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Master's Thesis

Decentralized Energy Policy in a Selected EU Country

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Theses guidelines

Objective:
The aim of the thesis is to analyse the laws and policies of an EU member country in order to enable community based, decentralized energy production and consumption.

Methodological approach:
Case study of an EU member country
The laws and policies of selected country
Statistical analysis (if necessary)
Assessment of selected countries aims and shortcomings in the implementation of policy.

Framework structure:
1. Introduction. Objectives.
2. Review of literature.
3. Methods.
4. Results, discussion.
5. Conclusion.
X. References
X. List of Annexes

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Recommended resources:

Eurostat: Monitoring report How has the EU progressed towards the Sustainable Development Goals? 2020.
European Commision: Clean energy for all Europeans package. 2020.
European Commision: National energy and climate plans (NECPs), 2019.
Bridget Woodmana, Philip Bakerb, Regulatory frameworks for decentralised energy, 2008, Energy Policy Journal.

J.M.Weinanda, R.McKennab, W.Fichtnera; Developing a municipality typology for modelling decentralised energy systems, 2019, Utilities Policy Journal.
Donal Brownab, Stephen Halla, Mark E.Davisc; What is prosumerism for? Exploring the normative dimensions of decentralised energy transitions, Energy Research & Social Science Volume 66, August 2020, 101475.

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Declaration

I declare that I have developed my master's thesis independently using only the sources and literature listed in the list of cited literature. I declare that in accordance with § 47b of Act No. 111/1998 Coll. in the valid wording, I agree to the publication of my master's thesis, namely - in the unabridged form/in the modification resulting from the deletion of marked parts archived by the Faculty of Economics - electronically in the publicly accessible part of the STAG database operated by the University of South Bohemia in České Budějovice on its website, namely with the preservation of my copyright to the submitted text of this qualification thesis. I further agree to the same electronic means being in accordance with the aforementioned provision of Act No. 111/1998 Coll. opinions of the supervisor and opponents of the thesis as well as a record of the progress and result of the defence of the qualification thesis are published. I also agree to the comparison of the text of my thesis with the thesis database Theses.cz operated by the National Register of University Qualification Theses and the plagiarism detection system.

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Justin Calvin Schaefer

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Justin C Schaefer

TABLE OF CONTENTS

1. INTRODUCTION

The European Union, along with the rest of the world, has in recent years been setting out ambitious goals to achieve a cleaner, low carbon and sustainable energy future. The reasons for this transition include environmental, economic, and social ones. The production and use of traditional sources of energy, such as coal, oil and gas, have resulted in significant greenhouse gas emissions that have contributed to climate change and global heating (UN, 2023). It is widely acknowledged that a transition to cleaner, renewable energy sources are needed to mitigate the impacts of climate change and protect the environment. Furthermore, The EU believes that the transition to clean energy will also provide significant economic benefits through the development of new innovative technologies that are becoming increasingly cost competitive with fossil fuels and so have the potential to reduce the EU's dependence on often expensive and volatile fossil fuel imports (European Commission, 2023). By investing in the renewable energy transition, the EU has social goals as well that aim to ensure that everyone has access to affordable energy while also reducing air pollution and other negative health impacts associated with tradition energy sources.

The current design of the energy system in most countries has been based on fossil fuels. This has made the energy system very flexible and reliable because large amounts of energy can be stored in liquid, gaseous, and solid forms via fossil fuels. This enables energy that can be provided "on demand", as long as there is a suitable fossil fuel storage nearby, whether as a diesel/petrol tank in a car, a gas tank for a boiler, or a coal storage facility for a power plant. In this way, fossil fuels have provided society with a lot of flexibility with large amounts of energy stored so that it is available on demand whenever it is required. The large steam turbines that run on fossil fuels as well as sources of energy such as hydro and nuclear power have also managed the task of balancing supply and demand and securing frequency and voltage on the gird mainly through centralised, large production units. However, transitioning to cleaner, renewable energy sources will limit this flexibility.

The last decade has seen the beginning of what is likely to be a fundamental transformation of the energy sector. This is the beginning of an energy transition from traditional fossil fuel-based systems to systems based on variable renewable energy sources (VRES) that will involve both technical and regulatory challenges. Digitalisation is part of the General-Purpose Technology (GPT) family which has now come to energy and combining this with decarbonisation will require a general societal transformation of the same sort seen in the information and communication sectors primarily due to the utilisation of digitalisation technologies into the energy sector. This technological change and the use of variable renewable energy sources is leading to the decentralisation of the energy sector due to the distributed nature of VRES with the large-scale integration of VRES into the electricity supply necessary for the future renewable energy system. Therefore, sooner or later such distributed production units will need to contribute to the task of securing the balance between electricity production and consumer demand.

For most parts of the world, decentralized energy means renewable energy since solar photovoltaic panels and wind turbines are scattered across residential rooftops and dispersed on acres of farmland. This constitutes a fundamental reversal of the paradigm of economies of scale that have dominated the economies of the energy supply industry throughout the 20th and 21st centuries. But what do we mean by decentralization and what reasons are there to justify an expensive and time-consuming transition to renewable energy sources?

Decentralization of energy supply means utilizing technologies that are in smaller capacity units and where their geographic distribution is wider. Indeed, decentralized, or distributed energy systems are synonymous, and as mentioned above, generally are concerned with the integration of VRES. It is envisioned as a system moving from a one-way, top-down, supply orientated operation of a few, large conventional fossil fuel power plants to an integrated system that is bi-directional, and demand focused with multiple, varied power generating units of all sizes. And what justifications exist for undergoing this transformation? Christof Burger et al. (2020) in their book "Decentralized Energy: A Global Game Changer" lists six reasons for why decentralization can be a key driver of the global energy transition which focus on the current trends that the energy sector is undergoing which include technical, regulatory, and economic arguments. These current trends are:

- The increasing competitiveness of renewable energy generation in liberalised markets. As costs have fallen, the economic incentive to install solar and wind power units has shifted from public support schemes such as subsidies to financial models that seek to achieve grid parity without government aid. Some industrialised countries with reliable energy systems have made significant investments in renewable energy and some have even at times been able to reach grid parity and are now moving towards whole system energy parity.

- The global spread of decentralised energy generation. Since 2010, there has been an estimated global investment of around US$400 billion in distributed energy production capacity. A lot of this investment has been on household rooftops or on small acreages which means that some households/private individuals are now stakeholders in the provision of supply services, and some countries have seen growth in community owned initiatives which engage local communities not only with regards to ownership and the economic benefits that come with ownership, but also with the operation of the grid infrastructure itself.
- Decentralised storage through batteries and other technologies is gaining importance as key technologies for dealing with the intermittent nature of renewable generation and increasing flexibility in the energy system.
- Decoupling growth and energy intensity through renewables and energy efficiency. Technological progress is improving the energy intensity of economies with energy consumption per unit of economic output stabilising or even falling in some countries.
- Value creation with decentralised renewable energy generation. There is an increasing share of employment in the manufacturing of wind and solar technologies as well as value creation in the installation, operation, and maintenance of these new technologies.
- Digitalisation as an enabler of disruptive changes in the energy markets. The gaining of core competencies in digitalisation lowers barriers to entry for start-ups and facilitates new business models, increased customer choice, and is a necessary precondition for decentralised transactions.

The trends listed above include some technical developments and economic incentives for the transition to decentralised energy which constitute a large part of the analysis undertaken in this paper. Another very important aspect in the energy transformation is the regulatory regime needed to be in place to enable a smooth transition. As the International Panel on Climate Change has stated, “the most likely and cost-effective way of decarbonisation is that of renewables suppling the majority of electricity, alongside energy efficiency measure” (IPCC, 2015). This will require new policies and changes in incentive schemes for generators and the associated grid infrastructure as well as the transformation of some governance mechanisms, be these institutions, market design and network rules, and of course the politics behind them. Creating a system that can efficiently integrate these new technologies implies a change in energy governance. The traditional regulatory frameworks have been designed to secure the reliable operation within a centralised power system, but new systems will require fundamental change to meet internationally agreed decarbonisation goals. In this sense, governance is a decisive factor for the successful transformation of the energy system and can act as an accelerator or decelerator of the transformation. The question for regulators and policy makers is therefore how to facilitate a rapid and smooth transition from the old energy system to a new one in a dynamic technological and economic environment.

This paper will examine Denmark's experience in the energy transition with a key focus on the technological, economic/financial aspects of the energy decentralisation model and the legal/regulatory frameworks necessary to achieve the international agreed aims of decarbonisation. It will further examine the citizen/community ownership structure of the Danish model that has shown quite significant success in the lowering of electricity prices as well as citizen acceptance of the energy transition policies. Citizen empowerment and participation are considered strategic for the EU's energy transition. Citizen ownership of energy would be the highest form of citizen participation.

2. AIMS

The large energy companies left over from the fossil fuel era have been specialised in coordinating the global allocation and distribution of fossil fuels. However, the transition to renewable energy implies a physical and economic decentralisation which will reduce the need for global and international coordination. This leads to a change in the characteristics of transactions in the new energy system and brings up questions about how the political process is influenced by different dependent and independent market actors and the tension between them. Dependant market actors (e.g., consumers, technology providers, international energy corporation, etc.) tend to advocate for their private interest in their discourse within the energy transition whereas independent actors (e.g., NGOs and the public debate) tend to advocate for an energy transition that will benefit society. This tension within the discourse of the energy transition influences the perception of what can be seen as rational and doable, both in terms of technology adoption as well as actor participation. It is with this in mind that this paper seeks to understand the dominant discourse taking place in Danish society regarding the chosen energy system pathway in terms of technology as well as ownership aspects to achieve societal goals and to what extent.

In order to do this, this paper will focus on the technical and organisational consequences of the transition from fossil fuels to mainly fluctuating renewable energy sources. In the Danish context, it will consider questions such as: can this change be managed within the traditional centralised model where excess power can be exported and where production plants are mainly owned by the former fossil fuel companies; or alternatively, whether the transition will rely on a decentralised model with smart energy systems and flexible energy consumption by integrating the entire energy system including power, heat, and transportation, accompanied with energy conservation? Furthermore, should this decentralised system be organised by cooperatively owned power plants synchronising supply-side investments? These are the contemporary questions shaping the development of the Danish energy system and I believe the answers can be very insightful for other countries behind Denmark but seeking pathways for their own decarbonisation, particularly within the European Union's framework Green Deal.

Denmark was chosen due to its leading role within the EU in implementing decentralised and community-based energy infrastructure beginning in the 1970s. Denmark's long-term experience in implementing renewable energy projects in localised small-scale settings make for an interesting case study especially with regards to citizen and community participation in its energy transformation. Therefore, the main research question is set as:

"Is it possible for an EU member country to replicate the policies, laws and processes of Denmark in order to decentralize energy production and consumption?".

Furthermore, I will seek to answer the following three sub-questions related to the main research question:

1. Does decentralized energy offer benefits to local citizens that centralized energy does not?
2. What kind of citizen ownership models have been implemented in Denmark?
3. Has Denmark been successful in developing decentralized energy?

3. STRUCTURE OF THE THESIS

The following section will layout the structure of the thesis before a section outlining the methodology used in the preparation of this paper and the reasons for selecting the academic papers and documents that I will employ in the Results and Discussion section. This Methodology section will also include a description of the framework of the Results and Discussion section in which I will analyse the three phases of the energy transition that Denmark has had or is going through with a key focus on the technical, legal, financial and community ownership aspects in all three phases. The Methodology is followed by a Literature Review which aims to set out the theoretical framework of the paper from the point of view of the general necessity for the transition from fossil fuel use to renewable energy sources with great emphasis placed on the EU's sustainable energy goals and the comprehensive frameworks set up to achieve these goals and in which Denmark participates in. There will also be a review of academic articles that discuss the role that decentralised energy may play in the energy transition, including its strengths and weaknesses as well as the legal, technological, and financial aspects required for its implementation.

After the Literature Review, the Results and Discussion section will draw heavily on academic papers, policy statements and legal documents focusing solely on Denmark's experiences during the above mentioned three phases. Throughout this section there will remain a key focus on Denmark's decentralisation aims and experiences as well as the important role of community engagement and participation through local ownership and the role that it plays in gaining citizens' support for the implementation of the energy transition. The analysis of Denmark's experience in this section aims to give the answers to the research questions and sub-questions laid out in the previous section.

The Insights and Policy Recommendations section will seek to answer the research questions regarding the adoption of decentralised energy and community involvement with the supposed benefits within Denmark but also about whether Denmark's experience is applicable to other EU member states and particularly for states without such long-term plans in place for the low-carbon sustainable energy future envisioned by the EU institutions. The paper will conclude with a short summary of the main insights gained from the research and lay out some weaknesses or shortcomings of the work and address the issue of how other EU member states with their own particular settings and conditions may benefit from this work.

4. METHODOLOGY

The analysis of the Danish energy system and government policies has been done through a thorough review of documents from international organisations, Danish national institutions, company reports, books on decentralised energy and academic articles. Most of these articles were found by keywords search in Google Scholar, Scopus and Web of Sciences databases, and others by using the reference lists of the chosen articles to analyse certain topics more extensively in articles that were cited by the authors found through the keywords search. A web search was used to find information provided by the international organisations. All these documents include policy statements, reports, statistics, technology descriptions, legally binding agreements and non-binding ones, reviews of the state-of-the-art renewable technologies and specific articles related to the Danish experience in implementing decentralised renewable technologies.

The international organisations include the United Nations, the International Energy Agency, the International Monetary Fund, and many European Union institutions. The organisations provided context for the problems of climate change, CO_2 emissions and other environmental problems that call for the introduction of renewable technologies. UN documents describing some of the international agreements about climate change were used, and many EU documents were also analysed. The EU documents covered a wide and diverse content, from policy documents from different EU institutions covering past, present and future climate and environmental goals, to the legally binding regulations. The use of these documents was essential to the paper as Denmark is an EU member state and the aim of the work is to analyse not just Denmark's policies and their implementation with regards to decentralised renewable technologies, but also whether Denmark's experience may be useful for other EU member states. The UN, EU, and other institutions provided a lot of important statistical information which was used in this paper as well.

The books I have used describe the processes of the energy transition from the traditional fossil fuel paradigm to the new renewable energy one. They helped with the theoretical understanding of the climate problems and discussed many possible pathways to take to achieve decarbonisation. They all focused mainly on decentralised energy since most, but not all, renewable energy technologies are inherently decentralised by nature. The books analysed different countries approaches to the problem and their different solutions and had short country reports on Denmark, but light on the technical and regulative aspects seen in the Danish energy transition. It was useful in comparing the conditions of different states and how this affects their national climate/energy plans and clearly demonstrated why a country like Denmark with its long coastlines and cloudy weather would choose the path of wind energy. It also gave important insights on how the Danish experience could aid other states developing their climate/energy plans even without the exact same conditions.

Furthermore, the books covered the different phases of the transition in a chronological order which I have utilised to understand the different legal, technical, economic and social conditions present at each phase of their energy transitions. This is absolutely key as each phase requires different regulations to achieve the technological implementation required in order to have economic benefits that lead to their acceptance by society. The different countries' various approaches are very insightful, for their successes as well as their failures, and give an important contextualisation of the problems of long-term planning with uncertain future results. For states seeking to replicate the success of countries like Denmark, identifying which phase of the transition they are in is fundamental for the establishment of regulations to support the implementation of technologies at each phase. The paper uses the three-phase framework for the analysis and discussion of the Danish transition. These phases are briefly defined as:

- Phase one: The deployment of niche renewable technologies into the energy mix.
- Phase two: The need to development solution to the intermittency of renewable technologies.
- Phase three: The need to development storage solution for renewable energy.

