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AALBORG UNIVERSITET
STUDENTERRAPPORT

Study:
Sustainable Energy Planning and Management (SEPM)

Title:
Electricity prices and public acceptance of renewable energy, in the face of the socio-technical transformation of the electricity system towards achieving Denmark's climate ambitions in 2030.

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Synopsis:

Synopsis: Denmark has made progress in increasing the renewable share of electricity supply, but of concern is how the large-scale introduction of renewable sources will influence electricity prices in future, and in turn, prices may influence public opinion towards renewable energy development. In addition, an increased renewable energy share may also impact on the transmission system operator (TSO) to maintain balance and grid stability due to the fluctuating nature of renewable sources, and as a result, the Danish TSO is planning to allow small household PV-units to participate in the balancing markets.
The aim of this study is to explore the relationship between electricity prices and public acceptance of renewable energy and what role society can play in the socio-technical transformation of the electricity sector, considering Denmark's climate ambitions towards becoming a climate neutral society by 2050.
The study is divided into four main parts. The first part is problem identification, which describes the Danish climate ambitions and strategy within the context of the liberalized electricity market. The second and third parts analyze price forecasting methods and the relationship between electricity prices and public support for renewable energy development, respectively. The final and fourth part of the study is aimed at modelling public participation in the balancing market.

Johan Edwin Kock

Preface

This study has been carried out at Aalborg University on the fourth semester of the Master programme on Sustainable Energy Planning and Management. The study is founded within the context of Denmark's long-term ambitions on the reduction of CO_2-e emissions as a societal-wide matter which takes into account issues around the balance between affordability, public support and increasing renewable energy in the electricity supply mix. Within this context, this study aims to explore the relationship between society and the techno-economic transformation of Denmark's electricity sector.

I would like to express my sincerest gratitude and deepest appreciation to my supervisor, Anders N. Andersen, for his guidance, support, patience and expert input throughout the study.

This report is divided into chapters, sections, and sub-sections. All the parts are numbered chronologically and sections are connected through the numbering system as seen in the table of contents.

Tables and figures are numbered as [X.Y] with the first number [X] being the chapter in which the table or figure appears, and the second number [Y] being the numerically order of the table or figure within that particular chapter.

Source references are according to the Harvard referencing system, which is shown as [Author, year] in the text. The sources appear in alphabetical order in the bibliography. Figures and tables which do not have a source reference in the text, are the author's own work.

Nomenclature

Abbreviation

km^2	square kilometre
CH_3OH	Methanol
CH_4	Methane
CO_2-e	Carbon dioxide equivalent
CO_2	Carbon dioxide
CO	Carbon monoxide
H_2S	Hydrogen sulphide
H_2	Hydrogen
NH_3	Ammonia
Nm^3/h	Normal Meter Cubed per Hour
N	Nitrogen
O_2	Oxygen
AEC	Alkaline Electrolysis
CAPEX	Capital expenses
CHP	Combined heat and power
Covid-19	Novel coronavirus (2019-nCoV)
DKK	Danish krone
DSO	Distribution System Operator
EU	European Union
FT	Fischer Tropsch
GIS	Geographic Information System
GJ	Gigajoule
GW	Gigawatt
kg	Kilograms
LCOE	Levelised Cost of Energy
LHV	Energy content, expressed as Lower Heating Value
MDKK	million Danish Krone
MJ	Megajoule
MW	Megawatt
MWh	Megawatt hour
M€	Million Euros
O&M	Operation and maintenance
OPEX	Operational expenses
PEM	Proton Exchange Membrane
PJ	Petajoule
PtX	Power-to-X

RE	Renewable Energy
RED	Renewable Energy Development
RES(s)	Renewable Energy Source(s)
SES(s)	Smart Energy System(s)
SNG	Synthetic natural gas
SOEC	Solid Oxide Electrolysis
TJ	Terajoule
TSO	Transmission System Operator
TWh	Terawatt hour
USD	US dollars
€	Euros

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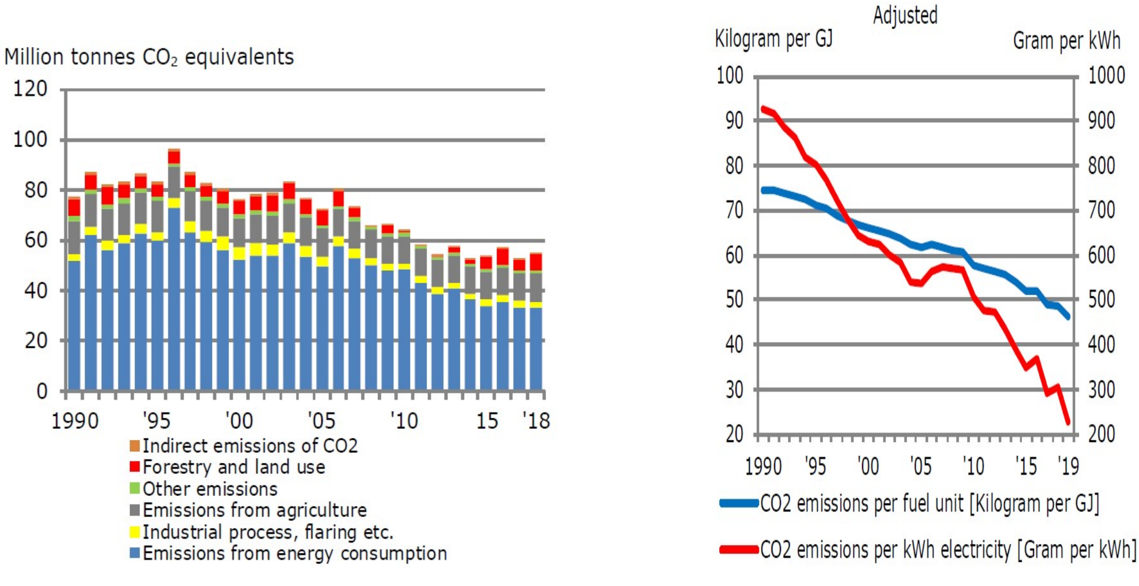
1 Introduction

Denmark has ratified the United Nations Framework Convention on Climate Change (UNFCCC) (1992) in 1993 and also ratified the Kyoto Protocol to the UNFCCC (1996) in 2002, which entered into force in Denmark in 1994 and 2005, respectively. Under the Kyoto Protocol, Denmark, and the other signatories to the Protocol, committed to reduce or limit emissions of six greenhouse gasses in the first commitment period under the agreement, from 2008 to 2012 [Weihe J et al, 2019]. The parties to the UNFCCC adopted the Paris Agreement in December 2015 at the 21st meeting of the Conference of the Parties (COP21) and Denmark ratified the Paris Agreement in 2016, which became into force in Denmark in December 2016. To meet the targets set by the Paris Agreement of limiting global warming to below 2°C, [UN, 2015], Denmark adopted a new climate law in June 2020, which has as its primary objectives to: 1) Reduce Denmark's' greenhouse gas emissions by 70% Carbon Dioxide-equivalents (CO_2-e) by 2030, as compared to 1990; and 2) Transform Denmark to a climate neutral society by 2050, [Retsinformation, 2020], [Klimarådet, 2020].

Figure 1.1 provides a perspective of the historical CO_2-e emissions from 1990 till 2018 for Denmark, in million tones (CO_2-e) in different sectors (Figure 1.1a), and in relation to emissions per fuel unit and per kWh electricity (Figure 1.1b), [Energistyrelsen, 2021a].



(a) Observed CO_2-e emissions from different sectors ***(b)*** CO_2-e emissions/kWh electricity

Figure 1.1. Denmark CO_2-e emissions per sector and relative to fuel units and kWh electricity produced, from 1990 till 2019, [Energistyrelsen, 2021a]

Observed CO_2-e emissions are adjusted to account for temperature variations relative to a normal weather year and foreign trade in electricity, [Energistyrelsen, 2021a]. Figure 1.1a shows that the total observed CO_2-e emissions for Denmark was 77,2 millionTonnes total CO_2-e in 1990, as compared to 54,8 millionTonnes total CO_2-e in 2018, representing a total reduction of approximately 22,4 millionTonnes total CO_2-e (representing a reduction of 29%) from 1990 till 2018. Thus, a further reduction of approximately 31,6 millionTonnes total CO_2-e is still required to reach the 2030 climate goal as set out in the climate law.

From Figure 1.1a it can be seen that emissions from energy consumption make up the largest contributor towards total emissions, which includes final energy consumption as well as energy consumption in the energy and transformation sectors. Figure 1.1b provides insight into emissions from the electricity sector from the total CO_2-e emissions per kWh electricity. As can be seen from Figure 1.1b, one kWh of electricity produced and consumed in Denmark in 2019, produced 226 gram/kWh of CO_2-e emissions, as compared to 929 gram/kWh in 1990. This represents a reduction of 76% in CO_2-e emissions per kWh electricity produced and consumed. This reduction can largely be contributed to the developments in renewable energy sources, especially wind energy, that have been achieved in Denmark since 1990, [Energistyrelsen, 2020].

Figure 1.1 illustrates that Denmark has made strides in reducing it's emissions footprint and much progress in increasing the renewable share of electricity supply. However, more is required if Denmark is to reach its climate goals in 2030 and 2050. In this regard, Mathiesen et al. [2020] has projected that the electricity sector will play a larger part in the climate goals as more traditionally fossil-fuel based systems are converted to electricity based systems from renewable energy sources, in particular wind power. However, the long-term reduction of CO_2-e emissions is a societal-wide matter and any strategy towards CO_2-e emissions reduction, need to take into account issues around affordability and also public acceptance of renewable energy development.

Within this context, this study aims to explore the relationship between society in general and the techno-economic transformation of Denmark's electricity sector.

Problem analysis 2

Based on the introduction as presented in Chapter 1, this study aims to develop a price simulation model to make a prognosis of electricity prices on the Nord Pool electricity exchange. The objective of this chapter is to describe the knowledge that are used to frame the problem of the study. Firstly, a reflection of the Danish energy sector is presented with a focus on the development of Renewable Energy (RE) and its role in Denmark's electricity supply system. Secondly, an overview of the liberalisation of the electricity market in Denmark and the regulatory environment is presented. Next, the relationship between Renewable Energy Development (RED) and electricity prices is explored and finally an overview of the Baltic-Nordic electricity market is provided, with a focus on the Nord Pool electricity exchange for which the price prognosis is made.

2.1 Overview of the Danish electricity sector

Figure 2.1 presents an overview of electricity production by type of producer for Denmark for the the time period 1990 till 2019, including large-scale coal fired units, large- and small-scale combined heat and power units, automakers who producers power (but who's primary product is not power), and wind, solar and hydro-power units, [Energistyrelsen, 2021a].

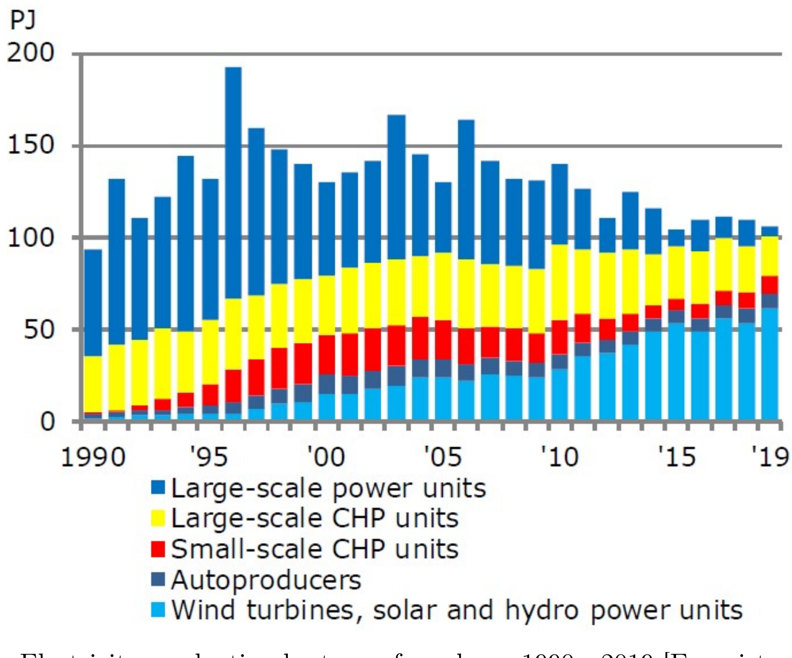


Figure 2.1. Electricity production by type of producer 1990 - 2019 [Energistyrelsen, 2021a]

As can be seen from Figure 2.1, Denmark has been steadily reducing it's dependency on fossil fuels for the production of electricity in large scale power units since the early 1990's. Over this time period, electricity production by renewable energy sources, in particular wind turbines, have increased steadily. In 2019, total electricity production was 106,3 PJ, which was 2.8% less than compared to 2018. Net imports of electricity was higher in 2019 as compared to 2018, which explains the reduction in 2019 production of electricity as compared to 2018. Power producers include large-scale power units (both large scale separate power units and large scale combined-heat and power (CHP) units), small-scale CHP units, wind turbines and by auto-producers (whose main product is something else and not energy).

Of the total 106,3 PJ of electricity produced in 2019, 27,0 PJ (25.4%) were produced from large-scale power units, which of 5,7 PJ (or 5.4%) as separate electricity production and the balance of 21,3 PJ was produced from large scale combined-heat and power (CHP) units. Separate electricity production varies on an annual basis, due to fluctuations in import and export of electricity. Production from small-scale CHP units and auto-producers in 2019 was 9,5 PJ (8.9%) and 8,1 PJ (7.6%), respectively. 58,1 PJ (54.7%) and 3,5 PJ (3.3%) of electricity production came from wind turbines and solar power units [Energistyrelsen, 2021a].

Over this time period from the early 1990's to 2019, electricity production from renewable energy sources grew from approximately 6,3 PJ to approximately 83,9 PJ (78,9% of total production) in 2019. In 2019, wind power contributed the largest portion of renewable energy (58,1 PJ or 54,7%) and biomass and biogas contributed 19,1 PJ (18,0%) and 3,0 PJ (2.9%) respectively. In 2019, total electricity production by coal, natural gas, oil and non-renewable waste had reduced to 11,9 PJ, 6,8 PJ, 0,9 PJ and 2,8 PJ, respectively [Energistyrelsen, 2021a].

Figure 2.2 presents an overview of electricity consumption, broadly categorised by the following type of use: manufacturing and industry; commercial and public services; and households, for the time period 1990 till 2019 [Energistyrelsen, 2021a].

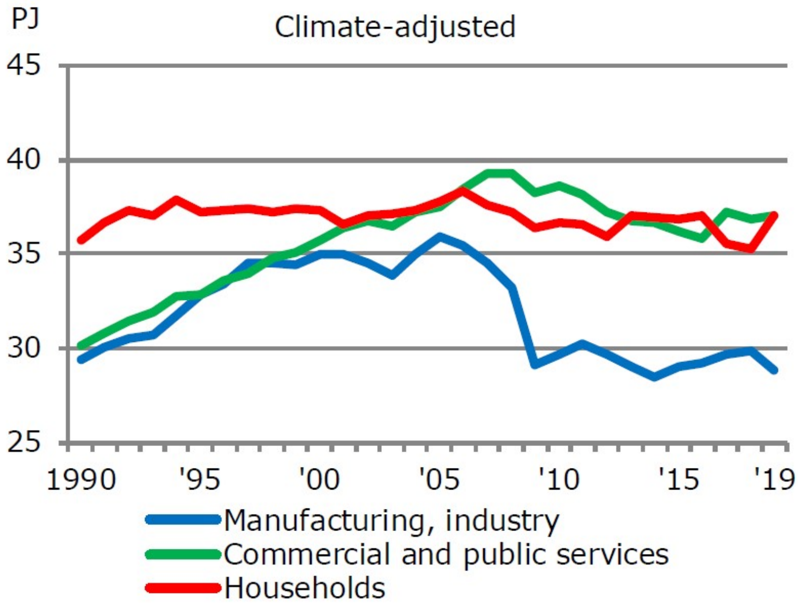


Figure 2.2. Electricity consumption by use 1990 - 2019 [Energistyrelsen, 2021a]

As can be seen from Figure 2.2, electricity consumption from the manufacturing and industrial sector was 2.0% lower in 2019, as compared to 1990. Consumption initially increased from the 1990's to the mid 2000's, after which it decreased steadily year-on-year. Compared with 1990, electricity consumption has increased in the commercial and public sector from 1990 till about 2008 by about 30%, and then declined by about 5% from the 2008 levels. In 2019, electricity consumption for this sector was about 0.5% higher as compared to 2018. In the period from 1990 to 2019, electricity consumption in the household sector remained almost constant, with a slight fluctuation between 35,3 PJ and 38,4 PJ. Electricity consumption was higher in 2019 as compared to 2018 by 5.2% and about 4.0% higher as compared to 1990 [Energistyrelsen, 2021a].

2.2 Renewable energy development and electricity supply

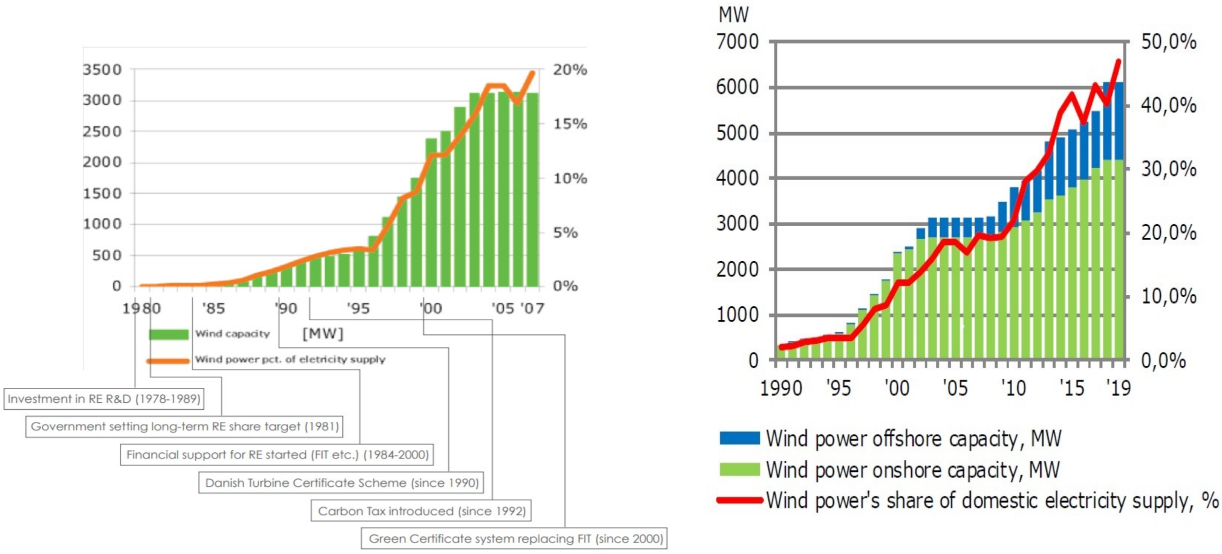
2.2.1 Wind energy development policy support and electricity share

Being surrounded by the ocean, Denmark is rich in wind resources. According to a study by Petersen [2018], the country has been experimenting with wind energy for electricity generation as early as the late 1890's and early 1900's. Throughout the early twentieth century Denmark saw numerous small scale wind turbines being erected, mostly on private property. However, following the events of World War 2, energy imports, mostly in the form of oil and coal, started to take centre stage and as the development of centralised electricity generation was prioritised, national interest in the development of wind resources declined [Petersen, 2018].

By the early 1970s, Denmark was importing more than 90% of its national energy consumption, but the oil crisis of the early 1970's motivated Denmark to investigate and find alternative energy sources, which would reduce its reliance on foreign oil and also provide future energy sustainability. The initial focus area was to move from oil to coal, but climate action concerns in the mid 1980's motivated a shift from coal to natural gas for electricity generation. However, the focus areas in the late 1980's and early 1990's shifted again and wind energy gained larger traction for electricity generation. The oil crisis essentially served as a "wake-up call" for Danish authorities, and this led to the establishment of the Danish Energy Agency (DEA) and the Ministry of Energy, who was tasked to develop and implement Denmark's long-term energy policy measures that focused on long-term energy planning initiatives, diversification of energy sources, efficiency, energy independence and the integration of a greater amount of renewable energy resources in the energy mix [Johansen, 2021].

Figure 2.3 [UN, 2012] [Energistyrelsen, 2021a] provides a perspective of policy development in correlation to wind energy capacity development and the corresponding share of wind energy in the electricity supply. Figure 2.3a shows the critical policy measures that shaped the development of wind energy capacity over the course of roughly three decades covering the period from the late 1970's to the mid 2000's, and in Figure 2.3b, it can be seen how the wind energy share of electricity supply in Denmark was initially slow and then started to increase from roughly 1995.

