.80		49.95		-1.02

Table 28. Comparison of electricity production and consumption in IDA 2050, LP 2050 week, and LP 2050

As shown in Table 28, electricity production and consumption is larger in IDA2050 compared to LP 2050 week like the comparison between LP2050 and IDA 2050. However, the gap between the models in electricity production/consumption is decreased from 1.73 TWh in comparison of LP2050 to 1.03TWh in the comparison of LP2050 week. The fuel consumption in LP 2050 week is 23.18TWh (21.82TWh for biomass and synthetic fuel 1.36TWh) which is larger than LP2050 (21.87TWh) but smaller than IDA 2050 (24.58TWh). This result implies that the longer forecasting for the future enables to fulfil the same demand by the less production of dispatchable plants thereby less fuel consumption.

6.9. Conclusion

As explained in Section 1.6, the objectives of this chapter are twofold; the first objective is to investigate the differences between simulating with a predefined dispatch order in EnergyPLAN (descriptive model) and simulating by finding a solution by a given criterion with linear programming (prescriptive model). The second objective is to investigate the value of future forecasting assumption – i.e. whether the model makes use of the full set of forecasted data as given as input parameters or only makes limited use of the input parameters.

For these purposes, this chapter endeavored to build an optimization model which resembles with EnergyPLAN in the level of aggregation, correlations and assumptions, to compare the models and to interpret the results with two above mentioned objectives.

As to the comparison results of these two models, total fuel consumption (including synthetic fuel) from the dispatchable plants in two scenarios presents 24.58TWh (IDA2050) and 21.87 TWh (LP2050). The fuel consumptions by technology, irrespective of which district heating grid, are similar in both models except the condensing mode power plants. The fuel consumption in condensing mode power plants is 3.59 TWh for IDA 2050, 0.9 TWh for LP 2050 respectively. When discerning fuel consumption of technology by district heating grid, significant differences were found in CHPs and boilers. The differences of fuel consumption in centralized and decentralized grid were attributed to the different efficiencies for their cogeneration. It is an example of how different results brought from predefined dispatch order and efficiency driven dispatch order. A comparison between the built in priority in EnergyPLAN and orders set according to the criterion in LP2050 was done. Two specific cases such as boilers and HPs are compared. HPs and boilers have higher efficiency than CHPs. However LP 2050, which considers the efficiency of plants to decide a priority order, presents similar annual results at least by technology, irrespective of DH it belongs to, as EnergyPLAN, which has higher priority to CHPs for heat generation. It was due to significant role of CHPs in electricity generation. More important rule for deciding priority order seemed to be the situational context in electricity sector brought from RES.

It was concluded that even though there are different approaches from these two models but the operation of dispatchable plants is similar at least for this case. However, these results would be a specific case to come from the coincidence to have adequate size and efficiency of dispatchable plants. The significant differences would be brought if different efficiencies were to be assumed e.g. the efficiency of CHPs were to be low compared to other dispatchable technologies.

Another question is about value of future forecasting ability. EnergyPLAN does not use the given future information for strategic operation of storage facility while LP2050 exploits to full capacity the given future information for the operation of storage facilities and dispatchable plants. As a result from the differences, LP 2050 consumes less fuel than IDA 2050 by 2.71 TWh which is about 11% of fuel for dispatchable plant. The gap between the models is decreased from 2.71TWh to 1.4TWh when the time frame of forecasting is shortened to a week. EnergyPLAN poses a more conservative attitude for the accuracy of forecast and LP2050 model poses an ideal attitude for the same matter. It is a dilemma on which model resembles more to the reality. The reality would be located in the middle of these two situations in operating the storage facilities. For reflecting of partly correct forecasting in reality, linear optimization model which assumes perfect forecasting within a given optimization period, adopts stochastic methodology. Linear programming which has merit of perfect forecasting at the same time the merit turn into weakness of reflecting with the reality where only partly correct forecasting is possible is subsidized with stochastic programming which reflect uncertainty in it. There has been research focusing on this stochastic character in a coherent energy system [126], electricity market [127] and wind forecasting [128,129].