The many academic articles I have reviewed cover four important aspects – technological, financial, regulatory, and community ownership – and are mostly related to the Danish experience. The first area covers the mainly technological aspects of decentralised renewable technologies and their synergies in the smart energy system discourse. This relied mostly on the state-of-the-art technologies, meaning technologies that exist now and can be implemented immediately. The focus was on technologies used in Denmark, but some others were discussed including some future possible technical solution regarding storage, for example. The technology review is what makes up the largest part of the Literature Review and this was to help set up a theoretical framework for the paper regarding the available technologies.

Academic articles were also extensively used in the Results and Discussion section. These included some more technical articles but mainly concerned the use of research into the ways that regulations shape the implementation, longevity, and acceptance of the energy transition. This second aspect covers articles that were mainly concerned with the issue in Denmark and here many Danish government documents were also utilised. The synthesis of government documents, policy statements and progress reports with the academic research is the main method used in compiling the Results and Discussion section. In this way, the paper may be seen as overview of the Danish experience covering a period of over 50 years. The government documents tent to be quite factual and positive about the transition and the academic articles allow for a more critical exploration of the issues surrounding the transition and highlight the successes and failures which is a key insight for other countries that seek to replicate Denmark's success.

Furthermore, the analysis of the regulatory regimes established in Denmark is key to the understanding of the third aspect which concerns the different financial and economic incentive mechanisms for enabling the transition as well as their problems regarding disincentives and so articles describing these mechanisms have been used. These include articles and discussions in government reports about citizen ownership and the different community ownership models that Denmark has designed. This fourth analysed aspect was very important for the paper as decentralised energy production and consumption brings technologies closer to the producer/consumer and therefore has the potential for citizen to become prosumers in the new energy system in ways that were not possible in the traditional, fossil fuel-based energy system.

5. LITERATURE REVIEW

Analysing the vast amounts of policy papers, academic articles and government documents is the main method I have used to compile this paper in order to have a comprehensive account of the Danish energy transition and experience. This has required exhaustive literature research in order to fully understand the complex reasons, problems, measures and issues connected with the transition from traditional fossil fuel energy systems to decentralised renewable systems. This quite large section will therefore be broken down into its constituent parts to better understand the theoretical aspects and background of the energy transition and the arguments for decentralised, community owned energy system.

The first sub-section will analyse the EU's approach to the energy transition with its funding and framework agreements and legally binding commitments of its members. As Denmark is a member of the European Union, a review of the EU framework agreements is necessary to understand Denmark's climate strategies which will make up the largest part of this paper in the Results and Discussion section. Furthermore, the aim of this paper is to analyse Denmark's decentralised energy plans with a key focus on the technical, legal, financial and community engagement policies. Therefore, the second part of the Literature Review will contain a detailed review of the supposed advantages and disadvantages of decentralised energy systems from different perspectives. This will be followed with sub-sections covering the technical aspects of decentralised energy, before finishing with legal/regulatory aspects necessary for the implementation of these new technologies as well as the financial incentives needed to be in place for the smooth transition to variable renewable energy systems (VRES). In each sub-section there will be integrated discussion of the community ownership models as well as some economic/financial considerations in connection with the different aspects.

It is important to keep in mind that this section's goal is to set a theoretical framework for the understanding of the issue of climate change, regulatory conditions governing the energy transition, debates on ownership structures the current state of technology, all in order to place Denmark's strategic plans to reduce greenhouse gas emissions into a contextual framework. As Denmark is an EU and UN member it has to work within the agreements signed within these two international institutions, including the Paris agreement although this agreement will not be thoroughly detailed in this part.

5.1 THE EUROPEAN UNION

The EU's transition to renewable energy requires a comprehensive and coordinated approach that involves policy, technology, and finance. The EU has therefore put in place a comprehensive framework that includes policies, targets, and funding mechanisms to promote the uptake of renewable energy technologies and increase energy efficiency. Below are five of the keyways that the EU is using to transition to renewable energy.

1. Renewable energy targets: The renewable energy directive sets a binding target to increase the share of renewable energy in the energy mix of 32% by 2030. This target is accompanied by national targets for each member state, which are tailored to their individual circumstances and potential for renewable energy generation (Renewable energy directive, EC, 2021). This target is currently under review due to the increased ambition of the EU outlined in its European Green Deal as well as the REPowerEU plan which came about due to the Russian invasion of Ukraine and the EU aim to end its dependency on Russian fossil fuel imports. The new currently discussed target under the REPowerEU plan is to increase the share of renewable energy to 45-55% of the energy mix by 2030 (European Commission, 2022).
2. Investment in renewable energy: The EU has created funding mechanisms to support the transition to renewable energy in its seven-year budget including through the European Regional Development Fund, the European Social Fund, and the Cohesion Fund. These funds support a range of activities, such as building new renewable energy infrastructure, increasing energy efficiency, and supporting research and development of new renewable energy technologies (EU renewable energy financing mechanism, EC, 2018). These funds are further complimented by the Recovery and Resilience Facility which makes up a key component of the NextGenerationEU Recovery Plan set up as a response to the Covid-19 crisis which directs one third of the available €1.8 trillion towards energy transition investments (A European Green Deal, EC, 2023)
3. Carbon pricing: The EU has implemented a carbon pricing mechanism, the Emissions Trading System (ETS), which puts a price on carbon emissions from large industrial facilities and power plants. This creates an economic incentive for these facilities

to reduce their emissions and transition to renewable energy sources (EU Emissions Trading System, EC, 2021).

4. Support for renewable energy technologies: The EU provides financial support and research funding for the development and deployment of renewable energy technologies, such as wind, solar, and biomass. It also supports the development of energy storage technologies, which are necessary to support the integration of intermittent renewable energy sources into the grid (Support schemes for renewable energy, EC, 2022).

5. Energy efficiency measures: The EU is also promoting energy efficiency measures, such as building renovation programs, energy-efficient appliances, and smart energy management systems. These measures help reduce the demand for energy and increase the efficiency of energy use, which in turn reduces greenhouse gas emissions and the need for fossil fuels (Energy efficiency directive, EC, 2018).

As can be seen, the EU's approach includes market instruments such as the Emissions Trading System (ETS), subsidies and incentives through its funding mechanisms as well as legally binding emission targets and energy efficiency measures. These measures are not static, but dynamic, and have and will change over time based on the necessity to adapt to market, global and political conditions. However, by implementing a range of measures and targets, the EU is making significant progress towards its goal of becoming climate neutral by 2050.

5.2 DECENTRALISATION

To analyse the centralisation versus decentralisation question, it is useful to compare the techno-economic character of both systems. As mentioned in the Introduction, fossil fuels are stored energy that can be used as needed but which require large investment in the extraction of them as well as their logistical management that is only possible for large energy companies and is therefore an inherently centralised technology. The intermittent nature of renewable energy however must be harvested when available. This leads to the necessity of integrated infrastructure that can either store or transport energy though interconnectors to other regions or countries where the energy is needed (Froggatt, 2020). As equipment and production costs for small scale renewables continues to fall, whole energy system parity is only likely to be achieved once integrated, smart energy systems or decentralised storage solutions are in place (Burger et al., 2020). Consequently, smart energy system (SES) technologies may inherently be more suitable for the decarbonisation goals and socio-technical solution than the fossil fuel-based system it replaces.

In the new decentralised system, the proximity to consumers of the energy production units makes it reasonable to assume that the complex coordination and integration involved in SES, whether at the operational and management levels, may have lower transaction costs in a decentralised system due to the more complex coordination with higher costs associated by conveying the adequate and timely level of information to a distant planning agency, whether industry or government (Hvelplund et al., 2020).

In both Burger at al. (2020) and Lund's (2014) books on the energy transition, they argue that as electricity diverges from the traditional model of large, centralized power generating units towards decentralised installations, we will also witness a change in ownership structures, moving from public ownership or large private entities who control the assets to a dispersed and fragmented ownership structure dominated by private individuals such as homeowners, farmers or energy associations such as municipal or community ownership models.

5.3 SMART GRIDS AND SMART ENERGY SYSTEMS

A lot of the literature focuses on the concept of the smart energy system (SES). This system deals with the large-scale integration of renewable energy and is seen as a way of approaching renewable energy systems. Smart energy systems are based on the idea of basing future energy systems on variable renewable energy sources (VRES) (Lund, 2014). According to Connolly et al. (2013) and Mendes et al. (2011) the main source of energy in the system will be from wind farms, photovoltaics, solar thermal, and other renewables and that this creates a large amount of VRES, especially in the form of electricity that may not timely meet the energy demand due to its variable production. A SES therefore needs to utilise system integration (Lund et al., 2012,) where all the different energy sectors are interconnected so as to create flexibility between supply and demand in 100% renewable energy systems.

A key component in the energy system is the electricity system and it will need to play a large role in the decarbonisation goals as more sectors become electrified and electricity demand is set to increase. Lund in his article "Smart energy and smart energy systems" (Lund et al., 2014) argues that the integration of the transportation and heating sectors into a SES can help alleviate the load bearing stress of the system and help establish a balance between production and demand and reduce problematic demand peaks. In another of his papers he goes on to give a formal definition of SES and states that “new technologies and infrastructures which create new forms of flexibility, primarily in the ‘conversion’ stage of the energy system” (Lund, 2017, p.560). According to him, the smart energy system is built around three smart grid infrastructures:

- Smart Electricity Grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.
- Smart Thermal Grids (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.
- Smart Gas Grids to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilized. (Lund et al., 2017).

All of the above authors have taken a whole systems approach to the research. However, others (and them as well) have often taken a sectoral or sub-sectoral approach to their research. This research can be split into the constitute parts of the smart energy grids system mentioned above. In the first place, research by Amin and Wollenberg (2005) investigates the use of heat pumps to convert excess electrical energy into heat, which can be stored in tanks, both in individual/residential housing and district heating plants. An analysis by Cummings et al. (2011) shows that the efficient use of thermal storage is more cost effective than electricity storage. Other authors who have investigated similar technical solutions are Hedegaard et al. (2012), who investigated the integration of wind power with household heat pumps, Fabian (2017) who investigates how combined heat and power plants (CHP) and heat pumps can help balance renewable power production and Miguel et al. (2017) who investigate the opportunities and shortcomings of battery technologies.

Heat saving strategies through insulation or better building designs as well as the importance of utilizing district heating plants for community heating are discussed by Person et al. (2014) and he argues that these heat saving will be vital in a low carbon future. The heating sector is one of the key sectors needing fundamental change to meet decarbonisation goals. Here, energy efficiency gains may facilitate reduced greenhouse gas emissions through a combination of highly efficient building designs, heat pumps as well as households as small micro generators of electricity (Kalogirou et al., 2016). In an article by Ayman (2014), he even defines the idea of a Net Zero Energy Building (NZEB) in which households exchange energy in certain hours but on an annual basis the net exchange should be zero.

Other papers have focused on using the batteries of electric vehicles as a storage system that allows for a bi-directional flow of energy to help balance the electricity grid and facilitate flexible demand and how this involves consumers in the operation of the power balance by using technological solution such as digitalisation or through economic incentives (Maarten, 2012, Willet, 2005). The technologies such as smart meters in households and sensors in the transmission and distribution networks are rapidly increasing the amount of information and the need to process it. The large amount of data collection in the future smart energy system raises security concerns, specifically over the privacy implication for these so called "prosumers" although some state that these concerns can be easily overcome (Wang et al. 2016).

The electricity supply industry is catching up with other industries through the digitalisation of the industry. The opportunities provided through data management technologies to be able to integrate micro-producers of energy into the balancing of the distribution network either as producers from rooftop photovoltaics or by releasing energy stored in their car batteries (Burger et al, 2020) and digitalisation may be a key technology to facilitate this. This so-called vehicle to grid (V2G) technology may play an important role in electricity grid balancing as all light vehicles (car and vans) are expected to be electric vehicles (Mathiesen, 2008), although Mathiesen argues that no single technology can solve the transportation "puzzle" in a feasible way. Large vehicles and aviation will still require gaseous or liquid fuels in the future and the ability to use excess wind and solar energy for the conversion of electricity into synthetic gases and "electrofuels", such as hydrogen, that can be used in power plants, combined heat and power plants as well as the transportation sector (Ridjan et al., 2013) can also help to mitigate the load bearing capacity of the electricity system.

Another source of low-carbon fuel is biomass that has been used for a while to produce gaseous and liquid fuels for vehicles. Biomass, however, has quite significant limitation regarding land use and food production as well as its limited production which will have to be supplemented by power-to-gas technologies (Ridjan et al., 2016). The use of "electrofuels" and "biofuels" may still play an important role in the energy transition because they can be easily stored in facilities such as gas tanks or in the gas grid (Connoly et al., 2016).

The industrial sector has not been covered in many academic articles, but the Danish Society of Engineers have made an attempt to estimate some of the benefits of integrating it into the smart energy system in their Energy Vision 2050 strategy paper (Matheisen et al., 2015). It argues that industrial waste heat can be utilised by integrating industry with the district heating plants mentioned above. Furthermore, the study estimates that industry will require not just green electrical energy but also green gas depending on the specific needs of different industries. In one study analysing how industry can decarbonise, the authors list three main categories of technical options for industry that include improved material efficiency, improved energy efficiency, and transforming to a less carbon intensive energy supply or carbon capture and storage (Ahman et al., 2015).

The above-mentioned papers regarding smart energy systems and smart grids all emphasise the importance of integrating the different parts of the energy system. These new technologies and infrastructures create new forms of flexibility, primarily in the conversion stage of the energy system. This has traditionally been achieved from a simple linear approach (i.e., fuel conversion to end-use), but in the new system, a more integrated approach is required (Lund, 2020). This simply means that by combining the electricity, thermal, and transport sectors so that flexibility in each sector can compensate for the lack of flexibility from VRES. The approach to a smart energy system is best done as a whole systems approach and not by looking at only one sector at a time. In this way, we should be able to find the optimal solution for the total system, as well as the best solution for each individual sub-sector. Henrik Lund, a Danish expert on renewable energy systems and other academics such as Davod Connolly have discussed several energy synergies and based on their work, I have compiled a list of their smart energy system synergies (Lund, 2013, 2014, 2020, Connolly, 2013).

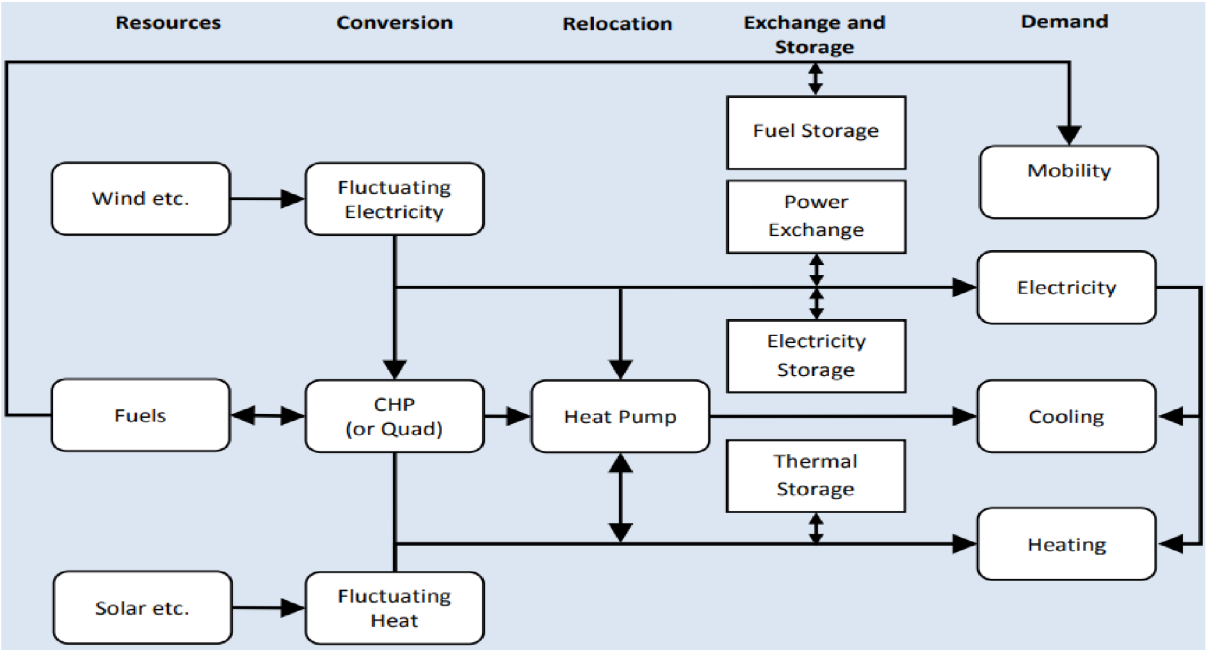
Such synergies include the following:

- Excess heat from industry and electricity production can be used to heat buildings via district heating.