Wind energy accounted for a 46.8% share of Denmark's electricity supply in 2019 as compared to 1.9% in 1990 [Energistyrelsen, 2021a]. In 2017 and 2018 wind energy supplied 43.2% and 40.2% of the domestic electricity supply, respectively [Energistyrelsen, 2021a]. The wind energy share of electricity supply varies year on year depending on the available wind resources and this is also an indication of the fluctuating nature of wind energy [Johansen, 2021].



(a) Wind energy development and energy policy 1980-2007, [UN, 2012]

(b) Wind energy development and share of electricity supply 1990-2019, [Energistyrelsen, 2021a]

Figure 2.3. Denmark wind energy development in perspective: policy development and electricity share.

According to Johansen [2021], Denmark currently holds a market share of approximately 40% of the global supply of wind turbine technology and wind energy technology has become one of the major export products of the country, with the wind energy industry accounting for approximately 70% of Denmark's national energy products exports.

2.2.2 Energy and Climate Plan 2019 and future projections

Energy and Climate Plan 2019 - Policy objectives

Denmark's Integrated National Energy and Climate Plan of December 2019, sets ambitious and clear targets for the period 2020 – 2050 and also let do the proclamation of Denmark's Climate Act in 2020 (Act No. 965 of 25 June 2020). The plan has been developed across six broad strategic areas: 1) Greenhouse gas emissions and removals; 2) Decarbonisation and renewable energy; 3) Energy efficiency; 4) Energy security; 5) The internal energy market; and 6) Research, innovation, and competitiveness [UN, 2012].

These strategic areas contain a number of strategic policy objectives which need to be implemented in the period from 2020 to 2030, amongst other the reduction of greenhouse gases by 70% by 2030 (relative to the 1990 level) and net zero emissions by 2050. Another key objective is the acceleration of the transition to renewable sources in the energy sector with a goal of at least 55% renewable energy in gross final energy consumption by 2030 and the phasing out of electricity production from coal in the period from 2020 and 2030 with the renewable share in electricity supply expected to exceed 100% in 2030. Another key policy objective is to achieve a high level of grid inter-connectivity with neighboring countries and to achieve large scale improvements of flexibility in the internal energy system. Support for development of Smart Energy Systems (SES) and developments in energy innovation and new technologies, are also high priority areas in terms of the plan [Klimaministeriet, 2019].

Based on these policy objectives in Denmark's Climate Plan, it can be expected that renewable energy will play a key role in the future development of Denmark's energy system, in particular in the electricity sector. It can also be expected that cross-border grid connectivity will increase and that trading of electricity on European 's electricity market will play a crucial role in reaching Denmark's long-term climate objectives.

Key Trajectories in the transition period 2020 – 2030

To provide context to the overall goals of Denmark's Integrated National Energy and Climate Plan, a number of key trajectories are provided in the plan, for the transition period of 2020 to 2030. The trajectory of interest for the purposes of this study is presented in Figure 2.4, which provides an estimated trajectory for the *renewable energy share for electricity supply*, during the transition period towards net zero emissions [Klimaministeriet, 2019].

As can be seen from Figure 2.4, it is projected that renewable energy will provide more than 100% of electricity supply by 2030, with onshore and offshore wind providing about 80% of electricity supply.

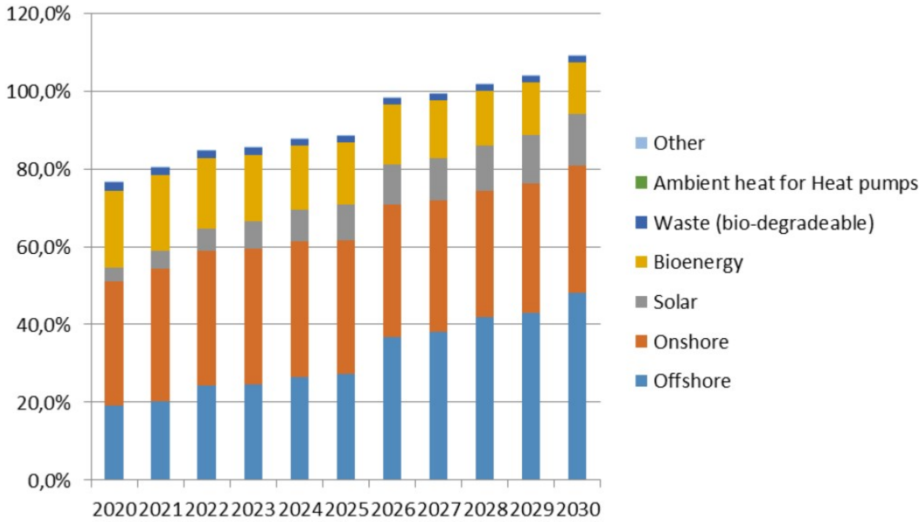


Figure 2.4. Denmark estimated trajectory for Renewable Energy share in electricity supply (RES-E) 2020 - 2030 [Klimaministeriet, 2019]

2.3 Liberalisation and regulatory environment

2.3.1 Historical context and regulator environment

Up until the late 1990's, the Danish electricity sector was still a vertically integrated and monopolized system which was not subjected to market forces. However, pressure in the early 1990's, from large consumers to be able to choose their own supplier, as well as parallel developments in the European Union (EU) on the free movements of goods and services, influenced the liberalization process of the sector in Denmark, [Klimaudvalget, 2012].

The liberalization of the electricity sector in the EU was first addressed in a green paper produced in 1988 and included the following key objectives: 1) Open access to the transmission grid for producers; 2) Removal of the monopolies in generation; and 3) Unbundling of the sector into separate generation, transmission and distribution systems. The green paper also projected advantages in estimated cost savings in the sector of up to 12% of total cost, should liberation be achieved [Danish Energy Agency, 2020].

Detailed proposals followed in 1991 and 1993, resulting in the first adopted EU directive on the internal electricity market in 1996. This directive set guidelines and directions with regards to: 1) The introduce international trade in electricity; 2) Unbundling of generation, transmission and distribution; 3) Fair and equitable access to the grid for generators; 4) Minimum component of liberalized consumers; and 5) Implementation into the national legislation of members states by February 1999, [Klimaudvalget, 2012]. The EU process towards liberation of the sector, from the initial green paper to the 4th adopted directive package in 2011, is illustrated in Figure 2.5, [Danish Energy Agency, 2020].

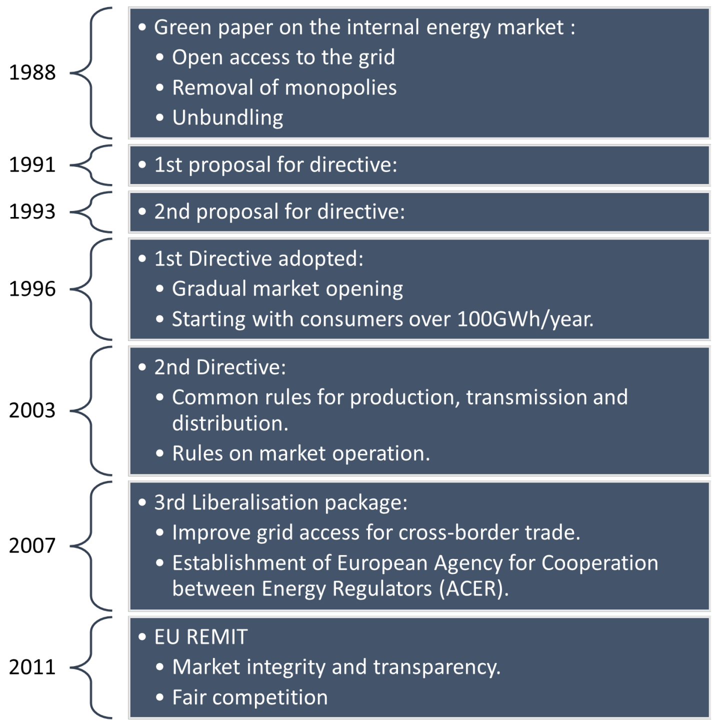


Figure 2.5. Chronological overview of EU regulatory milestones in the liberalisation of the electricity market 1988 - 2011 [Danish Energy Agency, 2020]

In response to the EU directive of 1996, Denmark introduced a new Electricity Supply Act in 1999. The new legislation paved the way for milestones in terms of market access of consumers, the creation of natural monopolies in transmission and distribution and the establishment of a new regulator for the electricity sector. The initial reform measures were followed by a number of other measures over the years as illustrated in Figure 2.6, to the extent that the sector is today considered liberalised, but still evolving [Danish Energy Agency, 2020].

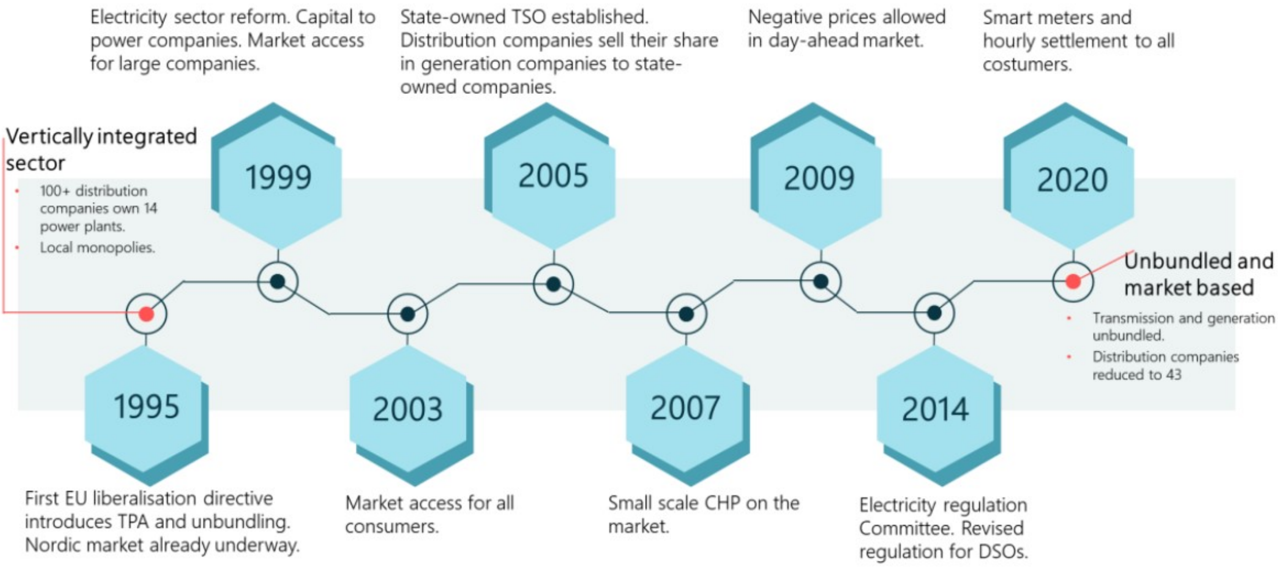


Figure 2.6. Overview of the liberalisation process of the Danish power sector 1995 - 2020 [Danish Energy Agency, 2020]

2.3.2 Impact on trade and renewable share of electricity supply

Chapter 2.3.1, presents the official start of the reform of the electricity sector in Denmark with the introduction of the new Electricity Supply Act in 1999. However, apart from the earlier proposals and the official 1996 directive from the EU with regards to the reform of the sector, the liberalisation of the electricity sector in Norway and Sweden during the early 1990s, also influenced the reform discussions in Denmark at the time and showcased the level of efficiency and savings that could be achieved through liberalisation [Klimaudvalget, 2012]. Being situated between the largely hydro-powered Nordic electricity system and the predominantly thermal German and Central European electricity systems, meant that Denmark could expand its transmission links to its neighbours in the post-liberalisation era, as shown in Figure 2.7, [Danish Energy Agency, 2016].

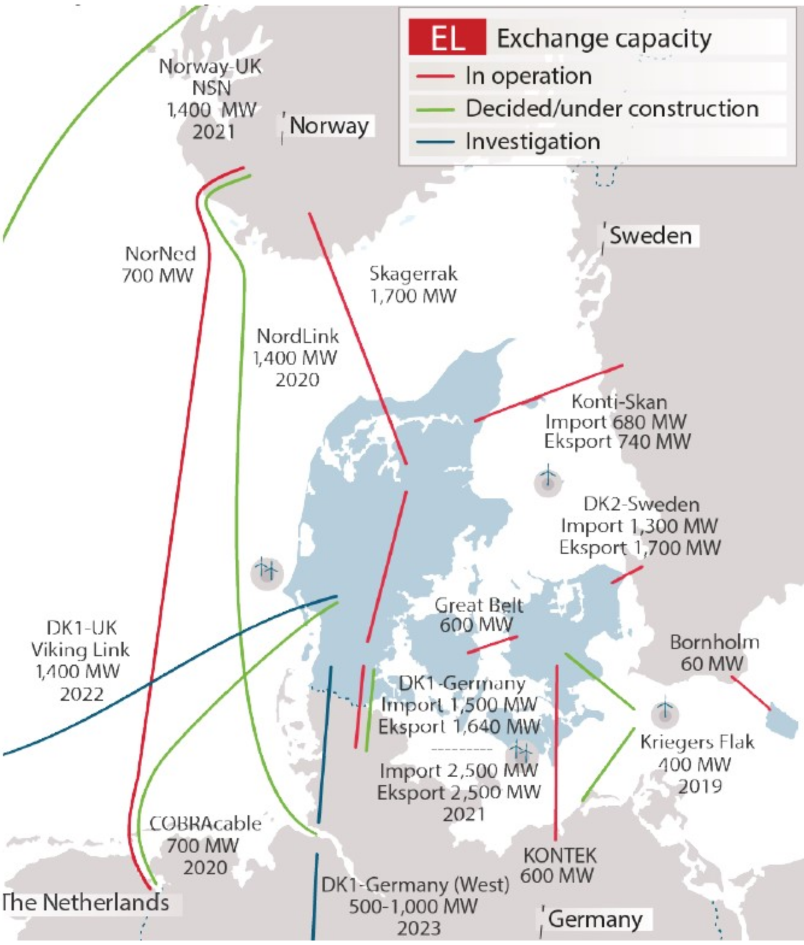


Figure 2.7. International transmission links between Denmark and nearby electricity markets, [Danish Energy Agency, 2016]

Liberalisation of the sector also meant that Denmark could use the advantage of its location on the hydro-thermal border, more effectively [Klimaudvalget, 2012]. These international links in the transmission system have promoted an increase in competition in the Danish electricity supply system and has contributed towards the cost-effective incorporation of renewable energy sources into the system [Danish Energy Agency, 2016].

With the largely hydro-power based systems in Sweden and Norway and the largely thermal power systems in Germany, Denmark is uniquely positioned to import electricity from Norway and Sweden and export to Germany, [Jakobsen, 2007]. The liberalization of the sector opened these opportunities further as can be seen from the increasing trend in net trade in electricity in Denmark as shown in Figure 2.8 [Danish Energy Agency, 2020].

Where trade between these countries, prior to liberalisation, was largely regional and based on bilateral agreements between power companies, liberalisation of the sector opened the trade opportunities significantly [Danish Energy Agency, 2020]. Figure 2.8 also shows the large year-on-year variance in trade prior to liberalisation, which occurred mainly through the influence of wet and dry years in the hydro-power sector in Norway and Sweden. Compared to the post-liberalisation period, it can be seen trade has increased, while the year-on-year variance in trade is not as amplified as compared to the period prior to liberalisation.

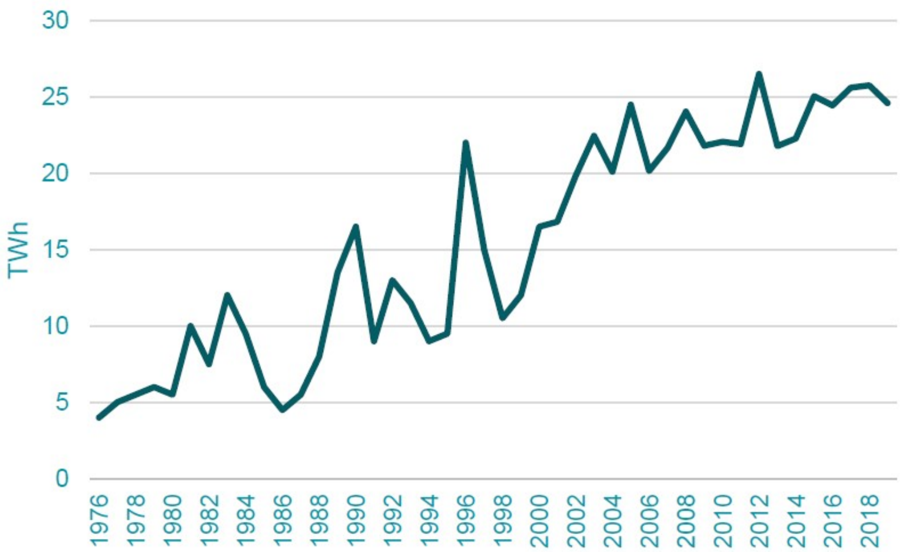


Figure 2.8. Indicator for trade - Sum of all import and export of electricity for Denmark 1976 - 2019, [Danish Energy Agency, 2020]

2.4 Electricity consumption and supply from wind sources

According to [Energistyrelsen, 2019], energy consumption in sectors which have traditionally relied on fossil fuels, such as the transportation sector and heavy industry, are slowly transitioning to renewable energy source. As the transition to renewable energy in these sectors progresses, there is a notable growth in demand for renewable energy sources and most of the final renewable energy consumption is in the form of electricity. Hence, the electricity sector will in future play a considerable role in the renewable energy transition in these sectors and it is projected that the renewable energy share in the electricity supply will be close to 100% in 2030 and will account for between 60% and 70% of gross energy consumption, [Energistyrelsen, 2019].

Figure 2.9 provides an overview of projected electricity demand in the period 2021 to 2040, where the projected demand is divided in terms of *"classical electricity consumption"* (which includes households and businesses) and electricity demand as a consequence of the electrification of the heat sector, transportation sector and large data centers. As can be seen from Figure 2.9, electricity consumption is projected to increase almost three-fold in the period from 2021 to 2040, [Energistyrelsen, 2021b].

The projected increase in electricity demand in this period is agreed upon by IDA's *Energy Vision 2050*, [Mathiesen et al., 2020], which is a smart energy system strategy towards achieving a 100% renewable energy sector in Denmark, and highlights the role of the increasing renewable energy capacity in the projected growth of electricity demand.

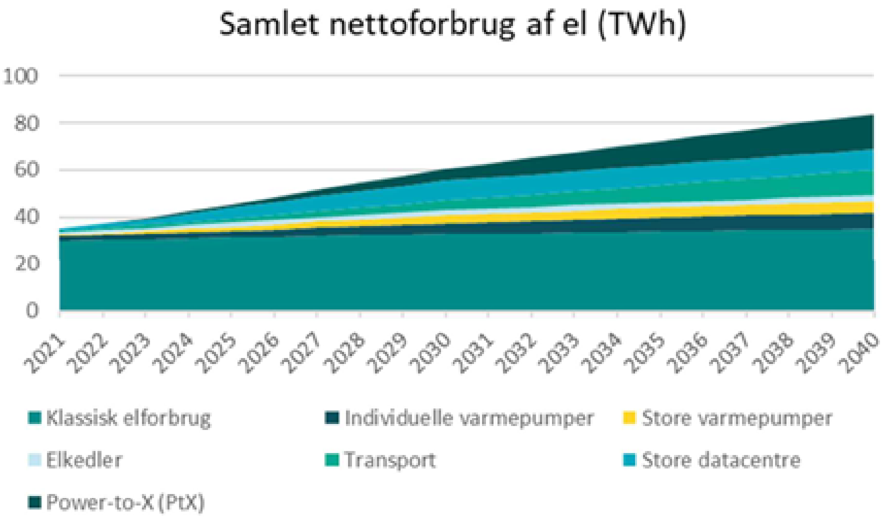


Figure 2.9. Analysis assumptions for Energinet 2021 - Projected electricity consumption 2021 - 2040, [Energistyrelsen, 2021b]

However, according to Lund [2014], a renewable energy system lacks the flexibility of the conventional fossil fuel-based energy system, where supply is synchronised with demand. This inherent inflexibility of renewable energy systems, where wind and solar power is the dominant source, therefore represent a challenge in terms of matching supply with demand.

