

Storage of Intermittent Excess Energy in the Öresund Region

Hydrogen technologies as a complement for balancing Wind Energy

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Abstract

This thesis provides an account of the storage strategies for mitigation of excess electricity production (EEP) from wind energy in the Öresund region of Denmark and southern Sweden, characterized by an increasing share of wind power. Hydrogen is a versatile storage technology with potential in both large and small scale options, and for utilization in several application areas. TIS framework and strategic niche management are used for analyzing the findings. It is found that hydrogen and storage systems are emerging technologies, which have greater potential than is being realized currently. This is primarily due to low articulation of demand, technological and regulatory factors.

Keywords: Storage, Wind Energy, Excess Electricity, Hydrogen, Technological Innovation Systems, Strategic Niche Management

Executive Summary

This thesis provides an account of the strategies for mitigation of excess electricity production (EEP) from wind energy in the Öresund region, with a focus on hydrogen and storage technologies. The Öresund, a border region of Denmark and southern Sweden, is characterized by a rapidly increasing share of wind power in its renewable energy portfolio, due to the presence of Lillgrund offshore wind power plant in the Öresund strait and increasing wind power in the Danish system. Wind power is an intermittent source of energy, not always supplying when the demand arises and often leading to excess electricity when demand is low. There have been problems observed in the region stemming from this intermittency of wind power, including selling electricity at highly reduced costs on the Nordic electricity market, called the Nord Pool Spot.

Of the several strategies to mitigate the effects of EEP from intermittent sources, the ones of relevance to the Öresund region are increasing transmission capacity to neighbouring regions and energy storage. Transmission of electricity by cables exists in the region already but with more penetration of renewable energies, the large scale use of wind power will ultimately require uptake via energy storage. Hydrogen is a versatile storage technology with potential in both large and small scale options, and for utilization in several application areas.

With that background, the research question to guide this thesis was formulated: “How can hydrogen technologies contribute to the amelioration of challenges related to excess energy production from wind power in the Öresund region?” The search was guided by several tasks within the research design, which adapted the technological innovation (TIS) framework given by Bergek *et al.* (2008) and Jacobsson and Bergek (2006), and strategic niche management by Kemp *et al.* (1998).

The thesis finds that the emerging TIS of hydrogen and storage technologies are still in the formative phase of development. The knowledge base of the system is expanding and there is seen to be knowledge dissemination occurring via international symposia, seminars and workshops. Several research projects exploring application areas in back up power for electric grids, wind-hydrogen integration and fuel cell electrolyzers for power generation can be observed. The power to gas concept was found to have a few proponents in both Sweden and Denmark. Integration of heat and energy sector was seen in Denmark, with the use of electrolyzer micro-CHP units in several demonstrations projects, of note being those on the island of Lolland. Transport was seen to be a major application area with several public procurement projects for hydrogen fuel cell electric vehicles (HFCEVS) and infrastructure development for refueling stations. Thus, the major drivers in the system were seen to be ‘knowledge development and diffusion’, ‘entrepreneurial experimentation’ and ‘legitimation’ as defined by the TIS framework.

These drivers also show that the potential of the system is far greater than is achieved currently. The articulation of demand for this wind-hydrogen complement has just started, but demand is more from the Danish side, than the Swedish. This is understandable since higher wind presence and thus, more demand for EEP mitigation is in Denmark. There are a few positive feedbacks and associated externalities but not by large orders of magnitude. The system is emerging with products and services that are far from being ready for commercialization; they are, at best, in demonstrative phase.

There are multiple factors for the emerging technology that are ‘technological’, ‘regulatory’ and ‘demand’ as given in strategic niche management. A few important actors shared that hydrogen is too far in the future for an investment of time and financial capital at the moment. Sweden’s energy intensive industries require low cost energy at all times – something

hydrogen is not equipped to provide currently. Denmark on the other hand, was seen to have national policies that encourage R&D in emerging technologies. In the discussion of hydrogen against a backdrop of emerging technologies, the overarching response from the relevant actors was to not advocate for a single technology, but to make all the options more competitive in the current fossil-fuel dominated system.

Thus, in conclusion, storage technologies have a role, albeit a minor one, to play in the ameliorating of excess electricity production from wind energy in the Öresund region. Hydrogen, however, is an emerging technology with a very small niche market in the Öresund region, with dual roles as an energy carrier and energy source. Hydrogen technologies have a launch pad in the region with a number of initiatives, demonstration projects, industry-government collaboration projects that provide an indication that the technology will be of importance in the future energy economy. At this point however, relevant actors have hydrogen in the discourse, but not on any official agenda.

Recommendations for further research include following the developments in the niche market in a different snapshot in time to see which actors would take up roles of niche managers. Entry of new actors and changing governmental roles as facilitators/enablers are some other changes to follow in this wind-hydrogen system.

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Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
CTF	Community Testing Facility
DC	Direct Current
DSM	Demand Side Management
DSO	Distribution Systems Operator
ECS	Electricity Certificate System
EEP	Excess Energy Production
ETS	Emissions Trading Scheme
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FIT	Feed-in Tariffs
FIP	Premium Feed-in Tariffs
GHG	Greenhouse Gases
GW	Giga Watt
GWh	Giga Watt hours
HFC	Hydrogen Fuel Cell
HFCEV	Hydrogen Fuel Cell Electric Vehicle
ICE	Internal Combustion Engine
MW	Mega Watt
MWh	Mega Watt hour
OHC	Off-shore Hydrogen Centre
P2G	Power to Gas

R&D	Research and Development
RD3	Research Development Demonstration and Deployment
RE	Renewable Energy
RES	Renewable Energy Sources
TIS	Technological Innovation System
TSO	Transmission Systems Operator
TW	Tera Watt
TWh	Tera Watt hours
ZEV	Zero Emissions Vehicle

1 Introduction

The opening chapter provides a brief context to this body of work, and sets out the general background relating to renewable energy. The problem statement and research questions are presented. The scope for the project is laid out and the limitations are stated. Finally, the thesis disposition is provided.

1.1 Background

We are confronted with the threats of irreversible climate change, a deficit between oil, coal and natural gas (collectively called fossil fuels) demand and supply, as well as rising levels of atmospheric carbon emitted from exponential growth in global primary energy use (Dong Energy, 2012; EC, 2006; REN21, 2011; Sørensen, 2008). The emissions of pollutants and greenhouse gases (GHGs) from fossil fuel-based electricity generation by combustion of hydrocarbons account for a significant portion of global greenhouse gas emissions that in turn are responsible for climate change (REN21, 2011; IEA/Nordon, 2013; Sperling and Cannon, 2004). Not to mention, the depletion of fossil fuel stocks and approaching peak oil/natural gas, are some irreversible effects for a human time scale and have already begun to impact current generations. But peak oil and gas arguments, however important they may be, are not enough to justify exploring alternatives. Even a 10-fold increase in global oil prices in the 1973 – 1983 period did not lead to more than just a marginal increase use of alternative energy sources (Kemp *et al.*, 1998). The other important motivations of the energy-related problems of energy security, air pollution and climate change – are problems that collectively call into question the fundamental sustainability of the current energy system, where a global shift to renewable energy has long been acknowledged as the solution (SET-Plan, 2010). Renewable energy technologies are those that convert renewable resources like wind, solar insolation, hydro, biomass etc. into forms of energy that can complement or replace conventional fossil fuel energy sources.

Europe's electricity system is undergoing profound changes. The EU is planning a decarbonization path that will see EU and other countries reduce their greenhouse gas (GHG) emissions by up to 95% by 2050 (SEA, 2012; Eurelectric, 2012). Within this, the Nordic countries have even more ambitious goals to be completely carbon neutral by achieving an 85% reduction in fossil fuels and 15% by international carbon credits¹ (DEA 2012; IEA/Nordon, 2013). Denmark aims to be able to use 100% renewables in energy and transport sector by 2050 (DEA 2012). Additionally, a more immediate goal is the EU's 20/20/20 Renewables Directive which requires 20% of all energy used to be supplied by renewable sources by 2020. Sweden, on the other hand, has raised the country's target to providing at least 50% of its final energy use from renewables (SEA, 2012) and Denmark to 33% renewable energy by 2020 (DEA, 2011). To reach this ambition of providing carbon neutral power supply, the electricity sector will be subjected to an increase in variable renewable energy resources (RES) like wind and solar in the energy generation portfolio (SEA, 2012; DEA, 2011, REN21, 2011; SET-Plan, 2010). RES are attractive energy generating options: they are inexhaustible, have low carbon footprints and can operate on small scales as well as large (REN21, 2011; SET-Plan, 2010).

Renewable energy namely, wind and solar power are variable, producing alternating and partly unpredictable amounts of electricity over time. The wind doesn't always blow, and the sun doesn't

¹ Permits that allow a country to produce a certain amount of carbon emissions and can be traded, even on an international stage, if the full allowance is unused.

always shine - neither follows peak demand (EWEA 2013a; IEA/Nordon, 2013; REN21, 2011). Herein lies the problem and results in the lack of widespread acceptability of these energy systems (REN21, 2011). As a consequence of increased intermittent renewables in the energy portfolio, the electricity system faces varying electric demand throughout the day, and also generation driven fluctuations. This leads to challenges in ensuring the stability of electricity supply (Eurelectric, 2012; REN21, 2011; Botterud *et al.*, 2010). Nord Pool Spot, the Nordic energy grid, requires electricity generation to match consumption on a second-by-second basis (IEA/Nordon, 2013; Botterud *et al.*, 2010). This raises concerns about grid reliability, security of supply and damages to the function of electricity market – all of which form barriers to investments in renewable technologies (DEA, 2012; IEA/Nordon, 2013; SEA, 2012; Botterud *et al.*, 2010).

In the case of Sweden and Denmark, the risk of higher oil prices is no longer a big threat, since the import dependency is lower and the effects of oil prices are abated by fuel taxes and strategic stocks (SEA, 2013; Neergard & Evanth, 2012). Sweden also imports its natural gas solely from Denmark, and Norway is its largest oil supplier (SEA, 2012). Both are politically stable countries making the secondary effects caused by the unrest in other countries a minor concern. Strategic stocks of oil products are also held to reduce the country's vulnerability to oil market fluctuations (SEA, 2012).

In the near future, expansion of wind power is planned in many European countries. The Swedish wind power share of total energy production was 5% (EWEA, 2013b) while the Danish energy system is characterized by approximately 27% of wind power, which is also expected to increase to 50% in 2020 (EWEA, 2013b; DEA, 2012; Hedegaard *et al.*, 2012). Slightly more than 80% of growth in Nordic generation capacity is expected to take place in wind power by 2030. This means that the Nordic countries are expected to have an electricity surplus of approx 58 TWh in 2030 (Vattenfall Annual Report, 2011). A border region of both Sweden and Denmark, the Öresund region displays wind as the RES of choice (DEA, 2012; IEA/Nordon, 2013; SEA, 2012).

This problem of excess electricity production (EEP) from wind energy has many potential solutions which include but are not limited to: EEP's conversion to heat and its subsequent storage (Hedegaard *et al.*, 2012; Mathiesen & Lund, 2009; Østergaard, 2013), or storage of EEP as electricity where it can be utilized in heat storage or storage for electricity. Technologies for heat conversion and storage include various types of heat pumps (Østergaard, 2013), electric boilers (Mathiesen & Lund, 2009), and the water storage infrastructure associated with district heating systems (connected to combined heat and power systems) (Østergaard, 2013), all of which play a role in integration of wind power into existing systems. Demand side management, the modification of consumer demand, is another option that has been discussed further on.

There has been considerable research on utilizing wind power for heat storage in heat pumps and the flexibility they offer to power systems with high wind quota (Mathiesen & Lund, 2009; Østergaard, 2013). Heat pumps can contribute significantly to increase wind power utilization and this was witnessed by the 8% reduction in EEP projected for the Danish system in 2020 with 16.5 TWh wind power, solely by the increased electricity demand resulting from heat pump installations (Hedegaard *et al.*, 2012). However, this reduction is limited in the summer period, where heat pumps operate only to satisfy hot water demand and not space heating. Electricity demand does not suffer seasonal fluctuations as significantly as heat demand, and thus a case for electricity storage, or for conversion into other energy carriers is possible (Hedegaard *et al.*, 2012).

A recent energy carrier that has surfaced is hydrogen, the simplest and most abundant element in the universe. The notion of a “hydrogen economy” is moving beyond the realm of scientists and engineers and into the lexicon of political and business leaders. Due to the rising technological advances in fuel cells and hydrogen internal combustion engine (ICE), and the advent of greater competition in the energy industry, hydrogen is gaining further traction and visibility (Andrews & Shabani, 2012).

In the previous versions of a hydrogen economy, it was envisioned that hydrogen would play the critical role of providing energy storage that would allow continuous base-load electricity supply in a system relying on intermittent RES, like those relying on wind. 21% of Danish electricity and 4% of Swedish electricity comes from wind power (IEA/Nordon, 2013). In recent years however, this role has been challenged by a number of stronger alternatives including batteries, super-capacitors, thermal storage and multiple RE input being geographically distributed over a large-scale grid, not to mention the barriers posed by high investment costs associated with completely new hydrogen storage and distribution networks. Unfortunately, the reasons outlined in the previous paragraphs are very much valid for switching to renewables, but cannot be stretched to be a major driving factor for a hydrogen economy transition today.

Andrews and Shabani (2012) argue that rather than seeing hydrogen as an exclusive fuel for the future, it is prudent instead to focus on specific roles to which it is uniquely suited in each major sector. With this approach, hydrogen would still play a substantive but supplementary role rather than compete with technologies such as batteries, flywheels and a variety of shorter term energy storage options for grid power. Hydrogen and electricity can therefore adopt complementary roles as *energy carriers*, while hydrogen fuel cells and batteries play complementary roles as *energy stores* – in transport, industrial, commercial and residential sectors.

Options that provide short term storage, such as batteries, supercapacitors and thermal storage – that essentially provide just short term storage (from seconds to a few weeks) – are valuable for solar energy with its diurnal cycles (Crabtree *et al.*, 2011; Margeta & Glasnovic, 2011; Sørensen, 2008). In regions like the Öresund, long term forms of storage – in the form of alternative energy carriers such as hydrogen – will probably be necessary for security of supply and be advantageous economically for energy arbitrage. The other proven mainstream option of choice, pumped hydroelectric scheme, is not applicable in this region due to the topography (Connolly *et al.*, 2012); lack of cables make distribution of the excess electricity over large distances problematic. These have been elaborated upon further in Section 2.4.

These options are all in different phases of emergence, with pumped hydropower being the one with most worldwide applications. Hydrogen comparatively is new technology for storage applications in a more widespread renewable energy system.

Renewable Energy Systems contain entire energy supply and demand systems based on renewable energy and the transition from traditional nuclear and fossil fuel-based systems to RE systems involves synchronized changes in the following (Lund, 2010):

1. Demand technologies related to energy savings and conservation (eg Demand Side Management),
2. Efficiency improvements in the supply system (eg. CHP),
3. Integration of fluctuating renewable energy sources (eg. Wind power).

The scope of this thesis is better integration of wind power into the current energy system in the Öresund region. However, it is difficult to talk about energy solutions in a system when all three are quite interlinked, hence demand and supply improvements have also been talked about in minor detail. The scope and limitation section outlines this further.

1.2 Research Objective and Questions

This work does not seek to "pick a winner" among the technologies nor does it try to establish processes for a specific technology to be the ultimate choice. Instead, the goal of this thesis is to ascertain how a specific technology system within the suite of possible systems can contribute to the amelioration of problems that arise when intermittent renewable energy supply leads to marked periods of excess electricity in a grid system. While the preliminary stages of the study have examined storage technologies in general, the special focus of this work is hydrogen. This is due to hydrogen's recent emergence as an intermittency management strategy coupled with the gap in knowledge in the Öresund region. Within this context, the following research question has been formulated:

How can hydrogen technologies contribute to amelioration of challenges related to excess energy production from wind power in the Öresund region?

To help delimit the study and contribute information that provides insights for the research question, the following tasks were designed:

1. Identify and describe the key problems in the Öresund region related to wind EEP and delineate the main technology systems being utilized for their amelioration.
2. Delineate the main function and different methods for utilising storage technologies and hydrogen systems within the context of intermittent EEP.
3. Review literature on technical system emergence and technological innovation systems and delineate a conceptual framework to support the study.
4. Establish how these systems match the phenomena of system emergence and technological innovation via a review of that literature juxtaposed against problems and forms of the system.
5. Examine the knowledge of, and views pertaining to hydrogen, as an amelioration technology, that are held by energy system experts (authorities) in the Öresund region.
6. Identify the key infrastructure components in the Öresund region that already exist that relate in some way to hydrogen.

1.3 Scope and Limitations

The geographical scope of this thesis was set to be the Öresund as the region of interest. The audience is thought to be the relevant actors in this region. By the structural and functional mapping of the wind-hydrogen-storage system, actors will know the key systemic issues.

Defamiliarization is the enabling of a native – of society, an organization, or an academic discipline – to see his/her world with new eyes (DiMaggio, 1995). Defamiliarization of the reader is an aim of this thesis, since the scenario being discussed is different from where we are now. The path that storage development has taken varies from the one hydrogen was on prior to 2008, and where it is currently. Many developments have occurred within that discussion of a hydrogen economy.

The selection of interviewees may have been biased in favor of choosing those more inclined towards hydrogen technologies and storage solutions. Availability of interviewees also represented an issue. A few relevant people within municipalities and private companies were unavailable to participate in interviews eg. DONG and Danish Energy Agency. Their information was primarily gathered from publications.

Language presented a slight limitation in the research process too. All the interviews were conducted in English – a non-native language in both Sweden and Denmark. Most interviewees had a very good grasp of English; however, the use of a non-native language as an interview medium increases the possibility of misunderstandings on both sides. It was found on three occasions that some interviewees struggled to explain concepts and terms in English and those topic areas were not discussed in detail. Some potential interviewees were also unable to participate due to the language barrier eg. the private home owners on the island of Lolland, Denmark.

1.4 Thesis Disposition

Chapter 1 contained the introduction

Chapter 2 is a literature review that talks about the problem arising from excess energy production from wind and the effects on electricity pricing and energy arbitrage. This is followed by an outline of the mitigation strategies in existence to deal with excess energy and sets the stage for Storage technologies as the main strategy. The 3 sub-chapters that follow are focused on Hydrogen Technologies: firstly, on its production and various methods of utilization, secondly, within the purview of storage, and thirdly, in the context of hydrogen as a fuel source and an energy carrier.

Chapter 3 is the framework and methodology section. It includes a literature review of the relevant technical frameworks looked at and the methodology of the research process.

Chapter 4 is the findings section

Chapter 5 provides an analysis and the discussion

Chapter 6 concludes and recommends directions for future research.

2 What did the Öresund wind farms say to hydrogen? We are big fans.

This section provides a literature review of the thesis topic under consideration. It aims to guide the reader of the current situation regarding storage and hydrogen technologies, the context for studying these technologies in the Öresund region and any additional background information.

2.1 The problem of excess energy production

Europe's electricity system was historically designed to balance supply and demand in a cost-effective and efficient way. A fundamental requirement is the ability of the system to accommodate peak load, where peak load refers to the maximum load on an electrical power supply. This ability is given by the presence of installed generation and network capacities that are often unused. Increased penetration of intermittent renewable energy sources, like wind and solar energies, are giving rise to questions on how loads can be made more flexible in order to optimize the use of these resources and assets.



Figure 1: Map of Öresund region showing constituent parts
Source: Reprinted from (AEBR, 2011)

Excess energy production is seen to be a reality facing regions with a high portion of intermittent renewable energy sources (RES), like wind and solar. The Öresund region (Figure 1) is a Danish/Swedish border region consisting of the Capital Region of Denmark and Sjælland (Sealand) Region on the Danish side and Skåne (Scania) on the Swedish side (AEBR, 2011; SCB, 2013). In the Öresund region, wind is seen to be the relevant renewable energy source due to the high wind potential off the coasts of Denmark and Sweden.

The Swedish Energy Agency foresees that Sweden will have an electricity surplus, available for export, of 24 TWh in 2020 (SEA, 2011). Expected excess electricity production in Danish scenario is 8.4 TWh in 2020 (Kempton, 2010). Hence, there will be a problem with electricity surplus in the near future.

2.1.1 From wind

Fighting climate change, improving energy security, enhancing competitiveness and maintaining the technological leadership is of importance to the European wind industry. With the European Commission and Member States, a European Wind Initiative was created with a budget of €6 billion for wind energy research and development in 2010-2020 (Vattenfall, 2011; EWEA, 2013a) Of this €6 billion, €2.1 billion are for grid integration of wind (EWEA, 2013a). The research programme aims at improving the technological performance wind turbines, achieve 20% share of wind energy in the EU's total electricity consumption by 2020, and create 250,000 new skilled jobs (EWEA, 2013a) in an industry that already employs 192,000 people (Vattenfall, 2011).

EU's total installed wind power capacity has been steadily increasing since 2000 (Figure 2). It increased by 11.7 GW and reached an 11.4% share of total installed generation capacity in 2012, up from 10.5% in 2011. This installed capacity would in a normal wind year², produce 231 TWh of electricity – enough to cover 7% of EU's electricity consumption (EWEA, 2013b). However, the total installed wind power capacity of 106 GW is still 1.6% below the installed capacity of 107.6 GW outlined in the 27 National Renewables Energy Action Plans (NREAPs) for EU. The Danish and Swedish targets for installed wind power were exceeded by 8.4% and 55.6% respectively (EWEA, 2013b).