- Electricity for heating purposes makes it possible to use heat storage instead of electricity storage, which is both cheaper and more efficient. Moreover, it provides a more flexible combined heat and power (CHP) production.
- Heat pumps for heating can be used to provide cooling for district cooling networks and vice versa.
- Electricity for heating may be used for balancing power and electric grid services: for example, in regulating power markets.
- Biomass conversion to gas and liquid fuel needs steam, which may be produced on CHP plants, and produces low-temperature heat, which may be utilized by district heating and cooling grids.
- Biogas production needs low-temperature heat which may be supplied more efficiently by district heating compared to being produced at the plant.
- Electricity for gas such as hydrogenation makes it possible to use gas storage instead of electricity storage which is cheaper and more efficient.
- Energy savings in the space heating of buildings make it possible to use low-temperature district heating which, in addition, makes it possible to utilize better low-temperature sources from industrial surplus heat and CHP.
- Electricity for vehicles can be used to replace fuel and provide for electricity balancing.

To fully understand how these synergies would work in a fully integrated smart energy system, I have used Fig. 1 below from Connolly's 2013 paper "Holistic and Integrated Energy Systems for the era of 100% Renewable Energy" (Connolly, 2013).

Figure 1. The smart energy system



Source: Connolly et al. (2013). Smart Energy Systems: Holistic and Integrated Energy Systems for the era of 100% Renewable Energy.

5.4 REGULATION

The above-mentioned key trends of competitiveness of renewables, the rising role of decentralised supply and storage, decoupling growth and energy intensity, enhancing local value creation, and digitalisation as an enabler of smart grids and new business models describe the uncertainty policy makers and company leaders are facing. First of all, smart energy systems will require a multifaceted governance system that promotes investments in, and the management of integration technologies. This begins with the development of incentive schemes to facilitate investments into wind and solar farms, district heating, heat pumps, storage systems, rooftop photovoltaics, and solar heating, and these should be structured to deal with the intermittent nature of renewable technologies (Ridjan et al., 2013). In later stages of the energy transition, the establishment of infrastructure for electric vehicles, wind and solar to gas systems, geothermal and other sources will ned to be fully integrated to achieve the EU's decarbonisation goals.

All of this will inevitably need to be placed under a regulatory regime. As seen at the beginning of the section, there already exist legally binding emission reduction targets as well as some market-oriented regulations such as the Emissions Trading System (ETS) and funding mechanisms all within the EU's Green Deal framework and this has led to a rise of renewable energies. Each country too must develop a legal/regulatory regime. What technologies are implemented and in which quantity and well as the ownership structure of the future energy system are dependent on legislative and economic incentives and considerations. States must consider two fundamental questions when developing their regulations. First, what technological options are constrained by the resources available to them (Kooij et al., 2018)? Secondly, how are technological implementation and ownership possibilities related (Hvelplund, 2014)? For example, it has been estimated the 47% of the installed renewable energy capacity in Germany in 2012 was owned by citizens (Yildiz, 2014). Citizen participation is a key aim of the EU in the energy transition and so policies and regulation that seek to empower citizens either as the final consumer of energy (energy efficiency gains) or as the producers in the SES (economic gains) are key to achieving the EU's decarbonisation goals. Regulations and financing together with the technological aspects of the smart energy system discussed above are the main components when moving towards the clean energy future. Governments have thus far offered generous subsidies for the manufacturers of renewable technologies, and this helped to scale their production and drive down cost. There have also been subsidies for households to buy heat pumps and photovoltaics. Now, however, as renewable energy is making up an ever-larger share of the energy system, politicians will have to find a way how to maintain a resilient system when most of the energy in the system will come from intermittent, weather dependant and decentralised energy supply.

Many authors studying the energy transition and decentralised energy have used a three-phase framework that places the technological and regulatory challenges into the different stages of the energy transition (Lund, 2014, Burger, 2020, Hvelplund and Djørup. 2020). In the Danish case, phase one includes the introduction of regulatory incentives for the deployment of renewable technologies such as feed-in tariffs (FITs) based on fixed prices per kilowatt hour fed into the electricity grid, especially from wind energy generation (Burger et al, 2020). These FITs contracts have a long-term horizon that offer priority access to the energy network and help to reduce the risk for investors and help gain access to finance. In this phase, the goal is to direct investments into renewable technologies that would not be competitive in a market-based approach with the cost passed on to consumers by their electric utility or directly subsidized by the government (Cox et al., 2016). The Danish government also put in place ownership regulations meant to encourage local ownership of the new technologies and to garner local support (Lund, 2014). Another interesting example in the case of Denmark in the first phase was the combination of renewable energy and industrial policies. The Danish wind turbine industry has greatly benefitted from direct and indirect subsidies and support schemes that the government implemented to promote the developed of a domestic wind turbine industry (Lipp, 2007). The Danish wind turbine manufacturer Vestas developed through the support of these domestic polices and is still one of the largest wind turbine producers in the world with 164 GW of wind turbine capacity installed in over 80 countries around the world (Vestas, 2023). This is an excellent example of where public and corporate interests have been aligned.

In phase two, as the cost of renewable technologies fall, policy makers must adjust their incentive systems as renewable technologies become more widespread. For the early mover countries like Denmark, this involves the cancellation of earlier subsidy schemes and moves towards more market-based mechanisms, such as auctions, as well as changes in the ownership regulations to facilitate a more widespread deployment of renewable technologies (Hvelplund, 2020). As the transition moves through phase two, regulators and governments also develop a better understanding of decisions they must make if they want a cost-effective approach to the renewable energy system as renewables make up a larger percentage of the energy system. In this current phase of the Danish energy transition, new governance frameworks are implemented in order to ensure stable market conditions that encourage innovation and the entrance of new market actors. As seen from the above research, this includes the integration of the different energy systems into the smart energy system which involves the electric, thermal, and transportation sectors (Connolly, 2013) and requires the management of the expectations of the various stakeholders to enable the adaption to the new circumstances which must include their participation.

In the third phase of the energy transformation, decentralised renewable technologies now become the dominant source of energy in the supply structure. While no countries are yet there, Denmark now experiences long periods in the electrical supply when renewable energies account for the main source or even produce an abundance of renewable electricity. This has consequences regarding the price of electricity where excess electricity is often sold to neighbouring countries at a relatively low price due to the almost zero marginal cost structure (Djorup, 2018) that leads investors to hesitate in investing in new renewable energy projects in a market system. We can conclude from this that the phase three smart energy system will be defined by its flexibility and that the governance system will require further adjustments in their market design, network rules, incentive and tariff policies (and others) for the coordination of the decentralised energy system in a decarbonised economy.

As a final reflection based on the literature, there seems to be quite a lot of research done into smart energy systems and the technological choices facing individuals, companies and governments moving towards a low-carbon future. Different states are at different stages of the energy transition and must cope within their respective national conditions and circumstances. The transition offers many potential benefits, but who realises these benefits may be key to fulfilling the climate change goals. Concerns over the ownership structure of the future SES may lead to biased discourses about the appropriate technological choices each state makes. It can be deducted that each stakeholder in the system will argue in their own self-interest, whether these be the large energy corporations that have owned the energy system so far or the new citizen ownership models that may make more sense in a decentralised system. In this regard, an analysis on the ownership of different types of technologies will be helpful to support the decision-making processes of different institutions in diverse states and that is exactly what I will do in the following section, using Denmark as a case study into these exact issues. The question then is, what characterises the organisational and economic requirements linked to the development and implementation of smart energy systems and what are the appropriate legislative and economic incentives needed to transition to a low carbon economy?

6. RESULTS AND DISCUSSION – THREE STAGES OF THE DANISH TRANSFORMATION

The transformation from a centralized to a decentralized energy system entails technological innovation and regulatory incentives for their implementation though entrepreneurial initiatives. Generally, there are three broad phases in moving from the traditional high-carbon, fossil fuel-based energy system to one based on renewable energy and energy efficiency. That is not to say that all countries will need to move through all three phases. Indeed, the work of other states and organizations may well make it possible from many states to skip phase one and perhaps move through phases two and three at the same time. This may well be the case as states are not energy islands and as the European Union continues to develop its single energy market, cross border trade in energy sources have the potential to mitigate disruptions to national energy supplies when moving through phases two and three.

Denmark, however, is one the first mover countries in the energy transition and has played a key role in developing first phase technologies and the development of the institutional know-how necessary for the implementation of the energy transition (Hvelplund et al., 2019). Denmark is also a member of the EU and does engage in international trade in energy and this is having a profound effect as Denmark moves from phase two to phase three. The socio-institutional develop within Denmark therefore make for an interesting case study for countries seeking to transition their own societies towards a low-carbon, decentralised future. Denmark's experience in establishing new regulatory frameworks, incentive mechanisms and various ownership structures can be very insightful for other countries during their transition, especially those within the EU that must operate within the EU's framework agreements and oversight. All EU member states have their own specific conditions, cultures, histories and institutions and I am not attempting to claim that other states can simply copy the Danish model. What I am stating however is that the socio-technical and socio-institutional experience and know-how gained by Denmark can be very useful for states seeking to develop their own regulatory frameworks and incentive mechanisms and due to Denmark's first mover and detailed strategy plans, these states even have the potential to "catch up".

In this section I will examine Denmark's institutional arrangements and implemented regulations that have so far been quite successful in its energy transition. I will focus on governance as an enabler for the implementation of new technologies as well as the importance of governance related to the socio-economic aspects that have so far made the transition feasible and with citizen support. This analysis covers a long period of time that have seen quite a few “hiccups” as political winds changed. This is an inevitable part of the democratic process where different stakeholders in a society have competing interests that are represented by different political parties who when in government often change or adjust regulations and incentives mechanisms that represent the interests of their supporters and so this will also be analysed in this section.

As mentioned above, there are three broad phases in the energy transition, and this is how I will organise this section. In the Literature Review, I outlined many of the technologies and regulations required for the energy transition and these can be roughly grouped into the three phase frameworks as:

- Phase 1: the niche deployment of decentralised renewable energies; feed-in tariffs (FITs) and incentive schemes; support for the renewable technology industry.
- Phase 2: renewable energy rises to become a major player in the energy supply industry; moves towards a market-based system; new governance framework to encourage the new flexibility requirements.
- Phase 3: renewables are now the dominant player within a flexible, well integrated energy system; energy storage becomes a priority, new market designs.

Therefore, this section will be organised into sub-sections comprising the three phases of the energy transition in Denmark. The first sub-section will analyse the period between 1975 and 2000; the second sub-section from 2000 to the present and will make up the largest part of this section; and for the third phase, I will analyse some of the technical and socio-institution factors and policy recommendations proposed to help Denmark achieve its ambitious 100%t renewable energy goals by 2050.

6.1 PHASE ONE: 1975 TO 2000 – FROM THE OIL CRISIS TO RENEWABLE ENERGY TECHNOLOGIES

6.1.1 THE 1973 OIL CRISIS

Denmark has had a longer experience in implementing renewable energy than most countries. It was spurred on by the energy crisis starting in 1973 because of Denmark's reliance on imported fossil fuels, mainly from the Middle East. While the full geopolitical context of the energy crisis is beyond the scope of this paper, Western support for Israel during the Yom Kippur War led the Arab Organisation of Oil Producing Countries (OAPEC) to decide to reduce the oil supply which coincided with the Organisation of Petroleum Exporting Countries (OPEC) efforts to increase oil prices (Rüdiger, 2014). By the 1970s, Denmark's energy system could be characterised by its large, centralised power production units and combined heat and power plants which had become popular to build in the 1960s with both mainly powered by oil imports. Indeed, by the time the energy enfolded in 1973, 90 percent of Denmark's energy consumption was based on oil, and 90 percent of the oil was imported from the Middle East (Rüdiger, 2014).

In hindsight, this dependence was obviously problematic and had made Denmark extremely vulnerable to fluctuations in the global oil market. The political class at the time were aware of the problem but seemingly enable to implement policies to reduce the threat of dependence of Middle East oil. This was a time of political conflict and uncertainty in the Danish political system as well as global economic challenges such as inflation, and also coincided with Denmark's entrance into the European Community (EC), the precursor to the European Union. Nevertheless, efforts to tackle the energy crisis and the realization of the need to develop a national energy policy won the support of all the responsible political parties of the time (Lidegaard, 2009). It became clear to the policy makers of the time that there was an imperative to establish national energy goals and a new regulatory regime to enable the construction of a more diversified energy supply. This is quite an interesting fact, that the beginning of the energy transition in Denmark did not begin as a response to climate change and with decarbonization goals in mind, but rather as a response to the oil crisis and Denmark's inherent need to diversify its energy supply. However, as the first stage moved forward and with ever increasing CO2 emissions, Denmark's and the EU's climate change mitigation goals became the main driver for the energy transition in the second phase as we will see below.

In order to understand how the Danish energy policy evolved, it is important to be aware that the establishment of a concrete market design occurred in a political setting consisting of different ministries, various lobby groups and the specific balance within the Danish parliament. These different actors all have their own beliefs about how the economy should function and their own understanding of political economy. The conflict between these “interest” groups shaped and continues to shape Danish energy policy. The interest groups that will be discussed include The Ministry of Finance, the Ministry of the Environment, the Ministry of Climate and Energy, the trade unions, Danish Energy Association (mainly fossil fuel-based energy production), the political parties and the environmental NGOs.

The beginning of the first phase may be characterised as a conflict between a centralised model of development based on the interests of the large fossil fuel companies, and a decentralised model of renewable energy development favoured by Danish NGOs, innovators developing new technologies and small industrial companies (Kooij et al. 2018). During the 1970s and the early part of the 1980s, the status quo of the centralized energy policy was supported by the majority of politicians well as the Association of Danish Industries (Burger et al. 2020) supported by fierce lobbying by the large power companies. These organizations supported the neoclassical approach to political economy where there should not be any direct support for renewable energy and that new technologies should enter the market when they are ready to be competitive even though they acknowledge the external environment costs of fossil fuels (Hvelplund, 2013). They argued that wind power and renewable energy were too expensive and therefore unrealistic and instead favoured traditional sources such as coal or the development of nuclear power generation to diversify the energy mix. However, the oil crisis made it clear to some policy makers that the energy sector could no longer be left to just market forces and that a national energy strategy and regulatory framework were necessary to guarantee energy security. This led to a significant government intervention in the energy sector such as the regulation of the energy mix as well as questions about how to decouple economic growth from energy consumption which had shown a strong correlation up to that point (Rudiger, 2014).

Policy proposals of the time can be divided into two groups; immediate government interventions to reduce the consumption of energy and strategic plans that would eventually lead to the restructuring of the energy supply and a more diverse energy mix. To reduce the consumption of energy, the government implemented policies that sought to change the behaviour of consumers such as subsidies for housing insulation, the lowering of room temperatures and speed limit reductions. These policies were accompanied with public awareness campaigns, but Rudiger suggests that the reductions in energy consumption was mainly a result of the high energy prices that led to changes in behaviour in the consumers' best interest, and not due to government interventions (Rudiger, 2014), although the effect of high prices was noted by the government and used in future tax regimes as a way of modifying consumer behaviour.