Figure 2.10 illustrates this phenomenon of the mismatch between supply and demand for the electricity supply from wind energy in the DK1 electricity pricing area for the period 01 January 2020 to 31 January 2020, [Energistyrelsen, 2020].

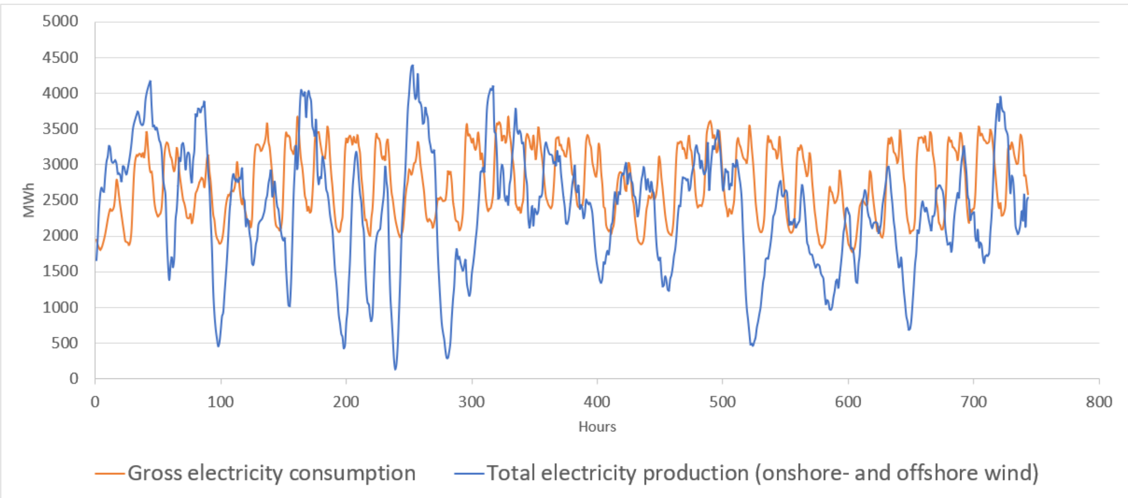


Figure 2.10. Graph showing gross electricity consumption in DK1 and the total amount of windpower being produced in the period 01-01-2020 to 31-01-2020, [Energistyrelsen, 2020]

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As can be seen from Figure 2.10, while the consumption displays the typical daily and weekly electricity demand curve with morning and evening peaks, the supply curve behaves totally different. From the supply curve it can be seen that the electricity supply sometimes exceed demand and at other times are also lower than the demand. In the liberalised and internationally linked electricity sector, this phenomenon is less of a problem, since the excess supply can be exported and shortfalls be filled in by imports. However, Figure 2.10 provides a good example of the fluctuating and unpredictable nature of an electricity supply system with a large share from wind energy.

2.5 The Baltic-Nordic electricity exchange Nord Pool

2.5.1 Establishment of the market

According to Houmoller Consulting [2019], in a liberalised electricity system, electricity becomes a commodity that can be traded on a market just like other commodities. Following the deregulation of the power trading market in Norway in 1991, the Statnett Marked AS company was established in 1993. The Statnett AS company was replaced by Nord Pool ASA, after Sweden joined when the Swedish electricity market was deregulated. Finland and Denmark joined in 1998 and 1999/2000 respectively and in 2002 the separate company Nord Pool Spot AS, which deals in the spot market, was established out of the Nord Pool ASA company. The company was later re-branded to Nord Pool and is currently majority owned by the pan-European exchange, Euronext, together with the transmission system operators of the Nordic-Baltic countries: Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania [Helseth et al., 2020].

Elspot is the Nord Pool day-ahead auction market, where electrical energy is traded in the 24hr period prior to delivery. Currently, Elspot consist of 15 price areas as shown in Figure 2.11, which are based on projections from the transmission system operators on which grid areas might experience an imbalance between demand and capacity.

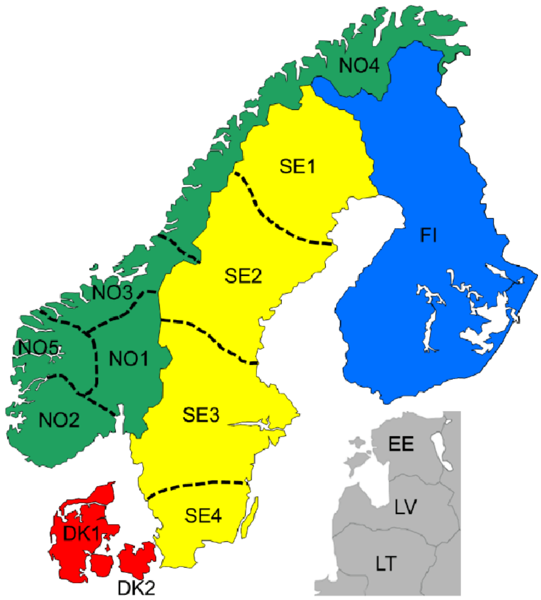

Figure 2.11. Nord Pool spot price areas, [Helseth et al., 2020]

2.5.2 Market participants

Various parties participate in the Nord Pool market in different ways and carry different roles and responsibilities, as depicted in Figure 2.12, [Danish Energy Agency, 2020].

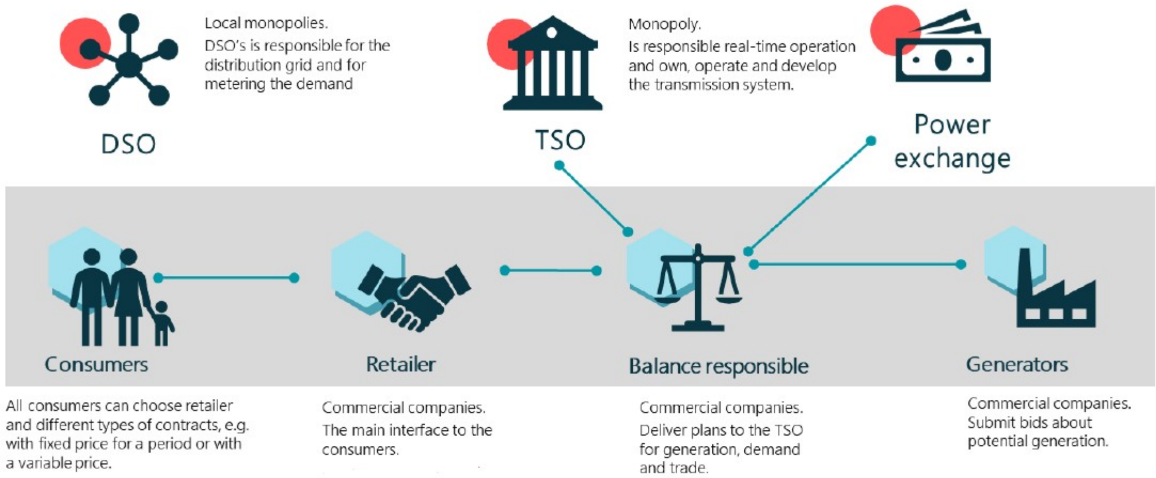

Figure 2.12. Key participants in the liberalised market, [Danish Energy Agency, 2020]

The roles and responsibilities of the key participants on the market, can be described as follows, [Energinet, 2022]:

Transmission system operator (TSO) in Denmark is *Energinet.dk*, which is a public entity responsible for ensuring security of supply and a well-functioning electricity market with suitable access for both consumers and producers. The TSO, who is a public monopoly entity, is also responsible for ensuring grid stability and to maintain a balance between consumption and generation.

Distribution system operator(s) (DSOs) are the entities who own and operate the distribution grid between the transmission grid and the consumer and are usually demarcated specific geographical areas. The DSO is responsible for collecting, validating, sending, and receiving metered data on consumption within its area. Retailers pay the DSO for the transportation of the electricity in its area of operation.

Generators are the plant operators who generate the electricity and sell it to the retailers. In Denmark there are numerous large-scale and small-scale generators as well as renewable source generators from solar power, wind, biogas and other sources.

Balance responsible parties are commercial entities responsible for submitting plans to the TSO on the expected electricity that is to be generate and consumed in the area they are responsible for ensuring balance between generation and consumption. The buy and sell electricity on behalf of retailers and generators and are financially responsible to the TSO for any imbalances that occur in their area.

Retailers or suppliers are commercial entities who act as the primary contact between customers and the electricity system. They purchase electricity from generators or balance responsible parties and sell it to consumers. They are responsible for registering customers on the system, supplying the customer with a metering point and the collection of a single payment that includes consumption charges, all taxes and all grid related fees.

Customers are responsible for choosing a supplier and a supply contract for the purchasing of electricity from retailers. Customers are responsible to make payment for their bills which include all the consumption charges, taxes/duties, grid related fees and other fees that might be included in their bills.

Other parties that are related to the electricity system, include: 1) The Danish Energy Regulatory Authority who is responsible for regulation of the industry and ensuring that charges are within the regulatory framework; 2) Metering point administrators who collect, validate and submit metering data to the market system; and 3) Other third parties such as brokers and agents who broker contracts between customers and retailers.

2.6 Market design

The current market design structure of the Nord Pool exchange is depicted in Figure 2.13, [Danish Energy Agency, 2020], and consists of the following different market elements:

- The financial market (including the long-term market).
- The spot market (comprising the day-ahead market and the intra-day market).
- The regulating power market (balancing market).

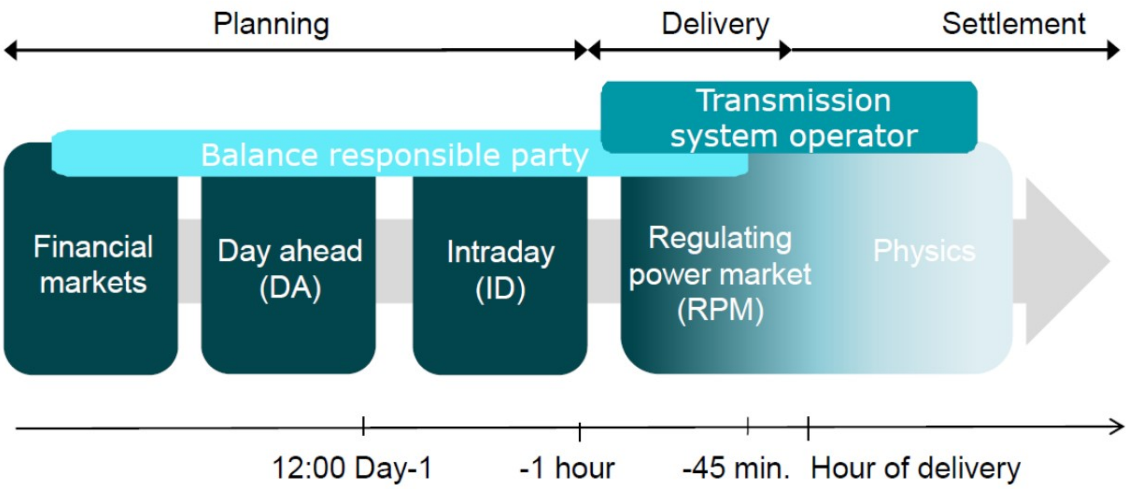

Figure 2.13. The current market design structure of the Nord Pool exchange, [Danish Energy Agency, 2020]

Figure 2.13 provides context to the role of the different regulating market players (Balance Responsible Party and Transmission System Operator) in relation to the timeline of the trade transaction and the hour of delivery of the energy in the different market structures. Figure 2.13 illustrates that trades in the long-term market normally take place much earlier (sometimes months) ahead of the physical delivery, while trades in the spot market close at 12-noon on the day ahead of the physical delivery. Trades in the balancing market take place during the hour of delivery and is the closest to the physical delivery of the energy.

2.6.1 The financial and long-term market

On the financial market, electricity is traded in advance of the time period of supply and consumption of the in financial contracts. Generators and retailers enter into a financial contract for a certain volume of electricity at a certain price for a specific hour at a date in the future and the contract is settled at the price difference between the contact price and the spot price for the hour in question. Financial contracts can take many different forms and are commercial products where not physical exchange of energy takes place, only a financial trade, [Houmoller Consulting, 2019]. The financial market is also the market where generators and retailers enter into long-term contracts well ahead of the date of delivery, but where there will be a physical delivery and off-take of energy in a certain hour in the future. Trades on the financial market is typical based on large volumes and can be used by market players to hedge their positions and protect themselves against the price volatility of the spot market. Market players can therefore use the financial market to mitigating their risk, or investors can use the financial market as a speculation instrument, similar to speculating in the future price of other commodities, [Houmoller Consulting, 2019].

2.6.2 The spot market

The spot market comprises the day-ahead market and the intra-day market, as illustrated in Figure 2.13. Market participants who want to buy electrical energy on the day-ahead market send their purchase bids on the previous day of the day that the trade is to take place. Similarly, market participants who want to sell electrical energy send their sale bids on the previous day. All bids close at 12pm Central European Time (CET), the day before the electricity is delivered to the grid. Bids include the quantity of electrical energy and the corresponding purchase or sale price. The purchase bids and sale bids for each hour of the day, are aggregated into a demand curve and a supply curve and the point where the two curves meet, represents the trading volume of electrical energy and the spot price for that particular hour of the day, as illustrated in Figure 2.14, [Houmoller Consulting, 2019]. At the meeting point of the two curves, the purchase volume and the sale volume of energy are the same.

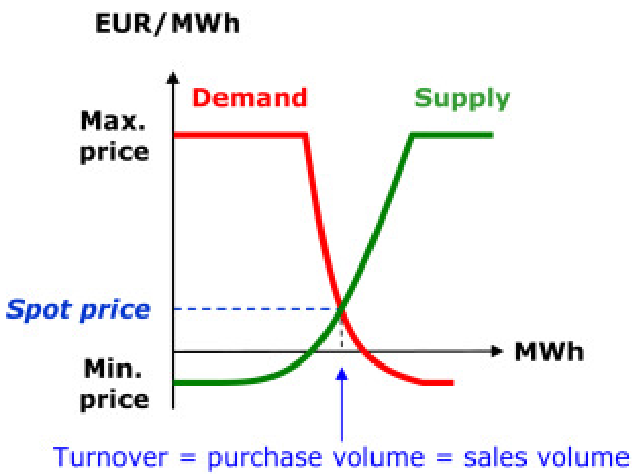

Figure 2.14. Spot price calculation for each hour of the day, [Houmoller Consulting, 2019]

This price calculation as described above, is done for each hour of the 24 hours of the day-ahead as illustrated in the example of spot prices in Figure 2.15 (depicts spot prices in Eastern Denmark on Monday, August 6, 2012, [Houmoller Consulting, 2019]). Each of the bars for each hour of operation in Figure 2.15 represents a meeting point of the demand and supply auction curves as depicted in Figure 2.14. This calculation of 24-hour spot prices is conducted for each of the price zones that make up the spot market.

The intra-day market opens once the day-ahead prices and trades are settled. On the intra-day market, electricity can be traded until one hour before the operating hour and are based on continuous and bilateral trade.

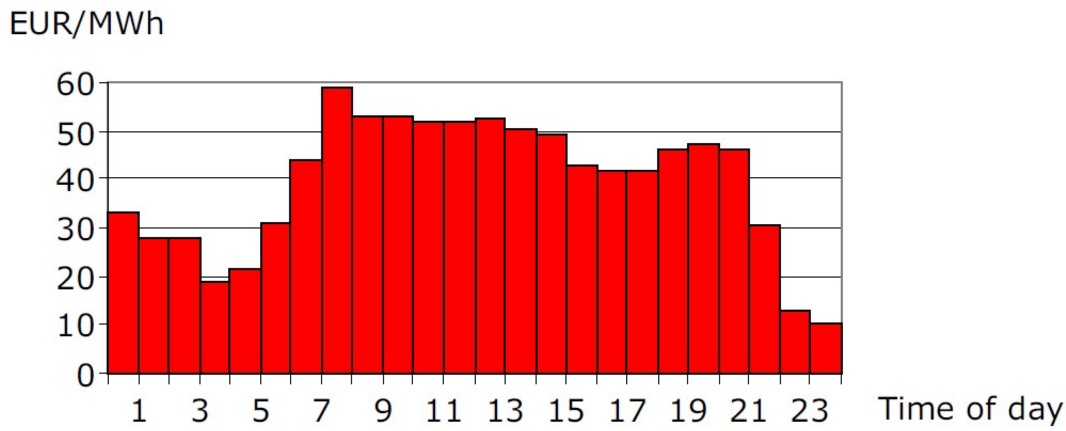

Figure 2.15. Example of spot prices for each hour over a particular 24-hour period, for a particular price zone [Houmoller Consulting, 2019]

2.6.3 The balancing market

The TSO is responsible to maintain grid stability and also to ensure security of supply, since the grid frequency needs to be kept at 50Hz (the frequency of alternating current in Europe). Should consumption exceeds supply, the frequency of the grid could fall below 50Hz and the grid can become unstable. In this event, the TSO purchases extra electricity from suppliers to maintain the balance between supply and demand. This extra energy that is purchased by the TSO is called procuring up-regulation. Conversely, should production exceeds consumption, the frequency of the grid could rise above 50Hz and in this event, the TSO would sell extra electrical energy to producers, which then results in the producer to produce less electricity and thereby lowering supply. This extra energy that is sold by the TSO is called procuring down-regulation. This trade of up or down regulating electricity by the TSO would occur within the hour of operation and is called regulating power or balancing power, since the purpose of the trade is to keep the grid balanced and stable, [Houmoller Consulting, 2019].

It is important for the TSO to ensure that there is capacity available from producers to be able to perform up regulation and therefore the TSO would procure balancing capacity from producers, which is done the day before. This capacity is usually manually operated capacity which can be mobilised quickly and within the hour of operation, and needs to be kept available by the producer should the TSO calls for it.

2.7 The balancing market design challenge

As presented in Chapter 2.6, and as illustrated in Figure 2.13, it can be observed that the regulating (or balancing) market is the last in a sequence of electricity markets: after the financial (long-term)-, day-ahead- and intra-day markets. It is also the market where the time-lapse between the financial transaction and the physical exchange of power is the shortest, and therefore demands its own design challenges.

The European Union: Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing [EU, 2017], as published by the Publications Office of the European Union, which defines **balancing** as:

"all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, the maintenance of system frequency within a predefined stability range as set out in Article 127 of Regulation (EU) 2017/1485, and compliance with the amount of reserves needed with respect to the required quality, as set out in Regulation (EU) 2017/1485".

Furthermore, EU [2017] defines the **balancing market** as:

"the entirety of institutional, commercial and operational arrangements that establish market-based management of balancing".

van der Veen and Hakvoort [2016] provides a basic breakdown of the structure of the balance market, as shown in Figure 2.16, and states:

"In vertically integrated electricity systems, it is relatively easy to maintain the system balance, but un-bundling in European energy markets, which was initiated by Electricity Directive 96/92/ EC, has separated the power transmission segment from power generation and supply. This has made balance management a much more difficult task".

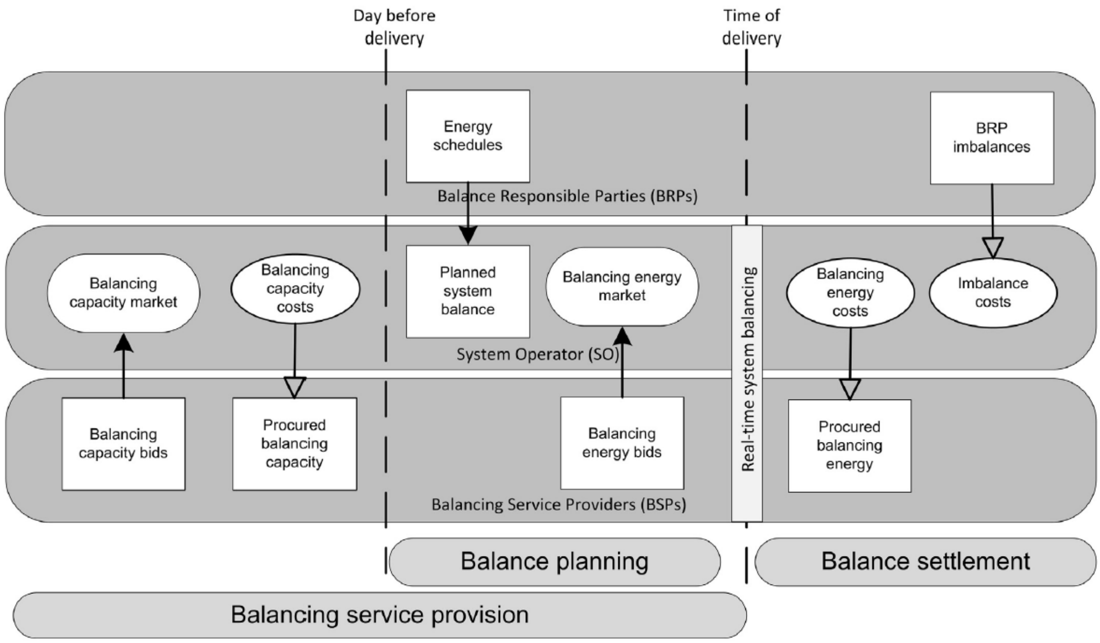

Figure 2.16. Basic structure of the balancing market, ordered by time of occurrence (horizontal) and by actor (vertical), [van der Veen and Hakvoort, 2016]

Considering that the EU directives, [EU, 2017], only provides a guide as to how the design of the balance market should look like and how it should operate, but no specific design directive, together with a very high emphasize of security of supply and ensuring stability of the system, it is understandable that the un-bundled electricity market coupled with an increase in the share of renewable energy sources in the electricity supply, is a cause of concern, [van der Veen and Hakvoort, 2016].