Nomenclature

Variable	
$Hp_{h,t}$	Hourly heat production from individual plant
$Ep_{h,t}$	Hourly electricity production from individual plant
$Ec_{h,t}$	Hourly electricity consumption for flexible means (electrolysers, HP, electric vehicle)
$F_{h,t}$	Hourly fuel consumption in technology
Eex_{h}	Hourly electricity amount exported
Eim_{h}	Hourly electricity amount imported
$Hstr1_{h}$, **$Hstr2_{h}$**	Hourly heat storage level in individual district heating group
$Hin1_{h}$, $Hin2_{h}$	Hourly heat amount stored in the heat storage in each district heating group
$Hout1_{h}$, **$Hout2_{h}$**	Hourly heat amount dispatched from the heat storage in each district heating group
$H2dh1_{h}$, **$H2dh2_{h}$,** **$H2car_{h}$**	Hourly H2 amount produced for CHP and boilers from electrolysers in each district heating group and for transportation
$H2dh1in_{h}$, **$H2dh2in_{h}$**	Hourly hydrogen input amount to hydrogen storage in decentralized district heating grid (1) and centralized district grid (2)
$H2dh1out_{h}$, **$H2dh2out_{h}$** **$H2carout_{h}$**	Hourly hydrogen output amount to hydrogen storage in decentralized district heating grid (1), centralized district grid (2) and transportation
$H2strdh1_{h}$, **$H2strdh2_{h}$,** **$H2strcar_{h}$**	Hourly status of hydrogen storage connected to electrolysers located in decentralized district heating grid (1), centralized district grid (2) and for transport
$Wflex_{h}$	Hourly distributed amount for weekly flexible demand
$Dflex_{h}$	Hourly distributed amount for daily flexible demand
$SHstrdh1_{h}$, **$SHstrdh2_{h}$** **$SHstrI_{h}$**	Hourly storage status solar thermal in decentralized district heating grid (1), centralized district grid (2) and individual household
$SHin1_{h}$, **$SHin2_{h}$** **$SHinI_{h}$**	Hourly heat input produced from solar thermal to solar thermal storage in decentralized district heating grid (1), centralized district grid (2) and individual households
$SHout1_{h}$, **$SHout2_{h}$** **$SHoutI_{h}$**	Hourly heat output from solar thermal storage to the grid in decentralized district heating grid (1), centralized district grid (2) and hourly heat output from individual solar thermal storage
$IHstr_{h}$	Hourly heat storage status in individual household
$IHin_{h}$	Hourly heat input amount in individual household
$IHout_{h}$	Hourly heat output amount in individual household

SET		
h	Hours for a leap year (8784 hours)	
t	Technologies to produce or consume energy in the system	
	CHP1, CHP2	Combined heat and power in district heating grid 1 and 2 respectively
	PP	Condensing power plant
	B1,B2	Boiler in district heating grid 1 and 2 respectively
	HP1, HP2, HPi	HPs in district heating grid 1, 2, and individual household
	ELdh1, ELdh2, ELcar	Electrolyser in district heating grid 1, 2, and for transport
	EV	Electric vehicle

Parameter	
Eld$_h$	Hourly electricity demand
RES$_h$	Hourly electricity generation from renewable resources
SHdh1$_h$**,** **SHdh2**$_h$ **SHI**$_h$	Hourly distribution of solar thermal production in decentralized district heating grid (1), centralized district grid (2) and individual households
Trans$_h$	Hourly distribution of transport demand
EVcap$_h$	Hourly charging capacity of EVs. Detailed information in EnergyPLAN manual [130]
IHd$_h$	Hourly heat demand in individual households
Hddh1$_h$**,** **Hddh2**$_h$	Hourly heat demand in decentralized district heating grid (1), centralized district grid (2)
Capacity	Capacity defined for every kind of generators and storage

7. Conclusions and future works

This chapter summarizes the main finding of individual analysis and answers the questions brought in Chapter 1. Also, possible future research which can improve the findings of this PhD dissertation are suggested in this chapter.