The strategic response was focused on long-term supply security and involved many government interventions in the market and regulatory frameworks to achieve the state's goals. The strategy's formation was outlined in four published papers in 1974, 1975, 1976, and 1979. The first task set out to redirect energy consumption from imported towards domestic energy sources. As the Danish Ministry of Energy at that time still believed that renewables would not become a reliable energy source quickly, they instead encouraged private companies to explore the Danish parts of the North Sea for natural gas reserves that could fuel the energy system and to use domestic coal resources. Although Denmark never found large natural gas reserves, their potential at the time led to the decision to construct a national gas grid with the fully state-owned natural gas company, DONG Ltd., responsible for its construction and for the distribution of the gas. Another tool enacted by legislation in 1976 gave the state the right to force energy suppliers to use certain types of fuel, mainly by replacing oil for coal (Wistoft in Rudiger, 2014). The strategy also called for the continued expansion of combined heat and power (CHP) plants that use waste heat from the production of electricity to heat homes and buildings. CHP is an inherently decentralised system due in part to its technical limitations, but its expansion was mainly as a result of local political support (Pedersen, 2017). This happened despite the opposition of the tradition power companies, but it should be noted that at that time, CHP stations were using mainly coal and coal gas as the input energy source.

The result of the oil crisis was a new regulatory regime with increased state intervention in the energy markets. This regulatory regime, combined with improved energy efficiency and a focus on energy savings, make up the permanent result of the crisis. Furthermore, by this time Denmark had become one of the world's most CO_2 emitting countries per capita and this coincided with the new awareness of the effects of CO_2 emissions on climate change which cumulated with the

Brundtland Report of 1987 (World Commission, 1987) and later with the establishment of the United Nations Framework Convention on Climate Change in 1992 (UNFCC, 2023). The growing local, national, and international awareness of environmental degradation and climate change led to another change where sustainability became the determining issue of Danish energy planning.

In this latter part of the first phase there is a change in the balance of the political economy away from the neoclassical approach towards what Hvelplund calls “The Innovative Democracy Approach” (Hvelplund). He notes that this paradigm appreciates that market rules are designed in political processes and that these political processes sometimes have to be redesigned, here implicitly, in order to overrule the powerful interest groups supportive of the fossil fuel dependency path inherent in the market conditions of the time. This change represented a shift from the top-down approach to a bottom-up approach to institutional reforms and was supported through considerable pressure from grassroots movements (NGOs), local district heating cooperatives and some members of the Danish parliament. In the late 1980s and 1990s this led to an increased expansion of decentralized energy technologies which will be examined in more detail in the following sub-section.

To conclude this sub-section, it is important to analyse some failures in the government interventions. One such failure at that time was the inability to include nuclear power into the energy mix. This was due to conflicts between the state and the utilities, as well as popular protests after the Three Mile nuclear incident in the USA in 1979 (Peterson in Rudiger, 2014). This led to a postponement of decisions regarding its implementation until in 1985 it was finally dropped from Danish energy planning. The International Energy Agency’s (IEA) recommendation at this time for states to create strategic oil reserves was also a failure, with Rudiger arguing this was because the state-owned oil and gas company (DONG Ltd.) that was instructed to buy these reserves had to pay higher prices than the international oil companies demanded of their subsidiaries (Rudiger, 2014). One last important failure already mentioned above was the failure to find domestic oil and gas resources in the Danish parts of the North Sea. Although this may be considered a failure in that the government wasted time and resources, if they had found large reserves, they may well still be relying on them today thus making the transition more difficult. Furthermore, the construction of a national gas grid did lead to Denmark eventually transitioning to “cleaner” natural gas as its primary energy source and this still has implications for the smart energy system discussed in later sections.

6.1.2 RENEWABLE ENERGY TECHNOLOGIES

From the late 1980s, the focus shifted from energy security by any means to energy security through the development of cost efficient and well-functioning single renewable technologies such as biogas plants, wind turbines, solar heating technologies, and others. Denmark was one of the first countries in the world to officially commit itself to CO_2 emission reduction goals in its 1990 action plan “Energy 2000” (Danish Energy Agency, 2015). The plan was sent to parliament with a target of a 15 per cent reduction in energy consumption and at least a 20 per cent reduction in CO_2 emissions by 2005. This was a milestone in energy policy, as climate and energy policies were integrated. In Denmark, one of the ways of achieving these goals was through the development of wind turbine industry which had a long tradition in Denmark. While the 1970s oil crisis led to many countries taking up research and development in this field, Denmark has been quite successful in developing this industry. Meyer in his article “Danish wind power development” claims this was due to the Danish model of building simpler small wind turbines before scaling them up and also because the development and production was carried out by relatively small companies with a single focus of wind turbine development all with a certification system to ensure quality (Meyer, 1995). Of course, state support has also been essential, especially after the end of the oil crisis when prices decreased significantly and the economic case for developing wind power meant many states and companies gave up on it. He also lists the Danish strategy for the promotion of wind power which combines the different elements but is listed below:

- long-term government support for research, development, and demonstration.
- national tests and certification of wind turbines.
- government-sponsored wind energy resource surveys.
- utility liberalization and buy-back agreements and regulations.
- long-term utility obligations for investments in wind power.
- long-term market stimulation incentives; and
- government energy planning processes with national targets. (Meyer, 1995).

The strategy began in 1977 with a programme for the development of wind turbines with the support of the national government and electric utilities. At the same time, some small and medium-sized industrial firms began the development of small-scale wind turbines to be used by private individuals. Furthermore, to support the new and vulnerable industry, a Danish testing programme was set up along with a formal certification regime to prevent sub-standard technologies from being marketed at home and abroad and to ensure the reputational value of Danish wind turbines. The success of these programmes is evidenced by the Vestas. It is one of the world's leading manufacturers of large-scale wind turbines, with a global share of 16%t and has installed more than 43,000 wind turbines in 66 countries on six continents (Vestas, 2023).

The development and implementation of wind power generation did not happen automatically, but as a result of 20 to 30 years of technology development since the mid-1970s. By 1992, more than 3,000 cooperative owned wind turbines were installed with each cooperative typically with small turbine of between 100-300 kW in electric power production and with anywhere from 20-60 owners. Hvelplund states that this was mainly as a result of lobbying by the Organization for Renewable Energy, a green NGO which fought for the cooperative model (Hvelplund, 2013). The model gained stable public support for wind power, and also helped the Danish wind power industry survive during the vulnerable years when the industry lost its export markets due to the reduction of global oil prices already mentioned above. In the latter part of the first phase, the share of wind powered electricity production grew to 13 per cent of total electricity consumption and wind turbines were now ready for large-scale deployment with large turbines of about 2-3 MW of capacity (Hvelplund, 2013).

One of the most important policies for the implementation of wind energy was a type of feed-in premium system for wind power sold to the public grid. Already in the late 1970s the first agreement was set up between the Association of Danish Electric Utilities and the Danish Wind Power Association. This agreement was renegotiated many times and in 1984, the Danish Parliament passed a law stating that utilities would receive a payment equivalent to the tax on electricity (Meyer, 1995). These feed-in premium agreements were complimented with another important policy, namely "The Electricity Supply Act" of 1985 which was based on another agreement between the Ministry of Energy and state-owned energy companies to increase electricity generation from wind turbines in pilot projects. The aim of the agreement was to allow for the cost of development to be included in the consumer electricity price, while the energy companies made large developments in terms of professionalising the wind energy industry (Meyer, 1995). In 1992, subsidies for electricity production from wind turbines were introduced, as well as state support for the completion of the district heating network and to promote the decentralised cogeneration and utilisation of bioenergy. The support for wind turbines was in the form of a fixed feed-in tariff, as at the time there was not an electricity market and generators received a constant price for generation.

It was also decided at this time that shares in wind turbine ownership should be local and distributed to many owners and so two important financial incentives were set up to facilitate this. The first was a tax refund of 0.27 Danish kroner per kWh and the other was a 30% reimbursement of the turbine's purchase price for private citizens who installed wind turbines from the Danish government (Meyer, 1995). This subsidy was reduced over time as the wind power economy improved during the 1980s until it was finally eliminated in 1989. The main condition to receive this subsidy was that turbine owners had to live within a 9 km radius from the turbine, and by the mid-1980s between 120 000 and 140 000 citizens had become local wind power shareholders (Gorrono-Albizu et al., 2019). Another government intervention was the necessity for electric utilities to commit to installing wind farms with agreements to install 100 MW signed in 1985 and 1990 (Meyer, 1995). These state interventions and incentive mechanism no doubt helped to contribute to the development of the wind turbine industry and reduce investment costs. Indeed, these policies gained strong and widespread public support resulting in parliamentary support for wind energy in spite of opposition from the traditional fossil fuel companies which allowed the Danish wind industry to begin to export its technologies beginning again in 1992 and by 2000 had achieved a 30-40% reduction in the cost of wind power electricity (Gorrono-Albizu et al., 2019). The innovative democracy approach allowed for systemic public interference in the energy market and broke the barriers to entry for wind power technologies.

The development and increasing share of wind power in the energy mix was accompanied with the use of cogeneration combined heat and power plants due to their flexibility in producing energy. A new Energy Agreement in 1986 mandated that the energy companies should carry out a demonstration program to develop 450 MW of decentralised CHP plants, which should be based on domestic fuels such as natural gas, straw, wood-based biomass, waste, and biogas (Meyer, 1995). These decentralised CHPs based on biomass were a new technology, and as such, the agreement mandated a demonstration program to gain the technical and economic experience necessary for wider expansion. CHP plants had thus far been mainly coal-based CHP units used in locally owned district heating systems and by 1988, all cities in Denmark with a population over 60 000 inhabitants had CHP units (Burger et al, 2020). In 1989, with a new Minister of Energy, the new energy plan "Energy 2000" claimed a much higher potential (1 400-2 000 MW) of CHP technology than had until then seemed feasible. This entailed a goal of converting coal-fired district heating plants to gas fired decentralised CHPs before 1996 and led to an expansion of combined heat and power (CHP) systems based on biomass and natural gas into smaller cities and villages. In June 1993, an Energy Agreement to promote biomass was made. This included a requirement to use surplus straw and wood chips for fuel. The main thrust of the agreement was a focus on converting large, central CHPs to biomass, starting with co-firing coal thermal plants. Then, newer plants would be installed with the aim of being solely biomass-fired, while simultaneously starting a large research program in order to bring down costs. At the same time, burning biomass on the land was banned. This was accompanied by some institutional changes including an obligation for utilities to purchase electricity from CHP plants according to “avoided cost” pricing based on the principal of long-run marginal costs as well as a “low CO_2 emission” subsidy of 0.0013 EUR/kWh given to municipal natural gas-based cogeneration plants (Lund, 1994). These concrete institutional reforms were enabled by the new Minister’s Energy 2000 plan and the Energy Agreements which were supported by grassroot organisation and community ownership cooperatives and is another example of the innovative democracy approach. Furthermore, these reforms had a huge effect, with power production from decentralised CHP increasing from 1% in 1990 to more than 30% by 2001 of total electricity consumption, and with around 60% of these CHPs organised as cooperatives and owned by the residents of small towns and villages (Lund, 1994).

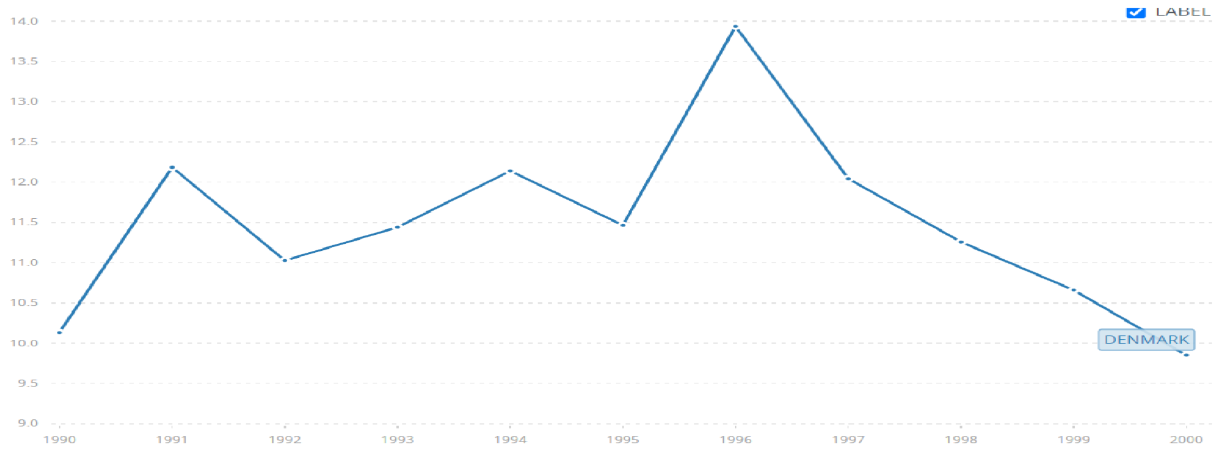
In the latter half of the 1990s, the EU Commission issued a number of directives aimed at gradually opening up the European power systems to market competition and to be part of the EU’s internal market. The First Energy Package for electricity was adopted in 1996 and set the stage for the liberalisation of European electricity markets, including Denmark’s (EU Fact Sheet, 2023). Denmark had a long and strong tradition for non-profit consumer and municipality ownership. Up until 2004, 100% of the distribution electricity infrastructure was owned by consumers and municipalities (Burger et al, 2020). At this time, power plants were sold and subjected to market competition on the Scandinavian Nordpool market. Somewhat ironically however, these assets were sold to the Swedish and Danish state-owned power companies, Vattenfall and DONG respectively, and so changed from consumer and municipality ownership to state ownership. The other major part of the energy infrastructure, the distribution network, at this time remained consumer and municipality owned and subject to a non-profit regime. The natural monopoly distribution system operators (DSO) generally do not have to right to use profits for purposes other than lowering prices for consumers, although they can charge for maintenance costs. Hvelplund calls this a kind of double regulation that, "by means of a combination of a non-profit regulation and consumer ownership, provides an incentive for low prices" (Hvelplund, 2013).

Consequently, the popularity of local ownership meant that proposed new energy plants in Denmark, particularly in regard to wind farms and CHP units, faced consumer opposition if not locally owned. In the first phase, wind power and energy conservation were driven to a large extent by small industries and energy NGOs with persistent resistance from the large, traditional fossil fuel companies and the Danish Association of Industries (Sonderriis in Hvelplund, 2020). This is an example of the close stakeholder engagement in policy development between the Ministry of Energy and the energy companies, through discussion with the relevant actors in society who were supported by NGOs and others without a vested interest in fossil fuel technologies, with the political goal of increased socio-economic welfare and environmental benefits. This has been referred to as the innovative democracy approach. In phase two where renewable energy production begins to make up a significant share of the energy mix, the conflict between the different interest groups again becomes problematic. This conflict revolves around the large power companies that seek to own the new technologies, and the consumers living near new power plants that only tend to accept their construction if they get a significant share in ownership (Linnerud et al., 2019).

6.1.3 SUMMARY OF PHASE ONE

In summary, Denmark started the first phase during a global oil crisis where the emphasis was on diversifying its energy supply with a specific focus on developing domestic energy resources in order to secure energy security and cut its dependence on Middle Eastern oil imports. Some of the government policies and initiatives such as the exploration for oil and gas in the North Sea or the development of nuclear power did not work out for reasons already mentioned above. This initially led to the short-sighted replacement of oil imports with regionally sourced coal. However, after the Brundtland Report was published, a new awareness of the impacts of fossil fuels on the environment and changing political winds with the inherent institutional reforms, and the growth of the innovative democracy approach, began the process of decarbonisation of the economy and the expansion of wind power and CHP plants. As can be seen from the graph below and perhaps expected, CO_2 emissions barely decreased between 1990 and 2000 (earlier statistics unavailable), but clearly show a declining trend after 1996. That is consistent with the analysis above that shows the acceleration of wind power expansion at that time.