Houmøller [2017], however, suggests that the intermittent renewable energy sources could be made part of the solution in the balancing market and should not be seen as problem, *"provided the TSO has an intelligent design of the market for regulating energy"*.

Problem definition 3

3.1 Research question

In Chapter 2, it is presented how the process to liberalize the Danish electricity sector started around 1995 and that by 2003, Danish electricity consumers could freely choose between several possible electricity suppliers. It is also presented how electricity prices in liberalized electricity markets with a large renewable energy share, typically display season related cycles that are often driven by supply. Large price spikes, both positive and negative, are not uncommon and are often contributed to the non-storability of electricity (apart from small-scale battery storage), non-elasticity of demand and the fluctuating nature of renewable energy supply. These factors make electricity price forecasting a challenging task in these markets. Furthermore, it is presented how renewable energy development has grown and has been playing an increasingly larger part in the electricity supply mix in Denmark where the electricity sector has been liberalised in 1999, and is continuing to evolve in its liberalisation. In Chapter 2, it can also be seen that projections for the electricity sector, in line with current climate policy measures, show a growth in demand as traditional fossil-fuel dependent sectors move to electrification. In addition, it is presented that the renewable energy share in the electricity supply is projected to reach more than 100% by 2030, as part of Denmark's climate ambitions.

Therefore, based on the analysis of the problem, as presented in Chapter 2, the following research question is put forward:

"What is the relationship between electricity prices and public acceptance of renewable energy, considering the fluctuating nature of the renewable energy share and the socio-economic transformation of the electricity system towards achieving Denmark's climate ambitions in 2030?"

The research problem consists of two different parts, with the one part dealing with society's acceptance of renewable energy in the light of the price volatility that is attributed to the fluctuating nature in the electricity supply which come from renewable energy sources. The other part of the research problem speaks to the economic role that society can play in the transformation in the electricity sector, considering the long-term technical expectation that electricity supply from renewable energy sources will be an increasing and dominate trend towards meeting Denmark's long-term climate ambitions.

According to Rienecker et al. [2013], research questions can be categorised based on where the question puts the focus of the research. In this regard, Farthing [2016] identifies the two main types of research questions in the subject area of planning research, as *Descriptive* questions and *Explanatory* questions, where *Descriptive* questions are defined as typically being *"What"*-type questions, while *Explanatory* questions are defined as typically being *"Why"*-type questions. However, Farthing [2016] also recognises a separate third category of research questions in the design of planning research, as *"How"*-type questions, which are defined as questions that are *Exploratory* in nature and that could promote change in policy or the way things are done.

Furthermore, Rienecker et al. [2013], suggests that the research question be divided into a main sub-question and other necessary working sub-questions, which together, could contribute towards a complete understanding of the different aspects of the research problem. Hence, the following **research sub-questions** are posed:

1. *"How does an increase in the renewable energy share of electricity supply, impact on electricity prices?"*
2. *"How does electricity prices impact on public acceptance of renewable energy development?"*
3. *"How can an analysis be made of how a single-family house with photo-voltaic (PV) systems in West Denmark could participate in the balancing market?"*

Research sub-questions 1 and 2 serve as working sub-questions and sub-question 3 is posed as the main sub-question. Together, the three sub-questions facilitate a holistic response to the research question of the study. The purpose and the contribution of each of the research sub-questions towards answering the research question, are further unpacked as follows:

Sub-question 1: *"How does an increase in the renewable energy share of electricity supply, impact on electricity prices?"*

From Chapter 2, it can been seen that the volatility in the electricity price can be attributed to the fluctuating nature of the renewable energy sources in the electricity supply mix. Research sub-question 2 will explore the social impact of the increasing share of renewable energy in the electricity supply, in so far as public acceptance is concerned. However, in building towards an understanding of this aspect of the social impact of renewable energy development, it is important to understand the general impact that renewable energy development may have on electricity prices, and this will be done through the exploration in sub-question 1.

Sub-question 2: *"How does electricity prices impact on public acceptance of renewable energy development?"*

Research sub-question 2 is aimed at contributing towards answering the part of the research problem which deals with the social transformation of the electricity sector and how public opinion towards that transformation is influenced by the price of electricity. Part of the building blocks in gaining an understanding of public acceptance towards renewable energy development is obtained from the findings to sub-question 1, which will explore the impact of an increased share of renewable energy in the electricity supply mix, on electricity prices.

Although it is acknowledged that electricity price may not be the only factor which may have an impact on the public acceptance towards renewable energy development, the focus of this study will be limited to the effect of prices only.

Sub-question 3: *"How can an analysis be made of how single-family houses with photo-voltaic (PV) systems in West Denmark could participate in the balancing markets?"*

Research sub-question 3 speaks to the second part of the research problem and will explore the transformation of the electricity sector with respect to the possible economic participation and role of society in the long-term transformation of the sector. According to Rienecker et al. [2013], for the case of *"How"*-type questions, the specification of method in the research question is encouraged, as it clarifies how the research is carried out. Rienecker et al. [2013] suggests that the inclusion of the description of the analysis method prepares the research for the later evaluations or designs that is carried out in the research. On this basis, the inclusion of participation from households in the balancing markets, in the research question, is considered as a good way of preparing for the analysis of the possible economic transformation of the sector and the role that society can play in that transformation.

3.2 Delimitation

In the interest of narrowing down the research, but still keeping the study broad enough to cover the subject sufficiently, it is considered good practice for the research to be delimited in terms of the following, [Rienecker et al., 2013]:

- time
- space
- persons
- phenomena

In Chapter 2.2 it is shown that wind energy is projected to be one of the corner stones in Denmark's long-term planning towards renewable electrification and that electricity is set to become a key driver in the decarbonation of sectors which have been traditionally dependant on fossil-fuels and which are difficult to convert directly to renewable energy sources. For this reason the focus of this study is on wind energy resources as a driving factor for price volatility as opposed to all renewable energy sources. In addition, since the electricity sector was liberalised, Denmark has joined the Nord Pool energy exchange as the primary market where electricity in traded. Wholesale electricity is traded primarily on the Nord Pool day-ahead market, and therefore the study is focused on the balancing market component of the day-ahead market (Elspot). In Chapter 2.5, it is presented that purchase and sale bids for wholesale electricity on the day-ahead market, is made separately for each of the 15 price areas, and therefore this study is delimited to only one price area, in order to keep the focus within the scope of a study of this magnitude.

The study is primarily concerned with the societal aspects of electricity prices within the Danish context and therefore the study is delimited to the West Denmark (DK1) price area, which keeps the focus within the Danish context and also since it is the price area where renewable energy sources (in particular wind energy) has the largest share in the electricity supply in Denmark, with an even projected larger penetration in 2030. In the interest of a focused analysis and to limit the scope of the study, the participation of households on the balancing markets is limited to households with photo-voltaic (PV) systems, as opposed to other onsite household electricity generation systems. Furthermore, it is acknowledged that electricity price may not be the only factor which may have an impact on the public acceptance towards renewable energy development, however, the focus of this study will be limited to the effect of prices.

Research design 4

The purpose of this chapter is to provide an outline of the structure of the study which is applied to respond to the research question and research sub-questions, as presented in Chapter 3. The structure of the research process is especially important in creating an understanding of how the different steps in the research process fit together and to lend credibility to the study. The research design of the study is illustrated in Figure 4.1.

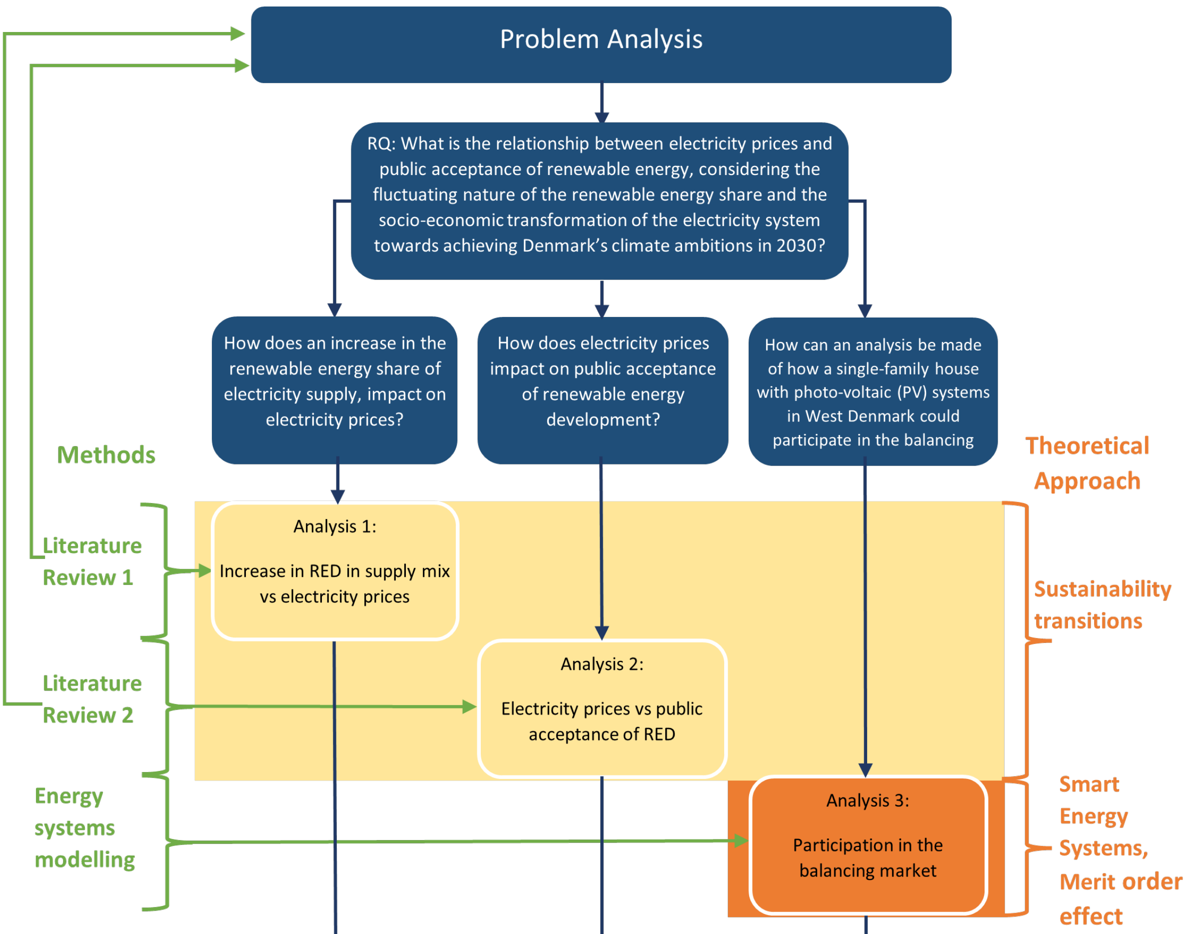

Figure 4.1. Research design of the study [Own diagram].

The research design provides a *blue print* of the research process of the study from the beginning as presented in the introduction and problem analysis, through to the end of the study in the form of the discussion and conclusion.

The research design illustrates how the problem formulation connects to the collection of data, the theoretical assumptions which is used as a basis for the analysis, the methods used for data collection and analysis, and ultimately the discussion and conclusion of the results of the study.

Theoretical approach 5

In this chapter, the theoretical approach to the study is presented. The theoretical approach is used as the foundation to the study and guides the selection of the appropriate methods for the study. Together with the appropriate chosen methods, the theoretical approach provides the framework within which the analysis of the study is conducted, to answer the research sub-questions, and thus ultimately, respond to the broader research question of the study.

First the concept of the *smart energy system* is presented. The smart energy system concept brings together the social, political, economic and technical solutions that is necessary to develop a energy system that can respond positively to the global climate change challenge. As such, the smart energy system acts as a blueprint for an optimal approach for integrating and developing renewable energy and energy systems within the broader society and as a theoretical foundations, it cuts across all the research sub-questions. However, certain elements of the smart energy system concept is in particular interest for the purposes of this study, and will thus form the theoretical foundation for responding to research sub-questions 1 and 2. To strengthen the theoretical base for responding to research sub-questions 2, the construct of *political economy paradigm* is introduced, in addition to the smart energy system concept. The theories of the *merit order effect* and *stochastic probability* form the foundation from which research sub-question 3 is analysed.

5.1 The Smart Energy System concept

IDA's *Energy Vision 2050*, defines the smart energy systems concept as: *"an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system."*, [Mathiesen et al., 2020].

Hence, by definition, it implies that the smart energy systems of the future contain a high degree of different technologies in terms of the energy sector (extraction and refining), the transformation sector (production of electricity, heat, and gas) and the final consumption of energy. It also imply that these technologies should be integrated with each other and with various storage technologies in an optimal and coordinated fashion, as is illustrated in Figure 5.1, which provides an overview of IDA's definition of the Smart Energy System concept.

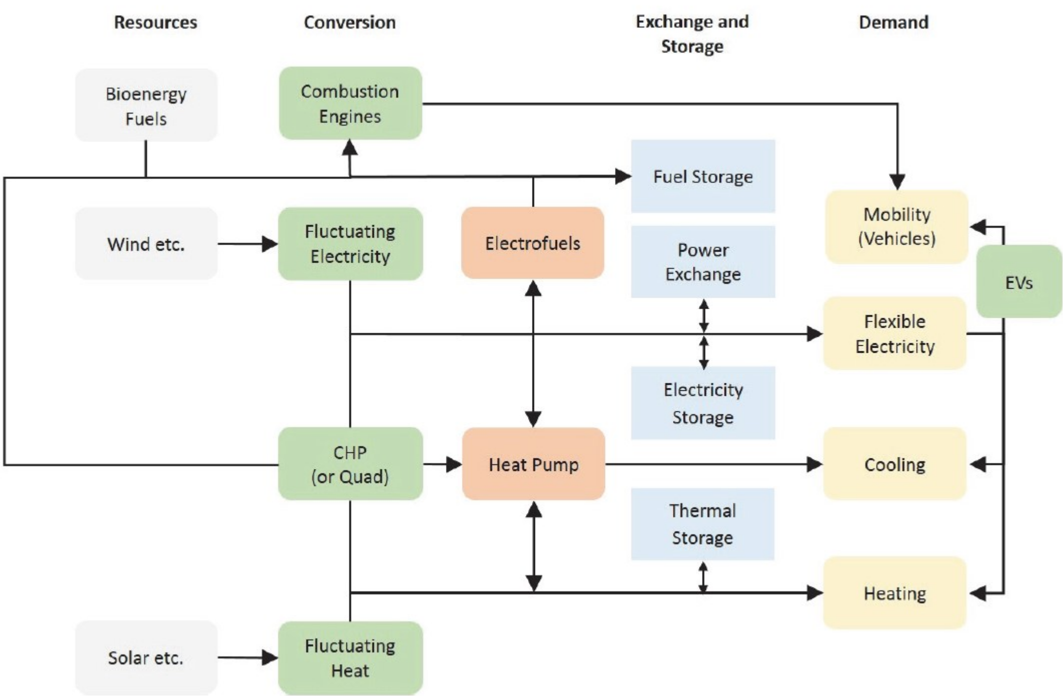

Figure 5.1. Overview of the Smart Energy System [Mathiesen et al., 2020]

As renewable energy systems form an integral part of the smart energy systems concept, the fluctuating nature and lack of flexibility from renewable energy resources, such as wind- and solar power, lends a degree of uncertainty to smart energy systems as compared to solely fossil fuel-based energy systems. It is therefore to be expected that such systems will experience a degree of supply volatility and therefore the need for the integration of storage technologies in future energy systems. It is therefore also important that the analysis, tools, and methods with which smart energy system are approached, are designed around the uncertainty and volatility that renewable energy supply bring to the system.

According to Dincer and Acar [2017], the energy system of today should be sustainable from a social, economic, technical and environmental perspective and thus defines the smart energy system in terms of the following eight critical expectations;

1. Energy quality: The system should have a high degree of efficiency in its conversion from extraction and refining, to transformation as usable energy and to final end consumption.
2. Energy security: The systems should contain a high degree of sufficient and plentiful resources that are preferably locally available and lends the system safe and with a high degree of security of supply.
3. Environmentally nonthreatening: Impact on the environment should be at a minimum throughout the system from source to end-user, with sustainability in mind. Minimum wastage and a high degree of re-usability of waste materials.
4. Economically feasible: Minimisation of losses and should be able to return economic benefits through out the system value chain.
5. Commercially viability: The system should be compatible with local and market conditions and be competitive and efficient.

6. Social acceptance: The system should be acceptable to local communities and also society at large.
7. Integrability: The system should be able to integrate easily with different systems, both internal and externally.
8. Reliable: The system should have a high degree of reliability and safety.

The eight expectations as defined by Dincer and Acar [2017], will serve as a reference in addressing research sub-questions 1 and 2, however, not all of these defined expectations are relevant for the purposes of the analysis of this study. Hence, for the purpose of research sub-question 1, the analysis will focus on the integrability of the system and the ability and effectiveness of the available modelling tools in dealing with the integration of different energy sources when making a price prognosis. For the purposes of research sub-question 2, the analysis will be conducted taking into consideration the expectation of the energy system being socially acceptable and commercially viable. These concepts are unpacked further as follows:

Commercially viable:

According to Dincer and Acar [2017] a key expectation of a smart energy system is that it needs to be able to function within the local market conditions and make use of resources that are readily and easily accessible and available. The system must be able to compete within the market and remain profitable. The tools which are used to forecast electricity prices, should also be able to provide functionality in terms of the local market conditions. The forecasting tools should also be able to consider those conditions that will render the system commercially viable, and this is a key aspect in the analysis of research question 1. In addition, renewable energy sources such as wind and solar have been shown to have low marginal cost in comparison to fossil fuel-based systems, and this low marginal cost has been having an impact on the commercial viability of these systems on the long term due to the merit order effect on the market price, [Ketterer, 2014].

In analysing the problem of the relationship between electricity prices and public acceptance of renewable energy development, as presented in Chapter 7, the commercial viability expectation of the system is also a key consideration. From the perspective of the end-consumers of energy, affordability is also a key aspect of commercial viability. To this end, the commercial viability expectation of the smart energy system concept, is a key aspect in analysing the relationship between electricity prices and public acceptance of renewable energy development.

Socially acceptable:

In analysing the relationship between electricity prices and public acceptance of renewable energy development, the socially acceptance expectation of smart energy systems, is a key consideration. According to Dincer and Acar [2017], for a smart energy system to be successful it should be accepted by the broader society and be incorporated in the daily lives of people. Hence, the socially acceptability expectation will be used as a theoretical base for analysing the problem as presented in Chapter 2.

Integrability:

Wind is a local renewable energy source that became easily integrated into the local energy system in Denmark as a result of the liberalization of the electricity sector, [Johansen, 2021]. The tools which are used to forecast electricity prices, should therefore also be able to deal with the system integration of locally available resources such as wind and solar energy sources. The forecasting tools should be able to consider those conditions that will render the system integrable, and this is a key aspect in the analysis of research sub-question 1.

5.2 Merit order effect

As presented in Chapter 2.3, electricity generators comprised from different technologies, compete on the Nord Pool market, including generators from a growing renewable energy sector. In Chapter 2.5 it is shown how the market is designed and how it operates. On the market, the different electricity generators compete in accordance with their generating capacities and marginal cost of operation. On the day-ahead market price bids are submitted for each hour of the following day according to the demand and at the closing of the bid window at mid-day, allocations are made to generators according to their winning bids. However, since the system is designed for price bids based on marginal cost (the cost of producing the next unit of electricity), all wining bids receive the bid price of the last generator to supply power on the demand curve, [Danish Energy Agency, 2017].