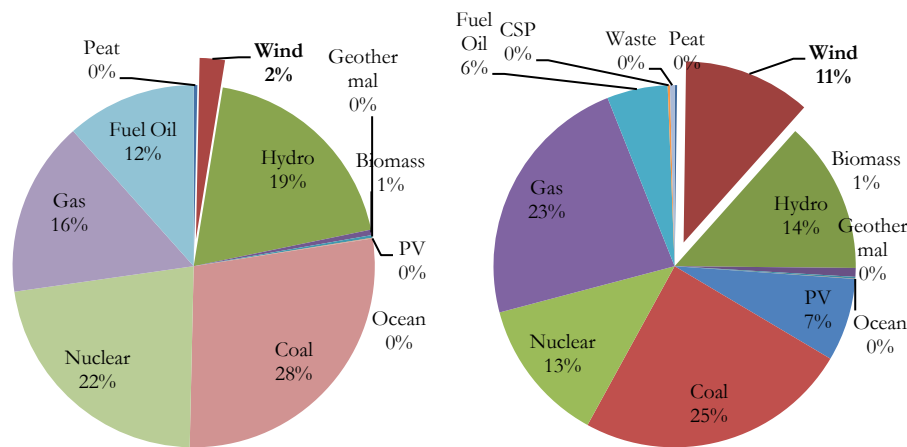


Figure 2: Increase of Wind in EU power mix from 2000 to 2012
 Source: Adapted from (EWEA, 2013b)

² A year with average wind activity is characterized by wind speed, turbulence, extreme gusts and also depends on the turbine. Average wind speed is 10m/s and average wind turbine size is 2.5-3 MW (EWEA).

Denmark is a pioneer amongst European countries to focus on wind power as an alternative to fossil fuels. Today, Denmark is one of the countries where the share of electricity demand met by wind is the highest, 2013 figures put it at 27% (DEA, 2012; EWEA, 2013b).

In 2012, Denmark installed 217 MW bringing its total installed wind capacity to 4,162 MW; Sweden installed 846 MW making its total installed capacity to 3,745 MW (EWEA, 2013b) (Figure 3). Sweden joined the wind energy group later but has since made up, having 7% of the EU member state market shares for new capacity installed during 2012 (EWEA, 2013b).

Though wind power has no fuel costs, the total cost per KWh produced is high due to investment costs and network capacity investments for new wind farms. In the future though, technological development and an increase in price of carbon dioxide (CO₂) emissions will make wind power more cost-competitive. Technological developments in wind include longer blades, improved power electronics and better use of fibre-reinforced plastics among others. (Vattenfall, 2011).

The RES are supported by regulatory policies - renewable standard in the US, the renewable obligation in the UK and closer home, the feed-in tariffs (FITs) in the Nordic countries. These supporting policies are however, being redesigned since the recent deregulation of the electric power industry (Nguyen *et al*, 2012). This brings market forces in the wind power industry as well, where the producers have to compete for generation and be responsible for the problems they cause in the electric power network; the largest problem, namely, of high uncertainty of predicting wind power output. This significantly decreases the competitiveness of wind in comparison to conventional power sources.

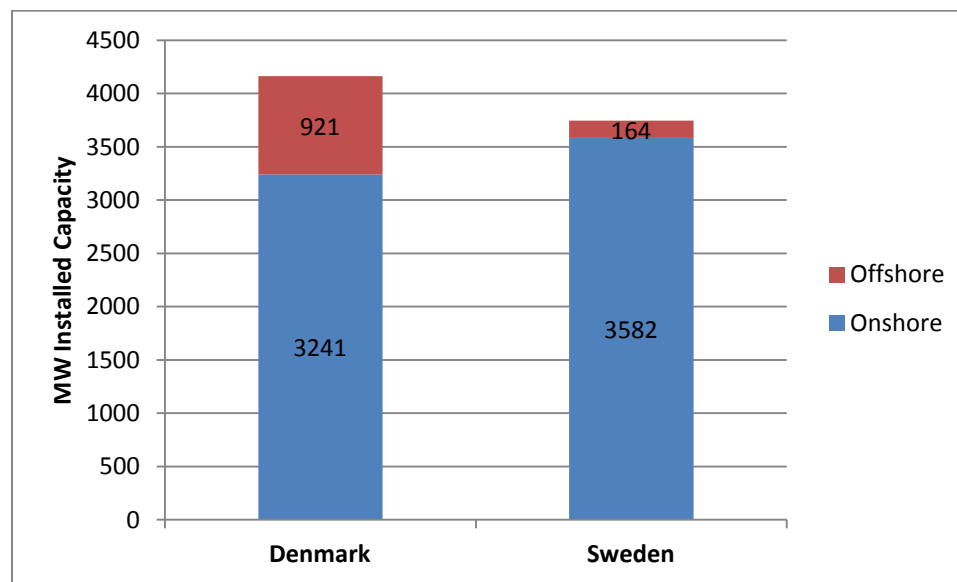


Figure 3: Wind Power Installed Capacity in 2012
Source: Adapted from (EWEA, 2013b)

In the Nordic countries, there has been a strong political will towards supporting wind power investments during the last few years (Kopsakangas-Savolainen & Svento, 2013; IEA/Nordon, 2013; EWEA, 2013a; DEA, 2012). As a result, the target for total wind power capacity has been placed at 25,600 MW to be reached by 2020 (Kopsakangas-Savolainen & Svento, 2013). Denmark

aims to have approximately 50% of electricity consumption to be supplied by wind power by 2020 (DEA, 2012). Electric power from wind energy will be increased to higher level in the time period 2020-2025 (Åfeldt, pers. comm., 2013).

The Lillgrund wind farm (Appendix 5) in the Öresund Strait (Figure 1) is Sweden's largest offshore wind farm (Vattenfall Annual Report, 2011) with an installed capacity of 110 MW. Not including Lillgrund, Skåne has an installed wind capacity of 174 MW (IWP, 2013).

The variability of RES is easily accommodated when demand and renewable supply are matched. But as is the case often with wind, it blows strongly overnight, usually when demand is low. The renewable generation, then, can only be used if conventional base-load generation is curtailed; this is an expensive and inefficient option that can cause significant reliability issues. On calm wind days, alternatively, the peak demand will need to be met entirely by conventional generation resources, requiring reserves that effectively duplicate the idle renewable capacity. It is reducing the cost of dealing with these two cases that is the major challenge facing renewable integration of wind (Crabtree *et al.*, 2011).

The mitigation strategies that this thesis discusses about ultimately boil down to improving the value of wind power in the deregulated electricity environment.

2.2 Electricity Pricing

Energy consumption in its various forms (eg. transportation, heating and electricity consumption) accounts for approximately two-thirds of global GHG emissions and is thus an important sector to look at. EU accounts for 14% of total global energy demand. Oil, coal and natural gas account for 54% of EU electricity generation.

An energy system is a value chain that starts with an energy source and finishes at end user. To utilize the energy in energy sources, it must be converted to an energy carrier- a material or process used to store and/or transport energy. The most common energy carriers are electricity and oil, but recently hydrogen as an energy carrier is moving into lexicon of people (EC, 2006; VisionGain, 2011).

Electricity is an energy carrier that is efficient in transporting energy over long distances, and has wider range of applications as compared to motor fuel, which is used solely to run vehicles (Eurelectric, 2011). In addition to being converted to work at high efficiency, electricity is also a commodity that can be bought, sold and traded in a market. The electricity market, then, is a system for exchanging bids to buy and offers to sell (VisionGain, 2011).

For electricity supply, parameters of importance are quality of service, quantity of service, security of supply, and several ancillary services. The required ancillary services are regulation services to track moment-to-moment fluctuations in load and supply, and reserve services for meeting intra- and inter-hour changes in supply and load curves. Key parameters that ensure a stable electricity flow are frequency, voltage and reactive power (Eurelectric, 2012).

Nordpool is the power pool in the Scandinavian Peninsula including Denmark, Sweden, Finland, Norway and Estonia³ (DEA, 2012; IEA/Nordon, 2013). In the Nordic power market, the wholesale

³ Estonia joined the common Nordic Power market in 2010.

trade of electricity is organized through Nord Pool power exchange which is owned by Nordic national transmission system operators (TSOs) (DEA, 2012; Kopsakangas-Savolainen & Svento, 2013). Nord Pool is characterized by a high share of wind power in total energy consumption (IEA/Nordon, 2013; Nguyen *et al.*, 2012); the market serves as a cost-efficient backup and balance for wind generation (DEA, 2012).

Nordpool market contains both the day-ahead market, called Elspot, and real-time, intraday market, called Elbas. In the day ahead market (also called a spot market – which is where Nord Pool Spot derives its name), producers and consumers submit bids which indicate the quantity of electricity and corresponding prices they are willing to sell/purchase. In the Real-time Market an independent system operator manages power imbalances caused by natural variation of loads and unconventional sources in real-time operation. The power imbalance refers to deviation from value decided in the day-ahead market (Nguyen *et al.*, 2012) At Elbas market, electricity can be traded up to one hour before physical delivery (DEA, 2012).

The transmission grid of the Nordic power market is operated by the national transmission system operators (TSO). If the transmission across borders is uncongested, there is only one market price (Kopsakangas-Savolainen & Svento, 2013). Nord Pool Market is owned by national grid companies, of which energinet.dk and Svenska Kräfnät are the ones operating in the Öresund region (IEA/Nordon, 2013; Vattenfall Annual Report, 2011).

The common power market came into existence because it was argued that the efficiency of production would be improved if market participants could trade between countries. The mix of production technologies in the Nordic Power market is quite large eg. thermal generation in Finland and Denmark, hydro-intensive Norway and hydro and nuclear in Sweden (IEA/Nordon, 2013; Kopsakangas-Savolainen & Svento, 2013). The role of hydropower in the Nordic electricity system is of balancing power and that of nuclear for base load production (Kopsakangas-Savolainen & Svento, 2013).

The average price of electricity for the Swedish region on Nord Pool was about 44 öre/KWh in 2011 (SEA, 2012). Post-October 2011, Sweden was geographically divided into four bidding areas (Appendix 1), where prices vary due to more electricity generation in the north and more consumption in the south ie. customers in southern Skåne region pay 30 öre/KWh more than those in northern Luleå region (Fleming, 2011). Danes however, pay one of the highest power prices in Europe (Nilsson, pers. comm., 2013) due to taxes where the selling price 35 öre/KWh but average consumer price is 205 öre/KWh (Pedersen, pers. comm., 2013).

The generalized statements made for Nordic countries, hold true for Sweden and Denmark including the Öresund region (Salgi, pers. comm., 2013). Local prices can be different and where applicable have been indicated as such.

2.2.1 Energy Arbitrage

Electricity markets depend on real-time supply and demand. When the market does not have a storable commodity, arbitrage then becomes important. Energy arbitrage is the storage of energy purchased during off-peak hours (high supply, low demand, lower price) and selling it during on-peak times (low supply, high demand, higher prices), where use and/or cost is more beneficial, hence making an arbitrage profit (Walawalker *et al.*, 2004).

This is an important concept to the functioning of electricity markets since the aim of most distribution grid operators, transmission system operators and utility companies is to make an arbitrage profit from energy production.

2.3 Smart Grids and Decentralized Production

As electricity generation from wind power and other energy sources with fluctuating generation increases, the need arises for an intelligent, flexible and reliable network. Current electricity networks were originally planned and constructed for centralized, large-scale electricity generation and distribution (Eurelectric, 2012).

On the supply side, the trend is expected to move towards a larger share of renewable energy sources and decentralization of production. Decentralized production may be a way to overcome infrastructural barriers associated with larger hydrogen outreach. Relying on a joint distribution for the supply of power from a diverse range of types and locations of RE generators should give greater continuity and reliability of supply than those obtainable from a small number of very large renewable power stations (Barreto *et al.*, 2003; Vattenfall, 2011) .

Due to such trends smart grid technology is being developed. Smart grids are flexible and reliable operations of distributed power generation that enhance possibilities to control and store electricity. They are visualized as being an important tool for efficiently integrating small- and large- scale wind power generation. Utility companies are conducting several smart grid technology research and development (R&D) projects aimed at ensuring secure and reliable network services, today and in the future (Barreto *et al.*, 2003; Vattenfall Annual Report, 2011)

2.4 Mitigation Strategies for Excess Energy from Wind

Due to the presence of Lillgrund offshore plant in the Öresund strait and increasing wind power in the Danish system (DEA, 2012; SEA, 2012), a large part of the RE in the Öresund region will be from wind. The subsequent EEP is a problem that wind producers, grid operators and utility companies are dealing with by looking at the array of existing strategies to ameliorate. Some of them are in use already; others are still in pre-demonstration phase. The sections below outline the state of affairs currently.

There are three ways to ameliorate excess electricity production from wind energy, two of which are the main competitors to storage (Pedersen, pers. comm., 2013). All three have been discussed in the sections that follow.

2.4.1 Demand Side Participation

Demand side participation consists of two parts: consumer engagement (ie demand response) and measures taken by utilities to ensure even supply for electricity (ie demand side management) (Eurelectric, 2011). This method of integrating renewable sources, places responsibility in the hands of the consumers; their role in the electricity market is increased.

Demand Response is a ‘bottom-up’ approach, where customers are active managers of their consumption incentivized by efficiency gains and the subsequent monetary benefits that follow. Demand Response is defined as the “changes in electricity usage by end use customers from their normal consumption patterns in response to changes in price of electricity over time” (Eurelectric, 2011). In other words, an incentive payment designed to induce lower electricity use at time of high

wholesale market prices or when system reliability is jeopardized. High energy costs can be linked to excess energy production from high wind activity. Customers' demand response can be manual – by seeing prices on display and shifting their consumption, or automated – automatically shifting consumption via technical signals based on an agreement previously established with the supplier (Eurelectric, 2011; Klinge Jacobsen & Zvingilaite, 2010).

Demand-Side Management on the contrary is a 'top down' approach where the onus of participation is on the power/utility companies. The aim of the approach, also called Load Management, is to “reduce energy consumption and improve overall electricity usage efficiency through the implementation of policies and methods that control electricity demand” (Eurelectric, 2011). DSM is usually a task for the utility companies to reduce or remove peak load, which they pay for because it is typically less expensive and easier to procure than traditional generation capacity (Klinge Jacobsen & Zvingilaite, 2010).

2.4.2 Transmission Capacity

With electricity being a carrier of energy, it works on the simple physics of needing to be transported via cables. Such cables exist currently in the Öresund region and there has been continual reinforcement of these cables to Norway and Germany (Nilsson, pers. comm., 2013; Pedersen, pers. comm., 2013). Denmark is connected to Sweden (2300 MW), Germany (1800 MW) and Norway (1000 MW) with strong transmission lines (Kempton, 2010). The long distance transmission of renewable energy provides access to larger pools of resources in order to balance regional and local excesses and deficits in addition to being cheaper and efficient.

Conventional cables are high voltage AC transmission lines. These are used for regional transmission covering one- or two- state areas. These cables have their drawbacks though, due to high losses during the conversion between AC and DC⁴ and the requirement of a single point of origin and termination. Superconducting DC transmission lines are used for longer distances and lose little to no energy, produce little to no heat and carry higher power density than conventional lines. They operate at moderate voltage, and reduce technical and cost challenges of AC to DC conversion (Eurelectric, 2012; VisionGain, 2011).

Power is usually transmitted through overhead power lines, but an increase in overhead transmission capacity has received criticism from the general public in Sweden as they are not aesthetically pleasing. Underground long distance power transmission can be cost prohibitive and have greater operational limitations but are still being examined by utility companies. With massive infrastructure, long distance and modest usage fee, the long term investment costs level out (Nilsson, pers. comm., 2013; VisionGain, 2011).

The limitation with this option is that the electrical energy cannot be stored in this distribution grid, so in the event of an increasing capacity, a sophisticated control system is required to ensure generation and demand are closely matched (Krischan, Seebacher, & Muetze, 2011)

⁴ Alternating current (AC) and direct current (DC) refer to the modifications in the voltage of electricity current that help in the long distance travelling of electricity.

2.4.3 Storage

As renewable penetration grows, storage of EEP will likely become more cost effective and necessary (Crabtree *et al.*, 2011). Storage can help smooth short-time fluctuations in generation as well as time-shift renewable generation resources from low-demand periods to high-demand periods.

Many studies have analysed and compared a wide range of energy storage alternatives for future energy systems based on electricity (Connolly *et al.*, 2012; Ekman and Jensen, 2010), heat (Connolly *et al.*, 2012, Lund *et al.*, 2009; Mathiesen and Lund, 2009), and even transport (Mohseni *et al.*, 2013; Neergard *et al.*, 2012; Sperling and Cannon, 2004).

2.5 Storage Technologies for Excess Energy Production

The electricity industry uses many types of energy storage technologies that together provide a large range of performances and capacities for different applications (Eurelectric, 2012; VisionGain, 2011).

Technologies and strategies like forecasting, geographical dispersion and interconnections to neighbouring systems via transmission lines, and sophisticated power electronics can help. However, because these strategies cannot completely mitigate the random nature of wind, large-scale use of wind power will ultimately require uptake via energy storage. (Beccali *et al.*, 2013).

2.5.1 Types of Storage Technologies

Various studies provide different cost benefit analyses for the same storage technology because of different market indicators, operational and grid conditions, valuation methods and price estimations. This technological comparison is made based on the specific objective of ameliorating effects of excess electricity via various applications areas of the storage technology.

Given the objective of the paper, a soft description of the most relevant technologies (Table 1) has been included here to provide an account to the reader, before delving in to hydrogen technologies.

Battery and flywheel technologies are less constrained geographically than hydroelectric and compressed air energy storage (CAES) since the latter are very large scale storage options. But Nguyen *et al.*'s (2012) analysis shows that battery technologies' high costs make it difficult to create profits from the variation of electricity prices alone. There would have to be optimal scheduling of existing battery energy storage with modifications like combination with other energy storage technologies eg. pumped-hydro plants.

Pumped hydroelectric energy storage (PHES) is the most utilised and mature large-scale energy storage technology currently available for electricity (Connolly *et al.*, 2012; Ekman and Jensen, 2010; Gonzalez *et al.*, 2004; Ibrahim *et al.*, 2008). Recent reports show that there is over 7 GW of new pumped hydro plants planned in the EU alone (Deane *et al.*, 2010), with potential in Sweden as well (Wiberg, pers. comm., 2013). Its major drawbacks for the Danish system are the lack of suitable sites in Denmark (Ekman and Jensen, 2010; Ibrahim *et al.*, 2008, Kaldellis *et al.*, 2009 and Kondoh *et al.*, 2000) and due to the CHP-dominated electricity system, there is no reason to construct a CAES facility (Lund *et al.*, 2009).

Other alternatives to electricity storage being considered include underground storage, magnetic wheels and capacitors but these systems are yet to be perfected, no matter which technology is chosen (Jacobssen, pers. comm., 2013).

Table 1: Most relevant energy storage technologies
Source: Adapted from (Eurelectric, 2012; Kempton, 2010; Walawalker et al., 2004)

Storage Technologies	Description	Properties	System Services	Maturity of Technology
Sodium Sulfur (NaS) Batteries	Electrochemical; Based on high temperature electro-chemical reaction between Na and S in electrolyte	No geographic constraints; high lifecycle; high maintenance costs	Peak shaving and load leveling at distribution level	Best economics for MW sized utility applications; over 55 installations worldwide
Flywheels	Store energy in angular momentum of spinning mass	High lifecycle; poor energy density; large standby losses; small scale; 15 minute energy storage capacity	Frequency regulation	Energy storage capacity is too short (15 minutes) for utility application
Supercapacitors	Non chemical; energy stored via charge separation	Small scale; withstand several thousand charge/discharge cycles without degrading	Frequency regulation	Not mature enough for utility application
Superconducting Magnetic Energy Storage (SMES)	Energy stored in magnetic field created by flow of current in a coil	High lifecycle; Small scale	Frequency regulation	Not mature enough for utility application
Pumped Hydro	Water pumped from lower elevation reservoir to higher elevation	Very large scale; geographic constraints	Load levelling	Most utilized and mature technology
Compressed Air Energy Storage (CAES)	Adiabatic storage generates power when compressed air is expanded	Very large scale; long lifespan; geographic constraints	Load levelling	Not demonstrated due to financial and technological risks

2.5.2 Comparison of Storage Systems

Based on Eurelectric (2012) characteristics of storage systems, there are a few important parameters to consider while evaluating the service application.

The power ie. the amount of the energy discharged per unit time (in KW), and the amount of energy that can be delivered within a time interval, together constitute a storage power rating. The lifetime of a technology is the duration of time between charge-discharge cycles. System round trip energy efficiency reflects the energy output relative to the energy put into the storage technology. Lastly, the response time reflects the time taken to respond rapidly to provide capacity when demand changes.