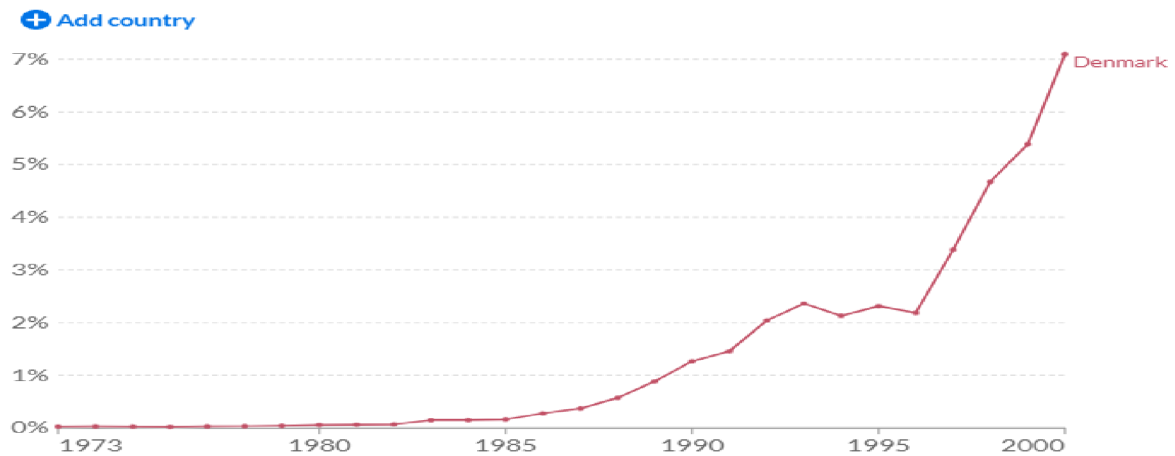
Figure 2: CO_2 metric tonnes per capita; Denmark 1990-2000



Source: World Bank, 2023

This declining trend of CO2 emissions negatively corresponds with the growth of renewable energy in the total energy mix reaching over 7% of total energy production by 2000.

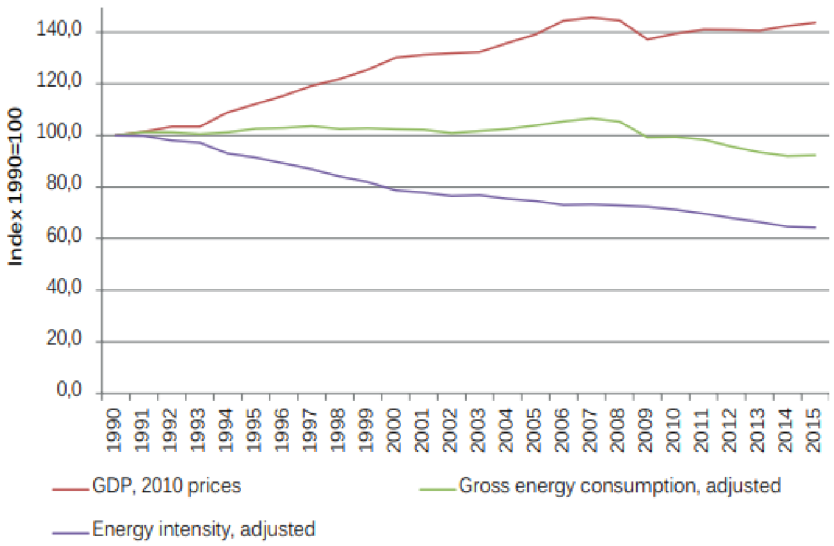
Figure 3: Share of primary energy from renewable sources.



Source: Our World in Data: Renewable energy sources include hydropower, solar, wind, geothermal, bioenergy, wave, and tidal. https://ourworldindata.org/energy/country/denmark

Furthermore, in this phase the Danish economy continued to grow which proved that it was possible to decouple economic growth from total energy consumption as during this period energy consumption remained steady which led to a decline in the energy intensity of the economy.

Figure 4: Energy Consumption, GDP and Energy Intensity, Denmark 1990-2015



Source: Danish Energy Agency (2017)

Despite some uncertainties in the first part of phase one on the direction of Danish energy policy, these indicators show that the implemented policies and regulatory changes in the second part of phase one enabled Denmark to begin its energy transition to green renewable energy sources all the while maintaining electricity prices for industry that were 18% lower than the EU average and household prices comparable to other EU member states without taxes included (European Communities, 2005). These trends were leading the way towards the second phase where the expansion of wind power and combined heat and power system accelerated.

6.2 PHASE TWO: 2000 TO THE PRESENT

In phase two of the energy transition, Danish electricity prices for industry remained lower than the EU average and therefore, there are good reasons to believe that the low Danish electricity prices including subsidies for renewable energy have made space for the extra costs of a first mover introducing the new renewable energy technologies years before they reached technological and economic maturity (Hvelplund et al, 2019). After quite significant success in the first phase however, Denmark in the second phase began to face the firstcomer challenge of having an increasingly large proportion of fluctuating energy sources and an increasing need to establish infrastructure systems that are able to incorporate fluctuations in large amounts of wind power

(Lund, 2009), and to establish reserve capacities for periods without wind. This is not only a technical challenge, but also a policy design challenge, and Denmark developed some policies that made it possible to establish such infrastructures based on the know-how acquired as a technological and regulatory first mover with renewable technologies and for their expansion.

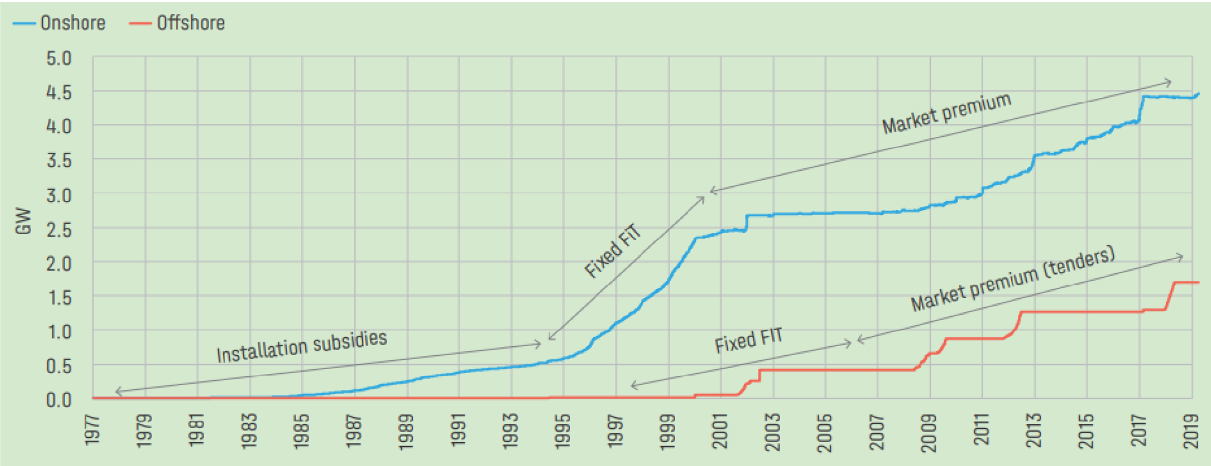
The new millennium started off with the liberalisation and reform of the electricity sector which was mandated by the EU with monopoly-based power production ownership changing to a market-based competitive system. In Denmark's case, this meant that power plants were now able to trade on the newly created day-ahead market, Nord Pool. The reforms were based on the premise that power plants could now trade electricity between different regions and that electricity generators could sell for a higher price in neighbouring countries and consumers could access a larger pool of generators and thus lower prices. This move towards the neoliberal market models saw the end of the innovative democracy process and a "non-policy" relying on existing market actors and existing market conditions was implemented. In this period the development of renewable energy was almost brought to a halt (Lund, 2014).

The following sub-section will investigate the legal and institutional changes and their implications for wind power development in this period. This will include discussions regarding the important role of policy makers in establishing a regulatory framework and incentive mechanisms to achieve a low carbon energy future at affordable prices. This will inevitably require an analysis of the socio-economic characteristics of the Danish energy system and the contemporary regulatory regime which will be analysed by investigating the ownership structure of wind turbines and district heating plants. This is followed with a sub-section on the opportunities for the integration of heat and power systems when renewable electricity generation reaches between 40-50% of total energy consumption along with some of the problems in implementation.

6.2.1 LEGAL AND INSTITUTIONAL CHANGES: WIND POWER DEVELOPMENT

At the turn of the millennium, onshore decentralised wind development slowed considerably as compared to the impressive growth of the 1990s. This was mainly attributed to two factors. The first was that with the newly established Nord Pool electricity market, the feed-in tariff support system for wind energy was replaced with a market premium subsidy. Henceforth, renewable energy producers were paid the market price for their generation plus a premium on top (Lund, 2013). This new system led to increased uncertainty of the electricity prices and coupled with very low prices in the Nord Pool market due to overcapacity which caused the business case for onshore wind to be less attractive. Secondly, the new European market led investors to more attractive markets in places such as Germany and the UK (Lund, 2013). Large, offshore wind project plans began to develop however, and in 2004, a new Energy Agreement was reached in Parliament, introducing the concept of an offshore wind tender.

Figure 5: Cumulative Installed Capacity of Wind Power in Denmark, 1977-2019



Source: Danish Energy Agency (2020)

In 2005, two important institutional changes occurred. The first was the introduction of the EU's Emissions Trading System (ETS) to combat climate change. The system worked according to the "cap and trade" principle, where a cap is set and reduced over time, and companies could trade from a finite number of emissions allowances (European Commission, 2023). The other important change was the creation of a national, state-owned transmission system operator (TSO) Energinet.dk that replaced the previously consumer and municipality owned system (Energinet.dk, 2023). A Transmission System Operator (TSO) is an entity entrusted at a national or regional level with the transport of energy in the form of natural gas or electricity over a fixed infrastructure whereas a Distributed System Operator (DSO) organizes a local market while respecting an exchange power schedule agreed with the TSO. Another change occurred in 2006, with the merger of six power companies: DONG, the electricity producers Elsam, Energi E2, and the public electricity distributors Nesa, Copenhagen Energy and Frederiksberg Utility, which resulted in the formation of the company DONG Energy (Orsted, 2017). This was a major merger, meaning that one company generated around 60 per cent of the power of Denmark at that time and was 81% state owned with

19 % remaining in the hands of Elsam and Energi E2 shareholders (Dong Energy, 2006) This new company had the capital necessary to invest further in offshore wind. These institutional changes and the movement towards large-scale offshore wind farms represent a more centralized model of energy production. DONG Energy portfolio at this time was 85% based on fossil fuels which made it one of the most coal intensive companies in Europe, responsible for about a third of Danish greenhouse gas emissions (Orsted, 2022)

In 2007, leaders across the EU established targets for an integrated approach to climate and energy policy that would tackle climate change, while increasing the EU's energy security and strengthening its competitiveness. This resulted in what is commonly known as the "20-20-20" targets, where a series of targets to be met by 2020 were agreed to by EU heads of state and governments. These included:

- 20 per cent cut in greenhouse gas emissions (from 1990 levels).
- 20 per cent of EU energy to be sourced from renewables.
- 20 per cent improvement in energy efficiency (EEA, 2023).

These targets were enacted in legislation in 2009 making them legally binding. They were however set as an average for the EU as a whole and distributed among countries depending on their starting point which meant that Denmark had to meet an even higher target. The Danish 2008 Energy Agreement set the country's target of sourcing 20 per cent of energy consumption from renewables by 2011 and 30 per cent by 2025. The medium-term goal of the agreement was to reduce consumption of fossil fuels by at least 15 per cent by 2025, with the long-term goal of the agreement to make Denmark completely free of fossil fuels. The agreement also included new additions such as: a revised subsidy scheme to improve the conditions for wind turbines (onshore), biomass and biogas and the announcement of a 400 MW offshore wind tender (Danish Energy Agency, 2012). These firm commitments by the Danish government appear to have sparked radical change in DONG Energy. A few months later, DONG Energy announced its intention to shift from a portfolio consisting of 85 per cent fossil fuels to 85 per cent renewables by 2040 (Orsted, 2022).

The Danish government and energy companies had by then learned important lessons in the tender process for large offshore wind power projects and offshore wind was also gaining the support of institutional investors, which helped to finance the capital-intensive offshore wind projects and spread the risk of equity investments. One of the most important overriding lessons from this tender was to systematically de-risk the process. A method to achieve this was to include industry in a market dialogue prior to the tender. This allowed industry and government to discuss all matters relating to the tender, which resulted in an adjustment to penalties and greater flexibility in the different milestones in the timeline for the next tender, and ultimately, a lower price (Danish Energy Agency, 2020).

In 2011, the Danish government published the Energy Strategy agreement, “Energistrategi 2050”, with ambitions to become free of fossil fuels by 2050. This led to the energy agreement “Our Energy”, which was published in late 2011. The agreement aimed to expand the development of renewable energy, especially as regards to wind, biomass and biogas, and was designed to replace coal and natural gas with biomass in CHPs, with a focus on greenhouse gas reductions (GHGs); specifically, a reduction of 40 per cent by 2020 compared to 1990 levels, and targets that wind should generate 50 per cent of Denmark’s electricity by 2020 and that by 2035, the heating and electricity sectors should be supplied by renewable energy only (Danish Energy Agency, 2012). Denmark also announced it would completely phase out coal by 2030.

From 2012, power producers and consumers have been able to share the saved tax on the fuel in CHPs for heat production with the heat customer. In 2014, an industry agreement was reached on the sustainability criteria for biomass, ensuring strict sustainability documentation requirements in line with internationally recognised sustainability standards for biomass procurement (IEA, 2020). In 2014, following the Danish government's incentives for the conversion of CHPs to biomass, DONG Energy decided to convert the Studstrup and Saeraek power plants to biomass. Denmark's total annual GHG emissions have been reduced by approximately 25 million tonnes from 2006 to 2016, and as of 2016, DONG Energy’s share of the reductions amounted to approximately 53 per cent (Orsted, 2022). The green transition of the company DONG Energy continued, and its financial health continued to improve and in 2017 the company, as DONG Energy, divested its oil and gas business and changed its name to Orsted (Orsted, 2020).

6.2.2 CHANGES AND TYPES OF OWNERSHIP STRUCTURES

6.2.2.1 DISTRIBUTION NETWORK SYSTEMS

The way in which ownership is organised in the energy system supply has a distinctive influence on both the energy prices and the transition process from fossil fuel-based systems to renewable energy and energy conservation-based energy systems. The distribution (DSOs) networks are natural monopolies and cannot be regulated in a market with different suppliers, as there is only one grid supplier available for the single consumer. Therefore, they must in general be regulated in other ways than through price competition. In the Danish case, state regulation has generally been a framework regulation, where the state by legislation amongst others required a non-profit regime, where the profit should remain in the electricity company and could not be used outside the electricity area for other purposes. This is the case with locally owned wind turbines and CHP plants. But consumer municipality ownership cannot be seen as isolated. We are dealing with a governance system consisting of consumer ownership of a natural monopoly, embedded in a public non-profit regulation regime and in a democratic system with a relatively high level of transparency and openness of information (Hvelplund et al., 2019).

The Danish regulation can be seen as price efficient due to the non-profit public regulation in combination with an efficient consumer ownership regime that meant that any profits were given back to the consumer via a price reduction. This incentive is supplemented by openness and transparency regarding prices and costs in an annually published electricity price statistics, where any consumer can read whether their electricity company is cheaper or more expensive than any other distribution system operator (DSO) (Hvelplund et al., 2019) which keeps pressure on the DSO directors to maintain competitive prices. This means that despite the impossibility of having price competition in a natural monopoly DSO, consumer ownership replaces an impossible price competition with possible production factor competition. This system of consumer representatives and openness of information thus represents a dynamic incentive system that seems to result in lower consumer prices. In 2000, Danish electricity prices were 18% lower for industry than the EU average (European Communities, 2005). This is an interesting statistic regarding the competitiveness of industry.