Prior to the addition of renewable sources to the electricity supply mix, generators were ranked on the supply curve in ascending order of their marginal cost, and typically in the order of hydro-power first, followed by nuclear plants, coal-fired-, combined-cycle gas turbines, open cycle gas turbines and lastly oil-fired units, since they have the highest fuel cost. This order of ranking on the supply curve is defined as the merit order, [Ketterer, 2014], as illustrated in left hand sub-figure of Figure 5.2, [Benhmad, 2015].

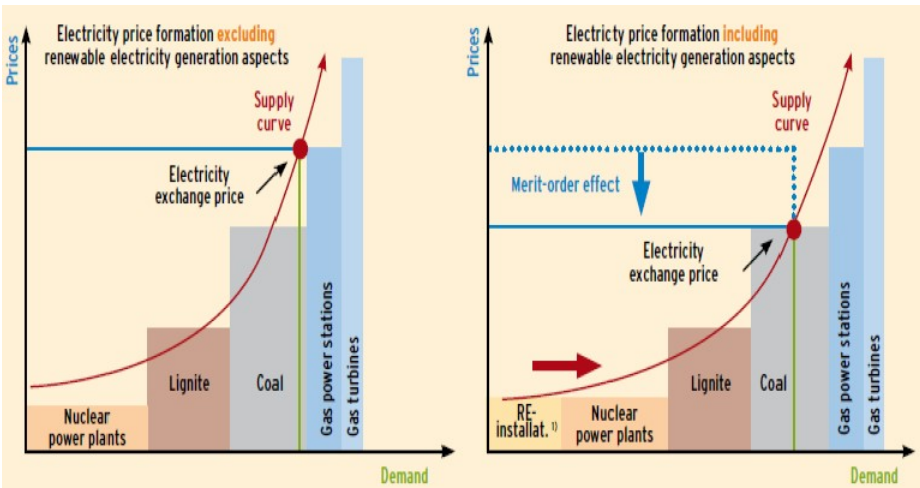

Figure 5.2. The merit order effect on electricity prices, [Benhmad, 2015]

Renewable energy sources occupy a higher priority for supply and appears first on the supply curve ahead of other energy sources such as hydro-power and nuclear power. Due to the near zero marginal cost from wind and solar energy sources, this result in a lower price point on the supply curve where the last supply bids coincide with the demand curve, as illustrated in the right hand sub-figure of Figure 5.2. The effect of lowering the price point where the supply curve and the demand curve intersect, is defined as the *merit order effect*, [Benhmad, 2015].

Chapter 2.2 presents the historic development of wind energy in the electricity supply of Denmark and also the planned future expansion of wind energy, with the objective of contributing towards Denmark's 2030 and 2050 climate ambitions. According to Hvelplund and Djørup [2017] wind energy is becoming the prevailing mechanism for setting prices on the Nord Pool market, since the cost structure of wind energy development involves high initial capital investment cost, but low short-term marginal cost. However, it needs to be understood that the real impact of the merit order effect, results not from the actual renewable energy power generation, but rather from the *forecast* of the amount of renewable energy that will be generated the day ahead. Considering the impact of the merit order effect on future electricity prices as more wind power is added to the electricity supply mix, the merit order effect forms an important theoretical base in the analysis of research sub-question 3.

5.3 Sustainability transitions

In Chapter 2 it can be examined how the liberalisation of the Nordic energy market took shape well before the renewable energy share of the energy mix started to increase rapidly in the mid-1990's and early 2000's. As a result many of the market policies and design choices were made well before the increase in renewable energy growth. In a study on the existing design of the zonal electricity market and its implications for the energy transition, Lindberg [2022], also examines the existing conditions under which sustainability transitions and transformations, such as the energy transition, take place.

According to Lindberg [2022], the sustainability transformation of socio-technical systems also requires structural changes in existing systems and identifies the electricity market as one of those systems where the structural design of the system needs to be in sync with the needs and requirements of the sustainable energy transition.

Hence, the theoretical field of *sustainability transitions* is a important component of the energy transition and examines how different transition subtleties can lead to different transition pathways, which as a result, may impact of the structural design of the system.

Methods 6

The purpose of this chapter is to present the applicable methods which are used in the analysis of the study. As presented in Chapter 4, the methods together with the theoretical approach, form the framework within which the analysis of the study is conducted. As shown in Figure 4.1, this study is designed around three separate research sub-questions, which read together, forms the response to the research question. The study thus comprises three separate analysis phases as shown in Figure 4.1, of which each is designed to respond to a separate sub-question. Research sub-questions 1 and 2 are analysed and answered through the application of a literature review and research sub-question 3 is analysed and answered through the development of a stochastic time change model. Hence, this chapter aims to firstly elaborate on the application of literature reviews as research methods, and secondly on how a stochastic model can be applied in the analysis and forecasting of the electricity spot price.

6.1 The literature review as a research method

6.1.1 Overview

Harman [2021] regards the principle of current research being built upon and substantiated in previous research and prior conceptual expositions, to be of such importance, that he considers detailed discussions on the subject as unnecessary and obscure. For this reason, Harman [2021] encourages the utilization of the literature review as an important research method in the appropriate circumstances. In that context, Harman [2021] defines a *"research method"* as a specific techniques or modus operandi used to collect and analyse data. Furthermore, Lamé [2019] argues that the literature review can be a valuable tool in the field of planning and design research, for the researcher to make to make sense of previous research in terms of identifying gaps where new contributions are needed and to make rigorous diagnosis and recommendations.

According to Whitaker and Fitzpatrick [2021] there exists many different approaches to literature reviews, with *"meta-analysis"* and *"systematic reviews"* as the primary or general approaches in doctoral studies and larger studies which consist of multiple research teams. In addition to these two types of reviews, which are essentially the same except that they follow different processes, Whitaker and Fitzpatrick [2021] also identifies the *"integrative review"* as more appropriate at post-graduate level studies conducted by individual researchers, and *"narrative reviews"* as a more simplistic approach to literature reviews.

The characteristics of each literature review type as proposed by Whitaker and Fitzpatrick [2021] is outlined in Table 6.1.

Approach	Systematic	Integrative	Narrative
Typical purpose:	Answers a single clinical question	Critical analysis of empirical literature, Draws attention to future research needs	Overview on a topic of inquiry
Research questions:	Single clinical question	Broadly defined-purpose question, and review questions	No
Search strategy:	Systematic search method	Systematic search method	No specific search method
Sample characteristics:	Experiential research	Experimental or non-experimental research, may include theoretical and methodological literature	Any scholarly work on the topic
Analysis and evaluation:	Narrative analysis with descriptive and qualitative synthesis (also meta-analysis)	Narrative and/or thematic analysis with descriptive and qualitative synthesis	Narrative analysis
Examples of contribution:	No evidence-based practice implications	Evidence based practice implications	Evidence based practice implications

Table 6.1. The different approaches to literature reviews according to Whitaker and Fitzpatrick [2021]

In a similar study by Snyder [2019], which aims to provide an overview and guideline on the application of literature reviews as research methods, the following three main types of literature review approaches are proposed, as can be seen in Table 6.2.:

- Systematic reviews;
- Semi-systematic reviews; and
- Integrative reviews.

Approach	Systematic	Semi-systematic	Integrative
Typical purpose:	Synthesize, and compare evidence	Overview research area, track development over time	Critique, and synthesize
Research questions:	Specific	Broad	Narrow or broad
Search strategy:	Systematic	May be systematic, or may not be systematic	Usually not systematic
Sample characteristics:	Quantitative articles	Research articles	Research articles, books, and other published texts
Analysis and evaluation:	Quantitative	Qualitative/quantitative	Qualitative
Examples of contribution:	Evidence of effect, Inform policy and practice	State of knowledge, Themes in literature, Historical overview, Research agenda, Theoretical model	Taxonomy or classification, Theoretical model, or framework

Table 6.2. The different approaches to literature reviews according to Snyder [2019]

This definition by Snyder [2019] largely agrees with the review types as identified by Whitaker and Fitzpatrick [2021], which lists *"meta-analysis"* as a specialised area of literature reviews under the systematic approach. Snyder [2019], however, introduces the *"semi-systematic"* approach as a transitional method between the more in-depth systematic approach and the interactive approach, where a full large scale systematic review is desired, but hindered by factors such as research undertaken by various researchers from diverse disciplines with vastly different conceptualization of the topic. In its evaluation, the study by Snyder [2019] excludes the narrative approach, as defined by Whitaker and Fitzpatrick [2021]. However, both studies acknowledge that other different approaches exist and suggest the approaches in Table 6.1 and Table 6.2, as the most commonly used in literature reviews. The authors also acknowledge that variations to these approaches can be applied to fit the purpose of the literature review.

6.1.2 Choice of literature review approach

As presented in Chapter 4, research sub-questions 1 and 2 are answered through the application of a literature review as a research method. To select an appropriate literature review method which can be applied in the response of each research sub-question, it is important to evaluate the purpose of the problem which is analysed through research sub-question 1 and 2, [Walshaw, 2015]:

Research sub-question 1 : "What electricity price prognosis methods are available and what are their characteristics?"

In the context of this study, the purpose of research sub-question 1 is to identify and provide an overview of available forecasting methods that can be applied to make a prognosis of electricity prices in the liberalised energy market, and the factors that characterise those methods. However, this research sub-question does not aim to evaluate and/or rank forecasting methods in terms of accuracy, reliability or any other criteria. The research sub-question merely aims to provide and overview and classification of methods in terms of characteristics and its applicability to the broader research question.

The purpose description of research sub-question 1, best fit within the framework of the is fits within the purpose of the *"narrative review"* as stated by Whitaker and Fitzpatrick [2021]. The literature review is to provide an overview of available forecasting methods and the outcome of the review may impact on the choice of method to be used to make a price prognosis. Hence, the outcome may have practise implications for the purposes of this study and also future research.

Hence, the based on the proposed approaches by Whitaker and Fitzpatrick [2021], the *"narrative review"* approach is chosen as the most appropriate review type for the purposes of of the analysis of research sub-question 1.

Research sub-question 2 : "What is the relationship between electricity prices and public acceptance of renewable energy development?"

The purpose of research sub-question 2 is to provide a synthesis of how electricity prices may or may not influence and impact on public support for renewable energy development. The research sub-question deals with the social-technical transformation of the electricity sector and seeks to explore the relationship between the renewable transformation in the electricity sector towards meeting Denmark's climate ambitions, and how public support towards this transformation is influenced by the price of electricity. The analysis in the case of research sub-question 2 is based on qualitative evidence and may contribute towards practice implications.

This fits within the purpose of the *"integrative review"* as stated by Whitaker and Fitzpatrick [2021] and Snyder [2019]. The contribution from research sub-question 2 are also expected to influence practise and may be used in a policy framework on public support for renewable energy development and possibly also choices of technology for renewable energy development.

Hence, based on the approaches defined by Whitaker and Fitzpatrick [2021] and Snyder [2019], the *"integrative review"* approach is chosen as the most appropriate review type for the purposes of research sub-question 2.

6.1.3 The literature review process

The process of conducting the literature review is based on the 5-step approach as recommended by Leite et al. [2019] and as illustrated in Figure 6.1:

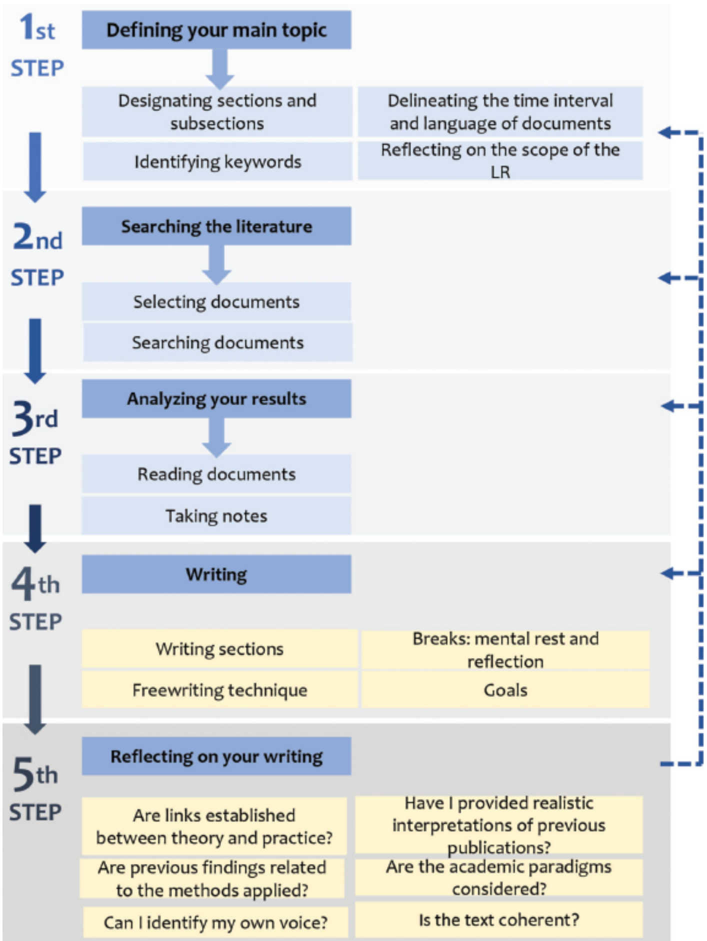

Figure 6.1. The five steps in performing a literature review, [Leite et al., 2019]

The stepped approach to the literature review, as depicted in Figure 6.1, is also recommended by Whitaker and Fitzpatrick [2021] and the process can be described as follows:

1. *Definition of the topic/problem:* In this step the background to the problem is defined and why the problem is considered important to be studied. This step concludes with a purpose statement, which could also be the research question or sub-question.
2. *Literature search:* This step describes which methods are used for the literature search, the search terms that are used in the search and which databases are used. Also included in this step are the inclusion/exclusion criteria which are used in the search. This step may also include the number of articles/references were included in the review and how it is narrowed down to the articles/references which are deemed most relevant.
3. *Evaluation and analysis of the results:* After the actual search has been concluded the next step is the evaluation of the findings/results. In this step a synthesis of the evidence is provided. The main points which have emerged from the literature is described. This step aims to provide a birds-eye view of the main points that have emerged and what the take-home message in the literature is.
4. *Writing the literature review:* This step involves the actual physical write up of the review.
5. *Reflection on the analysis:* This step provides a reflection of the results of the body of evidence which is found in the literature. The possible implications for practice and for future research is discussed as well as any limitations that the body of evidence may present. Typically, any common flaws in the body of evidence is also highlighted.

6.2 Energy systems modelling

Energy systems modelling is used to describe real world problems and possible solutions in an energy system, without having to build a life sized system. This section aims to describe the methods that are employed in analysing the energy system and to propose solutions, in particular relation to Research Question 3: *"How can an analysis be made of how a single-family house with photo-voltaic (PV) systems in West Denmark could participate in the balancing market?"*.

Pfenninger et al. [2014] describes the different dimensions of the energy system as three *"stylized scales"*, which interacts on two axis of uncertainty and spatial and time resolution, as shown in Figure 6.2.

Figure 6.2 shows the interaction between the social, economical and technical dimensions of energy systems and shows how the longer term planning dimension holds higher degrees of uncertainty with lower resolution in time and space, at at the same time higher degrees of social impact. In contrast, the shorter term operational planning dimension holds lower levels of uncertainty at higher space and time resolution and have higher degrees of technical impact. The scales as proposed by Pfenninger et al. [2014], illustrates the complexity of energy systems and the multi-dimensionalism which the energy systems planner need to consider in the analysis.

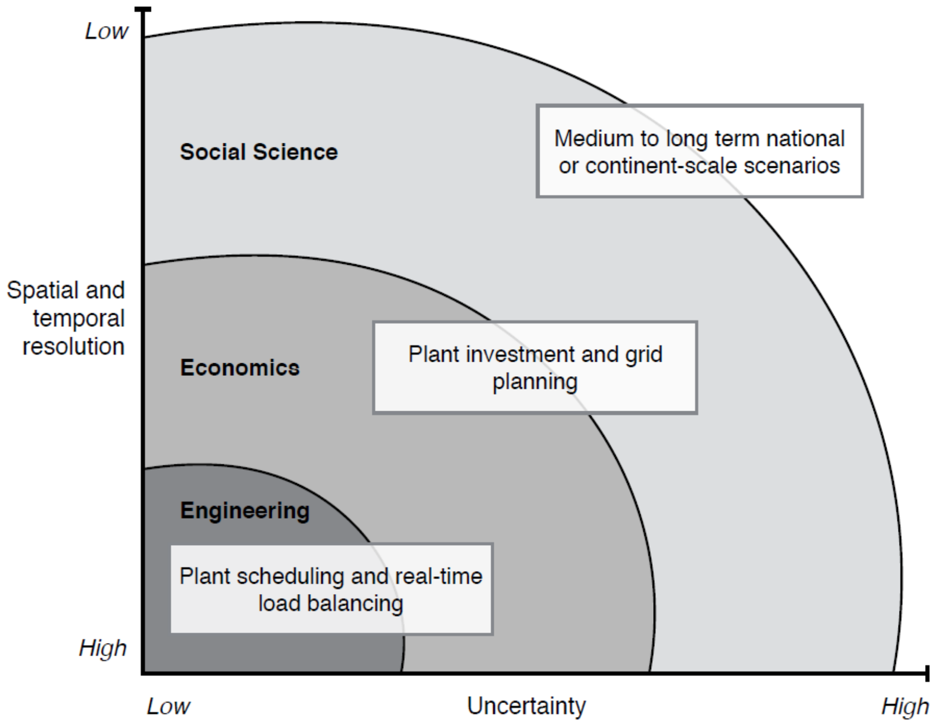

Figure 6.2. Three stylized scales relevant for energy systems, [Pfenninger et al., 2014]

Subramanian et al. [2018] classifies energy system modelling approaches in three broad groups: 1) Computational models; 2) Mathematical models; and 3) Physical models, as illustrated in Figure 6.3, where computational models are essentially mathematical models, but where much of the calculations are done through a computational system, program or software.

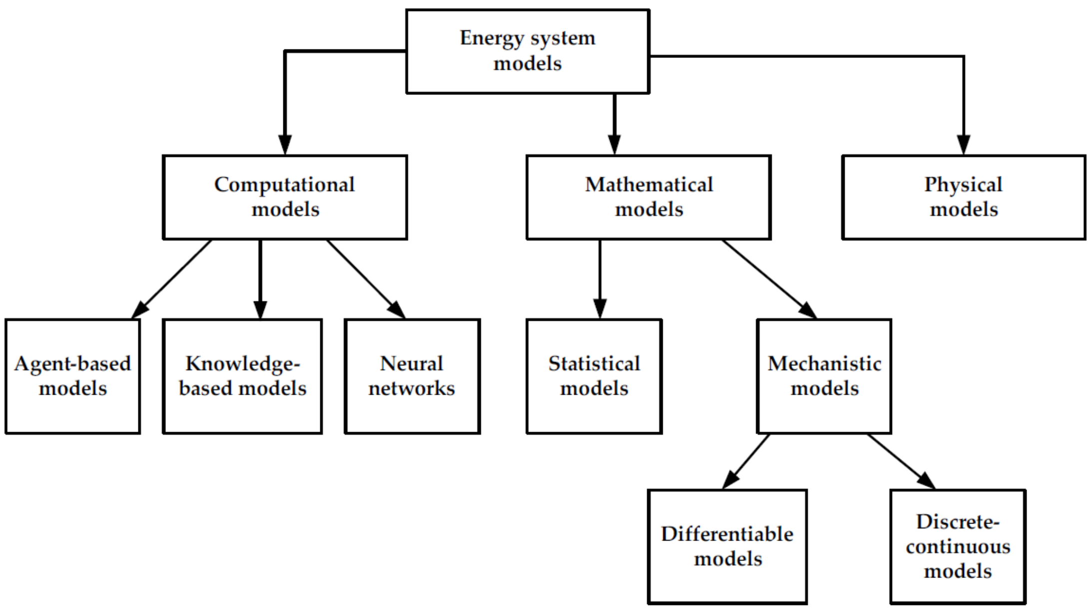

Figure 6.3. Classification of energy system models according to modeling approach, [Subramanian et al., 2018]

For the purposes of this study, the computational and mathematical modelling approaches are used in the analysis. The physical modelling approach relates to building the system at a model scale in real life, which falls outside of the scope of this study.

6.2.1 Mathematical modelling using Excel as a tool

In mathematical modelling, the real world is described in mathematical terms through a series of equations and relations, [Lawson and Marion, 2008].