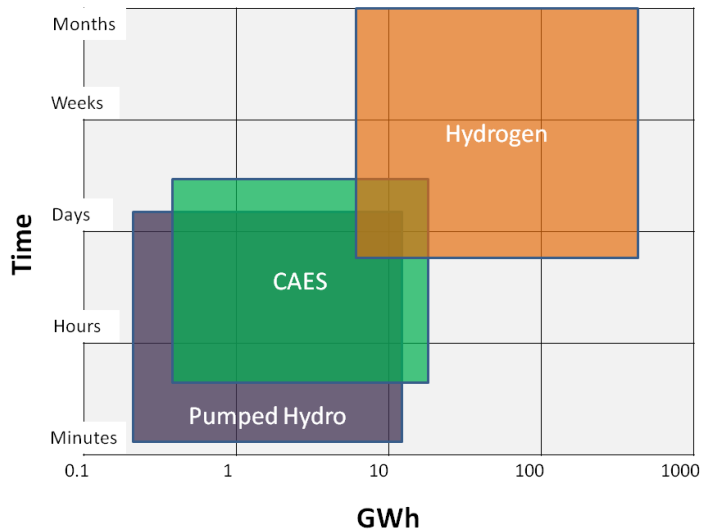


Figure 4: Comparison of Storage Systems for
 Source: Adapted from (Crotogino, Donadei, Bünger, & Landinger, 2010)

Thus, there are a number of different storage technologies in existence currently, but when it comes to storing large volumes of energy over long periods of time, there are only a handful of options (Crotogino *et al.*, 2010; Ehret, pers. comm., 2013).

When compared to other electrical energy storage technologies, hydrogen offers large scale energy storage capacity over longer periods of time (Vätgas Sverige, 2012). Hydrogen has 60 times more energy storing capacity than pumped hydro (Ehret, pers. comm., 2013). When compared with hydrogen, the volumetric density of pumped hydroelectric storage is also only 0.273 Wh_e/litre, compared to upto 0.47 Wh_e/litre for metal hydrides and fuel cells. The large volume that hydrogen presents is offset by its energy density; a kilogram of H₂ contains about 3 times as much energy as a kilogram of oil (Beccali *et al.*, 2013).

2.6 Hydrogen technologies

Hydrogen is recognized as being one of the very few near-zero emissions energy carriers that could be a significant part of the EU's future low-carbon energy and transport sectors (Amoretti, 2011; Andrews & Shabani, 2012; Beccali *et al.*, 2013; Bossel, 2006; CEP, 2011; FCH-JU, 2013). Hydrogen and fuel cell technologies are being considered as promising future tools internationally in countries such as Japan, Korea, US, Canada and China; preparations are already being made for broader deployment of these technologies (FCH-JU, 2013). As a medium of energy storage of large capacity, hydrogen also levels off fluctuations in the supply addressing a concern of EU policy-making.

Renewable energy systems include energy conversion technologies that convert one form of energy to another (eg. electricity into hydrogen), and energy storage technologies that save energy from one hour to another (eg. hydrogen storage technologies). The difference between the two is more to do with purpose of the technology than a specific technical aspect. If the purpose is to convert electricity into hydrogen to supply a vehicle with fuel, then the electrolyzer is a conversion technology and the role that hydrogen plays is of a *fuel source*. If the purpose is to store electricity, then the electrolyzer-hydrogen storage-fuel cell system is the storage technology and the role that

hydrogen plays is that of an *energy carrier* (Lund, 2010). This has been elaborated upon further in Sections 2.7 and 2.8.

2.6.1 Production of Hydrogen

Production systems for hydrogen have historically been fossil fuel-based, but are now evolving towards renewable resources. Due to vast expansion of wind power generation capacities in both on- and off-shore power plants, wind will turn into the main energy source for hydrogen production after 2020 (Ehret, 2012). Moreover, several studies (Andrews & Shabani, 2012; Barreto *et al.*, 2003; Beccali *et al.*, 2013; Bossel, 2006; Dunn, 2002) show the great potential for wind-hydrogen systems for leveling out fluctuations in the energy system – suggesting synergies ready for exploitation. ELYGRID and Reselyser are EU projects focused on sustainable hydrogen production coupled with wind turbines (FCH-JU, 2013).

There are several ways of producing hydrogen –from fossil fuel derived sources or in carbon neutral ways. Both are discussed here in detail because as much as a carbon neutral scenario would be ideal, utilizing the existing methods from industry could play a role in successful penetration of hydrogen. Hydrogen can be produced at an industrial scale by water electrolysis, steam reforming of natural gas and methane, and coal gasification (Barreto *et al.*, 2003; FCH-JU, 2013). Efforts are being made to adapt and improve techniques long used in petro-chemical and natural gas industries (eg. in Stenungsund and north of Gothenburg, Sweden) to sequester carbon and leave hydrogen behind (Wiberg, pers. comm., 2013)

Other methods for conversion of primary and secondary fuels into hydrogen, that have seen cost improvements are partial oxidation of fuel oil, solar thermal cracking, biomass gasification, and cogeneration of electricity and hydrogen via high temperature nuclear reactors (Barreto *et al.*, 2003). However, for the next 15-20 years, natural gas reforming and water electrolysis are likely to be the main sources of hydrogen (FCH-JU, 2013). Only water electrolysis contributes to a carbon neutral scenario on its own; steam reforming requires additional carbon capture and storage (CCS) methods to achieve the same result (Barreto *et al.*, 2003; Bossel, 2006; FCH-JU, 2013; Karakashev *et al.*, 2012; Markusson *et al.*, 2012).

Natural gas could play a crucial role in enabling successful penetration of hydrogen, since the latter would fit well into a natural gas-dominated energy system. Hydrogen can be produced from gas and could profit from its existing transportation and distribution infrastructures. The Swedish natural gas system, for example, is built on one transmission system that is 620 kms, several distribution systems that are 2,600 kms in total, and transmits 19TWh of energy annually. The gas comes from Denmark and supplies southern and western Sweden via an extended gas network. Natural gas accounts for 20% of energy usage in these regions, which is equivalent to the combined usage in the rest of Europe (SEMI, 2013).

Steam reforming is the most widely applied and least expensive method for hydrogen production. Barreto *et al.* (2003) think that developing highly efficient and cost-effective small-scale steam reforming technologies applicable in distributed production sites could be the key to overcome barriers to large-scale delivery infrastructure.

Decentralized small-scale reforming of natural gas would produce hydrogen close to the point of use, while profiting from existing natural gas distribution systems (Barreto *et al.*, 2003). This will

seem more feasible when natural gas production peaks, and a point is reached where using renewable sources of energy to produce electricity for electrolysis process could be cheaper. In recent years, solar- and wind- power based electrolysis systems have been set up in Germany, Italy, Spain, Switzerland, Finland, US and even Saudi Arabia (Amoretti, 2011).

Power to Gas (P2G) is a technology that produces hydrogen by using electricity. The process involves use of excess power to produce hydrogen by electrolyzing water, and if required, conversion of hydrogen into synthetic methane through a reaction with CO₂ – called the Sabatier reaction (Dunn, 2002; Mohseni *et al.*, 2013; Vattenfall, 2011). The resulting renewable gas can be stored and transported in the gas network and its distributed gas tanks. This can be done by feeding the gas into the natural gas grid. Alternatively, it can be burnt on demand in gas fired power plants and generate electricity when needed.

The efficiency of P2G is 60% and 35-40% for Power to gas to power (Eurelectric, 2012). This technology is to be used for energy management, from chemical industry. Economies of scale and technical conditions mean that such applications will fall in the range of several MW. It is bound to gas storage or gas pipelines and thus could utilize the Swedish natural gas system. The Sabatier reaction, though an efficient way of integrating hydrogen, carbon dioxide and a renewable energy system, does not exist on a commercial scale usage (Mohseni *et al.*, 2013).

Other exotic methods for producing hydrogen are from genetically engineered microbes, algae, cellulose and other biological processes. Heat produced by solar or nuclear power plants can also be used to crack water molecules thermochemically in a process under development currently (Christensen, pers. comm., 2012). Of these, hydrogen produced by algae was observed by the author, albeit still under development, at the Lolland Municipality facility⁵.

2.6.2 Fuel Cells

Fuel cells and other hydrogen-using technologies play a major role in a substantial transformation towards a more flexible, less vulnerable distributed energy system⁶ that meets energy needs in a cleaner, more efficient and cost-effective way. Fuel cells can also help small energy producers. Traditionally, producers would immediately put their energy in the distribution network, rather than storing it. HFCs enable more 'control' (on energy and prices) to small energy producers. Electrolyzers have the capacity to instantaneously match variable power supply. Hence, HFCs can be used to produce hydrogen, as well as to regulate the grid (Ehret, pers. comm., 2013).

The Fuel Cells and Hydrogen (FCH) Joint Technology Initiative, under the SET-Plan, works to speed up the development of hydrogen-supply and fuel cell technologies to enable mass market introduction by the industry in the timeframe 2015-2020 (SET-Plan, 2010; FCH-JU 2013). The FCH-JU has a budget of €1 billion for the years 2008-2013 financed in equal parts by the European Commission and the industry (SET-Plan, 2010). Fuel cell basic research includes stack development, development of membranes and catalysts, reforming technology, and fuel cell applications in domestic power supply, portable systems and mobile applications.

⁵ The author visited the island of Lolland on a study field trip on 26-27th November, 2012.

⁶ In distributed energy systems, fuel cells can play a role to give more control to small energy producers. This was outlined in section 2.3.

When it comes to balancing wind energy, fuel cell systems need hydrogen and consequently hydrogen storage (Figure 5). The flexibility that could arise from the use of electrolyzers for hydrogen production – depending on the installed capacity of electrolyzers and on the respective charging level of the storage – could be doubled (Heinz & Henkel, 2012).

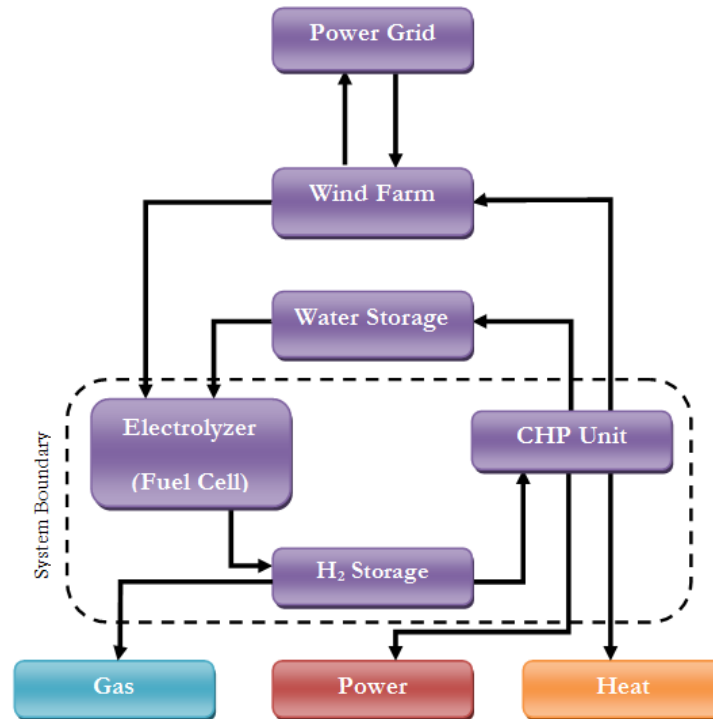


Figure 5: Wind-Hydrogen Cycle
Source: Created by author

Fuel cells (FCs) are favorable for the development of stationary plants due to low environmental impact and high electric conversion efficiency independent of size and production of heat for use in cogeneration cycles. The working of a HFC is shown in Appendix 3. For FCs to be entirely ready for commercial application, they need to achieve the following European Commission targets: cost of €1000/kW and lifetime of 40,000 hrs (Jacobssen, pers. comm., 2013; Wang *et al.*, 2005).

The main FC technologies are Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC) and Proton Exchange Membrane Fuel Cell (PEMFC) (FCH-JU, 2013) of which the Lolland project aimed to penetrate SOFC and PEMFCs into commercial markets (Jacobssen, pers. comm., 2013).

2.6.2.1 Fuel Cell Mobility

A fuel cell electric vehicle (FCEV) is a zero emission vehicle (ZEV), provided the energy source is renewable. The FC supplies electric power for electronics, heating and air-conditioning systems. FC drives in vehicles are also efficient and quiet, and high-torque electric motor replaces a generator and allow for seamless acceleration (CEP, 2011).

New fuel cell hybrid buses combine advanced fuel cell systems with significantly lower hydrogen consumption and longer service life with the innovative drive system of the Citaro G BLueTec

Hybrid. The recovery of braking energy substantially reduces the cost of operating the vehicle and reduces consumption of hydrogen; the new generation buses consume about 50% less hydrogen than the previous generation (CEP, 2011).

Hydrogen used as a fuel for FCEVs utilizes the key advantage of the fuel cell: energy-efficiency superior to that of conventional engines. The combined advantage of hydrogen and FCs may result in car emissions as low as 20 gCO₂/km, as compared to an average of some 160 gCO₂/km today. This exceeds current EU emission reduction targets. At the same time, FCEVs are now offering driving ranges and performances comparable to today's ICE cars (CEP, 2011). Mercedes hybrid can do 320 km on a single refuel (Jacobssen, pers. comm., 2013).

2.7 Hydrogen as a fuel source

For hydrogen to be a useful future fuel, it needs to be transported to the point of use and stored. Distribution of hydrogen includes transmission and distribution pipelines, compressors, pressure-regulating equipment and above- and under-ground storage facilities (FCH-JU, 2013). For storage of hydrogen, the most mature technology currently converts it to high pressure compressed form through utilizing cylinders (FCH-JU, 2013).

2.7.1 Transport

Hydrogen offers great potential as a transport fuel that can be produced from domestic renewable energies. By facilitating decarbonization of the transport sector and increased energy security, hydrogen contributes to achieving key EU policy goals. European Commission has aims for a competitive transport system that has a target of achieving fossil fuel independence and a reduction of at least 60% carbon emissions in transport sector by 2050 (Jespersen & Lohse, 2012). Transport and refueling infrastructures are major application areas under the FCH-JU's multi-annual implementation plan as they receive 32-36% of the budget (FCH-JU, 2013)

The transport sector consists of road traffic, rail traffic, aviation and maritime traffic (SEA, 2012) and along with food and agricultural sectors is one of the two most oil-dependent sectors in Sweden. The Swedish transport sector accounts for as much as 77% of the use of oil products, and in Denmark, the corresponding figure is 67% (DEA, 2011; SEA, 2012). In 2009, 94% of Swedish transport sector's energy use consisted of oil products and only a small proportion utilized electricity (used by trains), CNG (compressed natural gas), biogas or ethanol. In Denmark, it was 98% (Neergard & Evanth, 2012)

If electric vehicles are to be a truly zero-emission mode of transport, electricity must be produced from RE sources of electricity. Zero-emission can come from renewable sources, nuclear or fossil fuels with carbon capture and storage (Markusson *et al.*, 2012). Electrification of the transport sector results in better flexibility and improved fuel efficiency (Kempton, 2010). EVs include electric cars, electric boats, electric motorcycles and scooters, electric bicycles and other modes of transport involving electric propulsion rather than being powered by an ICE. EVs are characterized by the highest engine efficiency of existing propulsion systems and zero tailpipe emissions (Karakashev *et al.*, 2012). At present, EVs are mainly appropriate for light vehicle utilized in personal transport; EVs for heavy transport is not economical (Karakashev *et al.*, 2012). This is seen in statistics for the 2020 forecasts, where vehicles below 2 tons were predicted to be primarily EVs (Kempton, 2010).

The two main arguments that exist against using hydrogen as a fuel source in transport are related to the efficiency losses and to biofuels being a better alternative. That hydrogen is produced by electrolysis traversing a convoluted path of converting electricity to hydrogen, transporting and storing it, and then reconverting it back to electricity on board fuel cell vehicle is a path that has energy losses along the entire route (Andrews & Shabani, 2012; Mathiesen, pers. comm., 2013). Simply charging batteries in vehicles using grid electricity generated from renewables is a more viable option, since the electricity originates from and returns to one electrochemical device.

Both battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (HFCEVs) are zero-emission transport solutions. At first sight, energy efficiency from the renewable source to traction energy for BEVs appears higher than HFCEVs. For short term storage (up to a few days): the round-trip energy efficiency of a battery is in the order of 80%. For HFC, the energy efficiency of an electrolyzer is typically in the order of 90%, that for storage 95% and 50% for the fuel cell, giving an average comparable round-trip efficiency of only 43%. However, if BEVs are left without being used for some time, the batteries self-discharge and round-trip efficiency rapidly declines towards zero over a period of several months. Additionally, the BEV system charged from the grid will require long term storage to guarantee year-round supply. Thus, when these storage losses are taken into account, the average round trip efficiency of the overall BEV system is similar to that of the HFCEV (Andrews & Shabani, 2012).

Electric cars need major improvement in battery durability, distance range covered by charge and recharge time to be a realistic alternative to fossil fuels. BEVs are increasingly being used for shorter trips, whereas HFCEVs are utilized for longer trips (CEP, 2011; Karakashev *et al.*, 2012).

A preliminary reading concludes that HFCEVs have greater range (2-3x) for given volume and mass of storage system when compared to BEVs. In going along with the theme of not putting all eggs in one basket, the optimal energy storage system for vehicles requiring the range equivalent to today's petrol and diesel vehicles is likely to be a combined hydrogen and battery system (US DoE, 2010). The hydrogen system would provide the bulk energy storage, while a relatively small energy capacity battery would allow regenerative braking, meet power demands, and generally buffer the fuel cell against loads changes to extend its lifetime eg. demo car called FCX Clarity by Honda is commercially available, albeit in limited numbers.

The second argument, of biofuels is particularly relevant in the Swedish context. Biofuels, principally ethanol, various bio-oils and biodiesel are alternatives that have emerged to hydrogen as a transport fuel. Provided the energy used to produce and distribute these biofuels is obtained from renewable resources, they are also a zero-emission option. The added advantage of needing relatively minor changes to existing engines and fuel distribution infrastructure make biofuels a readily implementable substitute for petroleum fuels. Switching to hydrogen, on the other hand, would indeed require a completely new fuel distribution, storage and dispensing infrastructure, as well as a radical change in vehicle motive power systems and associated vehicle design.

Given the current state of technology, vehicles that meet today's customer requirements for comfort, dynamics, range of more than 500kms and quick refueling, are only feasible with hydrogen. FCEVs also have an electric motor that is supplied with electricity from the fuel cells, and can be regarded as a parallel development to BEVs. At the same time, because of their high level of efficiency and dynamic responsiveness, BEVs are a useful complement in urban transport, where demands on the range are lower (CEP, 2011)

Electromobility storage options: load factor of a car is 3-6% which means that the car is parked 94-97% of its lifetime, usually close to where the drivers stay such as home or work place. These car-driver locations are precisely where the demand loads arise (Barreto *et al.*, 2003).

In most situations concerning its use as a transport fuel, hydrogen would be transported from production site to end users as gas, via a pipeline. Ideally, the natural gas distribution system would be used for at least the initial stages of a transition to hydrogen. Hydrogen could also be shipped in liquid form, in tank trucks, rail cars, or for short distances, in vacuum-jacketed pipelines. The last option would be feasible only for shipment to large potential end-users eg. airports (Karakashev *et al.*, 2012).

Hydrogen internal combustion engine vehicles run on a bivalent ICE that can burn both hydrogen and diesel/petrol. The hydrogen internal combustion engine requires only minor technical adjustments to conventional engines, making the costs low and allowing the vehicle to also run on diesel. Hydrogen ICEs are not zero emission vehicles since NO_x⁷ are produced upon combustion with air. This is a piece of transitional technology (Ehret, pers. comm., 2013).

2.7.2 Transport in Öresund Region

The Danish Energy Agreement includes the use of electricity and renewable energy in transport as one of its action plans (DEA, 2012).

Sweden's target for renewable energy in transport sector is the same as the EU Directive of at least 10% of total demand of motor fuels to be from RES by 2020 (SEA, 2012). In addition, the country aims to have the vehicle stock fossil-fuel independent by 2030 (SEA, 2012).

During the last few decades, a large range of initiatives have been undertaken to bring about climate friendly solutions. These efforts resulted from local and regional initiatives in the form of projects and experimentations along with policy changes in Sweden and Denmark. (Carlsson *et al.*, 2012).

Danish taxes on oil and gasoline include energy, NO_x and a CO₂ tax. Despite this, the use of fossil fuels in transport has grown steadily in the past 40 years and the share of RE is only 3% (DEA, 2012). This low share is attributed to the fact that it is more expensive to use RE in transport than it is in other sectors eg. in electric cars which are today very expensive compared to traditional cars (DEA, 2012). The Öresund link has contributed to increased transportation between Sweden and Denmark as a core aspect of regionalization (Carlsson *et al.*, 2012). For entire Öresund region, 34% of travel with public transport is dependent on oil products (Neergard & Evanth, 2012)

But still, the share of electricity in total energy consumption is likely to increase given the fact that electricity in the long term is expected to replace, for example, petrol as the primary fuel for cars (Vattenfall, 2011).

By 2030, 80% of the Danish vehicles weighing less than two tones will be replaced by a combination of BEVs and HFCEVs, which will lead to a rise in the electricity consumption by 7.30 TWh/year and fuel savings by 20.83 TWh/year. It was also found that 12.6 TWh of gasoline can be replaced by

⁷ NO_x are oxides of nitrogen released with fuel emissions and are atmospheric pollutants.

4.4 TWh of electricity (Kempton, 2010). To promote the use of electric cars, these are exempt from purchase tax and annual owners tax (DEA, 2012).