In 2004, the non-profit public regulation regime was replaced with an income frame regulation, where the public energy inspectorate each year announces an income frame for the specific DSO. The new regulatory regime consists of two parts:

A. A top-down cost and income frame regulation designed and controlled by the national authorities, which consists of 1-3.

1. A price cap based on 2004 costs per kWh.
2. This cap is regulated upwards with the inflation index every year, and also frequently regulated downwards in order to further increase productivity.
3. Economic benchmarking

B. A bottom-up cost and price regulation by means of the consumer or municipality/state ownership governance (Hvelplund et al., 2019).

The income frame regulation constitutes how much a DSO is allowed to charge its customers and compared to the previous regime; DSOs can earn a profit if their costs are below the income frame. This change is meant to give incentives for innovative activities developed and implemented by DSOs and for profits to be used in projects for "the common good" such as other green projects or for the reduction of prices. The price regulation in the consumer and municipality owned distribution companies is still an incentive to use profits for lowering the consumer prices (Hvelplund et al., 2019) but now the consumer representatives can decide how best to use profits.

6.2.2.2 DISTRICT HEATING (DH) AND COMBINED HEAT AND POWER PLANTS (CHP)

In 2015, the total DH supply in Denmark amounted to 128 PJ and 68% of all DH was produced in cogeneration with electricity (CHP). This saves a significant amount of fuel compared to separate generation of heating and power (Danish Energy Agency, 2017). Ownership policies for DH and CHP are generally the same and these policies have been mainly constant and changes in economic and legislative incentives have affected technology implementation rather than the ownership mainly in the conversion of DH to CHP (Chittum et al., 2014). Besides regulations, the long lifetime of DH/CHP systems and the linear relation between the size of DH/CHP systems and number of consumers (payers) might also have influenced the steadiness of citizen ownership within DH/CHP systems. In comparison, wind turbines have a shorter lifetime, which implies shorter and potentially more diverse ownership cycles. For Denmark, this means citizen ownership has been represented either in the form of municipal companies (mostly in the large cities) or consumer owned cooperatives (mostly in rural areas). According to the Danish Utility Regulator (DUR), there were 407 DH/CHP companies in Denmark in December 2016, out of which 47 were municipal companies and 341 consumer cooperatives (DUR in Gorrono-Albizu et al., 2019).

Table 1: Summary of ownership of DH/CHP systems in Denmark in December 2016

General data	Quantified ownership categories	Number of DH systems	DH demand supply (%)
DH systems supplied heat and hot water to approx. 64% of all households in Denmark in 2016	Citizen ownership	388	96
	Municipal company	47	60
	Consumer cooperative	341	36
Approx. 52% of the DH demand was met with RE in 2016	Commercial company	13	4
	Others	6	0
	TOTAL	407	100

Source: (Gorrono-Albizu et al., 2019).

The dominance of citizen ownership in the Danish DH/CHP is the direct result of profit generation being prohibited (i.e., the non-profit rule), which makes investments in DH/CHP systems unattractive for commercial investors and attractive for consumers who benefit from lower energy bills (Chittum et al., 2014). The non-profit rule is one of the top-down measures to protect consumers from possible abuse by the monopolistic DH/CHP companies. As a bottom-up measure, in municipal and consumer cooperatives, consumers exercise their power over the DH/CHP companies through directly or indirectly elected representatives for the company board. Consumer ownership of Danish DH/CHP has put pressure on the management and decision-making of DH/CHP companies, leading to lower heat prices for consumers and a continuous development of the systems by adopting the best available solutions in the market (Chittum et al., 2014).

6.2.2.3 WIND TURBINES

The second half of the first phase saw the rapid expansion of citizen owned wind turbines which contributed to a larger onshore wind capacity installation than for large energy investors in periods with no ownership discriminatory incentives for this technology. According to Gorrono-Albizu (2019), this may indicate either higher investment attractiveness of this technology for citizens, higher implementation success rates (e.g., because of higher local acceptance), or a combination of both. On the other hand, citizen ownership of centralized renewable technologies such as large offshore wind farms remained insignificant. In the second phase, the loosening of ownership regulations and the more restrictive onshore wind planning due to local concerns of landscape aesthetics and the large amount of onshore wind turbines already installed brought important changes in wind ownership. This has led to a very high diversity of ownership models for wind turbines due to the regulatory and economic incentive changes. Furthermore, the areas with the best wind resources in Denmark tend to have low population densities, which might limit the potential of local citizen ownership in a context of increasingly large wind turbines due to capital availability and needs.

An important change occurred in 2000 when the local ownership restrictions were halted and since 2008 there has only been the obligation to offer 20% of the shares at cost price to local residents from developers (Johansen et al., 2018). One type of local ownership structure that saw increased growth since the 1990s is individual citizen ownership of households and farmers (Mey et al., 2018). These prosumers (those who consume their own production) generally install small wind turbines and sell the excess electricity to the grid. This trend has continued with examples of household prosumers illustrated by the installation of 1 278 small wind turbines with capacities equal or below 25 kW installed since 2008 (Gorrono-Albizu et al., 2019). The changes in regulations also resulted in new innovative forms of inclusive ownership beyond the traditional local cooperatives, which still remain, and include inclusive models that are not necessarily local. An example of this is the Copenhagen nearshore Middelgrunden Vindmøllelaug wind cooperative which owns 10 wind turbines with a capacity of 20MW which has over 8 000 members spread across Denmark (Gorrono-Albizu et al., 2019). Cooperatives are characterised by open membership and democratic decision-making (i.e., each member holds one vote). Another innovative form of citizen ownership was the development of wind guilds which are commercial partnerships with closed membership and voting rights based on the ownership of shares. An example of a more exclusive wind guild is a wind farm built in 2013 in Norhede-Hjortmose consisting of 22 wind turbines that have a total capacity of 72.6 MW. The project was started by 22 citizen investors and has 19 registered local and non-local owners (Gorrono-Albizu et al., 2019). All cooperative and guild wind projects must still comply with the 20% locally owned rule even if they are started by local investors.

A statistical analysis done by Gorrono-Albizu et al. (2019) estimates that 52% of the total existing installed wind capacity in Denmark in December 2016 contained a citizen ownership model and increases to 67% when excluding large offshore wind farms. He does state however that there is considerable uncertainty surrounding his analysis due to different legal registrations of wind cooperatives and guilds although they can both be considered citizen ownership structures although with an unidentified owner.

Table 2: Summary of ownership of wind turbines in Denmark in December 2016.

General data	Quantified ownership categories	Ownership of installed capacity (MW)	Ownership of installed capacity (%)
Existing wind turbines: 6,099	Citizen ownership	2,747	52
	Individual ownership	1,212	23
Decommissioned wind turbines: 3,051	Collective ownership	507	11
Existing companies: 2,942	Unidentified citizen ownership	1,028	19
Closed companies: 607	Large investor ownership	2,499	48
Wind energy produced 37% of the final electricity demand in 2016 and 43% in 2017 [40]	Unknown	0	0
	TOTAL	5,246	100

Source: Gorrono-Albizu et al.(2019).

Wind turbines in Denmark were initially installed based on local citizen ownership (either single or collective) and limited by the consumption criterion. With changes in legislation and incentive systems, more exclusive and distant citizen ownership models emerged. Moreover, after the elimination of the local residence criterium, large investor ownership and citizen ownership had the same opportunities to invest in onshore wind. This has led to some criticism about the 20% rule considering that the percentage might be too low to encourage a real bottom-up citizen participation process and it is designed in a top-down fashion and enters too late in the planning process, and therefore can be perceived as a “monetary compensation” instead of a real “benefit” (ownership) (Johansen et al., 2018). The investment attractiveness still sees a large contribution of installed onshore capacity by citizen owners in recent years but so far, all offshore wind tenders have been won by large energy companies (Danish Energy Agency, 2023) perhaps due to the high capital costs. The Danish Energy Agreement of 2018 shows a preference for large offshore wind power projects designed around a tender process. This suggest that Denmark will experience changes in the ownership structure of turbines moving into the third phase dominated by large investor ownership. Furthermore, 1 711 MW of existing and citizen-owned wind turbines were at least 15 years old in 2018 and will soon need to be replaced and these ageing turbines account for 69% of the citizen ownership in 2016, and thus the share of citizen ownership may decrease if policies to protect citizen ownership are not implemented (Krog et al., 2018). However, as the analysis of the new ownership structures above illustrate, the evolution of citizen ownership of wind turbines in Denmark demonstrates the capability of adaptation and reinvention of citizen ownership.

6.2.3 TECHNOLOGICAL DEVELOPMENTS

In the second phase, wind power development mainly concerned the increasing size of wind turbines and the entrance of large energy companies into the market both onshore and offshore. These larger wind turbines are more economical and therefore more attractive for investors and in the 2018 Energy Agreement list the expansion of offshore wind farms in "energy islands" as a key step in the next part of wind power development (Danish Energy Agency, 2023).

District heating plants continued to be converted to combined heat and power plants during this period and also began the process of switching from coal to biomass as the input fuel. From a technological perspective, the conversion of coal CHPs to woody biomass is not extremely challenging, given that proper framework conditions are there to incentivise the transition. The framework conditions in Denmark have led to considerable consumption of biomass for CHP and district heating production. Conversion of large-scale CHP plants from fossil fuels to biomass has been promoted through a combination of different schemes:

1. incentives, such as state aid for electricity production based on biomass.
2. tax exemptions for biomass as opposed to electricity and fossil fuels, and.
3. the possibility to use tax benefits to reduce electricity production costs (Danish Energy Agency, 2020).

The latter was introduced with the 2012 Energy Agreement. State aid for electricity production is closed for new plants and is being phased out for existing plants. In Denmark, biomass used for heat production is not subject to tax; in contrast, fossil fuels are subject to energy and CO_2 taxes, and so is electricity production, which is subject to an electricity tax. Fossil fuels used at large plants are also subject to the EU ETS, which means these plants must buy emissions allowances corresponding to the plant's CO_2 emissions that arise from burning fossil fuels for electricity as well as heat production. Up to 2012, a portion of the tax advantage of CHP plants linked to heat production (i.e., the majority of the tax advantage) went to district heating end users, which meant there was no incentive for CHP plants themselves to convert their production from coal to biomass

(Danish Energy Agency, 2020). The 2012 Energy Agreement gave large-scale power plants the possibility to divide their tax advantage, so that some of the advantage went to electricity production. This change proved significant for the conversion of large-scale power plants to biomass, as it made it advantageous for the plants to use biomass instead of coal. Consumption of solid biomass for electricity and heat production in Denmark has subsequently increased, from around 58 PJ in 2012 to an expected 105 PJ in 2020 (Danish Energy Agency, 2020).

The use biomass is not without controversy. The EU Renewable Energy Directive II (European Commission, 2018) includes minimum requirements for the sustainability of biomass fuels from forestry. This directive defines a methodology for estimating production chain emissions from the use of biomass fuels which consider the sum of net emissions of greenhouse gases from the cultivation, processing, transport and non-CO_2 emissions from biomass combustion. Biomass can only be regarded as "renewable energy" if these emissions are below a certain level and the GHG saving compared to fossil fuels is at least 70 per cent from 2021 and 80 per cent from 2026. Until the directive is in force, nearly all the forest biomass used for district heating and electricity is covered by a voluntary Danish industry agreement that was concluded in 2014 to ensure that the biomass used in Denmark fulfils internationally recognised sustainability criteria (Danish Energy Agency, 2020). Projections in the Danish national energy and climate plan from 2019 show biomass for energy consumption is projected to decrease by 12 per cent from 2017 to 2040. Biomass can be said to have played a role as a "transition fuel" in Denmark, in that it has played an important role in converting coal-fired CHPs, but its use is not expected to continue to grow. Furthermore, it has not experienced significant cost reductions as wind and solar have.

6.2.4 SUMMARY

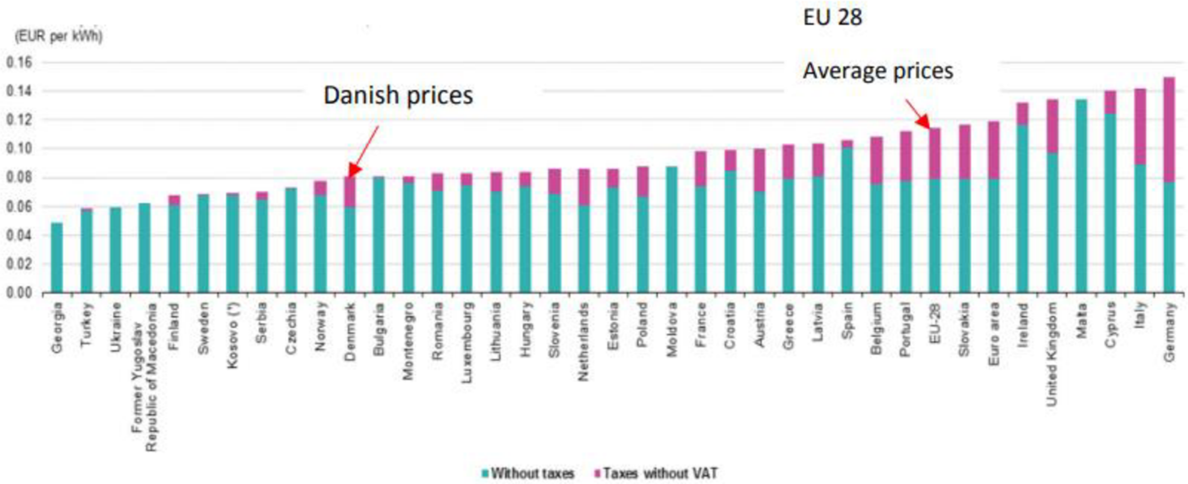
It can be reasonably argued that it is relatively easy to develop and implement new renewable energy technologies with their inherent intermittency if they only comprise a small share of the energy demand and consumption. This is because the minor supply from these renewable technologies can be easily fitted into the existing energy infrastructure without fundamental changes to the socio-technical energy system. In 2015 Danish wind power produced 42% of the total electricity consumed, as well as more than 600 hours of the year of wind power production exceeding the total Danish electricity consumption during those hours which was sold to neighbouring countries at continuously reduced prices (Hvelplund et al., 2017). Biomass accounted for a further 11.0% and solar energy, hydro and biogas accounted for another 3.2% with 11% of electricity consumed imported and the rest produced using fossil fuels (Danish Energy Agency, 2016).

In the second phase, renewable energy technologies make up to 40-50% of the electrical energy supply and so the development of an integrated energy system that can handle large amounts of intermittent electrical energy supply is required to meet the 100% renewable energy by 2050 ambitions of Denmark and the EU. Furthermore, policies for the implementation of storage systems that will become more important in the third stage need to be undertaken. In Denmark, the long-term development of district heating systems offers the opportunity for the integration of the electricity and thermal energy systems which will be discussed in phase three.

The widespread use of DH combined with the large share of cogeneration with electricity is one of the key reasons why it has been possible to increase energy efficiency, decouple the development in energy consumption and economic growth (GDP), and reduce carbon emissions over several decades. By 2015, the energy intensity of the Danish economy, adjusted at the 1990 rate with an index at 100, decreased to an index score slightly above 60 (Danish Energy Agency, 2017) which demonstrates a clear decoupling of energy consumption and GDP growth.