Dym [2004] provides a high level view of the process of mathematical modelling, as shown in Figure 6.4, where the process starts with a question or objective and ends with a valid and accepted outcome:

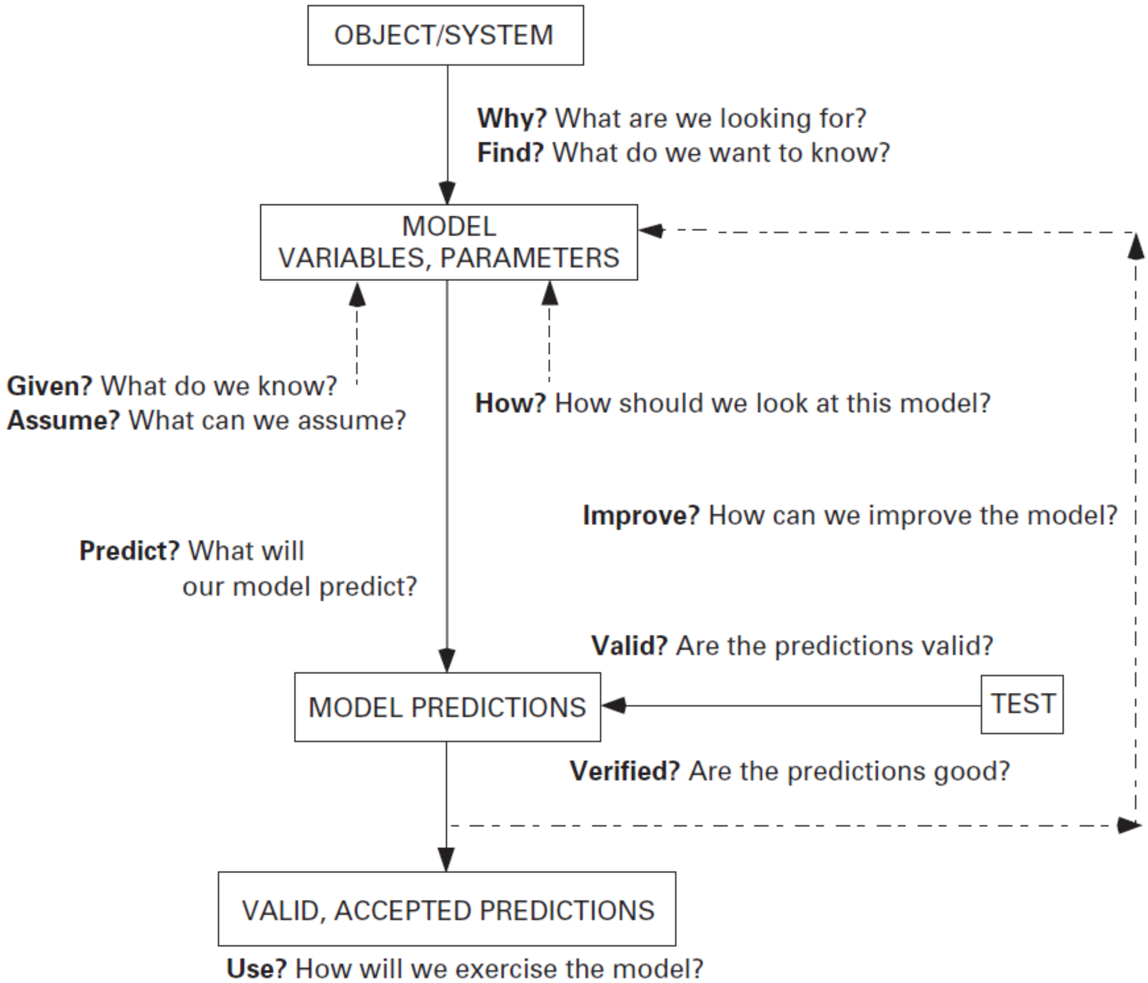

Figure 6.4. A first-order view of mathematical modeling, [Dym, 2004]

Through defining how systems work (mathematical theories and equations), and defining the relationship of the different element of the system (variables, parameters, data inputs), predictions of the behaviour of the system can be generated (model outcomes). A series of tests can be performed on the predictions to check the validity and variability of the predictions, and improvements to the variables and parameters (or data) can be made, sometimes through measurements in the real world. For the purposes of this study, Microsoft Excel is used a tool to build the mathematical model, as it is a tool that can handle a relatively large amount of data in a simplified manner, without the need for complicated computational code. Excel is also a useful tool to organize numbers and data with formulas and functions in a manner that is easy to visualise.

6.2.2 Computational modelling using EnergyPRO as a tool

More complex components of the energy system often requires a more robust tool with build-in functions, formulae and data sets, [Herbst et al., 2012].

In this regard, Østergaard et al. [2022] suggests that the EnergyPRO modelling tool as a tool which can be used at many different scales of the energy system, from a plant or household level to a country level. The EnergyPRO tool is also useful in the sense that it contains pre-loaded data sets on for example, weather patters and technical data of system components. For the purposes of this study, the EnergyPRO tool is used to model the output from the grid-tied photovoltaic and battery storage system for the single-family house.

7 Renewable energy development and the impact on electricity prices

7.1 Goals and objectives

This chapter presents an analysis of the development of an electricity price prognosis, for the purpose of predicting prices on the day-ahead market of the Nord Pool electricity exchange. As outlined in Chapter 4 and Chapter 6, time series modelling is used as a method to gather data and make the analysis. The analysis is based on the theoretical foundation of the Merit Order Effect and Stochastic Probability Theory, as presented in Chapter 5. The fluctuating nature of renewable energy sources can cause volatility in the electricity supply, and hence electricity price, especially in cases where renewable energy sources constitute a large share of the total electricity supply. Hence, the method to make a prognosis for electricity prices will take into account the increasing share of renewable energy in the electricity supply mix, in the light of Denmark's long-term climate ambition towards becoming a climate neutral society by 2050. In addition, when making an electricity price forecast, the chosen method have to account for the price volatility that is inherent to electricity prices in a liberalised market. The overall purpose of this chapter is aimed at dealing with the part of the research problem relating to the development of a price forecasting model, and which is contained in the following research sub-question:

From Chapter 2, it can been seen that the volatility in the electricity price can be attributed to the fluctuating nature of the renewable energy sources in the electricity supply mix. Research sub-question 2 will explore the social impact of the increasing share of renewable energy in the electricity supply, in so far as public acceptance is concerned. However, in building towards an understanding of this aspect of the social impact of renewable energy development, it is important to understand the general impact that renewable energy development may have on electricity prices, and this will be done through the exploration in sub-question 1.

This chapter presents an analysis of the the part of the research problem which deals with the social transformation of the electricity sector and the general impact that renewable energy development may have on electricity prices. From Chapter 2, it is presented that the volatility in the electricity price can to some extend be attributed to the fluctuating nature of the renewable energy sources in the electricity supply mix, and that intermittent over and under supply in electricity from renewable energy sources could lead to sudden price drops and volatile price spikes. As outlined in Chapter 4 and Chapter 6 , a literature review is used as a method to gather data and make the analysis. The analysis is based on the theoretical foundation of Smart Energy Systems, as presented in Chapter 5. The overall purpose of this chapter is to respond to the following research sub-question:

"How does an increase in the renewable energy share of electricity supply, impact on electricity prices?"

The literature review is conducted in the following 5-step approach as outlined in Chapter 6:

1. Defining the main topic;
2. Search the literature;
3. Results and analysis;

In the outlined approach to conducting the literature review, step 4 is the process of documenting the literature review and therefore steps 4 (Writing) and 5 (Reflection) are combined into one and are thus presented in one section.

7.2 Defining the main topic

The ambitious long-term plans of Denmark to become a CO2 – e emissions neutral society, do not only depend on technical and scientific plans and actions, but is an issue which is also highly dependent on many socio-economic factors. One of these issues is the acceptance of renewable energy technologies and initiatives by the broader society. As presented in Chapter 2, the electricity sector will play a crucial role in the reduction of CO2 – e emissions on the long-term. Denmark has also make strides in the increase of renewable energy sources in the electricity supply mix, [Johansen, 2021], and as a result the study of the impact of increased renewable energy in the electricity supply mix on electricity prices, has been the subject of many studies, [Iimura and Cross, 2018].

In a recent study by Djørup et al. [2018], correlations are drawn between wind power development and the price of electricity at a wholesale and at a sport market level are drawn.

In [Djørup et al., 2018], the correlation between the development of wind power sources and the wholesale price of electricity is shown for Western Denmark (DK1 price zone), which shows a positive correlation between wind power development and the wholesale price of electricity, with an overall reduction in wholesale prices in the period 2010 to 2017.

In Figure **??**, [Djørup et al., 2018], the correlation between wind power development and the spot price of electricity is shown for Western Denmark (DK1 price zone), and here it can be seen that there is a negative correlation between wind power development and wind power development.

The literature review also points to the volatility in the electricity price can be attributed to the fluctuating nature of the renewable energy sources in the electricity supply mix.

7.3 Literature search

As in Chapter 6, a narrative review is the approach that is chosen for the purposes of this analysis and the following databases are used: Web of Science, Scopus, Google Scholar and the IEE/IET Electronic Library is used as the primary source to conduct the literature search from a subject-specific source perspective and the Google Scholar database is used to cover the literature search within a broader general information source.

The *"berry picking"* model of information gathering, as defined by Booth [2008] is again chosen as the primary search strategy.

7.4 Results and analysis

The literature search yielded several studies which investigated the result between the development of renewable energy sources and the price of electricity. The literature review suggests that wind and solar power production have statistically and economically significant effects on day-ahead price volatility in, but no conclusive arguments can be found that renewable energy development leads to higher or lower electricity prices.

,

7.5 Reflection

Electricity prices and public acceptance of renewable energy development 8

8.1 Goals and objectives

This chapter presents an analysis of the the part of the research problem which deals with the social transformation of the electricity sector and how public support of renewable energy development are influenced by the price of electricity. The analysis presented here explores the connection between societal support for the renewable transformation in the electricity sector, considering the long-term technical expectation that the share of renewable energy sources in electricity supply is an increasing projected contribution towards Denmark's long-term climate ambitions. As outlined in Chapter 4 and Chapter 6 , a literature review is used as a method to gather data and make the analysis. The analysis is based on the theoretical foundation of Smart Energy Systems, as presented in Chapter 5. The overall purpose of this chapter is to respond to the following research sub-question:

"What is the relationship between electricity prices and public acceptance of renewable energy?"

The literature review is conducted in the following 5-step approach as outlined in Chapter 6:

1. Defining the main topic;
2. Search the literature;
3. Results and analysis;
4. Writing the literature review; and
5. Reflection

In the outlined approach to conducting the literature review, step 4 is the process of documenting the literature review and therefore steps 4 (Writing) and 5 (Reflection) are combined into one and are thus presented in one section.

8.2 Defining the main topic

The ambitious long-term plans of Denmark to become a CO2 – e emissions neutral society, do not only depend on technical and scientific plans and actions, but is an issue which is also highly dependent on many socio-economic factors. One of these issues is the acceptance of renewable energy technologies and initiatives by the broader society. As presented in Chapter 2, the electricity sector will play a crucial role in the reduction of CO2 – e emissions on the long-term. Denmark has also make strides in the increase of renewable energy sources in the electricity supply mix, [Johansen, 2021], and as a result the study of the impact of increased renewable energy in the electricity supply mix on electricity prices, has been the subject of many studies, [Iimura and Cross, 2018].

In a recent study by Djørup et al. [2018], correlations are drawn between wind power development and the price of electricity at a wholesale and at a sport market level are drawn, as illustrated in Figure 8.1 and Figure 8.2.

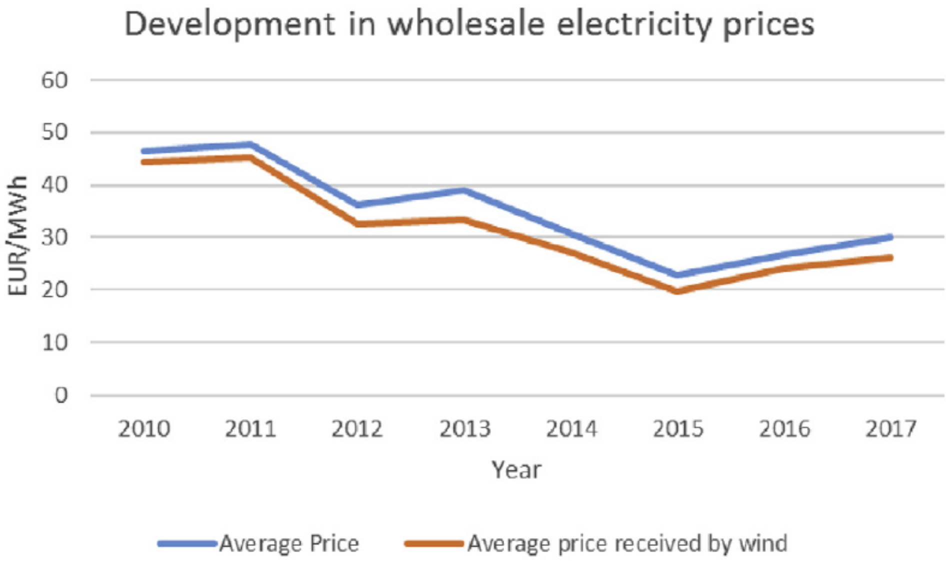

Figure 8.1. Development in spot market prices in Western Denmark (DK1) 2010-2017, [Djørup et al., 2018]

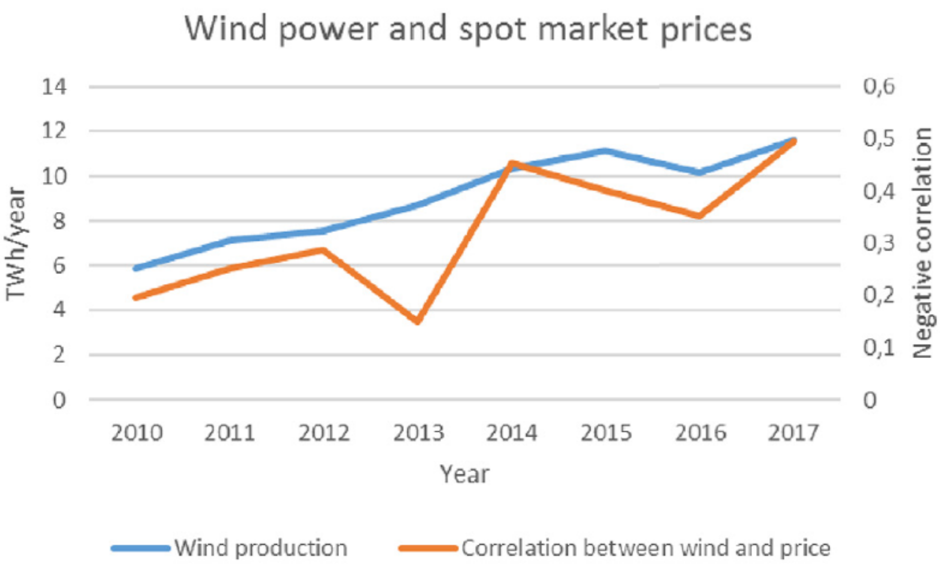

Figure 8.2. Development in wind power production and the correlation between wind production and market prices in Western Denmark (DK1) 2010-2017, [Djørup et al., 2018]

In Figure 8.1, [Djørup et al., 2018], the correlation between the development of wind power sources and the wholesale price of electricity is shown for Western Denmark (DK1 price zone) and it can be seen that there has been a positive correlation between wind power development and the wholesale price of electricity, with an overall reduction in wholesale prices in the period 2010 to 2017.

In Figure 8.2, [Djørup et al., 2018], the correlation between wind power development and the spot price of electricity is shown for Western Denmark (DK1 price zone), and here it can be seen that there is a negative correlation between wind power development and wind power development.

It is therefore of interest to see what the correlation would be between the price of electricity at a consumer level and the development of renewable energy sources, such as wind power.

8.3 Literature search

As in Chapter 6, a narrative review is the approach that is chosen for the purposes of this analysis and the following databases are used: Web of Science, Scopus, Google Scholar and the IEE/IET Electronic Library is used as the primary source to conduct the literature search from a subject-specific source perspective and the Google Scholar database is used to cover the literature search within a broader general information source.

The *"berry picking"* model of information gathering, as defined by Booth [2008] is again chosen as the primary search strategy.

8.4 Results and analysis

While the literature search yielded several studies which investigated the result between the development of renewable energy sources and the price of electricity, only two studies applicable to the European scenario were found that relates the price of electricity and public opinion/acceptance of renewable energy source development. The study by Aklin [2021] found that there is a generally negative relationship between high electricity prices and public support for renewable energy development.

In a study on how public opinion have evolved from the planning and development phase to the post-construction and operational phase of wind-power projects in Belgium, [Penneman et al., 2022] found that public acceptance to renewable energy developments actually increased with time and attributes it to the public growing accustomed to seeing and experiencing operational renewable power plants and installations in their environment.

8.5 Reflection

While the literature does not point to a conclusive argument for or against public acceptance of renewable energy development, the overall conclusion is that prices of electricity do play a role in public acceptance of renewable energy development, especially instances where projects are heavily subsidized through public funds and the public has to bear the cost of energy development projects. The general conclusion is that through putting too much of the financial burden of renewable energy development on the public purse, may negatively influence the public's willingness to support future projects.

Participation in the balancing market 9

In Chapter 2, it is presented how electricity prices in the liberalized electricity markets with large renewable energy penetration, will typically display price cycles. Large positive and negative price spikes are often experienced and can often be attributed the fluctuating nature of the renewable energy supply, the non-storability of electricity at large scale and the non-elasticity of demand. Growth in the renewable energy component in the electricity supply mix in Denmark is also projected, in line with current climate policy measures and Denmark's climate ambitions towards achieving a reduction of greenhouse gas emissions by 70% Carbon Dioxide-equivalents (CO_2-e) by 2030, as compared to 1990 and to transform Denmark to a climate neutral society by 2050. Chapter 2 also presents a growing challenge for transmission system operators in the liberalised electricity markets, to maintain grid balance and stability amidst increasing renewable energy penetration and a growing trend in consumers responding to lower prices by consuming more electricity. Since grid integrity needs to be maintained at all times to ensure security of supply, it is presented how the Danish TSO, Energinet, has started to think around the traditional approach to maintaining grid balance and are considering to allow households with small-scale photo-voltaic production, to enter the balancing markets.

To this end, the purposes of this chapter is to provide an analysis in response to the following research sub-question:

"How can an analysis be made of how a single-family house with photo-voltaic (PV) systems in West Denmark could participate in the balancing market?"

9.1 Goals and objectives

One of the goals of this study is to investigate the broader economic role that society is able to play in the ongoing social transformation in the electricity sector in Denmark, taking into account the long-term technical transformation of the sector as it continue to evolve from fossil fuels to renewable energy sources.

Subsequently, the objective of this chapter is to describe the specific actions and steps which is undertaken to achieve this goal. As such, to investigate the role of society in the long-term socio-technical transformation of the electricity sector, an analysis is made of how a single house in West Denmark can participate in the balancing market. This analysis is built on Sustainability transformations as a foundation theory and carried out through the employment of Energy Systems Modelling as a method, as outlined in Chapter 4 and Chapters 5 and 6.

As presented in Chapter 6.2, Energy Systems Modelling is used as a method to make the analysis and this chapter will further outline how the modelling is conducted, as follows: (1) The inputs from the photo-voltaic system into to the broader system model is simulated through computational modelling using the EnergyPRO package; and (2) A mathematical model is developed in Microsoft Excel to model and analyse the complete system of how a single Danish house can participate in the balancing market.

9.2 A single-family house in the context of the study

A single-family house is used as the basis for the analysis, as it is in line with the current direction of thinking of the Danish TSO, as a possible starting point for allowing a broader participation of consumers in the balancing market, [Energinet, 2023c].

In an authoritative study of Danish housing and housing policy since the early 20th centuary, Kristensen [2007] defines a single-family house as follows: *"As the name suggests, a single-family house is a building for a family surrounded by a garden"*.

According to Kristensen [2007], this type of house in Denmark became popular in the post-Wolrd War 1 period, with the country having seen a large increase in the construction of single-family houses in the 1960's and continued in the 1970s. The study further states that approximately 8,000 new single-family houses are built in Denmark every year, while a large number are being converted and extended each year.

Although the classic definition for a single-family house by Kristensen [2007] specifies a house or building which is surrounded by a garden, over time the definition has grown to include terraced, semi-detached and linked or row houses, since these house types still do have some garden space in front or back or both, and typically would be occupied by one single family.