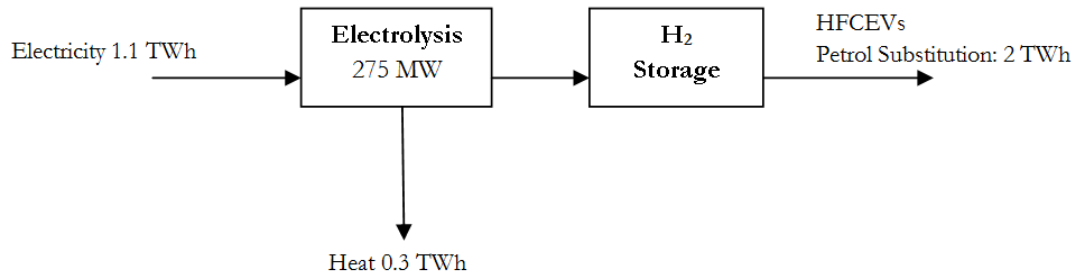


Figure 6: Transport Scenario with HFCEVs replacing ICE cars
Source: Adapted from (Kempton, 2010)

Sweden's transport sector accounts for about 123 TWh, approximately one-third of the country's final energy use. SEA (2012) figures indicate an increased use of energy in aviation. Within the transport sector, road traffic used the greatest proportion, 93% of total energy use (SEA, 2012). This is in part due to Sweden's geography which makes a large part of the inhabitants dependent on cars on a daily basis (Vätgas Sverige, 2012). At the end of 2011, 4.4 million vehicles were on the Swedish roads, of which 5.7% could run on a predominant proportion of renewable motor fuels (SEA, 2012).

Swedish CO₂ tax is levied on vehicles that emit above a certain value, which currently is 120 gms/km (SEA, 2012). Passenger cars with better environmental performance pay no vehicle tax for five years. This exemption is based on a max CO₂ emission level in relation to the vehicle's weight (SEA, 2012). These Swedish taxation rules also encourage selection of vehicles running on electricity or a green fuel and not petrol or diesel. The notional taxable value is reduced in that event, by 40% in 2012 and 2013 (SEA, 2012).

The Danish Energy Agency (2012) acknowledges that one of the ways to increase the use of RE for transport is by using electricity produced by wind turbines (and other RES). Research funds have been set aside within the Energy Agreement of 2012-2020 for investments in infrastructure regarding energy for transport and for prolonging the registration fee exemption for electric cars.

Hydrogen refueling stations were opened in Copenhagen by Shell in 2009, which can refuel 15-20 cars per day. Copenhagen municipality does have a strategy for hydrogen vehicles and is looking to expand the number of fuelling stations (Jacobssen, pers. comm., 2013; Karakashev *et al.*, 2012). There are only a limited amount of hydrogen-driven vehicles in use in the Öresund Region – 8 cars in Denmark, 1 car and some buses in Sweden. (Karakashev *et al.*, 2012). EcoMobility project seeks to reduce the environmental impact of transport while increasing economic growth and accessibility in the Öresund region (Jensen *et al.*, 2012).

2.8 Hydrogen as an energy carrier

The role of hydrogen, initially, was as a vehicle fuel, and only to a minor extent as a storage medium for leveling out fluctuations in wind energy. This thinking has changed with the technological progress that has been achieved since 2007 (Ehret, 2012). The change is reflected in the variety of applications and developments that have been seen all around the world.

The introduction of hydrogen as an energy carrier in society can be described in terms of an innovation system where the introduction and commercialization of the hydrogen in the energy system is a function of technological interactions (Vätgas Sverige, 2012).

2.8.1 Micro-CHP

In the Nordic energy markets, a large part of the conventional thermal power is produced by combined heat and power (CHP) plants. The technologies in use are oil fired condensing power plants as well as gas turbines (Kopsakangas-Savolainen & Svento, 2013).

Stationary power generation and CHP are major application areas under the EU's fuel cell and hydrogen initiative, getting 34-37% of the budget allocation (FCH-JU, 2013). Stationary applications where the energy supply is utilized for homes is seen as a major funding sink for hydrogen technologies. Micro-CHP systems are in the power region 1-10 kW (Ehret, 2012). The Danish Energy Agreement for 2012-2020 includes CHP production in its action plan (DEA, 2012).

The relevance of CHP plants in Denmark comes from the fact that Denmark has a very high percentage – more than 55% - of net energy demand from heating coming from district heating systems. The efficiency of electricity and heat production are increased by using the combined heat and power plants for production. In 2011, 63% of the electricity produced at thermal plants was in combination with heat (DEA, 2012). Kempton's (2010) analysis also shows that one of the key factors in flexible energy systems was to integrate small CHP stations and wind power to secure grid stability. The other factor was to operate the micro-CHP stations according to fluctuations.

The primary objective of having the CHP units is to get rid of oil boilers and at the same time solve the surplus wind energy problem (Jacobssen, pers. comm., 2013).

These units are 1.5 kW each for heat and electricity. 32 micro-CHPs are in use currently: 5 at a retirement facility, 6 in a school, households have 2 units and the church building has 1 (Jacobssen, pers. comm., 2013).

2.8.2 Existing or Near Future Hydrogen Centres

Off-shore Hydrogen Centres (OHCs) produce hydrogen from wave and wind power large scale by electrolysis of sea water for transport sector. A demonstration of this was seen by the author in Lolland, called the 'Floating Power Plant' (Christensen, pers. comm., 2012). Hydrogen can also be stored from season to season and be supplied to large-scale fuel-cell power plants to provide back-up electricity input to centralized grid to ensure continuous supply throughout each year as primary energy inputs from renewables fluctuate. OHCs can feed power directly to the main grid and the surplus to electrolyzers for hydrogen production (Andrews & Shabani, 2012). Theoretical wave power potential globally is estimated to be up to 9TW with 2TW potentially exploitable. The 2008 total world electricity demand was 2 TW. 2012 was a record year for offshore installations in the EU, with 1,166 MW of new capacity grid connected (EWEA, 2013b)

Hydrogen produced by OHCs can be pumped via pipelines for direct on-shore storage and usage in on-shore facilities but there is also the relatively new option of storing hydrogen in very large quantities in subsea depleted natural gas or oil reservoirs. These are thought to be technically feasible but little work has been done on it due to implications for natural habitats. However, off- and on-shore bulk hydrogen storage facilities could play crucial strategic roles in ensuring continuity of supply to transport and centralized electricity generation sectors. Bulk storage also have utility in large reserves for national and international purposes (Andrews & Shabani, 2012).

Coastal hydrogen centers located on land near the sea also electrolyze hydrogen from water and supplement the OHC supply to meet the requirements of the transport sector. The main storage options for hydrogen on-shore are underground in pressurized gaseous forms in depleted natural gas or oil reservoirs, aquifers, excavated rock caverns and solution-mined salt caverns. Land surface based large scale hydrogen storage facilities are compressed gas facilities at pressures up to 700bar (Andrews & Shabani, 2012). IDEALHY is an enabling project to develop an economically viable hydrogen liquefaction capacity for Europe (FCH-JU, 2013).

Autonomous hydrogen centres - stand alone energy supply and storage centers that supply new residential, commercial, industrial and agricultural development in areas not already served by the grid. This might have applications in far out areas in Northern Sweden, but for Öresund, it can be said that all areas are well connected so AHCs are not considered.

2.9 Institutional Stimuli

Wind power is encouraged by many regulatory policies such as the renewable standard in the US, the renewable obligation in the UK and feed-in tariff (FIT) closer home, in the Nordic countries (Nguyen *et al.*, 2012). These supporting policies have been redesigned since the deregulation of the electric power industry which puts wind power into market forces. But wind power producers (WPPs) have decreased competitiveness in comparison with conventional sources like coal-fired, gas-fired and hydro power plants. This is primarily due to the high uncertainty that comes with modern prediction tools (10-15%) along with a 1-2% error of load forecasting (Nguyen *et al.*, 2012)

Each EU country has its own individual support system for renewable energy. These support systems are designed to strengthen the competitiveness of RES and thus contribute to the necessary conversion of Europe's energy system. Under the European Wind Initiative, EU and national authorities are to allocate an average of €288 million annually to ensure the implementation of the initiative (EWEA, 2013a).

However, the low EU budget and lack of coordination between the EU and national funds are slowing down the implementation of the initiative. These are issues to be addressed in the next EU programming period (2014-2020), where more effective EU-national cooperation mechanisms should be put in place and sufficient EU funds allocated (EWEA, 2013a).

In the Nordic power market, renewable energy implementation is supported through two mechanisms: indirectly via the European Commission's internal emission trading (EU ETS) and directly through national support schemes (Kopsakangas-Savolainen & Svento, 2013). The institutional stimuli discussed in this section pertain to wind, but the system of support would be the same in the event for supporting emergent technologies.

The EU ETS makes it more profitable for wind producers to produce during hours when conventional sources are the market clearing technology by increasing the variable costs for conventional sources. The instrument is meant to keep the pre-defined total emissions quantity within the prescribed limits for the company under the scheme (Kopsakangas-Savolainen & Svento, 2013).

Denmark uses “feed-in tariffs” whereas Sweden uses an “electricity certificate system” (DEA, 2012; SEA, 2012; Vattenfall, 2011). A basic feed-in tariff (FIT) is a renewables promotion policy that pays a guaranteed price for power generated from a renewable energy source, most commonly for each unit of electricity fed into the grid by a producer, and usually over a fixed long-term period (typically 20 years). Feed-in tariffs guarantee producers of RE a fixed rate and have guaranteed market for electricity produced. The FIT payment is usually administered by the utility company or grid operator and is derived from an additional per-kWh charge for electricity (or other energy source, such as heat) that is imposed on national or regional customers, often spread equally to minimize the costs to individuals. Tariffs may be differentiated by technology type, size and location, and they usually decline over time (DEA, 2012; Dong Energy, 2012).

In Sweden, the Act (2011:1200) concerning Electricity Certificates will increase renewable electricity generation by 25 TWh by 2020 over 2002 levels. The producers of renewable electricity receive an allocation of electricity certificates that are awarded to them by the state in proportion to generation. Electricity suppliers buy certificates in proportion to how much they sell (“quota requirement”). This creates demand for certificates and a market is formed where certificates are traded (SEA, 2012; Vattenfall, 2011).

Variations of FITs exist - market-independent mechanism eg. seen in Germany, and premium FIT (FIP), a market-dependent mechanism eg. Spain. The policy community broadly agrees that a ‘true’ FIT includes three provisions: 1) guaranteed grid access 2) long-term contracts for electricity (or heat) produced, and 3) prices based on the cost of generation plus a reasonable rate of return. (REN21, 2011). The fixed FIT depends on the wind power investment costs with the promotion of market access of wind power (Böhringer, Rutherford, & Tol, 2009; Heinz & Henkel, 2012). The premium based feed-in tariff (FIP) is based on the view that the tariff should depend on the technology’s own cost and also on the costs of the technology which it is going to replace in the market (Kopsakangas-Savolainen & Svento, 2013; Lipp, 2007).

There is a need for direct support mechanisms (such as FITs) apart from the support that EU ETS gives to increased investments in renewable energies. The argument lies in the kind of electricity market is seen in this region. If the market had only energy sources which were under the EU ETS, the FITs would not be needed. In the Nordic power market however, electricity production relies on a mix of sources, of which over half are hydro and nuclear power. In these markets if incentives are given through emission trading for wind, they require relatively high emission permit prices which in turn increase the spot prices. An increase in spot prices means higher prices for those sources not involved in the ETS, which increases the windfall profits for those technologies. Thus, instead of paying direct supports for wind power producers, the market pays increased price for the whole production system (Kopsakangas-Savolainen & Svento, 2013). This market does have both, the ETS and the Nordic direct renewable-promoting mechanisms (Kopsakangas-Savolainen & Svento, 2013).

In the Nordic countries, if the aim is to minimize production costs per installed wind capacity, the FIP is a better choice; for a target of minimizing emissions (regardless of costs), it is best to rely on

ETS (Kopsakangas-Savolainen & Svento, 2013). In Sweden, the aim would be to reduce production costs, so a national policy would make more sense than the EU ETS. It is preliminarily thought that Denmark would have the same situation since it is doubtful if either of the two countries have an immediate need to cut down on emissions to reach their targets. Sweden has the highest percentage of renewable energy within the Nordic countries (IEA/Nordon, 2013) and supportive policies for Danish RE have spurred economic growth nationally (Magnoni & Bassi, 2009).

The price of CO₂ emission allowances are based on supply and demand. As a result of the current economic situation in the EU, the supply of CO₂ emissions allowances is large. Until year-end 2012, power utilities received a large share of their CO₂ emission allowances free of charge, but starting in 2013, this allocation will be stricter, as all emission allowance for electricity generation will be auctioned. The EU is currently looking into the opportunity to make the requirements in the trading system more stringent and thereby push up the price of CO₂ emissions allowances. The consequence of this would be a sharp increase in costs for companies that generate electricity with fossil fuels (Vattenfall Annual Report, 2011).

2.10 Community Testing Facility, Lolland, Denmark

Lolland is an island, also classified as a peripheral community region of Denmark, though it is only 150 kms. from Copenhagen. Due to this remote location and low population density (Magnoni & Bassi, 2009), it is expensive to extend the grid and have the houses close by to the source of energy. Thus electrolyzing process is being built into the micro-CHP units to be independent of the grid (Jacobssen, pers. comm., 2013). Hydrogen on the island of Lolland has seen a wide audience and lots of interest. The community testing facility (CTF) is a very large demonstration project⁵.

Lolland implements renewable energy projects as a way to promote economic growth in a relatively remote area. The development strategy is seen in the Lolland Community Testing Center Facilities (CTF) where a forum is created between private sector, research institutions and local political authorities. Synergies among green investments provide an international testing and demonstration platform (Christensen, pers. comm., 2012; Magnoni & Bassi, 2009).

Currently though, the hydrogen technologies are being primarily demonstrated for micro-CHP and not as a wind-hydrogen system (Jacobssen, pers. comm., 2013). The main aim of the project is to demonstrate fuel cell technology in private houses. In the future, it is visualized that with smart grids, there can be a correlation between wind production and energy storage (Jacobssen, pers. comm., 2013).

Funding for the Lolland project comes partially from Danish micro-CHP governmental funding and partially from project participants that include the utility company Dong, energy company SEAS-NVE, and fuel cell R&D company IRD, among others (Jacobssen, pers. comm., 2013).

2.11 Germany

There have been several references to regions outside of the Öresund previously, but this section focuses more on Germany as the developments there have been of a larger scale with widespread governmental involvement and industrial collaboration.

Germany is in more need of energy alternatives as it has recently begun the process of shutting down its nuclear plants and begun importing coal from the US to substitute an energy source. As a

result, there is a concern regarding emissions and thus, the need to switch rapidly (Nilsson, pers. comm., 2013). Additionally, all the pumped hydro potential has been saturated in Germany. The other option, CEAS, has lower capacity and is more expensive (Ehret, pers. comm., 2013). As a result, an open market exists for storage and hydrogen technologies.

Of note is the The National Organization Hydrogen and Fuel Cell Technology (NOW GmbH) that manages the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). NIP was set up by the German federal government in 2006, to support preparations for market introduction of hydrogen and fuel cell technologies in mobile and stationary sectors (Ehret, 2012). The federal ministry of Transport, Building and Urban Development provides funding for demonstration projects and the federal ministry of Economics and Technology towards R&D (Ehret, pers. comm., 2013; Garcke *et al.*, 2009). NIP's active promotion of R&D of hydrogen and fuel cell technology are resulting in state of the art technology that is setting international standards as well as findings that are valuable for future development efforts (NIP, 2007).

The Clean energy partnership (CEP) is one such project, which is also Europe's largest demonstration project for hydrogen mobility. The project started in 2004, and by the second phase, 2008, the project was focusing on developing relevant technologies proving that they fulfilled requirements under practical, everyday conditions. The range of vehicles was increased to 790 kms per tank of fuel (depending on vehicle), which made hydrogen cars competitive with conventional cars. Also, because of technological advances, there was a reduction in costs of hydrogen storage and fuel cell systems. At least half of the hydrogen at CEP filling stations comes from renewable sources (CEP, 2011).

The Enertrag Hybrid Power Plant is another demonstration project. It showcases the wind-fuel cell system with three wind turbines, each 2MW capacity and an electrolyzer of 600-700 KW (Ehret, pers. comm., 2013).

The Germans also see the emerging niche market as a business opportunity. Promotion of the emerging hydrogen and fuel cell industry in a targeted manner would provide a unique opportunity to influence the process and speed up commercialization. There is a fuel strategy in place along with the active participation by the Federal Ministry of Urban Development and Transport Planning and the Federal Ministry of Economics and Technology (Ehret, 2012; Garcke *et al.*, 2009).

3 Framework and Methodology

This section includes an account of the various frameworks that were looked at, why the TIS framework (Jacobsson & Bergek, 2006) has been used to classify the findings, Kemp *et al.*'s (1998) paper on technological regime shifts and strategic niche management for the analysis and discussion of the findings.

3.1 Frameworks examined

While performing the literature review, there were many frameworks reviewed. The frameworks ranged from socio-technical viewpoints (Markusson *et al.*, 2012), to frameworks for guiding policy makers in developing countries (Jacobsson & Bergek, 2011), guiding hydrogen economies (Amoretti, 2011), those for institutional activism in automobile industry (Rao, 2004) and transformation of an energy sector (Jacobsson & Bergek, 2004). Within the innovation systems literature, papers (Edquist & Hommen, 1999; Klein Woolthuis *et al.*, 2005; Smith, 2000) seemed also to focus more on system failures without evaluating its effects on the innovation process.

This thesis aims to outline the innovation system in the Oresund region currently, for which deeper understandings of system processes are needed. This body of work is thought to be at an average level of contribution to theory, called a “tester”, where moderate levels of theory testing and low levels of theory building has been performed. Theory testing here is said to be the degree to which existing theory has been applied, moderate levels of theory testing imply that something other than theory has been used to ground the hypothesis (Colquitt & Zapata-Phelan, 2007). In the case of this thesis, interviews were conducted. Theory building then is the degree to which an existing theory has been supplemented or clarified by introducing relationships and constructs that may serve as the foundations for a new theory (Colquitt & Zapata-Phelan, 2007).

Of the frameworks examined (Amoretti, 2011; Bergek *et al.*, 2008; Jacobsson & Bergek, 2004, 2011; Markusson *et al.*, 2012; Rao, 2004), it was found that the technological innovation systems (TIS) given by Bergek and Jacobsson (2006; 2008) and processes of niche formation (Kemp *et al.*, 1998) were the best fit for this thesis. Bergek *et al.* (2008) give a systematic step-by-step approach to analyzing innovation systems, and describing and assessing performance.

The previously established relationships within the wind-hydrogen system have been dissected by identifying the processes and actors of the system and classifying them within the findings section, under seven ‘functions’. This was done by using the conceptual arguments of the TIS framework (Jacobsson & Bergek, 2006) after certain modifications. For analysis of the findings, the reasons for regime shifts for sustainable technologies and strategic niche management (Kemp *et al.*, 1998) were used.

Using Kemp *et al.* (1998) paper’s ‘factors’ as guidelines, the inducement and blocking mechanisms have been identified in the hydrogen system. These mechanisms observed have been classified in the seven ‘factor’ categories quite similar to the ones given by Jacobsson and Bergek (2006). Both have been used here to understand the way the hydrogen system works, since they both give a different account. Jacobsson and Bergek’s (2006) ‘functions’ are used to ascertain *what* stages of evolution the TIS is in currently, whereas Kemp *et al.*’s (1998) ‘factors’ are used to ascertain *why* the TIS is in the current stage. Kemp *et al.*’s (1998) paper aims to determine the factors for under-utilization, whereas Jacobsson and Bergek (2006) aim to identify if the TIS is in fact under-utilized.

3.2 Technological Innovation Systems (TIS) Framework

The framework of analysis is principally derived from the work done by Bergek and Jacobsson (2006; 2008) from Chalmers University that focuses on technological innovation systems. According to them, an innovation system (IS) is defined as

“.. primarily an analytical construct ie a tool used to better illustrate and understand system dynamics and performance. This implies that the system in focus does not have to exist in reality as fully-fledged. Instead, it may be emerging with interactions between components..” (Bergek *et al.*, 2008)

The components of such innovation systems are actors, networks and institutions that contribute to overall development and diffusion of the products (an example relevant to this work would be goods such as hydrogen fuel cells and services such as storage of intermittent electricity) and processes. Since this system is still developing, the interactions between the components may be unplanned and unintentional, and the actors may not necessarily have to share the same goals, nor be working together consciously towards the same goals.

The Technological Innovation Systems (TIS) are socio-technical systems focused on development, diffusion and use of a particular technology, in terms of knowledge and product both.

The analysis of TIS (Bergek *et al.*, 2008) was the most suited for the steps involved in conducting the research. In this thesis, the TIS theoretical framework has been used as such, but with constructive replication, where delimitations were drawn to create a more stringent test of the findings. The original framework includes processes as an item for clear data collection to assist in policy recommendations but this component has been excluded from this body of study, since the policy recommendations fall outside the scope. The framework for emerging innovation systems (Jacobsson & Bergek, 2006) was the best fit for classifying the findings and Bergek, Jacobsson, & Sandén's (2008) work was used for further elaboration on the formative phase in the emergence of an innovation system. The Jacobsson and Bergek (2006) paper is designed to identify key issues in specific innovation systems and discuss the application of emerging technologies. Bergek, Jacobsson & Sandén (2008) further improve on the formative phase of an emerging technology.