7.1 Conclusions

Chapter 3 reviewed the preexisting Danish future scenarios; IDA 2050, CC 2050, and CEESA. The first point of the review was to compare the scenarios in terms of fuel consumption, installed capacities, and main assumptions for the future. The three scenarios share some leading principles e.g. wind and biomass as two main pillars for the system, but at the same time have individual characteristics. The IDA 2050 scenario depends more on biomass resources, CC2050 assumes a more electrified energy system by installing high capacity of wind and encompassing high international exchange, and CEESA focuses on reducing biomass consumption by scrutinizing more on environmental effect of biomass. The models used for the scenarios were reviewed and the roles of the models were also identified. The more recent scenario uses more detailed analysis and more broad area where adjacent to energy area are concerned.

Further comparison was done between the IDA 2050 and CEESA scenario by the analytical frameworks of radical technology development as defined by Hvelplund and evolutionary technology development as developed in this thesis. The comparisons were viewed in three aspects; biomass potential assessment, transportation model, and electricity grid perspective. The result was that a more transparent, quantitative analysis is performed in CEESA scenario by using more models and closer communication with other academia. The CEESA scenario is also based on a more radical technology development perspective than the other scenario mostly due to less use of biomass resources.

The potential of biomass in the future might make systematic influences to whole energy sectors including interconnection capacity. The larger availability of biomass resource would bring the less challenging future in terms of technology development and societal change.

Chapter 4 endeavored to answer the question; which way of using biomass, a limited but useful resource of the future energy system, would be better. The focus was on whether heat or power production by using biomass resources was the more effective from system perspective. Two series of system configurations were formulated for the reduction of biomass in two sectors. The means for reducing biomass in two sectors were offshore wind and HPs. The base line for these two variations was IDA 2050. The results were compared in terms of increasing amount of international exchange to the reduction of biomass consumption, fuel efficiency and total costs. The results from the reduction of biomass in a moderate level in both cases were similar, however when the amount of biomass is reduced over 50% of biomass amount which was supposed to be used for heat or electricity sector the from the two cases started to be deviated from each other. It was concluded that the reduction of biomass in the heat sector is better than the alternative reduction in the electricity sector in every aspects except biomass fuel efficiency.

It is noted that several uncommon or less optimal alternatives were found especially when the bigger biomass reduction is carried out. These are definitely uneconomical and not likely to happen in reality. These extreme alternatives are only found for the purpose of seeing which sector of biomass usage is more valuable.

Chapter 5 assessed the potential of flexible demand in the future by a technical, bottom-up approach. This approach was differentiated from the market and aggregated approach otherwise seen in literature which focuses on behavior change of consumer as a response to price change. The technical approach rather focuses on technical boundary of individual process in assessing potential of flexible demand. This approach was applied to whole energy sectors even including industry demand. The results showed that approximately 24% of electricity demand can be flexible in short time frame (2hrs) and 6.9% of electric demand can be flexible in long time frame (24hrs). Most of flexible demand in short time frame was found in thermal related demand e.g. refrigerator/freezer, ventilation, and space heating. The demand for washing equipment and pumping was assumed to be a long time frame flexible demand. The assessed potential of flexible demand was analyzed in EnergyPLAN to assess the system effect. The effect was not substantial. It can decrease import and export by 0.25TWh and 0.81TWh respectively. Also the assessed level of flexible demand can decrease electricity production from the condensing mode power plants by 0.34TWh. It might be due to the large scale for short time frame of flexible demand and existence of other flexible means in the future energy system. From the other end, a level of flexible demand from top-down approach to make a significant system change was endeavored to find. Here it was found that the level of flexible demand which can decrease international connection by half would need to be approximately 13TWh of flexible demand within a month. Monthly flexible demand in such large scale is rarely found in practice. Flexible demand within the classic demand can thus not contribute sufficiently if this level of reduction in international exchanges is required.