The exact definition of a single-family house may vary between juridical or statistical bodies, but generally includes three elements:

1. The building is usually occupied by just one household or family,
2. The building typically consists of just one dwelling unit or living unit and where multiple dwellings are part of the building, there is usually a vertical separation between dwelling units, and
3. Short-term accommodation buildings (such as hotel, motels, inns, etc) and large-scale rental accommodation (such as boarding houses or condominium) are generally excluded from the definition.

Hence, For the purposes of this study, and to create context and a common understanding of definitions, it is important to review which house categories are considered as *"single-family houses"* by the main data agencies where data relates to houses.

Housing data from Statistics Denmark categorises house type according to use, with the different data categories for houses as follows (the categories for *"single-family houses"* are marked in ***bold italics***), [Statistikbanken, 2023] :

- ***Detached houses / farmhouses***;
- ***Terraced, linked or semi-detached houses***;
- Multi-dwelling houses;
- Student hostels;
- Residential buildings for communities;
- ***Cottages***; and
- Other.

The Danish TSO, Energinet, who provides energy consumption data for households, also recognises single-family houses as one of three main categories of house types. The Energinet house categories are then further broken down into sub-categories within each of the three main categories, as follows (the categories for *"single-family houses"* are marked in ***bold italics***), [Energinet, 2023a] :

- ***Detached and townhouses***:
  - Farmhouse for agricultural property;
  - Detached single-family house;
  - Combined single-family house;
  - Row, chain or semi-detached housing (vertical separation between houses);
  - Terraced, chain and cluster house;
  - Annex in connection with year-round residence; and
  - Second unit for year-round living.
- Apartment buildings:
  - Residential in apartment building, apartment block or two-family house;
  - Student residence; and
  - Residential accommodation in residential care.
- Other:
  - Farm outbuildings such as pig houses, barns, etc.
  - Machines shops, workshops, agricultural garages, etc.
  - Greenhouses, agricultural production buildings, etc.

9.3 Model description

This section briefly describes and illustrates the flow of inputs and outputs for the model and how the inputs and outputs interact. As outlined in Chapter 6.2, the field of energy systems modelling attempts to create a representation of the real world as realistically and representative of the real world as possible, to enable planners to recreate different scenarios under which different elements in the energy system interact with each other and yield a certain result.

For the purposes of this analysis, a single-family house, situated in West-Denmark (Nord Pool price zone DK1, as outlined and motivated in Section 3.2) is used as the basis to create a representation of a possible real-world scenario. The house is connected to the electricity grid and has an annual average electricity and heat demand that is representative of single-family houses in Denmark. Figure 9.1 illustrate the the different elements of the model in a simplified manner.

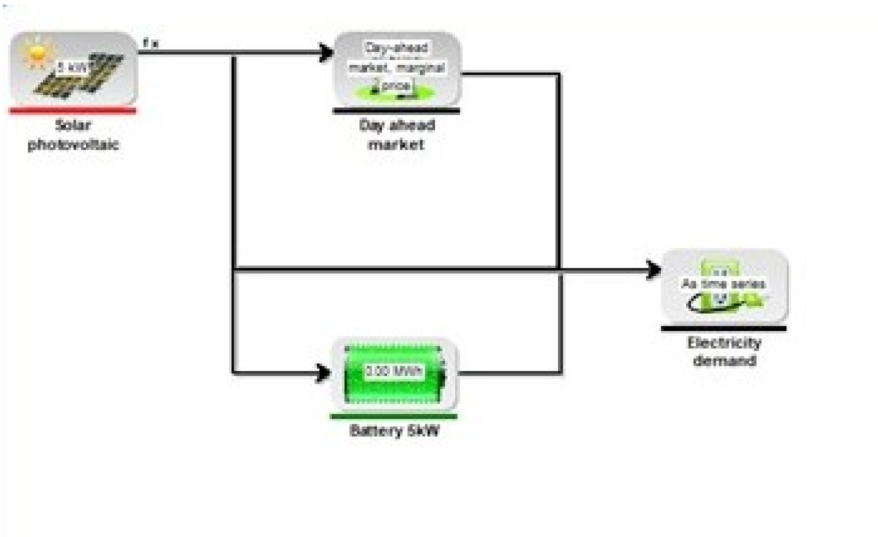

Figure 9.1. Simplified graphical representation of the model, [Own figure]

The electricity demand is supplied through the grid and a grid-tied photo-voltaic (PV) unit that is installed on the southern facing roof and has a capacity of 5kW and is connected to an inverter and battery storage of capacity of 5kW. The heat demand is supplied through an electric heatpump that has a cold water connection. The battery is not re-charged from the grid.

The model is set up for a time horizon over a 1-year period in 1-hour resolution, based in input data from 2023 (Data for 2022 is used in instances where data is not readily available for 2023).

9.4 Electricity demand

The electricity demand forms the foundation of the model and the approach is taken to base the demand on real historical data to provide a greater degree of validity and variability to the model outcomes. In addition, the *"single-family house"* is a key component of the foundational aspects of building the model as it forms a critical component of Danish society, [Kristensen, 2007], [Lähtinen et al., 2021], and could also be used as a broad-based vehicle that is accessible for a large part of Danish society, to create socio-technical participation in the electricity market.

Electricity demand data is obtained from the Danish TSO, Energinet, dataset for: *Private Consumption per Housing and Heating Categories and Industry Consumption by Municipality and Hour*, [Energinet, 2023a].

The dataset provides actual measured historical hourly electricity consumption of all private households by housing category, heating categories and industry consumption by municipality code. The following parameters were used for to obtain electricity demand data from the applicable dataset:

- Housing category: *Detached and townhouses.*
- Heating category: *Electric heating or heat pump.*
- Municipality number: *Applicable municipal code obtained from the Danish Customs and Tax Administration (Skatteforvaltningen).*
- Resolution for consumption data: *Hourly.*
- Time period: *01 January 2023 - 31 December 2023.*

The DK1 (Western Denmark) Nordpool price zone consists of 3 of the 5 regions of Denmark, as indicated in Figure 9.2: 1) North Jutland Region (Nordjylland); 2) Mid Jutland Region (Midtjylland); and 3) Southern Denmark (Syddanmark).

Figure 9.2. Regions of Denmark, [Freeworldmaps, 2023]

To determine a representative data set for electricity consumption for the purposes of the model, electricity consumption data for single-family houses with electrical heating or heat-pump were obtained from the Energinet data set for the largest and second-largest (by polulation) cities/towns within each of the 3 regions in DK1:

- North Jutland Region: Aalborg, Hjørring.
- Mid Jutland Region: Aarhus, Viborg.
- Southern Denmark: Odense, Vejle.

Figure 9.3 presents the total electricity consumption for all single-family houses for the three largest cities: Aalborg, Aarhus, and Odense.

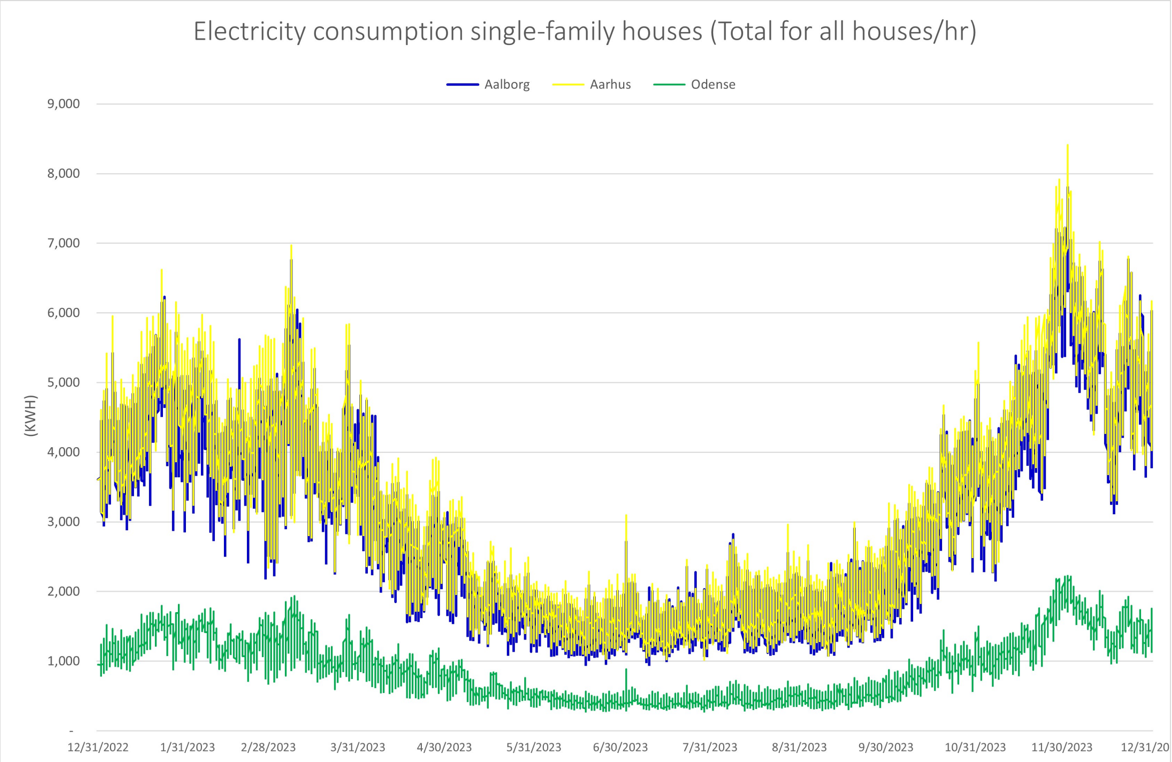

Figure 9.3. Hourly electricity consumption for all single-family houses - Aalborg, Aarhus, Odense (01 Jan 2023 - 31 Dec 2023), [Own figure]

As can be seen from Figure 9.3 the total electricity consumption patterns for the cities of Aalborg and Aarhus follows each other very closely. However, not only is the consumption patterns almost identical, but the total amount of kWh of electricity consumed in each hour, is also very close for the two cities. However, the graph for electricity consumption for the city of Odense is very different from the other two cities in both pattern and magnitude. The consumption graph does not display the typical seasonal variation that is expected for electricity consumption and is more evened out with a relatively small summer peak. The graph also displays much lower values of consumption. The difference in consumption pattern and magnitude for Odense could be contributed to the energy savings initiatives of the Odense Municipality since the early 1980's.

Figure 9.4 presents the total electricity consumption for all single-family houses for the three second-largest cities in the three regions that made up the DK1 price zone: Hjørring, Viborg, and Vejle.

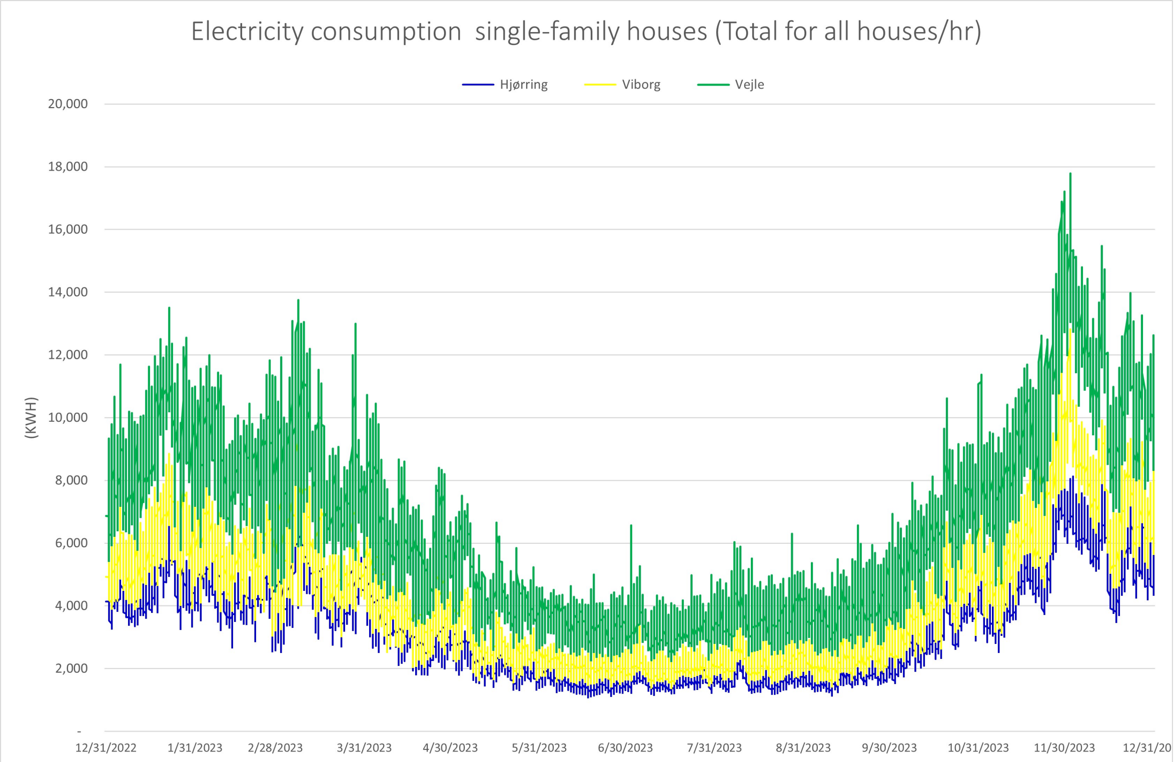

Figure 9.4. Hourly electricity consumption for all single-family houses - Hjørring, Viborg, Vejle (01 Jan 2023 - 31 Dec 2023), [Own figure]

As in the case of Aalborg and Aarhus, the electricity consumption graphs for Hjørring, Viborg, and Vejle, display very close similarities in consumption pattern and also consumption volume, with Vejle and Hjørring having the highest and lowest consumption respectively, and Viborg approximately mid-way.

To determine the average electricity demand per house, the total number of single-family houses, consisting of the total number of houses in the following categories, is obtained from the housing data base of Statistics Denmark, [Statistikbanken, 2023]:

- Detached houses / farmhouses;
- Terraced, linked or semi-detached houses; and
- Cottages.

Figure 9.5 presents the electricity consumption per single-family house unit for: Aalborg, Aarhus, and Odense. For electricity consumption per house, the demand curve for Aarhus represents the midpoint for the tree cities.

Figure 9.6 presents the total electricity consumption per single-family house unit for: Hjørring, Viborg, and Vejle. As can be seen from Figure 9.6 In the case of the smaller towns, the demand curves per house is also similar in pattern, with Hjørring representing the mid-point between the three smaller towns.

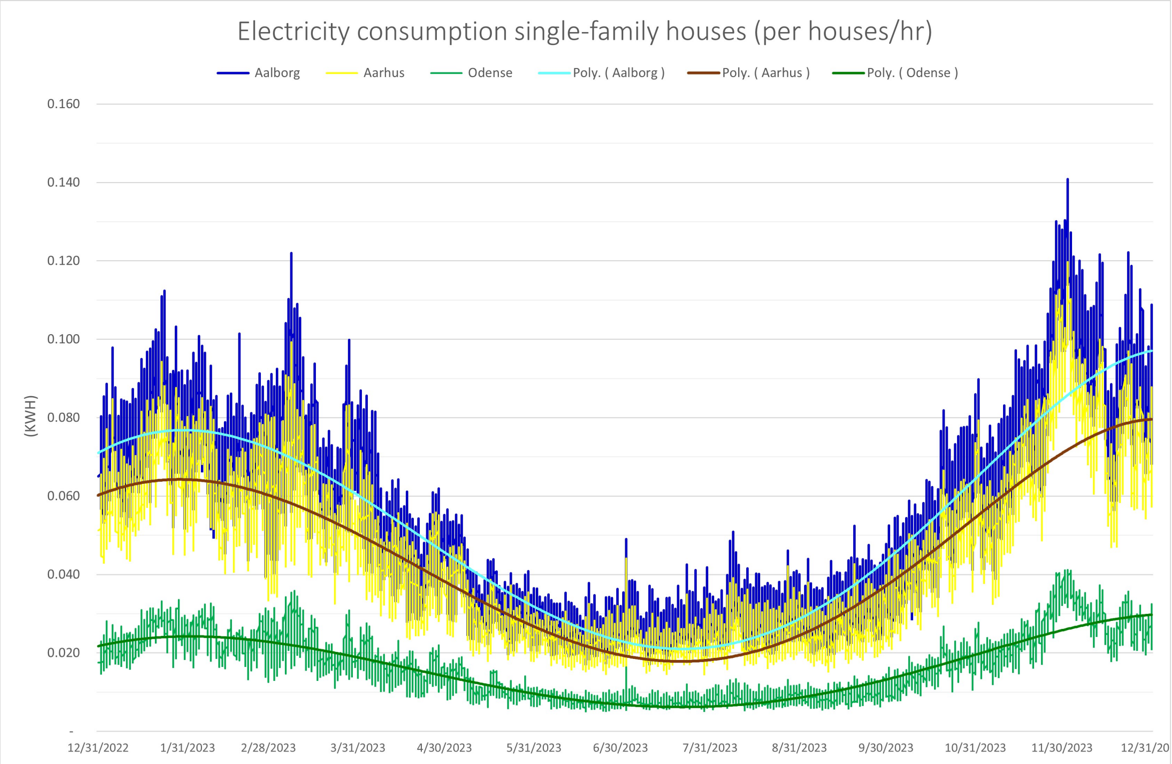

Figure 9.5. Hourly electricity consumption per single single-family house unit - Aalborg, Aarhus, Odense (01 Jan 2023 - 31 Dec 2023), [Own figure]

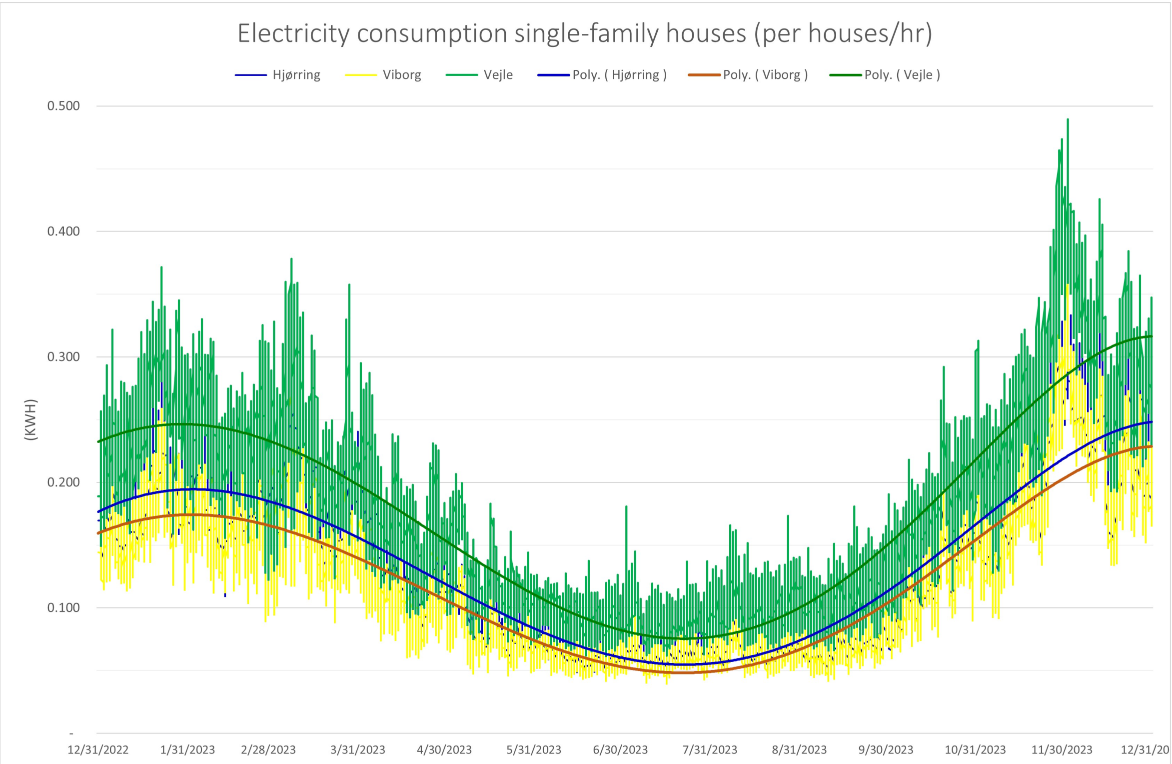

Figure 9.6. Hourly electricity consumption per single-family house unit - Hjørring, Viborg, Vejle (01 Jan 2023 - 31 Dec 2023), [Own figure]

Table 9.1 provides a summary of the number of single-family houses, and the average, minimum and maximum hourly electricity consumption per house for each of the selected two largest cities of the regions in the DK1 price zone (2023).