3.3 Formation of Niches and their Management

An account of the different factors that affect the development of new technologies and how they impede the shift to more sustainable technologies has been given. The barriers – so called ‘factors’ – are discussed here.

The TIS in question is the entire regime system of the “complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of the technology” (Kemp *et al.*, 1998). This definition is comparable to the one given previously in the TIS framework and thus is seen to be compatible with the objectives of the thesis.

Kemp *et al* (1998) also provide an account of niches that is a fit with this thesis. Niches are seen as platforms for interactions shaped by many actors. Strategic niche management then explores options for co-evolution of technologies and its contexts. Niches are important to the development of any new technology; they give system builders a take-off platform. Apart from demonstrating the

viability of a new technology and providing financial means for further development, niches help to build a constituency behind a new technological system. The technological system, as defined earlier, is developed in a niche. Thus, the factors given are helpful for identifying the driving and blocking mechanisms in this wind-hydrogen-storage technological innovation system.

It must be stressed here that, strategic niche management and its criteria are being used as transition tools, rather than a market introduction strategy. Reiterating that aim of the thesis is to provide an account of how hydrogen technologies can contribute to amelioration of wind EEP, not how to make hydrogen technologies more acceptable on the market.

3.4 Methodology

The research in this thesis was performed by building theory using an inductive model (Colquitt & Zapata-Phelan, 2007). Observations were made first, which were then used to generate theory using inductive reasoning. The structural mapping of the TIS was an iterative process where additional pieces of information were added as the analysis proceeded.

While the data describes *which* empirical patterns were observed, theory explains *why* empirical patterns were observed or are expected to be observed (Sutton & Staw, 1995). The difference between these two will be seen in Chapter 4, the findings and analysis part of the thesis, where the information gathered from interviews and the TIS framework will determine patterns in the hydrogen-storage system and the strategic niche management framework will help identify why the patterns exist.

The scheme of analysis used is a combination of two papers by Bergek *et al.* (2008) and Jacobsson & Bergek (2006). The steps are as follows:

1. Setting the starting point for the analysis ie defining the TIS in focus.
2. Identifying the structural components of the TIS (actors, networks and institutions).
3. Moving from the structural components to functional components. The identification of the functions following the general approaches delineated by Jacobsson & Bergek (2006).
4. Normative step: how well the functions are fulfilled and set process goals in terms of a 'desired' functional pattern.
5. Identifying mechanisms that either induce (drive) or block a development towards desired functional pattern. Analysis of factors following the approaches delineated by Kemp *et al.* (1998).

3.4.1 Defining the TIS in focus

The focus of attention of this thesis is the knowledge field of amelioration of excess electricity production from intermittent wind energy. This has been described in Section 2.4. The level of aggregation of the study is specified to storage and hydrogen technologies. The range of applications includes applications of storage in stabilizing the grid and in transport; for hydrogen use as an energy carrier and a fuel source. These are the applications that have been discussed in the literature review to give the reader an idea of how things are now, and then the thesis proceeded to highlight the applications of interest to the Öresund region ie. transport, stationary applications and to some extent, the stabilization of the grid.

While development and diffusion of storage systems and hydrogen technologies are being done globally, it is most relevant for the focus to be on a spatially limited part of the system in order to capture other aspects. The spatial focus is the Öresund region, as the set of actors in this regional context are better understood. However, despite this geographical delimitation, the analysis will still refer to international components (pan European and/or Japanese technologies to compare) as a global context is necessary for proper understanding and assessment of a global TIS. Of course, uncertainties are involved when an analysis concerns an emerging TIS, thus the early focus should therefore be seen as a "snapshot" valid currently.

3.4.2 Identifying the structural components of the TIS

The structural components of the system are the actors, networks and institutions. Identification of these structural components then helps with task 5 – examining knowledge of, and views pertaining to hydrogen as an amelioration technology held by the energy system authorities in the Öresund region.

Actors were identified using Bergek *et al.*'s (2008) proposed methods:

- Industry associations, exhibitions, company directories, catalogues/brochures, attendee lists at 'integration of wind conferences' and content list of such conferences.
- Bibliometric analysis (volumes of publications, citation analysis etc.) provided a list of the most active organizations in terms of published papers etc. These organizations included universities as well as institutes and firms.
- Interviews and discussions with technology or industry experts as well as with universities, research organizations, financiers and trends analysts were used to identify further actors; using the "snowballing" method.
- Patent analysis could reveal volume and direction of technological activity in different organizations and among individuals and thus may be a useful tool to identify firms, research organizations or individuals with a specific technological profile. However, once the analysis was performed, there wasn't necessarily a link between patents and mastering a technology. This method was, hence, not included.

Interviews with the actors were performed via 9 phone interviews, 2 e-mail correspondences and 1 in-person interview in a semi-structured format (Table 2). For e-mail correspondents, the interview protocols were sent via email. Sample interview protocols have been included in Appendix 4, 5 and 6. Questions and topic areas were prepared and sent to the interviewees 24 hours before the scheduled day of interviewing. Phone and personal interviews were audio recorded, after permission, for easier playback and were transcribed to assist in accurate recollection of information. A sample transcribed interview is included in Appendix 7.

The second structural components of interest were **networks**, both formal and informal. Some were orchestrated to solve a specific task eg. standardization networks, technology platform consortia, public-private partnerships or supplier groups having a common customer. Other networks evolved in a less orchestrated fashion and include buyer-seller relationships and university-industry links (Bergek *et al.*, 2008). In this, some networks are oriented around technological tasks or market formation and others have a political agenda of influencing the institutional set-up eg. Hydrogen Sweden and H₂ Skåne. Social communities such as professional networks and associations or

customer interest groups were also identified eg. Lolland Community Testing Facility. Formal networks are easily recognized, whereas informal networks require discussion with the previously determined actors, or analysis with co-publishing or collaboration (eg. joint ventures like most of the transport advancements and joint university-industry projects).

Table 2: Personal Communication Data

S.No	Interviewee	Organization	Designation	Date	Correspondence
1	Mats Nilsson	Vattenfall – Sweden	Economist, Vattenfall Strategy	4 th April 2013	In-person
2	Allan Schrøder Pedersen	Risø-Danish Technical University (DTU)	Head of DTU Energy Conversion	8 th April 2013	Phone
3	Martin Ragnar	Swedish Gas Technology Centre (SGC)	CEO	8 th April 2013	E-mail
4	Brian Vad Mathiesen	Aalborg University	Associate Professor in Energy Planning	11 th April 2013	Phone
5	Anna Cornander Anna Tibbelin	H ₂ Skåne	Executive Directors	12 th April 2013	E-mail
6	Oliver Ehret	National Organization Hydrogen and Fuel Cell Technology (NOW GmbH)	Program Manager Hydrogen Provision	18 th April 2013	Phone
7	Georges Salgi	Vattenfall – Denmark	Energy Market Analyst	19 th April 2013	Phone
8	Jens Jacobssen	SEAS-NVE	Project Manager	22 nd April 2013	Phone
9	Erik Wiberg	Hydrogen Sweden	Trends Analyst/ Project Manager	23 rd April 2013	Phone
10	Sten Åfeldt	Swedish Energy Agency	Energy Technology Department	2 nd May 2013	Phone
11	Alice Kempe	Swedish Energy Agency	Bioenergy and Biofuels	2 nd May 2013	Phone
12	Peter Kasche	Swedish Energy Agency	Programme Manager	2 nd May 2013	Phone
13	Leo Christensen*	Lolland Energi Holding A/S	Vice-President	26-27 th Nov. 2012	In-person

*Leo Christensen was interviewed during a study field trip to Lolland-Falster island for a term paper on Hydrogen Fuel Cells in the Öresund region.

Third component, **institutions**, such as laws, regulations and routines were identified. Generally, institutional alignment needs to occur if a new technology is to diffuse. Institutional alignment is not automatic or certain; firms compete over the nature of institutional set-up. Key institutions such as EU regulations or directives concerning broad areas of wind power and storage were recognized. Lack of institutions were also of interest for example lack of regulations for hydrogen safety.

3.4.3 Identifying the functional components of the TIS

Mapping the functional pattern of the TIS constituted the core of the analysis. Identifying these structural components of the system in Step 2 provides a basis for this step, which is classifying the TIS in functional terms.

The functional analysis is a tool for finding key issues; it helps to systemically map 'what is achieved' in terms of seven key processes in evolution of an IS (Jacobsson & Bergek, 2006):

Key processes in the evolution of an IS are given by Jacobsson and Bergek at two levels, structural and functional. The structural level analyses dynamics of how system components ie. the actors, networks and institutions, come into existence and thus, is irrelevant to this thesis and has been omitted. Instead, the functional analysis will guide the research process.

This functional analysis pertains to what is going on in the system in terms of processes and has a more direct and immediate impact on the performance of the system. According to the TIS framework (Jacobsson & Bergek, 2006), these processes are called 'functions' and seven have been identified from various fields (economics of innovation, entrepreneurship, sociology of technology and political science, and experimental application of the framework to a number of innovation systems). For the purposes of this thesis, all developments will be sought to fit into the following seven functions:

1. **Knowledge Development and Diffusion:** Refers to the knowledge base of an IS, and how a local system is vis-à-vis the global system. This function aims to capture the breadth and/or depth of the knowledge base and how that knowledge has been diffused and combined. Since this is very broad function, there has been a distinction made between:
 1. Different types of knowledge eg scientific, production, design, market and,
 2. Different sources of knowledge eg. R&D, new applications, production, imitation.
2. **Influence on the Direction of the Search:** For the development of the IS, a whole range of components have to enter, that not only possess the ability to identify new opportunities but see sufficient incentives/pressures to undertake investments in the IS. This function combined the strengths of factors influencing the search and investment behavior in this IS, for example, beliefs in growth potential, regulations, articulation of demand by leading customers, technical bottlenecks. There is also a need to coordinate investments between actors for example, shift to fuel cell-powered automobiles requires simultaneous investment in the development and production of fuel cells, fuel cell-driven cars, production of energy carriers for fuels cells, recharge stations for fuel cells, and so on. Coordination then requires that a range of actors supplying complementary products/services are influenced in their respective search and investment processes.
3. **Entrepreneurial Experimentation:** Entrepreneurs were defined as those conducting experiments, delving into uncertain markets and technologies, and challenging institutions. These uncertainties are fundamental to development of emerging technologies and without experimentation, the TIS will stagnate. The experiments continuously probe into new applications, where many fail and some succeed, but in this learning process knowledge formation occurs. Though the uncertainty is primarily seen in the formative phase of this TIS, such is not always the case. This knowledge formation is more of an applied nature, hence has been stated here, rather than under the first functional heading “knowledge development and diffusion”.
4. **Market Formation:** For an emerging technology, markets may be greatly underdeveloped. This function, in its original form assesses which phase the TIS market is in currently and if found to be underdeveloped, the reasons. Questions to be asked included facts on market size and

customer groups, qualitative data on actors' strategies, the role of standards and purchasing processes etc. But since this thesis does not focus on making an emerging technology market ready, the delimitations were set to just seek out which developments fall under this market function and *not* any further analysis.

5. **Legitimation:** This refers to social acceptance and compliance with relevant institutions; the new technology and its proponents need to be considered appropriate and desirable by relevant actors. This leads to resources mobilization (Function 6, below), for demand formation and for attaining of political strength by actors in the TIS. Legitimacy also influences expectations among managers and, by implication, their strategy (and, thus, the function 'influence on the direction of search'). Even in organization theory, legitimation is acknowledged to be a prerequisite for formation of new industries (Rao, 2004) and as Jacobsson and Bergek (2006) would add, for new innovation systems as well. Legitimation may take considerable time, since it is a social movement as well as economic and can be complicated by competition from existing systems. Hence, the formation of 'advocacy coalitions' sharing a certain vision and the objective of shaping the institutional set-up forms a key feature of the process of structural change influencing this function (Jacobsson & Bergek, 2006).
6. **Resource Mobilization:** As the TIS evolves, a range of different resources – technical, scientific, financial etc. – are mobilized and so on. This function assists in understanding the extent to which this system is able to mobilize human capital, financial capital and complementary assets. These were quantitatively measured by indicators like rising volume of seed and venture capital, changing volume and quality of human resources, changes in complementary assets etc.
7. **Development of Positive Externalities:** As a TIS evolves, the 'learning space' allows for the generation of positive external economies. Entry of more actors was found to be crucial, where new entrants give validation and encouragement for others to do the same. They resolved the uncertainties that existed with Function 3, 'experimental entrepreneurship'. More actors also strengthened previous functions like Function 2, 'direction of search' and 5, 'legitimation'. Improved legitimation then further positively influenced three Functions: 6, 'resource mobilization', 4, 'market formation' and 3, 'experimental entrepreneurship'. The new entrants conferred positive externalities on other firms; related further spillovers like specialized intermediate goods providers and information transfer occur. This function is not independent but indicates the dynamics of the entire system as the other functions interacted amongst themselves.

3.4.4 Analysing the functionality of the TIS

After classifying the developments into the seven key processes in the previous step, the functionality of the emerging TIS was assessed. This was done by determining the phase of development of the TIS, by distinguishing between the formative and growth phases.

Table 3: Indicators for Formative and Growth Phases of the TIS Framework

Formative phase	Growth phase
Volume of diffusion and economic activities	Rapid rate of diffusion

that is but a fraction of the estimated potential	
Price/performance of products not being well developed; absence of positive feedbacks	Rapid growth in economic activities
Large uncertainties prevailing; demand being unarticulated	Need for resource mobilization increases by orders of magnitude
Volume of activities is small and many experiments take place ("experimentation" and "variety creation" are key words)	System expansion

These indicators may seem to be general, but have been isolated from Bergek, Jacobsson, & Sandén (2008) and Kemp *et al.* (1998) since the functional dynamics of a TIS is such that developments do not necessarily follow a rigid path. Upon establishing the phase of development, the research then went to analyse the findings according to Kemp *et al.* (1998) paper.

3.4.5 Analyzing patterns in the TIS

The mechanisms that either induce or block the development of an emerging technology towards the desired functional pattern were identified. Analysis of ‘factors’ following the approaches delineated by Kemp *et al.* (1998).

Factors for under-utilization of sustainable technologies were written with transport technologies in mind (Kemp *et al.*, 1998), but the slow diffusion of environmentally preferable technologies is not exceptional. The same patterns emerge for storage technologies also.

1. **Technological Factors:** Phenomena which show that the TIS under observation do not fit well into already existing systems. The use of the new technological system may require complementary technologies that are unavailable, in short supply and/or expensive to use. This may be identified by under development of user needs or low-scale production of the technology that still needs larger scale consumer testing or infrastructural change. If there is an expressed need for redesigning and/or further optimization, the TIS has a technological factor at play.
2. **Governmental Policy and Regulatory Framework:** Identification of governmental policies that may be committed to environmental protection but do not specify new technologies. Nearly all new technologies are stimulated by some form of institutional stimuli, but their role in a larger system may be unclear. This is seen to give risk averse manufacturers uncertainty in investing in those technologies. Existing regulatory frameworks and adaptations of legislations also come under this factor.
3. **Psychological Factors:** When the association with existing infrastructure may be difficult to break as unfamiliarity with the alternatives often leads to skepticism beforehand. The actors mentioned judge the new technological system on the basis of the characteristics of the dominant technology, and not the TIS on its own. This can be observed in most transport related research.

4. **Demand Factors:** These are economic factors that are consumer-centric, related to the actors' preferences, risk aversion and willingness to pay. The insecurities and aversions of the *consumer* are main reasons for the manufacturer to not market new technologies. Or the new technologies may not meet the specific demands of consumers, which means an alteration of demands and preferences may be required to introduce the technologies. The important step to perform is identifying which actors also play the role of consumers in the technological system. The price of product also features in this factor, where the expense is due to economies of scale not in the favor of the TIS yet.
5. **Production Factors:** These are factors that hinder development from the first stage of prototype to last stage of mass production. The chance to develop a new market exists, but the incentive is low because either consumer interest isn't explicitly stated or no external factors exist (such as legislation) that may incentivize sales. Larger actors can see the new technology as competing with their core competencies – competencies that they are technically and organizationally aligned towards. Alternatives to investing in new technologies can be seen in production strategies like cost leadership (offering products at lowest price on the market) and differentiation (exclusive products for a large market). Producing for market niches is mostly not the production strategy of choice.

New enterprises can market new products, provided they have sufficient capital backing. The question of funding then brings added uncertainties since banks are reluctant to invest in risky projects and governments grant subsidies for R&D not marketing a new product.

6. **Infrastructure and Maintenance:** Adaptation of the infrastructure is seen as a major affecting factor. The introduction of the new technology also requires maintenance, and trained personnel to handle the maintenance. Though of note is the fact that threshold values matter with infrastructure and maintenance investment. Only with a relatively high number of product deployment, does it start to be profitable, so it is the initial costs and development of infrastructure that are crucial to this factor.
7. **Undesirable Social and Environmental Effects of New Technologies:** A new technological system may come with its own set of problems. This is seen to be a factor that is pertinent in the long run when it is necessary to find out if such problems exist and how they can be solved. In the current stage, they mostly affect the image and performance of the emerging technological system. eg. safety issue with hydrogen.

Of course, these factors do not act separately as a containment force but are interrelated and often reinforce each other to give rise to inertia and specific patterns in the direction of technological change.

4 Findings

The findings have been structured according to the functional areas found in the TIS framework of analysis (Table 4). Each of Jacobsson & Bergek's (2006) categories have been used as sub-headers and phenomena observed have been placed under there with an explanation of their relevance to that category.

Table 4: 'Functions' in the evolution of a TIS

Jacobsson & Bergek 'functions' in the evolution of an Technological Innovation System (TIS)		
Used to ascertain which stages of evolution are seen currently in the IS		
Findings Section		
1	Knowledge Development and Diffusion	Capture breadth and/or depth of knowledge base and how that knowledge has been diffused and combined.
2	Influence on the Direction of the Search	Factors influencing the search and investment behavior; Coordinate investments between actors.
3	Entrepreneurial Experimentation	Applied nature of knowledge formation; Conducting experiments, delving into uncertain markets and technologies and challenging institutions.
4	Market Formation	Assess the phase of current market
5	Legitimation	Social acceptance and compliance with relevant institutions; Influences expectations among managers, their strategies; Is a social movement as well as economic.
6	Resource Mobilization	Range of different resources – technical, scientific, financial etc. mobilized as the TIS evolves.
7	Development of Positive Externalities	Entry of more actors, resolve uncertainties with “experimental entrepreneurship” and strengthen previous functions like “direction of search” and “legitimation”; Improved legitimation then further positively influences “resource mobilization”, “market formation” and “experimental entrepreneurship”.

4.1 Knowledge Development and Diffusion

This function is to provide an account of the knowledge base of the TIS, and how the local Öresund system is compared to other regions of interest.

Knowledge dissemination occurring via international symposia, seminars and workshops have given a high degree of visibility to the Öresund region as a knowledge center for large-scale wind power integration (Interreg IV, 2011). Research is conducted to explore the wind-hydrogen-storage area. The municipality of Hyllie is discussing heat and electricity storage, and that of Malmö is looking into heat storage solutions. These discussions are with community and industry actors; projects are yet to be designed (Åfeldt, pers. comm., 2013).

Hydrogen Sweden and H₂ Skåne are major actors in the Öresund region when it comes to hydrogen and fuel cell technologies. Their vision is for hydrogen to play an important role in Skåne and

Sweden alike. Both are member based organizations that work to supply up to date information about HFCs around the world and in Sweden via workshops and seminars. The actors also work with other EU projects and regional projects within Sweden (Vätgas Sverige, 2012; Wiberg, pers. comm., 2013). H₂ Skåne is organizing a study trip to Germany to learn more about hydrogen and the P2G solution. They also organize seminars⁸ on hydrogen and fuel cells (Cornander & Tibbelin, pers. comm., 2013).

The important sectors for hydrogen in the future are seen to be transport (as a fuel in vehicles), fuel cells as backup power systems and stationary fuel cell applications (Cornander & Tibbelin, pers. comm., 2013; Wiberg, pers. comm., 2013). Fuel cell projects in stationary applications for backup grid power are being examined more closely. Trials and demonstration projects are underway for backup power both in telecommunication systems (landlines and cell phones) and within electric grids for backup power. In the electric grid, it is backup power for critical components within the electricity grid, but not on grid scale (Wiberg, pers. comm., 2013)

With private cars, the HFCEVs are being looked at as an alternative than can provide greater electro-mobility than BEVs. BEV driving range is considered a hindrance and is a valid option only for city drivers, over smaller distances. In places like Sweden, the US and Canada, where large distances need to be covered, HFCEVs come into the picture. BEVs' round trip efficiency is higher, but convenience to consumer is not (Pedersen, pers. comm., 2013).