As mentioned in Section 5.2, the potential of flexible demand has been assessed with a technical and a decomposition method. Therefore, this analysis could overlook some potential of flexible demand which could have reflected in market and aggregated way. For example, there might be more potential of flexible demand in industrial sector than the assessed amount in this research. It was attributed to the fact that unlike residential and commercial sector there would be a managerial activity to shift an array of processes which are interlocked from one period to another in a response to electricity price level. This is a limitation in the methodology to assess potential of flexible demand however, one of objective in this analysis is to find potential of flexible demand with the least behavioral change of consumers. However, it is not believed to be a serious limitation.

Chapter 6 establishes a) the differences between a model which has a predefined priority order and a model whose priority order is defined by efficiency and b) the value of forecasting ability in the future energy system. For addressing these two issues, a linear optimization model was built and the results of the model were compared with IDA 2050 analyzed using the EnergyPLAN model. The differences of predefined order and order determined by efficiency were found among the heat generation plants; CHP, boilers, and HP. The significance of cogeneration was emphasized in EnergyPLAN not only for heat generation but also for power production. This highly emphasized priority order of CHPs synchronizes with the results of the linear optimization model built in the chapter. However, it is noted that the efficiency of cogeneration and those of other competing technologies are well balanced otherwise the results would deviate. The value of electricity even from fuel consumption perspective is defined by the system context such as whether the other alternatives are available or not, and how high efficiency of the alternatives compared to the cogeneration. This is evidenced by the results from the different efficiency of centralized and decentralized CHPs. As to the value of future forecasting ability in models, forecasting ability is associated with storage function and enables to avoid the situation of utilizing less efficient plants by storing energy. The shorter time frame of forecasting in the linear optimization model would bring results closer to those found with the EnergyPLAN, which uses the given information on future more conservatively.

7.2. Recommendation for future research

This chapter presents areas for further investigation determined during the PhD period. They are mostly related to the methodologies for scenario analysis.

- Operation strategies for uncertain future

In Chapter 6, there were comparisons between the operation strategy to take advantage of given information on future limitedly and the operation strategy to utilize the future information fully. As mentioned before, the reality is located somewhere between no future forecasting ability and perfect prediction. It was also mentioned that the linear optimization models involve stochastic function to reflect this reality. A simulation model could cope with this reality by having several options of operation strategies for the uncertainty.

In the energy system analysis, various parameters are associated to such future forecasting issues (i.e. electricity, heat, and transport demand, production from RES). There are different levels in forecasting accuracy for these parameters. Compared to future production from RES, the demand forecasting can be done with higher accuracy since it has certain regularity and a pattern which does not deviate much from a typical pattern. Therefore using the typical demand which might be based on past data some operation strategies for storage facility could be considered e.g.

1. Operation strategy to follow a typical demand
2. Operation strategy to set a certain point for daily i.e. 50% storage level at 9 am
3. Without any operation strategy just save when it is available and dispatch when necessary

By comparing these operation strategies, one can see which strategy can present the best performances in terms of a certain criterion i.e. cost, fuel consumption and emission. A similar methodology is used to evaluate the performances of operation strategies of remote hybrid energy system by comparing several dispatch strategies with the linear optimization which assumes perfect foresight within the period as a benchmark [131]. The difference from this study is that the research is done in more coherent energy system.

- Demand profiles correlated to weather conditions

Second suggestion is to enhance demand profiles. Using EnergyPLAN there needs hourly distribution profiles such as demands for heat, electricity and transport, and energy production from RES for the emulation. The weather conditions can make an impact the demand patterns i.e. correlation of heat demand and wind blow, solar radiation and air condition demand. Especially for Danish situation, wind profile and heat demand would be correlated each other. Therefore, it would be interesting to investigate whether the input parameters which reflect such correlations would bring different results in the system level. The hourly distribution profiles used in the future scenarios IDA2050 and CEESA are based on empirical measurement in the same year. However, there happened to be no available hourly data for the same year. In those cases, it is better to use weather factored demand instead of using demand distribution profiles in different year.

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