Hourly electricity consumption per single-family house						
City/Town	Aalborg	Aarhus	Odense	Hjørring	Viborg	Vejle
No. of single-family houses	55 432	70 237	54 023	24 408	34 188	36 346
Min hourly elec. cons. (kWh)	0.017	0.015	0.005	0.045	0.040	0.062
Ave hourly elec. cons. (kWh)	0.053	0.045	0.016	0.137	0.124	0.177
Max hourly elec. cons. (kWh)	0.141	0.120	0.041	0.343	0.375	0.489

Table 9.1. Summary of the number of single-family houses, and the average, minimum and maximum hourly electricity consumption per house for the two largest cities of the regions in the DK1 price zone (01 Jan 2023 - 31 Dec 2023), [Energinet, 2023a], [Statistikbanken, 2023].

Considering the demand per house, Hjørring represents a mid-point in comparison with the other cities. The demand from the three smaller cities compares well with each other and should not yield significantly different results. Hjørring is this chosen as the test city to use in the model.

9.5 Additional model assumptions and input data

To create a representation of the real world, which will be 100% accurate is near impossible and therefore a number of assumptions are usually made in an effort to create a model that can achieve an acceptable level of representation of the real world. Therefore a number of assumptions are applied to the input data and model parameters, which is presented in this section.

In addition to assumptions, to build the model in a manner as to represent a real world scenario, several data inputs have to be made in terms of economic, technical and physical parameters. In some instances, it may be necessary to derive key data inputs from aggregated or averaged data measurements and this approach is necessitated within the context that the scope of this study does not allow for accurate and long-term data measurements that can be used as data inputs. The various input data and the data source are also presented in this section.

Heat demand:

For the purposes of the model it is assumed that the total heat demand is already accounted for in the electricity consumption, since the dataset for single-family houses within the heating category of *"houses with electric heating or heating by means of a heat-pump"*, is applied, [Energinet, 2023a].

The relatively higher electricity consumption which can be observed from Figure 9.3 and Figure 9.4, during the winter months, as compared to the summer months, actually reflects the heat demand being accounted for in the electricity demand.

Electricity pricing:

The following assumptions apply to the electricity pricing:

- The house is paying the hourly price for electricity.
- When electricity is consumed from the PV unit directly or from the battery, then the household does not pay for grid tariffs and taxes.

The Elspot day-ahead hourly electricity price for the DK1 price area for the period 01 Jan 2023 - 31 Dec 2023, is obtained from the Energinet dataset for: *Espot prices: Day ahead spotprices in Denmark (DK) and neighbouring countries*, and is shown in Figure 9.7, [Energinet, 2023b].

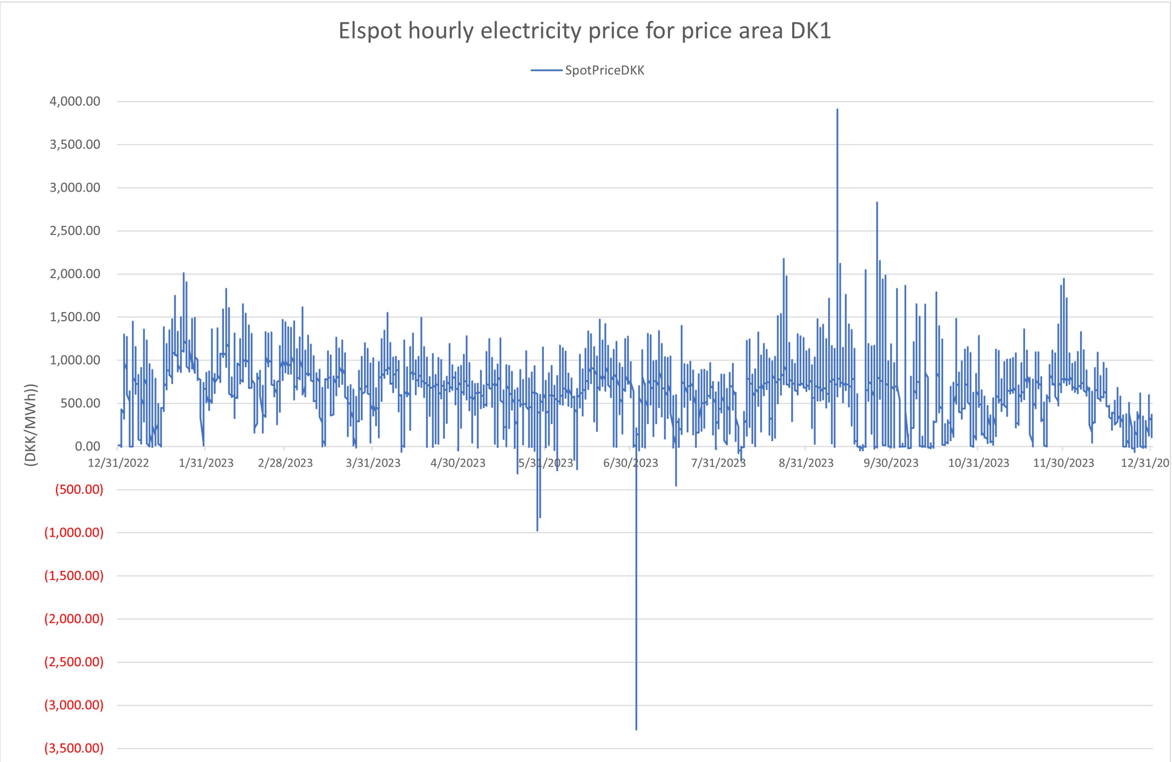

Figure 9.7. Elspot day-ahead hourly electricity price for the DK1 price area (01 Jan 2023 - 31 Dec 2023), [Energinet, 2023b]

Regulating / balancing price:

The following assumptions apply to the Regulating pricing:

- The house is receiving the hourly price for regulating power.
- The house participates in up-regulation and not in down-regultion.
- Surplus electricity production from the PV unit is first used to satisfy the demand and then always purchased for up-regulating power, except when the hourly Elspot electricity price for the price area is negative, in which case surplus production is stopped from feeding into the grid.

The up-regulating hourly price for the DK1 price area for the period 01 Jan 2023 - 31 Dec 2023, is obtained from the Energinet dataset for: *Regulating and Balance Power, Overall*

Data: mFRR activation, balance power prices and imbalance, overall data, and is shown in Figure 9.8, [Energinet, 2023d].

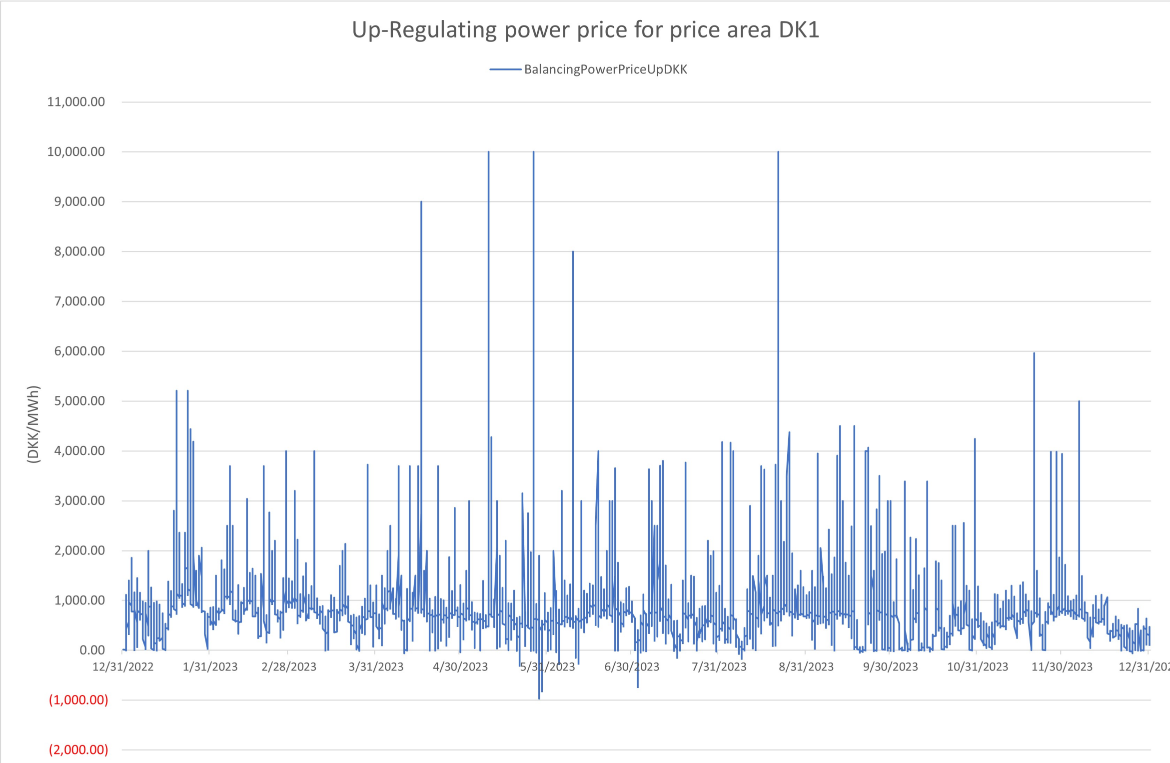

Figure 9.8. Up-regulating hourly price for the DK1 price area (01 Jan 2023 - 31 Dec 2023), [Energinet, 2023d]

Grid tariffs and taxes:

Since grid tariffs and taxes make out a large component of the final electricity price, it is assumed that the household does not pay grid tariffs and taxes, for the purposes of this study.

Electricity produced by the PV unit:

The electricity produced by the PV unit is calculated in EnergyPRO and serves as an input to the mathematical model. The following data inputs applies to the modelling in EnergyPRO of the electricity production of the PV unit, as shown in Table 9.2.

Input data - PV unit	
Capacity	5 kW
Nominal capacity panels	318 W
Number of panels	16
Temperature coefficient	-0.35% / degC
NOCT	45 degC +/- 2 degC
Losses	10%
Solar radiation	CFSR2 timeseries
Location	Longitude 10.02E Latitude 57.55N
Orientation and roof inclination	South 35 deg

Table 9.2. Input assumptions and data for modelling the PV unit in EnergyPRO

Load distribution:

The electricity demand is based on actual historical data and hence the load distribution is also the actual.

9.6 Model results

The results of the PV unit energy conversion vs the electricity demand is shown in Figure 9.9, Figure 9.10, for the the full year and the first month of the year, respectively. As can be seen from the two figures, on a larger resolution the PV seems to be converting energy most of the time, but when it is zoomed in to a smaller resolution, it can be seen that on most days the demand outstrips the generated energy. However, it should be considered that the first 30 days of the year are winter days and this could have an impact on the number of sunny days.

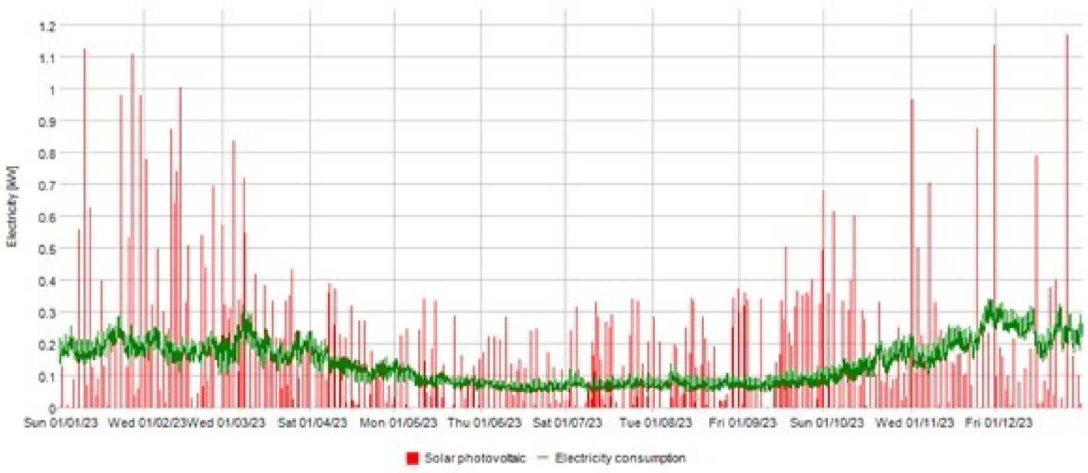

Figure 9.9. PV unit converted energy vs demand (01 Jan 2023 - 31 Dec 2023).

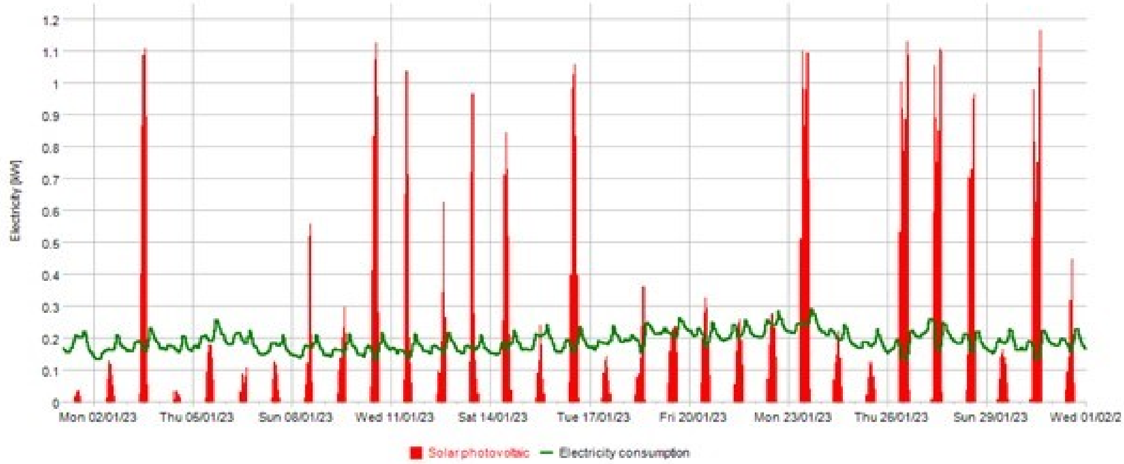

Figure 9.10. PV unit converted energy vs demand (01 Jan 2023 - 31 Jan 2023).

The results from the Excel model show that the household consumes a total volume of 1,196kWh of electricity while the PV unit generates a total volume of 689kWh. The result is a net purchase of electricity of DKK 322.040 for the year.

The Excel model for the study is attached as Appendix A.

Discussion 10

Denmark has made progress in increasing the renewable share of electricity supply, but of concern is how the large-scale introduction of renewable sources will influence electricity prices in future, and in turn, prices may influence public opinion towards renewable energy development. Preliminary data suggest that during summer in periods of low prices, private houses react with higher consumption of electricity. In addition, an increased renewable energy share may also impact on the transmission system operator (TSO) to maintain balance and grid stability due to the fluctuating nature of renewable sources, and as a result, the Danish TSO is planning to allow small household PV-units to participate in the balancing markets.

The aim of this study is to explore the relationship between electricity prices and public acceptance of renewable energy and what role society can play in the socio-technical transformation of the electricity sector, considering Denmark's climate ambitions towards becoming a climate neutral society by 2050. To this end the following research question is posed:

"What is the relationship between electricity prices and public acceptance of renewable energy, considering the fluctuating nature of the renewable energy share and the socio-economic transformation of the electricity system towards achieving Denmark's climate ambitions in 2030?"

To respond to the research question the following research sub-questions have been formulated to assist in responding to the research question in a holistic manner:

1. *"How does an increase in the renewable energy share of electricity supply, impact on electricity prices?"*
2. *"How does electricity prices impact on public acceptance of renewable energy development?"*
3. *"How can an analysis be made of how a single-family house with photo-voltaic (PV) systems in West Denmark could participate in the balancing market?"*

From Chapter 2.2, it can be seen from Figure 2.4, that the policy trajectory for Denmark is for renewable energy to provide more than 100% of electricity supply by 2030, with onshore and offshore wind providing about 80% of electricity supply by 2030. In Chapter 2.4 it is presented that electricity is set to become a key driver in the decarbonation of sectors which have been traditionally dependant on fossil-fuels and have up to now been experienced as challenging and/or expensive to convert directly to renewable energy sources. This is essence mean that as decarbonisation of the Danish society is set to increase by 2030, electricity demand is projected to increase correspondingly. Chapter 2.3 presents how liberalisation of the electricity sector and the international links between Denmark and the predominantly hydro-power based northern systems, and the predominantly thermal-based southern systems, has assisted the development of the wind energy sector in Denmark. These factors made it possible to feed more more electricity from renewable wind energy sources into the system, and hence wind power development will continue to play a large part of the Danish electricity supply sector. However, Chapter 2.4 also presents the challenge in balancing supply and demand, which is a factor that is inherent from renewable based electricity systems due to its fluctuating nature, and this fluctuation in the supply-demand balance can have a challenging impact on electricity prices and may even lead to negative prices in some instances.

Chapter 2.5 presents the operation of the Nord Pool day-ahead market and from this part of the problem analysis, a pertinent question arise on the response of the established market design to the on-going transformation of the electricity sector.

Subsequently, the following key concepts emerged from the presentation in Chapter 3 :

1. Sub-question 1 will examine part of the economic aspects of the transformation - Increased prices.
2. Sub-question 2 will examine part of the social aspects of the transformation - Social acceptance of RE.
3. Sub-question 3 will examine some of the socio-technical of the transformation in the participation of society in the balancing market.
4. Together these concepts will form an analysis of the socio-economic and socio-technical aspects of the transformation.

In Chapter 5 and Chapter 6 the chosen theoretical approach and methods for the study is presented.

To be able to respond effectively to the analysis of this study, which straddles social, economic and technical areas of the energy system, it was necessary to draw from a theoretical approach which would be able to respond to complex systems. As a result the Smart Energy System concept and the Merit Order Effect was chosen as theoretical foundation to draw from. Furthermore the relatively new theoretical field of sustainability transitions is a important component of the energy transition and examines how different transition subtleties can lead to different transition pathways, and as such this theoretical foundation was used to build the analysis of broader possible societal wide participation in the balancing market.

The literature review was chosen as a method to respond to research sub-questions 1 and 2:

"How does an increase in the renewable energy share of electricity supply, impact on electricity prices?"

"How does electricity prices impact on public acceptance of renewable energy development?"

However, it was found that the method did not respond well to the questions in hand, since literature reviews generally applies well to questions that fall within one particular subject field. Energy systems are generally complex systems which encompass the three fields of social, economic and technical, and as such a better methods could have been interviews or questionnaire which could have been targeted at a wide audience.

While the literature review does not yield the desired conclusive arguments, it does point to an overall conclusion is that prices of electricity do play a role in public acceptance of renewable energy development. However, there is no conclusive arguments presented in the literature which points to an increase of electricity prices with an increase in renewable energy development.

Energy systems modelling was chosen as a methods to analyse research sub-question 3:

"How can an analysis be made of how single households with photo-voltaic (PV) systems in West Denmark could participate in the balancing markets?"

In this regard, Microsoft Excel and the EnergyPRO modelling tool, as a tools, were highly effective methods in deploying the to conduct the analysis.

The analysis yielded good results that are consistent and can be validated and verified. However, although the analysis point to a single-family house being able to participate in the balancing market, it does not point to any a net zero or near zero electricity bill over the course of a 1-year period. A factor which is definitely worth considering as possibly playing a role, is the generally low electricity usage from Danish houses and the increasing drive to improve energy efficiency. Hence, the base from which the model work is relatively low and as a result any gains are also relatively low.

The results from the Excel model show that the household consumes a total volume of 1,196kWh/year (or 99.67 kWh per month) of electricity while the PV unit generates a total volume of 689kWh per year (or 57.41 kWh per month). The result is a net purchase of electricity of DKK 322.040 for the year.

Conclusion 11

The long-term reduction of CO_2-e emissions is not only a technical matter, but also straddles many different socio-economic factors, which brings many complexities in trying to reach emissions reduction goals.

The institutional framework of the Nordic electricity market shows a progressive and world leading system. However, the historical and institutional background of the liberalisation for the electricity sector might lead to stagnation in the response of the system to structura needs in the transformation of the sector.

While the literature reviews in the study does not yield the desired conclusive arguments, it does point to an overall conclusion is that prices of electricity do play a role in public acceptance of renewable energy development. There is no conclusive arguments presented in the literature which points to an increase of electricity prices with an increase in renewable energy development, except that volatility is a factor. The analysis point to a single-family house being able to participate in the balancing market, it does not point to any a net zero or near zero electricity bill over the course of a 1-year period.

Appendix A - Excel model 12

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