However, within transport, hydrogen cannot address aviation due to lack of advanced technologies. The Soviet Union back in the 80s had jet aircrafts using hydrogen, so it has existed for a while, but the aviation sector is smaller than the sector for automobiles which resulted in hydrogen-running aircrafts to not gain as much traction in the market (Wiberg, pers. comm., 2013). Marine transport continues to have natural gas on the agenda (Wiberg, pers. comm., 2013). Though there exist projects assessing power generation through fuel cells for auxiliary power units aboard ships for lighting, none have been extended towards fuel for propulsion (Ehret, pers. comm., 2013; Wiberg, pers. comm., 2013). These auxiliary power units are quite big, at the scale of several MW (Wiberg, pers. comm., 2013).

P2G has a strong future ahead as there is much happening on a European level in UK, Germany, The Netherlands and Spain (Ragnar, pers. comm., 2013), but it will take some time for it to be economically viable on a larger scale in Sweden (Pedersen, pers. comm., 2013) where it is in pre-demonstration phase (Wiberg, pers. comm., 2013). Swedegas has submitted an application to the Swedish Energy Agency to further explore the P2G concept within Sweden and has also succeeded in bringing together stakeholders to discuss the topic over the past year (Ragnar, pers. comm., 2013). However, there is an extensive natural gas grid available to the municipalities of southern and western Sweden (Cornander & Tibbelin, pers. comm., 2013; SEMI, 2013) and P2G option could potentially be used along those pipelines (Wiberg, pers. comm., 2013). It may be more likely that the P2G concept will be utilized in a way that methane is produced via the Sabatier process (Mohseni *et al.*, 2013) from hydrogen and carbon dioxide to get a fuel that people know how to handle already (Ragnar, pers. comm., 2013).

⁸ The author attended one such seminar workshop "H₂ Skånes träff om vätgas" on 11th December 2012 in Malmö, Sweden.

In the Danish context, integration of heat and energy sector is important because electricity is a high value product, which is also why it is banned as a heating source (Mathiesen, pers. comm., 2013; Nilsson, pers. comm., 2013). Thus micro-CHPs and heat pumps enter the Danish scene (Mathiesen, pers. comm., 2013). Micro-CHP will however, probably not be widespread in Sweden due to two main reasons: 1) electricity is fairly inexpensive in Sweden compared to the rest of Europe, and 2) not only is gas expensive, but the gas pipeline network is limited, and does not traverse all the way to individual homes. That infrastructure would need to be built which is probably not economically feasible (Wiberg, pers. comm., 2013).

The National Energy Agencies have interactions with actors in the power industry, utilities like Vattenfall and Dong, municipalities and academia. Vattenfall is the largest wind power operator in Sweden (with approx 10% of wind power market) and largest offshore wind power operator in Europe (Vattenfall Annual Report, 2011). Dong is the Danish utility company and at the end of 2013 will have a wind power capacity of 1,388 MW (Dong Energy, 2012; Ingeniøren, 2012).

Vattenfall is seen to be more active in Germany that holds the world's largest hydrogen fuelling station (Garche *et al.*, 2009; Wiberg, pers. comm., 2013). The German Federal government along with representatives from research organizations and various industry sectors were involved in designing the National Innovation Programme Hydrogen and Fuel Cell Technology in 2006 (Ehret, pers. comm., 2013; Garche *et al.*, 2009).

4.2 Influence on Direction of Search

The developments that influence the search and investment behavior in the TIS have been put under this function.

The Swedish Energy Agency predicts that investments in wind power are going to increase in the future depending on the increase in electricity prices and a more stable financial situation (Åfeldt, pers. comm., 2013). Main drivers for investing in hydrogen in Denmark are reduction of fossil fuel use, better electro-mobility and insufficient home heating (Jacobssen, pers. comm., 2013). In Sweden, it is seen that the hydrogen discourse is mostly around transport. Co-operations with international energy agencies and research programs on fuel cells are focused on the transport sector (Åfeldt, pers. comm., 2013).

In Sweden, bio-fuels are gaining increasing attention and are seen to be a key substitute for fossil fuels moving forward (Mohseni *et al.*, 2013; SEA, 2012), since the natural gas grid already exists in southern and western Sweden and uses a conventional technology (Mohseni *et al.*, 2013; Ragnar, pers. comm., 2013). However, bio-fuels will not be sufficient to cover Sweden's transport sector since their utility is in other applications as well (Cornander & Tibbelin, pers. comm., 2013; Wiberg, pers. comm., 2013) and there are views that it is truly sustainable only if it comes from waste and not the farming industry (Jacobssen, pers. comm., 2013). The role of hydrogen in the transport sector then is to help produce synthetic fuels such as methane or methanol, to save biomass resources. According to Wiberg (pers. comm., 2013) transport is a compelling area in Sweden since a lot of the emissions come from this sector, and electrification may be the path of choice.

The use of hydrogen in transport was not cohesively supported by all the interviewees. Mathiesen (pers. comm., 2013) felt that the use of hydrogen as fuel was unwise because of overall losses and reintroducing electricity to the electric grid (vehicle-to-grid-concept) was also unwise.

The problems arising from excess wind power may be more evident in the future, when traditional fossil fuel plants will be closed down (Pedersen, pers. comm. 2013) and the ancillary services that the latter provide for electricity systems will be unavailable. The nuclear power plants in Sweden are going to be phased out, and the replacement is yet to be determined (Cornander & Tibbelin, pers. comm., 2013). Nuclear has fewer marginal costs, but when spot prices decrease due to increased wind in the portfolio, it becomes a less attractive option (Salgi, pers. comm., 2013). Hydropower in Sweden is unlikely to be developed further due to environmental issues (Cornander & Tibbelin, pers. comm., 2013).

When time shifting of energy production will have to occur, the storage technologies will come up as a mitigation strategy (Pedersen, pers. comm., 2013). Apart from storage technologies, demand side management (DSM) and reinforcing transmission capacity via cables are considered. Where the need arises for better energy arbitrage to connect a producer in a low cost area to a high cost area, cables are being looked at as the primary solution (Nilsson, pers. comm., 2013).

Though connections to Germany and Norway are constantly being reinforced, there are environmental concerns about the interconnections. People do not like the overhead cables and converting it to underground lines is expensive (Nilsson, pers. comm., 2013; Pedersen, pers. comm., 2013). For large scale storage, only pumped hydro is used. CAES is short term storage (10 hours) for price arbitrage between night and day (Salgi, pers. comm., 2013) There are only 2 CAES in use worldwide— in Germany and the US (Pedersen, pers. comm., 2013; PNNL, 2013).

There are a number of companies, utility, gas and car manufacturers, that are interested in hydrogen or working with components for fuel cells in Sweden. Big companies like Linde, Oge, Toyota are working with hydrogen technology. Next Move project is a public procurement project for vehicles (Wiberg, pers. comm., 2013). High degree of visibility for Öresund region is coming from the number of international symposia, seminars and workshops organized under the Vind I Öresund project. The project and its results have been presented at over 50 international and national conferences (Interreg IV, 2011).

With the Nordic electricity surplus of approximately 58 TWh by 2030, there are favorable options to export electricity from low-emitting sources to the European continent (Vattenfall Annual Report, 2011). Sweden will have a more interconnected electricity grid with the rest of Europe in the future (Wiberg, pers. comm., 2013; SEA, 2012) so if there is the possibility of storing electricity in Sweden, the option should be looked at. There are certain points on the grid where reinforcing or introducing electricity storage could be an option. Grid operators can have contact with the fuelling station operators to be able to produce hydrogen quickly to help regulate the grid. Fuelling stations can have large stores and produce hydrogen when the electricity is inexpensive. HFCEVs could then be used by a large number of car consumers in Sweden (Wiberg, pers. comm., 2013).

As discussed previously, storage in the Danish system is mostly in the form of heat in district heating (Mathiesen, pers. comm., 2013; Pedersen, pers. comm., 2013; Ehret, pers. comm., 2013). Denmark has no large scale energy storage (Pedersen, pers. comm., 2013), but there is great interest in the P2G concept (Ragnar, pers. comm., 2013). In rural areas that have no district heating, electricity storage is also more feasible alternative eg. Western Lolland uses wooden and oil boilers since they aren't suited for heat pumps (Jacobssen, pers. comm., 2013).

The Danish situation is already prevalent on the island of Gotland in Sweden where a lot of energy from wind power is generated from 183 MW installed capacity (IWP, 2013). The insufficient transmission capacity to mainland Sweden results in over-production at certain times (Ragnar, pers. comm., 2013), thus the incentive to have a demonstration project exists.

There is interest in regions in Sweden and Denmark apart from that seen in the Öresund. There are discussions about a demonstration project in Gotland, financed by the Swedish Energy Agency, that will have a component of electricity storage in it (Åfeldt, pers. comm., 2013), and the example of the island of Lolland has been extensively quoted in the literature review. Even Japanese governmental officials have visited the Lolland CTF demonstrations, since after Fukushima, they are looking to branch out their renewables portfolio (Jacobssen, pers. comm., 2013). Under the EU's SET-Plan, the Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) was established in 2008. It is a public private partnership between the European Commission and the industry and research communities, getting a budget of €1 billion from public funding as well as private (FCH-JU, 2013; SET-Plan, 2010) for knowledge dissemination and demonstration projects. Storage technologies are being developed in projects to complement RES pathways and help establish the supply chain for hydrogen. Eg. the HyUnder project is looking at the storage of excess power from intermittent RES (FCH-JU, 2013).

There have been considerable investments and R&D in the Fuel Cells and Hydrogen sectors; there are plans for larger and broader deployment in the EU for the next seven years to 2020 (FCH-JU, 2013). Sustainable hydrogen production is a priority with various projects that couple water electrolysis with RES (FCH-JU, 2013). These support systems for intermittent renewable energy are important (Salgi, pers. comm., 2013). FCEVs and Hydrogen Refuelling stations have seen an increase in volume and interest, but have not reached a level where mass production is the natural next step. Though the vision in Sweden is to have larger integration of a wind-hydrogen system, fuel cells will not be a part of the energy storage and hydrogen at the very beginning; instead gas turbines play more of a role. Energy storage is a more likely option in the long run (Wiberg, pers. comm., 2013). However, stationary technologies are bridging the gap between prototypes and pre-commercial systems (FCH-JU, 2013).

4.3 Entrepreneurial Experimentation

Research, development, demonstration and deployment (RD3) refers to strategies that recognize the importance of combining “technology push” with “demand pull” mechanisms to promote the diffusion of emerging technologies (Barreto *et al.*, 2003). Demonstration projects are of importance to emerging technologies as they increase the likelihood of fiscal and public opinion support (Wiberg, pers. comm., 2013). Promotion of international RD3 partnerships and the introduction of incentive-based mechanisms allow development and fast diffusion of cleaner and more efficient technologies. Co-operation schemes permit local capacity building and successful technology transfer towards regions developing the newer technologies. Audiences for these demonstration projects are usually industry or policy makers. Demonstration projects also help with technology acceptance in the industry as well as in the general public. NextMove project.

The Vind I Öresund project aims to exploit the “first mover advantage” that Denmark and this region possess. Öresund region is aiming to be the first CO₂ neutral region in Europe through strategic development (Interreg IV, 2011). The second aim of the project concerns the demonstration and deployment of new technologies in Bornholm, Denmark, in Malmö, Sweden and

at Risø, DTU, Denmark. The Bornholm experience is to be used in Lillgrund to ensure electricity supply to the city of Malmö in the event of a major power outage (Interreg IV, 2011).

Many of the fuel cell projects that look at stationary applications are demonstrated once a company buys the fuel cell system. With stationary applications, the objective was to demonstrate to industry, utility companies, manufacturers of base stations and data centres of the functioning of the HFCs (Wiberg, pers. comm., 2013). The industrial actors do not work purely with hydrogen, but on synergies; the main synergies assessed are in transport by producing hydrogen fuel for vehicles and optimizing it with the electricity grid (Wiberg, pers. comm., 2013).

Scandinavian Hydrogen Highway Partnership is an umbrella organization for all Scandinavian hydrogen associations (SHHP, 2012; Wiberg, pers. comm., 2013). In 2009, Daimler, Ford, GM/Opel, Honda, Hyundai, Kia, Renault, Nissan and Toyota signed a Memorandum of Understanding to have a series of hydrogen powered cars for sale by 2015 (Vätgas Sverige, 2012). Lolland has focused more on exploring new technologies than looking at energy efficiency in new buildings since the rural Danish houses are not insulated well enough for heat pumps to work, and are not well connected to district heating (Jacobssen, pers. comm., 2013). Lolland CTF experiments with making the micro-CHP independent of the grid for ease of use for private home owners (Jacobssen, pers. comm., 2013). RD3 is building up around the world as well.

EnerTrag hybrid power plant in Germany is a demonstration project to show the wind-hydrogen system at work. It has 3 wind turbines, of 2 MW each and an electrolyzer of 600-700 KW capacity (Ehret, pers. comm., 2013). Japan has installed a substantial number of 43,000 micro-CHP units around the country not just for technological validation but also for consumer acceptance and to show the politicians and governmental officials that the technology works and should be promoted (Wiberg, pers. comm., 2013).

4.4 Market Formation

This function is under represented in this thesis since market formation has not taken place yet. Some developments like the roles of prices and purchasing processes have still been included in this section, since they do play a role in the evolution of an emerging TIS.

Looking at energy efficiency in the context of price gives a different idea of the market for energy storage (Salgi, pers. comm., 2013; Wiberg, pers. comm., 2013). If energy is sold at a lower cost at the moment of production, then storing energy with a low efficiency (say 50%) and selling it later at 8 times the price makes far more sense. In such a situation, even low efficiency storage would be better for energy arbitrage than no storage at all (Wiberg, pers. comm., 2013). If the electricity market works in a way that wind companies cannot get reimbursed for the electricity prices because they are unable to deliver a certain amount of electricity 24 hours a day, then energy storage can provide additional support and secure what needs to be delivered. The net revenue from energy arbitrage is highly sensitive to energy storage efficiency (Walawalker *et al.*, 2004).

The energy storage capabilities of hydrogen and pumped hydropower are different and hence, have different audiences. Wind companies need to sell their commodity at the highest value. Small wind companies will see an application area for hydrogen to assist them in that energy arbitrage, because hydrogen can be utilized on a smaller scale; while a pumped hydro facility does not make sense for a small wind owner, specially not in the southern part of Sweden (Wiberg, pers. comm., 2013).

Purchasing price for hydrogen buses in general have improved since 2009 (FCH-JU, 2013) and projects for cars in Malmö and the rest of Skåne obtained through public procurement were delivered this spring (Wiberg, pers. comm., 2013).

Similar improvements were seen in micro-CHP units in Lolland, where due to economics of scale, the units have become more cost competitive. The units started out at 330,000 DKK and have seen a reduction till 130,000 DKK currently. The goal is to have them be competitive with gas boilers, at a price of 60,000 DKK (Jacobssen, pers. comm., 2013).

Mathiesen (pers. comm., 2013) shared that the reason for the interest in electricity storage currently could be that it seems like the latest best-selling solution to solve this problem. There could be more focus on other high energy consuming sectors like transport and housing, instead of on electricity.

4.5 Legitimation

The functions that refer to acceptance either socially, in compliance with relevant institutional actors or gaining of political strength have been discussed under this sub-heading. Formation of ‘advocacy coalitions’ where actors share a certain vision of shaping institutional re-form are also explored.

Low-carbon transition is a policy goal on both sides of the Öresund strait; the city of Copenhagen plans on becoming carbon neutral by 2025, and both Malmö and the regional parliament of Skåne have similar goals (Khan, 2012). No policy instrument is able to reach all desirable targets simultaneously of lowest emissions and cost efficiency but success depends on the prioritized target. If the reduction of costs per installed wind capacity is the goal, a premium FIT should be used; if lowering emissions is the aim, the ETS should be used (Kopsakangas-Savolainen & Svento, 2013).

Feed-in tariffs (FITs) have been by far the most successful amongst the various methods attempted to encourage development of RES for electricity production (Sandeman, 2010; Mendonca, 2007). Mendonca (2007) shows that variants of FITs in 41 countries, mostly in Europe but also India and China, have had positive effects on the rise in investment and employment in the RE sector – exceeding that of carbon trading schemes. To reach the Nordic target without windfall profits, a premium based feed-in tariff (FIP) (see Section 2.9) was found to be the best incentive mechanism (Kopsakangas-Savolainen & Svento, 2013).

From an economist’s point of view, FITs may distort the market (Nilsson, pers. comm., 2013). However, if support is pinpointed such as heavy taxes on fossil fuels, then it makes it easier for millions of consumers, and hence the market to make that decision (Pedersen, pers. comm., 2013). FITs are *one* way to bring higher investment into renewables (Salgi, pers. comm., 2013).

The ‘advocacy coalition’ of H₂ Skåne and Hydrogen Sweden informs policy makers and relevant actors in this region, by organizing seminars and workshops. The study trip to Germany in the coming autumn is organized by H₂ Skåne and is aimed at Skånian politicians (Cornander & Tibbelin pers. comm., 2013; Wiberg pers. comm., 2013). H₂ Skåne helped get hydrogen vehicles in Malmö municipality (Wiberg, pers. comm., 2013). The transport sector was seen to have positive developments where Swedish Energy Agency announced the 15 million SEK support to research for fuel cells in transport. It is a collaborative fuel cell project called FFI, with Vinnova for 3 years (2014-2016) (Kasche, pers. comm., 2013; Wiberg, pers. comm., 2013).

Hydrogen R&D initiatives are also often driven by a combination of governmental push and industrial investment, as is observed in Denmark. Danish industrial players have been seen to express a strong need for support in the process to push fuel cell and hydrogen technologies from the R&D stage into the commercial domain. Governments are supporting initiatives since they realize the dependence on fossil fuels must be weakened, and climate change must be taken into account (Pedersen, pers. comm., 2013). It is increasingly seen that political will for hydrogen technological system is present in Denmark; the new Danish energy minister is keen on hydrogen technology and has made several visits to demonstration projects all over the country, including the one in Lolland (Jacobssen, pers. comm., 2013). The Danish micro-CHP area was granted 60 million DKK till 2012, but this was extended till the end of 2013 (Jacobssen, pers. comm., 2013).

German federal ministries for transport and urban development, and of economics and technology have set up programs for RD3 in hydrogen technologies (Ehret, pers. comm., 2013). It has been observed that previously unsupportive actors were expressing interest in hydrogen as a storage medium and were joining initiatives such as the Clean Energy Partnership (CEP) (Ehret, 2012). The NOW GmbH coordinates and implements the € 1.4 billion National Innovation Programme Hydrogen and Fuel Cell Technology (NIP) of the German Federal Government (Ehret, 2012; Garche *et al.*, 2009).

Looking at a composite picture of the EU, industry and research players are fully committed to supporting the sector's development and have expressed the desire for public authorities to enhance their support. There is close integration between the European commission, research and industry communities (FCH-JU, 2013).

EU ETS cap and trade system is the environmental policy issue that has had the greatest impact on Vattenfall's result of operations and financial positions both in the short and long term. The fee system for nitrogen oxide emission in Sweden is also another economic environmental policy instrument that has had an impact (Vattenfall Annual Report, 2011).

4.6 Resource Mobilization

This function is to help understand the extent the TIS is able to mobilize resources such as human and financial capital. This is an extension of the legitimation section with a more quantitative angle, but since the TIS is still emerging, there are limited instances of proven mobilization of capital.

Under the Vind I Öresund project, comprehensive courses such as “how to integrate wind power into the electricity system” are being taught at the Danish Technical University (DTU) and at Lund Technical University (LTH) that include storage technologies as solutions (Interreg IV, 2011). The project had positive impacts on cooperation between both universities. The experience from the Danish Bornholm system was used for security of electricity supply in the Swedish Malmö system (Interreg IV, 2011). Another impact was that female students' interest in environmental engineering at LTH and DTU increased due to the presence of the collaborative project (Interreg IV, 2011)

Investments in Lolland were returned with more venture capital and beget the image of it being an island with clean-tech expertise, business opportunities and availability of human and natural resources.⁵

A change in the complementary asset of refueling stations was also observed. The IDEALHY project, under the European FCH-JU seeks to accelerate infrastructure investment and enable rapid spread of hydrogen refueling stations across Europe (FCH-JU, 2013).

4.7 Development of Positive Externalities

As a TIS evolves, generation of more positive externalities are seen that may or may not be directly related to the technology, but will assist in the evolution in some way. Another avenue can also be pursued to lead to the same path of evolving of the TIS.

A McKinsey study confirmed that technological breakthrough in fuel cells and electric systems have increased the efficiency and cost-competitiveness of hydrogen refueling stations significantly. It even says that focus has now shifted from demonstration to planning commercial deployment of FCEVs (Vätgas Sverige, 2012) Entry of more actors in the hydrogen and fuel cell TIS, indicators of a growing market, can be credited to the advancements in various application areas. With increase in wind in the energy portfolio, several wind companies are interested in hydrogen eg. Apoidea as energy storage (Wiberg, pers. comm., 2013). The smart grid concept can be seen as a positive externality that develops with increased wind in the energy portfolio and utilizes hydrogen fuel cells to provide more flexibility to smaller producers for energy arbitrage, as was seen in Section 2.2.2.

There have been technical advances in FCEVs relating to their size and efficiency (Ehret, pers. comm., 2013). The costs of the fuel cells are dropping (Ehret, pers. comm., 2012; Jacobssen, pers. comm., 2013) and there are policies to help the technology along. Up to 5000 new jobs can be created in this sector till 2020 with fair support mechanisms and incentives (Vätgas Sverige, 2012).