Furthermore, Denmark has been able to maintain its low electricity price in the second phase which has significant socio-economic implications for the public acceptance of continued development of renewable energy systems. Indeed, in 2017 the Danish electricity price for industry was between the lowest in EU 28, despite the fact that the electricity price includes Public Service Obligation (PSO) payments used for subsidies paid to the development and implementation of renewable energy technologies in the Danish energy supply system. This is quite a significant achievement and argues well for the success of government regulation and incentives schemes implemented by the Danish government/parliament.

Figure 6: 2017 Electricity Prices



Source: Hvelplund et al., (2019)

The ability to increase the share of renewable energy into the energy mix while maintaining low energy prices and decoupling economic growth from energy intensity has been a remarkable achievement for Denmark and offers a dynamic approach for other states seeking to decarbonise their economies. Ambitious goals supported in legislation and a regulatory regime including local ownership structures and that encourage technological development can be seen as the key policy instruments in implementing this phase of the energy transition. Denmark has shown an ability to be flexible in its policy development as well, which certainly seems to have been a key component allowing for the continued expansion of renewable energy technologies begun in the first phase. The decentralised power production from locally owned wind turbines and DH/CHP plants continue to play a large role in the energy transition but as we saw above, there seems to be shift towards centralised large-scale offshore wind farms expansion leading into the third phase to achieve the 2050 targets. As Denmark is now moving into phase three with the ambition for 100% renewable energy, new problems arise that will have to be overcome as we shall see in the next section.

6.3 PHASE THREE: A 100% RENEWABLE ENERGY FUTURE?

For the transition from fossil fuels to a system based on 100% renewable energy and energy conservation to succeed, there must be a better understanding of the needed technical and institutional changes and its regulatory framework. The political process to deliver both the renewable energy capacity already in existence by 2020 and the later commitment to 100% renewable energy generation did not and will not flow smoothly. For development to proceed in the period 2020–2050, several areas must be addressed, including: development of new policies, the competition and conflicts between interest groups, and acceptance questions regarding new renewable energy projects.

Policies to deliver new renewable technologies, such as wind turbines, solar energy, and biomass energy are, on their own, inadequate to enable the successful integration of an intermittent supply into the energy mix (Ridjan et al. 2013). Despite recent governmental activity demonstrating a greater recognition and acceptance of such requirements inherent in this shift to renewables, this has not been followed up with an accompanying shift to concrete policies to support the necessary inter-sector integration that is required (Hvelplund et al., 2017). In their place there is an unclear assumption that the increasing amounts of renewable energy sources can be managed by building additional electricity interconnectors from Denmark to the Netherlands, the United Kingdom, Germany, etc. But this seems questionable as these other states also aim to have 100% renewable energy by 2050 using similar technologies. This means that during the third phase the future direction for achieving the sustainability goals of decarbonisation are not yet set and that decentralisation and the development of the smart energy system are just one of many possibilities for achieving these goals.

This section will draw a lot on the technical aspects outlined in the Literature Review as well as the Danish Society of Engineers (IDA) "Energy Vision 2050: A Smart Energy System strategy for 100% renewable" report (IDA, 2015). This report is not offered as a solution to all questions regarding the energy transition but aims to be an input into the debate around sustainability and how to reach the political goals of replacing fossil fuels completely. At the same time, the transition of the energy system is an exciting opportunity for citizens and businesses. The intelligent transformation of the energy system may create a direction which can initiate exports and jobs, benefitting all citizens. This is, of course, from a technological point of view and political considerations will need to be included when designing new legislation and regulations.

6.3.1 ENERGY SYSTEM INTEGRATION

In the first two phases of the energy transition, the pace and types of development of renewable technologies was to a large extent determined by the national governance framework working in coordination with all the stakeholders (i.e., local governments and administrators, citizens and cooperatives, and energy companies). In the third phase, electrification occurs in new sectors such as heat and cooling systems and transport which require a governance framework that needs to enable the co-existence and integration of different systems. Furthermore, the importance of a distribution level system coordinator increases, to not only manage technical operations in the interest of all stakeholders, but also to stimulate new markets and thus enable new entrants and innovators.

At the heart of the future system must be performance-based regulation, which not only ensures supply obligations to be met, but also wider social and environmental sector goals to be delivered. This means that reforming regulation will encompass how to deal with winners and losers, and this is more than creating an open and transparent decision-making process. With intermittent solar and wind intake, there will be a resource abundance at certain times, and extreme scarcity (and high prices) at other times. Hence, storage will become a major issue for policy makers.

The need to rapidly decarbonise the economy imposes targets and objectives that require the deployment of low-carbon technologies even at a faster rate than the market would ordinarily deliver. This may lead to additional policy-driven market interventions. Under the right regulatory environment, the next wave of technologies could be rapidly deployed at scale, as they have uses beyond the traditional power sector. While the development of batteries is being driven by and for electric vehicles, it will have important implications for both grid level and individual household electricity storage.

The balance between public and private ownership and engagement within the power sector varies between countries. However, in general the most rapid move towards phase three will occur within systems which encourage innovation and entrepreneurship, and this is likely to be delivered by the private sector, providing the market is fair and transparent and constructed to value the characteristics of renewable energies and demand-side response, and appropriate governance mechanisms are in place.

6.3.2 ELECTRIFICATION OF HEAT AND COOLING SYSTEMS

As is currently the case, wind power production outcompetes centralised fossil fuel and CHP electricity production on the Nordpool spot market due to its almost zero marginal production costs and thus reduces the full-time production hours at both the large and the many small CHP systems, undermining the economic case for these types of production. Centralised power plants and CHP units have natural gas input costs and so higher short-term marginal costs. This is an interesting phenomenon when comparing the value chain of fossil fuel-based systems to renewable energy ones. Both systems have upfront capital costs (long-term costs), but only fossil fuel systems have marginal costs (short-term) for fuel as well as production (Hvelplund, 2014). Since wind turbines and photovoltaics produce their energy from the wind and sun, during windy periods or sunny days, the energy produced by these systems can be sold for low prices in the Nord Pool Spot market because it is designed as an hourly auction. In principle, it will be the hourly supply cost, which becomes the marginal costs that shape the market prices. Having no fuel consumption, wind power, and photovoltaics have no marginal costs within such a market structure. The effect of this is well known in the literature and is usually referred to as the merit order effect (Hvelplund et al, 2013, Cludius et al, 2014). Combining the textbook theory from economics with the knowledge of trade procedures at the Nord Pool Spot, the expectation that the introduction of wind power and photovoltaics into the electricity system should have a downward pressure on market prices. This has very important implications for policymakers as well as for investors who may end up with stranded assets.

In this phase, the question is not only whether single renewable technologies such as a wind turbine, biomass plant, or photovoltaic unit can produce energy cheaper than a fossil fuel plant, but rather on how to develop a reliable energy system when an increasing share of the energy produced is supplied by intermittent renewable energy technologies. In this case, what is required is a comparison of the different energy systems that can supply energy when needed, in the right amounts and quantities and make sure the economics of renewable energy is affordable. The point here is that renewable energy sources (RES) must combine the large-scale integration of the energy system with energy conservation and system efficiency improvements. It is with this in mind that the Danish system with a large share of CHP based district heating can be regarded as a system well suited for the integration of renewable energy. In any such system with a high share of district heating and CHP, CHP units should be operated such that they produce less when RES electricity input is high and more when it is low.

According to Hvelplund, Denmark is now at a stage where the integration of thermal and electric energy is a must since wind power is becoming the dominant supplier of electricity and fossil fuels are becoming the supplementary energy source in the energy system (Hvelplund, 2013). This clearly necessitates the establishment of an infrastructure that can handle the intermittency within wind power generation. Technically, this is done by investing in district heating, industrial and household heat pumps and heat storage systems all power by renewable electricity energy sources. For example, an analysis by Nielsen et al. (2011), claims that when including heat storage capacity, such measures are likely to integrate fluctuating RES up to around 20 percent of the demand without losing fuel efficiency in the overall system. After this point, the system will begin to lose efficiency as heat production from CHP units is replaced by thermal or electric boilers. Institutionally, by giving the right incentives for using wind power for heat in periods with very much wind power.

However, a significant problem may arise here. Today these incentives do not exist to a sufficient degree in Denmark, where tax on electricity for heat are 3 times higher than tax on oil and gas for heat, and 6 times higher than the tax on biomass resources for heat (Hvelplund, 2020). If the heat and electricity markets were integrated in the right way, wind power would never have to be sold for a price lower than the cheapest heat alternative, which would be around 3-5 Eurocent per kWh. Without this integration, wind power is often sold for 1-3 Eurocent at the Nordpool market, resulting in increasing problems for the economy in wind power projects (Hvelplund, 2020). In systems where the bulk part of primary energy supply is sourced from wind turbines, the sustainability of electricity market structures becomes vital for the system as these should financially sustain investments in wind turbines. As discussed in phase two, the Danish government considers biomass as a transition fuel and so it can be assumed that the tax for electricity to heat will be amended to better reflect the 100% renewable energy goals. Using wind power for heat will not, however, solve the problem of intermittent wind power and so perhaps biofuels or electro-fuels will replace biomass in some form. The critical question is, therefore, whether the implications of the described economic properties are so significant that it will prevent the transition from succeeding, as the market conditions might make needed investments in wind power unfeasible for investors.

6.3.3 WIND POWER AND THE SMART ENERGY SYSTEM

Danish wind power produced 46.5% of total electricity production in 2020 with the largest share of this coming from onshore wind turbines (Statistica, 2023). While onshore wind capacity is set to increase, mainly by replacing old turbines with newer large ones, the Energy Agreement of 2018 aims to shift wind power production to large offshore sites and in 2020 the Danish Parliament approved the creation of two "Energy Islands" in the North and Baltic Seas that will quadruple Denmark's total offshore wind energy capacity by 2030 and could meet electricity demand of 7.7 million European households. (Danish Energy Agency, 2020). Energy islands act as hubs, allowing the connection of several offshore wind farms, distributing power between the countries connected to the island.

This was made possible by legislation in the Danish Parliament in 2019 called the Climate Act that obligates Denmark to reduce its greenhouse gas emissions by 70% by 2030 (compared to 1990). To meet this target, the Government is pursuing a Climate Action Plan that will require emission reduction across all sectors, including agriculture and transportation.

The question from above remains though. What is the economic incentive to invest in new wind power capacity when we are seeing falling wind power supply prices with increased capacity? One obvious answer to the question is that Denmark does not have 7.7 million households so clearly they plan to export a lot of electricity. That brings up another question already asked above, namely, if all states are pursuing the same goals of decarbonization and the electrification of their economies, who will buy the excess energy and at what price? Clearly, by 2030 many EU states will be willing to buy cheap wind power if they are still behind Denmark in renewable technology development. Moreover, the agreement includes the adoption of the smart energy system and will also transform the Danish heating sector by lowering taxes on renewables and incentivize the replacement of oil and gas heaters with heat pumps and district heat energy. Furthermore, it will fund charging stations for electric vehicles and help the industrial sector decarbonize through energy efficiency measures and increasing the use of renewable electricity and biogas (Ministry of Climate, Energy and Supply, 2020). This seems to deal with the issue mentioned above regarding DH/CHP systems where heat pumps can be installed and where relatively easy technical changes can be made to convert DH/CHP units from natural gas to biogas.

The Minister for Finance, Mr. Nicolai Wammen has stated that "*we will invest in sustainable fuels, a sustainable heating sector and help decarbonize the industrial sector. I am extremely proud that we have managed to conclude a broad-based agreement that not only moves Denmark closer to reaching our national climate goal, but also creates numerous jobs in the years to come*" (Ministry of Climate, Energy and Supply, 2020). Furthermore, the agreement will provide significant investments in the development of carbon capture technology and sustainable e-fuels such as green hydrogen.

To create a rational economic basis for wind power is to increase its market size by integrating electricity and heat and transportation. It is very important to involve the new flexible technologies such as CHP, heat pumps and the electrification of transport (batteries and electrolysers) in the grid stabilisation tasks, i.e., to secure and maintain voltage and frequency in the electricity supply. In this way, by integrating wind power into a smart energy system, the economics of wind may improve to a level where it escapes falling prices created by the merit order effect, meaning that it may pay to build the needed wind power capacity to deliver the 100 per cent renewables by 2050 scenario. The EU has recently reached an agreement obligating that all new cars and vans registered in Europe be zero-emission by 2035 (European Commission, 2023). Most of these new vehicles will be electric (EV) so that they will not only create new markets for renewable electricity producers that may help in reducing the steady fall in electricity prices resulting from the merit order effect and therefore increase the attractiveness of investor in wind power, but also may function as back-up electricity suppliers when wind power is insufficient to meet demand through vehicle-to-grid (V2G)technologies (IDA, 2015). V2G, smart charging during times of low total demand, and battery storage are all technologies enabled by digitalization and offer partial solutions not only to the intermittency of wind power generation but can also help to conserve energy. Battery technologies development are being driver by the EV industry but once batteries have degraded to some 80 per cent of their capacity, they may no longer be suitable for vehicle usage, but may still be suitable to stationary storage where size and weight are no longer critical factors in decentralized municipal stage facilities (Burger et al., 2020).

Lund et al. (2016) however claim that hot water storage is cheaper by a factor of 100 per MWh for large heating systems compared to electric battery storage systems. Hot water storage systems cost approximately €24,000/MWh stored for single houses, and between €500 and €2,500/MWh stored in the larger repositories in a city with district heating, it is a cheaper by a factor of 10–50 to store intermittent energy in district heating systems than in single house systems. This point clearly illustrates the need for very careful consideration of policymakers when developing laws and regulations. Moreover, society as a whole has to enter a public discourse over price stability and security of supply, jobs and corporate interests, climate change and effects on the local environment, for example wind turbines or large PV fields, and how to deal with stranded assets. Some technologies such as carbon capture and storage, V2G, power-to-gas, etc., still have to be proven as feasible and economic and that leaves clear uncertainties about where to invest, what incentives systems to implement and which technologies should be utilised. This will certainly also be accompanied by new business models that offer opportunities to entrepreneurs that will need to be facilitated by policymakers.

All of this is connected to the centralisation and decentralisation paradigms and perhaps even to who will be the “winners” and “losers” in the energy transformation. Decentralised, local ownership regulations have made a large impact thus far in the Danish energy transition, but their future is now in doubt as the need to increase wind energy production increases with the 100% renewable energy goals. That is not to say that decentralised wind turbines and DH/CHP units will cease to exist, but that their potential does seem to be finite and therefore will coexist with large-scale centralised systems in the 100% renewables future.

7. INSIGHTS AND POLICY RECOMMENDATIONS

The analysis of the Danish energy system through the three phases framework offers important insights for policymakers, technologists, citizens, and most importantly perhaps, for other EU members states with the same ambitions as Denmark to achieve a 100% renewable energy future. Phase one can be associated with a niche deployment of decentralised renewable technologies, contributing less than 10 per cent to total power generation. In Phase two, their contribution to total power generation amounts up to 40 per cent and becomes a major factor in the supply portfolio. Phase three is characterised by decentralised renewable energies being accompanied with centralized energy solutions where renewables are now the dominant player within a flexibly operated system with an increasing number of fully autonomous solutions through digitalisation.

This section will begin with the potential answer to the main research question before checking the sub-questions. The main research question is: "Is it possible for an EU member country to replicate the policies, laws and processes of another EU member country in order to achieve the same goal of decentralizing energy production and consumption?" and the three sub-questions are:

1. Does decentralized energy offer benefits to local citizens that centralized energy does not?
2. What kind of citizen ownership models have been implemented in Denmark?
3. Has Denmark been successful in achieving its decentralized energy goals?

7.1 RESEARCH QUESTION

"Is it possible for an EU member country to replicate the policies, laws and processes of Denmark in order to achieve the same goal of decentralizing energy production and consumption?"

This question at first may seem at have an easy answer. EU states all operate under the same regulatory regime and so replicating Denmark's policies should be straightforward.