5 Analysis and Discussion

To begin the analysis, the functionality of the hydrogen system was assessed. It was found that the phase of development of the TIS currently is that of a formative phase (Table 5).

Table 5: Indicators for Phase of Development of the TIS

Formative phase	Growth phase
Volume of diffusion and economic activities that is but a fraction of the estimated potential	Rapid rate of diffusion
Price/performance of products not being well developed; absence of positive feedbacks	Rapid growth in economic activities
Large uncertainties prevailing; demand being unarticulated	Need for resource mobilization increases by orders of magnitude
Volume of activities is small and many experiments take place ("experimentation" and "variety creation" are key words)	System expansion

The indicators, as were outlined in the methodology section, show that, in the ‘functions’ the “knowledge development and diffusion”, “entrepreneurial experimentation” and “legitimation” were the major drivers towards making the system achieve its purpose of providing amelioration for excess wind energy. Additionally, these functions also drive the development of the TIS towards a more formative stage by outlining that the potential is far greater than currently being achieved. The demand for this wind-hydrogen complement has just started to be articulated, but more on the Danish side. There are a few positive feedbacks and associated externalities but not by large orders of magnitude. A few demonstration projects are seen, but for the most part, the system is far from being viewed as a system that has products ready for mass production or a system that will play a significant role in present energy systems.

It was also noticed that there are other options in the current system before storage is reached, that the problem can be tackled from different angles. They include flexible consumption, demand side management and district heating (Åfeldt, pers. comm., 2013; Salgi, pers. comm., 2013). The option of district heating is more economical and feasible in Denmark (Ehret, pers. comm., 2013).

Thus, the system is still in formative phase. With this outcome in mind, the next step was to understand *why* the system is in formative phase. This was realized by indicating the factors (Table 6) for under-utilization of sustainable technologies observed in Kemp *et al.* (1998). Though these factors were written with transport technologies in mind, from the findings in this analysis, the same patterns emerge for hydrogen also.

Table 6: 'Factors' for analysis of the TIS

Kemp et al. 'factors' for under-utilization of sustainable technologies		
Used to ascertain what are the factors leading to under-utilization of the IS		
Analysis/Discussion Section		
1	Technological factors	New technology doesn't fit well into existing system; Complementary technologies are unavailable or expensive to use.
2	Governmental Policy and Regulatory Framework	Governmental policies do not specify new technology; Role of stimulated technologies is unclear; Existing regulatory frameworks and adaptations of legislations are also included.
3	Psychological factors	Association with existing infrastructure difficult to break; Unfamiliarity with the alternatives leads to skepticism; Actors mentioned compare new technology on basis of characteristics of the dominant technology.
4	Demand factors	Identify which actors play the role of consumers; Consumer-centric economic factors related to actors' preferences, risk aversion and willingness to pay; New technologies may not meet specific demands of consumers; Price of product and economies of scale not in favor of TIS.
5	Production Factors	Hinder development from prototype to mass production; Low incentives when consumer interest not explicitly stated and no external factors (such as legislation) exist to incentivize sales; Not producing for niche markets; Competing core competences.
6	Infrastructure and Maintenance	Adaptation of the infrastructure is a problem; New technology requires maintenance and trained personnel; Threshold value of investment requires high number of product deployment
7	Undesirable Social and Environmental Effects of New Technologies	New technologies may come with their own set of problems; Affect image and performance of emerging TIS currently; More pertinent in the long run.

5.1 Technological Factors

An important factor in the under-utilization of the hydrogen storage TIS is that some components do not fit into the systems in use currently.

It is difficult to promote large scale electricity storage in Skåne now (Wiberg, pers. comm., 2013). If Sweden were to shut nuclear power down, then the need for storage would arise but since Sweden is yet to utilize its pumped hydropower potential yet, that would be the first and more cost effective option. This could be done at existing hydropower plants, and Sweden has the topography for it. Energy storage will be needed in the southern parts of Sweden, but pumped hydro and reinforced transmission lines were found to be the options of choice (Nilsson, pers. comm., 2013; Wiberg, pers. comm., 2013). There are currently no connections in the Öresund strait, but there is one connection

from Denmark to Sweden across the Kattegat. Transmission capacity to Norway and Germany from Denmark are being reinforced as well (Pedersen, pers. comm., 2013).

If Sweden were to replace nuclear with wind, there would be a larger need for energy storage. But Sweden is yet to utilize its pumped hydropower potential yet, and this could be done at existing hydropower plants. Hydropower is used for flexibility currently (Salgi, pers. comm., 2013). In Denmark, the coal power plants are quite flexible as they can go from minimum to maximum production, and vice versa, in a short period of time (Salgi, pers. comm., 2013). The fossil free target may be an argument of value to make against coal power plants at this point, but flexibility does exist in the system due to them (Mathiesen, pers. comm., 2013). It was also seen that the Danish future energy system would see bigger role of energy storage in district heating, since they have a storage capacity that can be used and a large share of wind power (Ehret, pers. comm., 2013).

In terms of lifespan, fuel cell micro-CHP units cannot compete with oil boilers, since the latter has a life span of 40,000 hrs – double that of the fuel cells currently. This is a major problem to producing the units at a large scale commercial level. In addition to the lifespan, the electrolyzer stack for domestic micro-CHPs could be more cost effective (€5,000/Nm³/h) if the stack production was up-scaled to 100 units (FCH-JU, 2013).

In demonstration sites around the world, the order of priority of usage, is electrolyzers first, hydrogen second and then hydrogen in gas turbines. This is because it is cheaper when sites become large scale, the effectiveness of turbines increases with size (Wiberg, pers. comm., 2013).

As a result, hydrogen then is on the agenda as a mitigation strategy for excess energy, but further in the future and not as a priority at this moment.

Hydrogen seems to not be a large priority in the discussion for transport either. Aviation and marine sectors require a quality fuel with high energy density – which may be a chemical fuel (Pedersen, pers. comm., 2013). Hydrogen will have a role to play in transport by 2020, a minor one at that. There may be advancements in the fuel cell industry, but it will take several years for a vehicle fleet to be updated to what the latest technologies are. Seven years is too soon a time for hydrogen to play a larger role (Wiberg, pers. comm., 2013) because the technology as well as the general public have yet to observe hydrogen's utility. Major automobile manufacturers are planning to produce series of fuel cell cars but will not begin until 2015 (Wiberg, pers. comm., 2013). As such, infrastructure for transport should be developed first after which systems for storage should be created (Ehret, pers. comm., 2013). Another factor hindering the wind-hydrogen system is that the wind producers are still 'builders', when compared to other energy source producers eg. nuclear who are 'managers'. The long term managing of this resource is yet to be performed (Nilsson, pers. comm., 2013).

5.2 Governmental Policy and Regulatory Framework

Climate policy need not cost a lot, but imperfect implementation implies excess costs (Böhringer *et al.*, 2009). In Sweden, the governmental R&D funding for wind power was channeled solely to knowledge development of large turbines, which where unsuccessful. Contrastingly, in Germany the funding allowed for very broad search and knowledge development on various turbine sizes and models (Jacobsson & Bergek, 2011; Nilsson, pers. comm., 2013). The need for governmental funding has been expressed by multiple actors, but dissimilar to the Swedish policy of past. Jacobsson and Bergek (2011) refer to the Swedish policy as an institutional weakness.

More work in the area of integration of fuel cell and hydrogen technologies with RES is required, as has been expressed by the industry and research players also. Though the FCH-JU (2013) acknowledges the potential of hydrogen for large scale storage of energy from intermittent RES – it is one of their main objectives to integrate hydrogen with renewable power.

There is still no actual project focused on centralized large scale production of hydrogen via water electrolysis. The fact that an EU wide hydrogen/fuel cell development project still considers large scale hydrogen-RES systems as not being significant in the hydrogen scene indicates that until 2020, this technological system is not ready for large scale industrial use. It was also noted that the implementation plan had limited targets, most of them being techno-economic ones. These are not seen as sufficient enough to steer boosts in quick growth emerging technologies (Klein Woolthuis *et al.*, 2005) and more detailed application specific targets would yield a better breakthrough for the technological system (Kemp *et al.*, 1998).

Two other barriers to the commercialization of the hydrogen energy technologies were found by the European Commission (2006). These were 1) the lack of safety information on hydrogen components and system used in a hydrogen fuel infrastructure and 2) the limited availability of uniform international codes and standards necessary to standardize the technology.

The Swedish Energy Agency follows hydrogen technology but no research is being done as such, primarily because they think it is too far in the future for an investment of time now (Åfeldt, pers. comm., 2013; Kasche, pers. comm., 2013; Kempe, pers. comm., 2013). In the SEA documents (2012) while the taxation exemptions for cars is applicable to those running on electricity as well, the focus is mostly on bio-fuels as the main fuel source of choice when it comes to a renewable source for transport. Indeed, between 2010 and 2011, there was a 20% increase in the use of biobased motor fuels like biodiesel, ethanol and biogas.

There are a large number of methods and ideas necessary for integration of large amounts of wind into the energy system. But the Vind I Öresund project also identified a number of obstacles to the realization of these methods and ideas in the form of national or obsolete regulations. These regulations are: a) Nord Pool regulations where the market doesn't facilitate integration of large amounts of renewable energy currently; b) financial incentive and economic potential is lacking to implement smart grids; c) current taxes on energy consumption are not adapted to future energy solutions, dynamic tariffs should be looked at (Interreg IV, 2011). The taxation for hydrogen refueling stations is also unclear currently, as is the form through which the energy and carbon taxes will be used (Wiberg, pers. comm., 2013). There is little known about the position of Swedish Energy Agency in relation to P2G, apart from some skepticism about the relevance of the concept to Sweden, since intermittent RES do not dominate the Swedish electricity supply in the same way that they do in Denmark (Ragnar, pers. comm., 2013) and large scale pumped hydro storage will be feasible in parts of the country. According Cornander & Tibbelin (pers. comm., 2013) the political unwillingness was thought to be due to the fact that hydrogen technologies are relatively new, expensive, complex and will demand changes in legislation. And since politicians act on public trends (Pedersen, pers. comm., 2013), there are factors from both sides that drive the unwillingness.

It is unclear if Swedish support, if any, should be for just Swedish manufacturing companies, for investment in a technology in general or for wind. Governments need to examine different types of subsidies and which of those would be best for promoting ZEVs in general (Wiberg, pers. comm., 2013). In Denmark and Germany, tax exemptions for EVs exist (DEA, 2012; Ehret, pers. comm.,

2013; Jacobssen, pers. comm., 2013) and assist in speeding up fuel cell vehicle production in the car fleets than those in the Swedish ones (Wiberg, pers. comm., 2013).

As a large utilities company, Vattenfall is of the view that the institutional stimuli for wind must be decreased, and there should be an increased role of the EU ETS. If subsidies continue, the companies will be concerned only with receiving capital and innovation will be inhibited (Nilsson, pers. comm., 2013). Vattenfall is also of the view that the subsidies for wind can be slowly phased out, as they can survive on the market now (Nilsson, pers. comm., 2013). By extension, if the subsidies for wind do not exist, subsidies for ancillary services to wind power will not get institutional support either. Thus, storage technologies and/or hydrogen would require the support to be grouped not under a wind mitigation strategy but as an exploratory emerging technology. This has been observed in a few of the practical applications of hydrogen technologies, where the transport sector sees more demonstrations and entrepreneurial experimentation. The FCH-JU (2013) application area scope also does not include hydrogen for the large scale storage for energy from intermittent RES.

Yet this opinion for disbanding wind support was not a common opinion. Mathiesen (pers. comm., 2013) shared that wind power plants were still not ready to compete on normal market terms. Most actors on the market need to have 10-20% profit and a very short payback time – conditions that wind power plants are still unable to provide. So even though wind power is a good idea from societal and consumer point of view, without the institutional stimuli, they would not be constructed. Decentralized production could be of assistance in regions, like Southern Sweden, requiring energy arbitrage. The roadblock is actually in obtaining permits. The permitting process increases costs and ultimately makes Northern Sweden a relatively inexpensive region to produce electricity (Nilsson, pers. comm., 2013). Laws prohibiting distribution systems from owning generation, storage or bundling resources (Nilsson, pers. comm., 2013) were implemented before issues of excess energy surfaced. The limitations of these laws need to be re-assessed so that the distribution systems can own storage (like decentralized grids) and different stakeholders can be responsible for keeping values local (Nilsson, pers. comm., 2013) and therefore more cost-effective and prevalent. According to Swedish law, distribution of electricity should be commercial investment and not public ones, which disqualifies system operators as owners. There is no political debate on changing this system operators' mandate in the future (Salgi, pers. comm., 2013).

The Lolland projects have been technologically successful but the owners of the private homes do not understand the exact functioning. The private home owners get electricity subsidized by the project, so even if the micro-CHP is not running, the homes are heated by very expensive Danish electrical heating. The actual price is 200 öre/KWh and the subsidized rate to consumers is 30-40 öre/KWh (Jacobssen, pers. comm., 2013).

5.3 Psychological Factors

These factors lead to under-utilization because associations with existing systems may be tougher to break, and leads to skepticism beforehand. It is an extension of the first factor of technological hindrance, but the actors play a role in judging the TIS. Most of the transport related research and interviewees were prone to fall into this category of association with the existing technology and infrastructure.

Actors of importance to the utilization of an emerging technology are the general public. Research has found that the public may prefer RES in the energy system but are not necessarily willing to pay for it which is a trade off when it comes to the transport. Electric engines are much more efficient than combustion engines (Cornander & Tibbelin, pers. comm., 2013) - in ICE vehicles, the round trip efficiency of energy conversion⁹ is 20%, whereas in EVs it is 30%, but the preference is still to use traditional ICE cars (Pedersen, pers. comm., 2013) because that is what is familiar.

Political unwillingness may also stem from the required changes in legislation that will have to be incorporated. New regulation will be necessary to assess the safety in vehicles and at gas filling stations, management of gas filling stations, and hydrogen storage close to buildings among others (Cornander & Tibbelin, pers. comm., 2013).

There is also an acceptance issue when it comes to storage technologies (Nilsson, pers. comm., 2013). Long term is unviable for hydrogen in Sweden (Nilsson, pers. comm., 2013) because the country's energy intensive industries make it a priority to have low cost energy at all times (Nilsson, pers. comm., 2013) – something hydrogen is not equipped to provide. The electrical storage that *is* being examined by the Swedish Energy Agency is more on batteries for stabilizing the grid. These are batteries with capacity on MWh scale, in Gotland (Åfeldt, pers. comm., 2013). Within the transport sector in Sweden, the vision for fuel cells and hydrogen is for 2030-2040. Currently plug-in vehicles, hybrids and battery vehicles are being focused on (Kasche, pers. comm., 2013)

Alternative solutions to electrical storage altogether are to shut off the fossil fuel power plants in Denmark (Mathiesen, pers. comm., 2013), since they have flexible power production from all plants (Salgi, pers. comm., 2013). Heat sector can be expanded, more flexible demand side management can be applied and there can be more inclusion of electric vehicles in the system (Mathiesen, pers. comm., 2013)

5.4 Demand Factors

These factors are very consumer driven and as a result are seen in applicable technologies that are already at the market stage where consumers have a role to play. In the hydrogen system, it was noticed that the technologies are not at market stage yet and this factor aims to determine why that is so.

The expressed demand for storage technologies and hydrogen in the Öresund region is yet to surface in the traditional EEP argument. The clear link between excess electricity from wind and the need for storage technologies exists in Germany, and to some extent in Denmark, but is currently missing in Sweden.

Between Sweden and Denmark, Denmark is less energy intensive and can thus afford to have national policies that encourage R&D in emerging technologies. Whereas Sweden, with its primary industries of pulp and paper, mining and steel, and the chemical industry (SEA, 2012) being so energy intensive, it will always give priority to low cost energy despite the country's environmental inclinations. In 2010, the use of energy by industry amounted to 148 TWh, or 37% of Sweden's total final energy use (SEA, 2012). As a result, emerging technologies like hydrogen will find more proponents on the Danish political discourse, than in Sweden (Nilsson, pers. comm., 2013). This

⁹ Round trip energy conversion is defined as the ratio of output energy with energy put into the system (Wang *et al.*, 2005).

was observed by Jacobssen (pers. comm., 2013) in the new Danish environmental minister who was seen to have an interest in hydrogen technologies, and visited various demonstration projects around the country.

It must also be kept in mind that utility companies, like Vattenfall, are technology-using, rather than product-developing (Nilsson, pers. comm., 2013; Salgi, pers. comm., 2013). Hence, the technologies that they are using give a rather good indication of the technologies that are on the market currently and are seen as economical to use. However, TIS actors, like gas companies and car manufacturers are researching these hydrogen storage technologies as they foresee economic feasibility in this product (Wiberg, pers. comm., 2013). The Japanese car manufacturer, Toyota is seen as leader in hydrogen R&D for transport. It is worth noting what Toyota does to have an indicator of where the car industry is heading in technological developments (Jensen *et al.*, 2012; Sperling & Cannon, 2004).

New applications will exist in areas where the chance for market integration is largest. Trucks for long haul, private cars and public buses are the main areas of focus (Ehret, pers. comm., 2013). In transport, it is seen that major motor and energy companies around the world including German and Japanese car manufacturers anticipate the market introduction of fuel cell vehicles and the build-up of refueling infrastructure by 2015. The same is not observed in Swedish car manufacturers like Volvo. This can be attributed to the fact that Sweden, with a population of 9.5 million (SCB, 2013), and 4.4 million passenger vehicles (SEA, 2012) is not the largest of markets to warrant specific technology investment (Wiberg, pers. comm., 2013). It is the same reason for there being no HFCEVs in Iceland either (Wiberg, pers. comm., 2013).

There was also found to be a majority response from the interviewees that the objective is not to support one technological solution over the other (Kempe, pers. comm., 2013; Nilsson, pers. comm., 2013; Pedersen, pers. comm., 2013) but that the decision can be left up to the market forces. The actor's role was to provide the policy makers and/or consumers the information and allow them to make the final decision (Cornander & Tibbelin, pers. comm., 2013; Ehret, pers. comm., 2013; Wiberg, pers. comm., 2013).

5.5 Production Factors

It is a long and cumbersome process to move from the first stage of prototype development to demonstration phase and then to mass production. Volume building towards mass commercialization of hydrogen vehicles remains a challenging target (FCH-JU, 2013). Mercedes Benz had announced a hydrogen vehicle to be commercially available by 2010. That was postponed to 2013, then 2015, and now to 2017 (Jacobssen, pers. comm., 2013). German manufacturers have been doing R&D on fuel cells, but not much has been seen from Swedish manufacturers [Volvo representatives were unavailable for interviews] (Wiberg, pers. comm., 2013).

The joint statement from the global car industry to produce a series of hydrogen vehicles by 2015 was a way to encourage stakeholders to begin build-up of a commercial network of hydrogen refueling stations. The Scandinavian Hydrogen Highway Partnership in collaboration with Hydrogen Link, Denmark aims to make Scandinavia one of the first regions where one can drive an HFCEV and refuel with ease (SHHP, 2012). The four Swedish regions of Halland, Västra, Götland and Värmland are also members in HyER, the European Association for Hydrogen and fuel cells and Electro-mobility in European Regions (FCH-JU, 2013).

For micro-CHPs, there is a need for better lifespan of the fuel cell and material advancements before the micro-CHPs can go from demonstration phase to commercial phase. The positive development is that the need for improvements has been recognized and there are projects that address this need. These include a Danish project looking at material replacements, a half research-half commercial German-French collaboration project on extending the lifespan of the fuel cells (Jacobssen, pers. comm., 2013). Costs of the micro-CHP are an obstacle to overcome as well. The goal is to have one unit be at 60,000 DKK to be competitive with a gas boiler. It started out at 330,000 DKK, and economies of scale have brought costs down. The price paid currently to IRD is 130,000 DKK, though that is slightly subsidized by the project (Jacobssen, pers. comm., 2013).

There was also the view that the technology may be emerging mostly because of delays and because the technology does not work in a stable manner (Jacobssen, pers. comm., 2013).

5.6 Infrastructure and Maintenance

Though adaptation of infrastructure for a technological system is seen as an affecting factor, the assumption is that the technology has progressed far enough for there to be substantial infrastructure development. As expected, this was not observed yet for the hydrogen system, but more for wind power and predecessors to a pure hydrogen system such as gas turbines.

A gas turbine hydrogen system can integrate newer parts much better since it is familiar. Electrolyzers have also been on the market for some time. Hence, initial systems will incorporate known processes and later on fuel cells may enter, depending on the scale of energy source used (Wiberg, pers. comm., 2013).

Vattenfall sees significant growth opportunities within wind, but profitability is seen as being dependent on support systems. Dealing with the intermittency problem of wind power with storage solutions could be a significant part of this support system, but has yet to be observed. This was evident from the Vattenfall Annual Report (2011) where storage solutions were not considered in optimization of output from high winds but instead “new wind power developments must therefore target areas with reliable and predictable winds” (Vattenfall Annual Report, 2011, pg 86)

Public-private alliances together with international collaboration and coordinated technology policies help to share costs and overcome risks associated with developing innovative technologies

In as short a policy period as 2013-2020, the long time taken for infrastructure construction would have an impact on the deployment (Böhringer *et al.*, 2009).

5.7 Undesirable Social and Environmental Effects of New Technologies

This factor, like the previous one, is pertinent in the long run for a TIS such as hydrogen which is still in formative phase. In the current stage, it mostly affects perceptions of the TIS.