Furthermore, decentralized energy generally means renewable energy since solar photovoltaic panels and wind turbines are scattered across residential rooftops and dispersed on acres of farmland and the decentralization of energy supply means utilizing technologies that are in smaller capacity units and where their geographic distribution is wider than the traditional fossil fuel large generating units. It is as a system moving from a one-way, top-down, supply orientated operation of a few, large conventional fossil fuel power plants to an integrated system that is bi-directional, and demand focused with multiple, varied power generating units of all sizes. Therefore, while the answer to the research is seemingly "yes", an analysis of the answer is quite a bit more complicated.

We should begin with an analysis of the process Denmark has implemented to achieve its renewable energy ambitions. Although some EU member states may still be designing their own energy plans to achieve the decarbonisation goals, the EU has already passed some legislation regarding short to medium term goals that Denmark has viewed as the minimum goals. The processes that Denmark has developed were not straightforward and without problems and interruptions as we have seen in the discussion section. However, at this time we can now formulate an effective process based on Denmark's experience. Therefore, this section will review each of the processes in detail and discuss how this know-how can be utilised by various EU states with their own specific conditions. The processes can be broken down into two stages:

1. National energy plans.
2. Concrete legislative reforms.

7.1.1 NATIONAL ENERGY PLANS

This would be the place to start as stable, transparent, inclusive, long-term policy and planning provide confidence to developers and investors when followed by concrete reforms and are essential in gaining public support for the energy transition. Governments need to make energy planning and policy a priority to support the development renewable energy technologies. Long term energy plans decades into the future give confidence to investors and companies that a market is worth investing in. Transparency is important in terms of the data available, for giving citizens and companies an understanding of the assumptions and scenarios used in energy plans. For citizens this is important for the acceptance of the plans and gives them confidence that they are achievable and economic and that they will receive benefits from the energy transition. For companies, this gives confidence that they are all provided with the same information and are competing on a level playing field. Stability refers to the nature of the plans themselves. Adjustments may be necessary over time, but large, retroactive changes to subsidies or taxes can have long-lasting negative consequences on the certainty of renewable energy markets. Stability can also be shown through reliable and realistic targets, which are then followed by documentation of progress and fulfilment of stated policies. A proven track record helps negate the perception of risk from investors and increases confidence in future plans. The plans must also be designed in an inclusive manner. A transparent and inclusive dialogue between government and stakeholders will also ensure the necessary inputs from the involved parties are received, thus considering the needs of the players when designing the rules. Positive engagement between government and stakeholders can lead to benefits for all sides. Government support and engagement is also important, as local communities hosting or implementing potential projects should also be involved in the process, as their opposition can pose project development risks for the realisation of renewable projects.

The main steps when designing national energy plans are relatively straightforward but not necessarily simple. As each state has its own conditions, a logical place to start would be to evaluate the different technologies available and decide which would perform the best within the constraints of the state. Denmark has clearly chosen wind power as its main source of renewable electricity. The Jutland peninsula and Danish islands surrounded by the North and Baltic Seas make wind energy are clear choice. The flat terrain of the land has made onshore wind power feasible, and seas have offered the opportunity to develop large offshore wind farms as well. However, some states do not have this option, or at least, not as much wind power potential as Denmark. Southern, sunnier states would probably be better off utilizing solar energy or a combination of wind and solar energy. Even some central EU states like Germany have followed this path so far (Ohlhorst, 2020).

Another key part of planning is assessing what phase of the energy transition the state finds itself in and what is its current energy mix. States with no or little renewable energy can begin implementing their chosen technologies without regard for its intermittency as the energy produced will not lead to load balancing tasks. However, many EU states are already producing renewable energy from technologies such as biomass or hydroelectric power. Hydroelectric power production is a traditional renewable resource which has been implemented at large scale in countries with the ability to do so (European Commission, 2022). Other states use nuclear power to supply a lot of its electricity needs. While its "green" credentials are hotly debated, it is a key source of very-low carbon electricity for some member states. Whatever technologies are being utilised in these states, those with a supply of electricity over 20% are better understood to be in the second phase in their analysis. This is mainly because these technologies are considered as baseload energy suppliers which cannot be easily switched off and so the problem of renewable technologies' intermittency will have to be considered immediately when designing their plans to avoid future problems regarding the economic feasibility for investors. Pumped storage hydropower can use excess electricity produced from other sources by pumping water from lower elevations to higher reservoirs and thus can help store energy in times of excess electricity supply.

A key technological development that happened in Denmark was the conversion of district heating (DH) plants into cogeneration combined heat and power plants (CHP). Many countries in the EU use district heating systems (especially in the north, central and eastern member states), with about 25% of the EU's DH supplies already produced from renewable sources (IEA, 2021). Converting DH plants to CHP has the potential to mitigate the intermittency of renewable energy technologies in the second phase and also, as we saw in the Danish case, to decrease the energy intensity of the energy system by using the waste heat from thermal electric turbines to heat homes and business. Of course, the key consideration here is what fuel these CHP plants will use. Converting them from coal to natural gas fired systems helped decrease CO2 emissions in Denmark and may be seen as a medium-term solution although Denmark is now converting them to biomass as its input energy source and is planning to change this to biofuels. The Danish experience here can help by encouraging states to convert directly from coal to biogas and thus skip one of the conversion stages Denmark went through and save money.

For those states that have a high share of nuclear power in their energy mix, the opposite should be considered. This would mean utilizing the waste heat in the form of water from the thermal electrical turbines and converting nuclear power plants into cogeneration plants or by pumping the waste heat to DH plants. For states without DH units, a policy for the implementation of household heat pumps or solar heat collectors should be considered.

These technological examples need to be analysed within each states' natural conditions and the national energy plans must be built around these considerations. By engaging with all the stakeholders, it should be possible to find the optimal solution to each country's needs, and the centralisation and decentralisation paradigms need to be discussed in order to have the public's support and involvement in the transition which is a key aim of the EU as has been mentioned many times in this paper. The main point here is that all technological considerations should reflect the current state of renewable technologies which best fit the natural and economic conditions for each state and the need for wide consultations with all stakeholders to ensure that everyone can benefit for the energy transition.

Another key consideration for other states lies in the ownership structure of DH plants. Ninety-six percent of DH/CHP units in Denmark are citizen owned either in the form of municipal company or a consumer cooperative. The distribution (DSOs) networks are also owned by municipalities and the majority of wind turbines as well. A lot of this was the result of the Danish cultural legacy of community ownership and this tradition certainly helped gain citizen approval for the energy transition when communities could see clear benefits for themselves and were engaged in the debates about the transition through what Lund termed the innovative democracy approach (Lund, 2014). Citizens gained with the public non-profit regulation regime and in a democratic system with a relatively high level of transparency and openness of information. When this process stalled in the 2000s as wind turbine development almost completely stopped until the first Energy Agreement was signed in 2011. The Energy Agreements were designed with the support of the vast majority of political parties in the Parliament and with them Denmark began to rapidly expand its renewable energy and decarbonisation goals and they have remained the main mechanism for the stable, transparent, inclusive, long-term policy planning that is essential in the energy transition. Governments in EU states will need to work with the opposition in their respective parliaments (as well as other stakeholders) if they want to replicate the success of Denmark to ensure the long-term stability of their regulatory regimes.

If policymakers have designed plans that take all of this into consideration, then the next stage of creating the legislation and regulations to achieve the plans aims should encounter less opposition and technological difficulties that have costs in both financial and societal acceptance terms.

7.1.2 OTHER RECOMMENDATIONS

Energy plans should be supported by legislation through concrete reforms to achieve the targets. This section aims to outline the main learnings from the policy makers' and developers' sides. It must be said that the Danish model was made for Denmark. Many learnings can be used in other countries, but the timing and initiatives must be adapted to local circumstances. The role of stability in long-term policy decisions cannot be overstated. While not everything has been perfect, Denmark has a long history of broad political agreements with a long-term time horizon. This has helped secure robust and continuous political commitment toward the green transition despite changes in government over time. This framework allows policy makers to devise clear, transparent, and stable policy signals with regards to the future development of electricity markets, grid investments and environmental policies. Furthermore, politicians across different parties in the Danish parliament have broadly supported the transition; as a means to reach energy independence from imported fuels, local job creation, as well as a transition to a low-carbon energy system, thus limiting climate change. In other words, the transition helps fulfil multiple political goals, further promoting an environment of financial stability that has been key for the success of the transition.

Stability and transparency in long-term policy decisions are key to the development of renewables, guaranteeing subsidies and CO_2 taxes (which might otherwise be modified or removed retroactively), reducing the risk for developers and investors, and so further promoting investments in technologies that are in line with long-term policy goals. When long-term policy goals are set, the regulatory framework needs to reflect this. The regulatory framework should be designed to de-risk projects in order to achieve policy goals and can include elements as listed in the below:

- Planning - Long-term, stable, inclusive, and transparent energy planning procedures, supported by legislation, concrete reforms, and dialogue with industry and with the public, are an essential part of the green transition.
- Demonstration projects - Demonstration projects provide invaluable regulatory, technical and engineering learning and boost investors' confidence, proving the scalability of the technology.
- Economic incentives - Subsidies, taxes and CO2 prices have proved instrumental, when designed in a transparent manner to reduce regulatory risk.
- Competition - An electricity sector built on the fundamental concept of competition creates incentives to innovate and lowers prices.
- Permitting and de-risking - Appropriate allocation of risk and the streamlining of permitting procedures reduce regulatory risk and potential delays.

7.2 SUB-QUESTIONS

1. Does decentralized energy offer benefits to local citizens that centralized energy does not?
2. What kind of citizen ownership models have been implemented in Denmark?
3. Has Denmark been successful in achieving its decentralized energy goals?

These three sub-questions may be answered together by reviewing the insights gained in the Results and Discussion section. The citizen ownership models saw that local citizens have benefitted from the decentralised onshore wind turbines and DH/CHP units. Starting with citizen owned DH/CHP units, we have seen that they represent 96% of heat energy demand and comprised of 388 decentralised units either as a municipal company mainly in large cities (60% of demand supply), or consumer cooperatives in smaller settlements (36% of demand supply). Ownership policies for DH and CHP are generally the same and these policies have been mainly constant and changes in economic and legislative incentives have affected technology implementation rather than the ownership mainly in the conversion of DH to CHP. This is importantly co-dependent with the Danish non-profit public regulation which in combination with an efficient consumer ownership regime meant that any profits were given back to the consumer via a price reduction.

The dominance of citizen ownership in Danish DH/CHP is the direct result of profit generation being prohibited (i.e., the non-profit rule), which makes investments in DH/CHP systems unattractive for commercial investors and attractive for consumers who benefit from lower energy bills. The non-profit rule is one of the top-down measures to protect consumers from possible abuse by the monopolistic DH/CHP companies. As a bottom-up measure, in municipal and consumer cooperatives, consumers exercise their power over the DH/CHP companies through directly or indirectly elected representatives for the company board. Consumer ownership of Danish DH/CHP has put pressure on the management and decision-making of DH/CHP companies, leading to lower heat prices for consumers and a continuous development of the systems by adopting the best available solutions in the market. Local ownership therefore gives benefits to locals through their agency in the decision-making process of DH/CHP companies and by having lower energy bills.

The case of wind turbine ownership is not so clear. The second half of the first phase saw the rapid expansion of citizen owned wind turbines which contributed to a large onshore wind capacity installation. The local ownership structure that saw increased growth since the 1990s is individual citizen ownership of households and farmers represented by prosumers who generally installed small wind turbines and sold the excess electricity to the grid. This was facilitated through government support schemes (subsidies) and ownership regulation that turbine owners had to live within a 9 km radius from the turbine. This has since changed and now the main local ownership regulation is that 20% of the shares at cost price must be offered to local residents from developers. There have been many cases of the 20% ownership share being actually owned by a few local residents and thus it is more exclusive than the past ownership models. The changes in regulations also resulted in new innovative forms of ownership beyond the traditional local cooperatives, which still remain, and include distant models that are not necessarily local as wealthier citizens from other regions in Denmark have taken a stake in onshore wind turbines. Another possible future problem is that ageing turbines account for 69% of the citizen ownership in 2016, and thus the share of citizen ownership may decrease if policies to protect citizen ownership are not implemented. The non-profit and local ownership rules certainly gained local acceptance as demonstrated by the rapid development of wind turbines close to their homes and saw benefits as seen in electricity prices below the EU average in 2017. This also achieved one the EU's priorities in including citizens in the energy transition. However, as argued in the Results and Discussion section about the third phase, these benefits are under threat due to the now open competition in European energy markets and Denmark's move towards larger offshore wind farms which require the capital to develop that local actors may lack.

Whether Denmark has been successful in achieving its decentralised energy goals has perhaps already been answered from the above discussion about the other research questions. Lower energy prices, reducing the energy intensity of the economy, citizen acceptance, participation and ownership all point to the success of Danish decentralised energy. Already in 2015, 42% of total electricity consumption was supplied by wind power (52% of this is decentralised and citizen owned). The question is mainly whether this will continue to be the case. DH/CHP units and the distribution networks are natural monopolies and decentralised by nature and so will continue to be the case even when converted to biomass or biogas. For wind turbines the case is not so clear. As mentioned, in the third phase when moving towards 100% renewable energy, centralised offshore wind farms seem to be more suitable for future development, and so the future a combination of both seems to be the way forward for Denmark.

8. CONCLUSION

Conceptualising the energy transition as three distinct phases allows citizens and policy makers to better understand the challenges and opportunities which may be applicable to any state. However, every state has its own conditions, histories, and culture that will affect the implementation of renewable energy systems but the analysis of Denmark's experience as a first mover allows political and economic decision makers from other states to prepare for the different phases of the energy transformation by thinking from phase three backwards to leapfrog or to allow the three energy phases to co-exist. For states beginning their energy transformation, the ability to analyse the future difficulties with full energy system integration may well allow policymakers to avoid mistakes and implement solutions even before the future integration problems arise.

For EU states behind Denmark time may be running out due to the strict and binding agreements that they have agreed to. While this paper, and others, may help achieve an understanding of what the energy transformation requires, the building of human capital to achieve their aims takes time. States should immediately begin training technicians for the installation, management, and operation of renewable energy systems. While developing policies it may be possible to copy other states, although adapted to local contexts, how-know takes time to acquire and as all states are commented to the same goals, those with the know-how on operating renewables projects will be in high demand and a lack of them may be an impediment to the quick deployment of renewable technologies.

Regarding decentralisation, it is the opinion of the author that the future 100% renewable energy future will have to have aspects of decentralisation and centralisation. In Denmark, the key technologies so far have been wind turbines and DH/CHP units. Moving forward new technologies will need to be implemented, some decentralised (household battery storage, vehicle to- grid, heat pumps, rooftop solar, etc.), and some centralised (offshore wind farms, electricity to-gas, etc.) and the ability of governments to include local stakeholders, NGOs, and businesses in the development of national energy plans will remain key to achieve the sustainable energy future.

9. SUMMARY

The main aim of the thesis is to analysis the past fifty years of energy policy in Denmark to gain insight on how Denmark has become one of the European leaders in decarbonising its economy and developing renewable energy resources. A thorough review of academic articles, government and international institutional reports, and books on decentralised energy and climate change were essential for the research required for this work and make up the literature review section. The analysis and results section is divided into three parts that cover the three phases of the Danish energy transition and analyses the different government policies implemented during the different stages and how well they were in achieving the government's goals.

- Phase one: Adding renewable energy production into energy system.
- Phase two: Seeking solutions to the intermittency of renewable energy technologies when renewable energy production is between 40-50%.
- Phase three: Seeking storage solutions in an 100% renewable energy system.

The research led to some important insights that may be useful for other states seeking to decarbonise their economies within their own contexts and some policy recommendations conclude the paper.

Keywords: Denmark, decentralized energy, decarbonisation, community ownership, smart energy systems, renewable energy, wind turbines.

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11. FIGURES AND TABLES