Safety issues with hydrogen storage were the main issues raised during the research of this thesis. However, views on safety issues regarding hydrogen varied according to the application area of hydrogen and the organizations the interviewees represented. The interviewee from Swedish Gas Technology Centre felt that safety issues did exist about feeding hydrogen gas into a transmission grid for methane (Ragnar, pers. comm., 2013). From SEAS-NVE, one of the project partners on the demonstration municipality of Lolland-CTF, Jacobssen (pers. comm. 2013) found that hydrogen was

easier to keep safe than methanol. Methanol leakage, or steam inhalation could be poisonous and has to be secured, much like gasoline. One of the private home owners, an elderly gentleman, was also reportedly unafraid of hydrogen storage or using hydrogen in his micro-CHP unit.

A poll done by NOWGmbH evaluating hydrogen safety also showed that a large majority were unafraid of living next to a hydrogen filling station, and were sure the hydrogen vehicles would be safe once sold (Bonhoff, 2013).

5.8 Concluding remarks

The structural transformation that is required of the Öresund energy system brings with it improvements in energy intensity, security of supply, decarbonization of the energy mix and subsequent low climate impacts. Such an energy-system path might still not be sufficient to protect against the risk of high climate sensitivities, but hydrogen-based technologies could emerge as flexible options for the energy system and thus would be prime candidates for not only alternative energy storage but also a risk management strategy against an uncertain climate future.

Hydrogen fits to a certain degree with existing infrastructure and can assist in building sustainable technology foundations in sectors other than just electricity. It was found that transport was a sector of focus in the region, P2G is seeing interest and integrating industrial energy consumption is also a possibility.

In the Öresund region, strategic niche management is seen to be at work. In practice, different actors may be niche managers: state policy-makers, regulatory agency, local authorities (eg. development agency), NGOs, citizen group, private company, industry organization, special interest group or an independent individual, depending on who is best qualified to take on the task (Kemp et al., 1998). Strategic niche management is a collective endeavour; collective and often negotiated outcome of different interactions at different levels. Some actors can however, take on a more dominant role as “niche managers”.

It was difficult to ascertain a single niche “manager” since the Swedish and Danish context is often different. This thesis however, can ascertain with the limited knowledge gained during research that in Sweden, the ‘advocacy coalition’ of Hydrogen Sweden and H₂ Skåne could come close to being niche managers. Actors like Vattenfall and Dong, who have vested interests in other technologies will generally not be interested in stimulating a new, competing technology. The same can be said for the Swedish Energy Agency. In Denmark, the role of niche manager had no single actor, but combinations of activities by different actors were seen to be helping the technology inch forward.

Niche markets such as Lolland, where convenience, reliability and environmental criteria are important, see hydrogen technologies as attractive. HFCs are seen in applications where their cleanliness, reliability and fuel flexibility compensate for high costs such as supplying electricity to sensitive loads with stringent reliability-of-supply standards. Fuel cells are expensive, because (like any new technology) their production has not yet reached the critical threshold where economies of scale kick in to significantly reduce the cost per manufactured unit. However, in the longer run, HFCs may assume a role in the distributed generation sector.

Beyond the role as a fuel, hydrogen also emerges as one of the most promising options for integrating vastly increasing volumes of wind power into the energy system, and by extension,

tackling a serious challenge to the security of the energy supply (Ehret, 2012). The future energy economy will have an important role for hydrogen as a clean CO₂ neutral energy source. The major advantage then, is the lack of polluting emissions since the utilization of hydrogen either via combustion or via fuel cells, results in pure water (Karakashev *et al.*, 2012).

For better penetration of hydrogen, using the existing gas network seems to provide a strong launching point. The expertise to handle hydrogen from P2G concept is there already; what is lacking is the infrastructure. There is hence, a good reason to build an entirely new infrastructure for reduced costs.

It was thought to be unusual that many of the demonstration projects had industry actors as an audience, instead of being the facilitator (Pedersen, pers. comm., 2013; Wiberg, pers. comm., 2013) But development of the technology need not be dominated by industry anyway, but users and ‘third parties’ can also contribute their ideas (Kemp *et al.*, 1998). Indeed, Lolland incorporated mostly bottom-up tools to achieve macro-political goals for sustainability and competitiveness.

The views on institutional stimuli were similar, with most actors agreeing that some form of governmental support would be necessary to help the wind-hydrogen-storage system along. Companies were found to have restricted technological horizons and bounded visions, which focused their exploratory activities upon problems posed by existing products. This was found also to be a major roadblock to more RD3, or even more discussions regarding a new system.

6 Conclusions and Recommendations for future research

The introductory chapter stated the research question and gave background to the problem posed. The chapters following provided an in depth account of the topic.

6.1 Conclusions

The research focus of this thesis was:

How can hydrogen technologies contribute to amelioration of challenges related to excess energy production from wind power in the Öresund region?

Answering this question has required an in-depth examination of the pros and cons of various storage technologies in the Öresund region. It has been found that there are marked differences between the Danish and Swedish sides in terms of energy requirements and policies.

Both the literature review and interviews show that the Danish side has more of excess energy from wind than the Swedish side. This is due to the larger presence of wind in Denmark currently; almost 30% of energy production is from wind. In contrast, only 5% in Sweden is from wind, though it is estimated that the Swedes will be expanding their energy portfolio to include large wind plants. Sweden's alternatives to fossil fuel power plants are large capacities of nuclear power plants and hydropower. Of the five nuclear power plants currently operating in the Nordic countries, three of them are in Sweden (Kopsakangas-Savolainen & Svento, 2013). As a result, the disparity between EEP from wind exists between the two countries that constitute the Öresund region.

Given this difference, the argument for using storage technologies to mitigate EEP from wind falls short in Sweden, and may be outcompeted by an incumbent Danish system. In Denmark, it is seen that district heating has a role to play in the utilization of excess wind energy. Sweden on the whole, has very little excess energy to begin with.

In southern Sweden, including Skåne and Gotland, wind in the energy portfolio is a larger percentage of the whole than it is on a national level. The regional interest, then, in storage technologies is seen to already exist, and there is a better case for regional policies to be implemented, than national ones that will subsequently trickle down. The projected increase however, will only come a few years down the line with a substantial increase of wind power in the renewable portfolio. The projected increase also arises from the assumption that wind will be the substituting for nuclear power plants when they will be shut down, of which there were confirmations from a few sources. However, such shutdowns remain quite some distance in the future.

In the event that storage is needed, it is held to be more practical to utilize the pumped hydro potential in the North of Sweden and increase existing transmission capacity to transfer the excess electricity to the South. The costs for a larger magnitude investment in increasing transmission capacity were found to be lower – lower than investing in an entire new system for new storage systems – and in particular, hydrogen technologies.

Approaching the storage technologies from another angle ie. stabilization of particular parts of the grid where production of intermittent electricity is particularly prevalent, seems to be a better way to

justify the presence of this emerging technology. The argument then, for hydrogen in the purview of storage is that it is easily available, and can be used in synergy with existing technologies. Some actors saw the penetration of hydrogen systems to be more straightforward with the role of hydrogen and electricity as complementary energy carriers. The hydrogen TIS was observed to have a slowly growing market due to entry of more actors into the system. This can be credited to costs dropping, improvements in technology, the role of collaborations and successful demonstration projects.

For increased deployment of important facilitating components of the hydrogen TIS, such as hydrogen fuel cells, vehicles and micro-CHP, the costs must come down further, there must be better investment and infrastructural development. Such initiatives could come from industry, as was the case in HFCs for transport, or it could be a governmental push, as was the case in Lolland.

The lack of governmental regulations was also seen to factor into the under-utilization of the hydrogen system. Institutional support has always been necessary to nurture and steer emerging technologies and this deficiency of political legitimation does play a part. A positive development has been seen in a sub-area where the Swedish Energy Agency allocated research funds for fuel cells in transport.

In the discussion of hydrogen against a backdrop of emerging technologies, the overarching response from most informants to this study was to not advocate for a single technology. It was clear that there are many potential technology systems that may be applicable, but there was reticence “to pick” a specific technology. Indeed, that is exactly how the global dependency on fossil fuels occurred; because at the advent of the 20th century, fossil fuels were picked as the source of choice. The trend must move away from this – for environmental and social reasons rather than pure market considerations. Thus, practically every interviewee and most of the literature reviewed, pointed to the fact that all the renewable options relevant to this region must be explored. Their job in this entire emerging technologies discourse was to help their chosen audience (be it policy makers, consumers or even industrial actors) be aware of all the options and have that information at hand. The underlying goal, then, of most partnerships, initiatives and institutional stimuli was to make all emerging technologies, hydrogen included, more cost competitive with the dominating fossil fuel sources.

When it comes to consumers, despite having environmental inclinations, they do not necessarily want to pay for environmental benefits. Lolland CTF had subsidized electricity rates for the community micro-CHP participants. The reasons can also be more political, namely the failure of policy-makers to make environmental benefits an integral part of the structure of incentives and constraints in which people trade and interact. With both financial and regulatory reasons, the importance of niches is highlighted as they are important for the development of a new technology. They demonstrate the viability of a new technology, provide financial means for further development, help build a constituency behind a new technology and set in motion interactive heuristic approaches in problem solving and institutional adaptations – these all play a role in a wider diffusion and development of the new technology.

Another important fact to remember is that wind itself is still not at a point where it can be called an entirely mature technology. A point of *managing* this energy source was brought up in an interview, and the conclusion was that wind producers are still not managers ie. there is a lack of long term

planning. Considering that hydrogen technologies for storage are being seen as ancillary services of wind power, it is not surprising that these technologies are only at an emergent phase.

In conclusion, it can be said quite confidently that hydrogen technologies are definitely an emerging technology with a very small niche in the Öresund region. It remains to be seen how this niche will further develop and be managed.

6.2 Recommendations for future research

The “tester” nature of this thesis (Colquitt & Zapata-Phelan, 2007) indicate that effects have been examined that are the subject of theorizing but not of empirical study yet. While it may not add to the ideas presented in areas of focus, but it does open up new avenues for more theory-driven research in the future. Seen in that context, the following areas can use this thesis to build on and research further in the future:

Having preliminarily identified a suite of potential niche managers for hydrogen technologies in the Öresund region, it would be interesting to follow up and see if this conclusion is valid as time progresses. Also, it will be helpful to follow the changes in the niche market as well as potential changes in who takes the lead in organization. It may be changing of governmental roles as facilitators/enablers or even industry and NGOs that are well placed to initiate and run niche projects.

The larger aim of strategic niche management is of course, to enable the new technology demand to be articulated. A future research project could be created using this as a springboard to determine how further development and use of the technology can be undertaken. It is more likely to act as a stepping stone, which facilitates – rather than forges – change in a new direction. A potential next step could be the estimation of market formation for this wind-hydrogen emerging technology, where the factors for under-utilization could be used to make policy recommendations.

One can also view a particular part of the field – that of transport – where the shift from fossil fuels has been more difficult than in the electricity or heat markets. Transport played a major role in this hydrogen system but there is a discursive struggle between technical solutions to transport problem and the fundamental change in transport patterns. So far the discourse on alternative transport fuels follows a technical solution path, where the transport volume is unchanged but it remains to be seen which one is more relevant to a hydrogen scenario.

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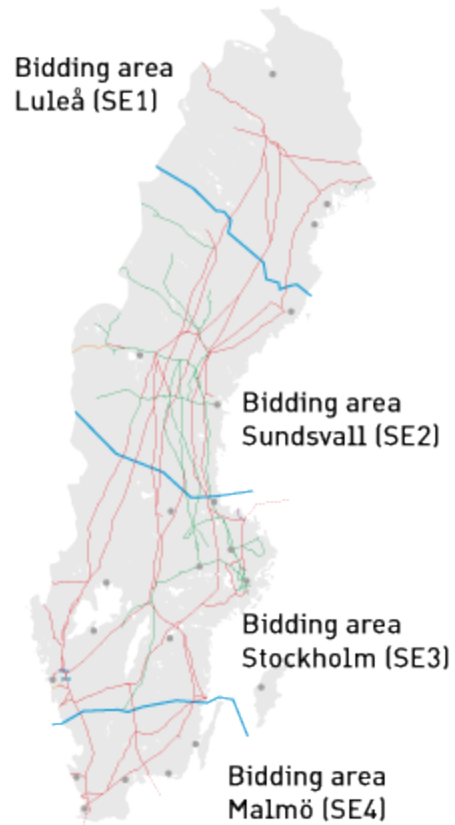
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Appendix 1



Bidding Areas of Swedish Electricity Market
Source: Reprinted from (Svenska Kraftnät, 2011)

Appendix 2



Lillgrund Wind Farm off the Öresund coast

Source: Anette Greenfurt at Dansk InfoDesign, date unknown

Appendix 3

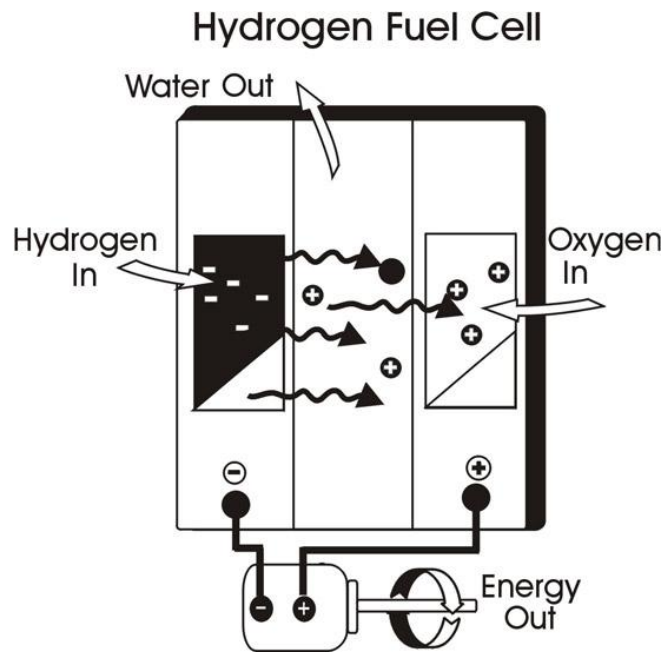


Figure 7: Working of a Hydrogen Fuel Cell
Source: Reprinted from (AE Hydrogen Fuel, n.d.)

Appendix 4

Sample Interview Protocol 1

Interviewee: Brian Van Mathiesen

Organization: Aalborg University, Associate Professor in Energy Planning

Interview Date and Format: 11th April, phone interview

S. No.	Topic Area	Question	Framework Function Being Addressed	Context (if required)
1	EEP in heat storage vs. EEP in electricity storage	In many papers, while talking about what to do with excess electricity production (EEP) from wind power, an assumption is that it can be put into electricity storage. Is this a wrong assumption and/or why should excess electricity be used in heat storage rather than electricity storage?	Knowledge development and diffusion; influence on direction of search	Difference between Sweden and Denmark?
2	Heat storage and electricity storage complement	Seasonal fluctuations that come along with heat pumps (heat storage) aren't present with fuel cell devices (electricity storage). Do you envision there being a complementary role for both in the future?	Development of positive externalities	Demand for heat during summer months is lower
3	Storage for Öresund	Within electricity storage devices, which do you think is most feasible (in whichever aspects you deem important) for the Öresund region?	Knowledge development and diffusion; Influence on direction of search	Aspects can be economics, environment, political backing etc.
4	P2G for Öresund	How feasible do you think the power to gas method is for the Öresund region? What do you think about Grid Energy Storage?	Entrepreneurial Experimentation; Influence on direction of search	Sabatier process produced methane injected into existing gas network
5	Future Hydrogen Economy	Views on the following scenario for the future: <ul style="list-style-type: none"> Hydrogen and electricity complementary roles as energy carriers Hydrogen fuel cells and batteries complementary roles as energy stores 	Development of positive externalities	Andrews and Shabani (2012)
6	Renewable Energy Markets and Institutional role	What do you think of the FITs that exist for wind power? Do you think some institutional stimuli should exist for storage technologies also?	Knowledge Development and Diffusion; Market Formation; Development of Positive Externalities	Change in complementary assets Compare with Vattenfall's answers
7	Smart Grids	What are your views on smart grids for integrating wind power generation to deal with demands on electricity networks?	Entrepreneurial Experimentations; Development of Positive Externalities	Optional question

Appendix 5

Sample Interview Protocol 2

Organization and Description: Vätgas Sverige (Hydrogen Sweden) is a non-profit Public Private Partnership with members and financiers from industry, academia, NGO's and local, regional and national government. The partnership promotes a balanced and pragmatic approach to hydrogen. The partnership's mission is to facilitate the introduction of hydrogen as an energy carrier in Sweden. To do so we initiate demonstration projects, disseminate information and strengthen the collaboration between actors from various fields with a joint interest in hydrogen. We are also open to exploring synergies with other technologies.

Name and Designation: Erik Wiberg, Trends Analyst

Interview Date and Format: 23rd April, Phone interview

S. No.	Topic Area	Question	Framework Function Being Addressed	Context (if required)
1	Role of hydrogen in today's system and the one in the future	What role do hydrogen and fuel cells play in today's systems?	Knowledge Development and Diffusion	Situation now
2		Do you think we will have a decarbonized energy system in the future? What role do you envision for hydrogen technologies in that future system? Any sectors in particular?	Influence on direction of search; Development of positive externalities	Trends to the future?
3	Hydrogen techs	Why hydrogen technologies?	Influence on direction of search	Complementary or competitive role seen vis-à-vis other techs?
4	Hydrogen-Wind link in Sweden	Is there a link in Sweden between hydrogen and wind? If yes, can that link be further used to suggest hydrogen techs as an option for storage of excess electricity production (EEP)?	Knowledge Development and Diffusion	Trying to find a natural path to my thesis research question
5	Regulations	What are the regulations in Sweden that directly affect Vätgas Sverige's working?	Influence on direction of search	Helpful or hindrance
6	Synergies with other techs; P2G	What synergies is Vätgas Sverige looking at currently? What do you think of the power to gas option in Sweden? Others that are more feasible?	Entrepreneurial experimentation; Development of positive externalities; Resource Mobilization	

7	Swedish national political will	I remember from the last interview in December that the general consensus was that there isn't much political support nationally for hydrogen. Do you see this changing in the future?	Legitimation; Influence on direction of search	Context for national, regional or local variations within Öresund
8		If yes, why. If not, what can be done to affect this change?	Legitimation; Influence on direction of search	
9	Investment	Why should there be investments in hydrogen? What are the barriers to investment thus far?	Influence on direction of search	Is it fair to use Danish argument of EEP here
10	Institutional stimuli	Are there any institutional stimuli (eg. FITs) that you think would be relevant for hydrogen?	Influence on direction of search	
11	Oppositions to hydrogen	How do you respond to skeptics who say the following: <ol style="list-style-type: none"> 1. Hydrogen is too expensive a technology currently 2. The roundtrip energy efficiency of energy conversion is too low 3. Hydrogen in transport doesn't make sense because in Sweden biofuel would take priority 4. Nuclear and hydro are more relevant to the Swedish context 	Knowledge Development and Diffusion; Entrepreneurial Experimentation	
12	Hydrogen for Storage	What are your views on hydrogen technologies as one of the options for storage of excess electricity?	Knowledge Development and Diffusion	
13	Smart Grids	What are your views on smart grids for integrating wind power generation to deal with demands on electricity networks?	Entrepreneurial Experimentations; Development of Positive Externalities	Optional question

Appendix 6

Sample Interview Protocol 3

Organization: NOW (national organization for hydrogen and fuel cell technology). Established in 2008. NOW is a component of national hydrogen and fuel cell technology innovation programme (NIP), launched jointly by the federal ministry of transport, building and urban development, the federal ministry of economics and technology, the federal ministry of education and research and the federal ministry for the environment, nature conservation and nuclear safety. NIP provides common framework for numerous hydrogen and fuel cell research projects conducted by academic institutions and industry. Is a public-private partnership scheduled to run for 10 years. Federal government and industry each provide 500 million euros over the period.

Name of Interviewee: Oliver Ehret

Interview Date and format: 18th April, Phone Interview

S. No.	Topic Area	Question	Framework Function Being Addressed	Context (if required)
1	Wind Power as an RES	What does NOW think of wind power as a renewable source of energy for the future? Is there a belief in its growth potential? What about the wind-hydrogen interplay?	Knowledge Development and Diffusion	Knowledge base for wind
2	Driver behind format	How did the format of public-private partnership come up for NIP?	Influence on direction of search	
3	Driver behind format	How did the political will for NIP come about?	Legitimation; Influence on direction of search	MoU for H2 Mobility before Fukushima
4	Wind's ancillary services in Germany	Has there been articulation of demand for wind energy and ancillary services (like storage) in Germany?	Legitimation; Influence on direction of search	Or was it mostly just a reaction to Fukushima?
5	Access to industry developments	The technical advances in FCEVs – are these new and improved vehicles available for Swedish/Danish regions also?		
6	EEP	Is there concern about the effect of excess electricity production from wind power? Is it viewed as an actual problem? If yes, problem in which aspect? Is NIP a way to mitigate these?	Influence on direction of search	Complementary products/services being looked at
7	Hydrogen tech	What kind of hydrogen technologies are being	Entrepreneurial	Applied knowledge formation, R&D

		looked at?	Experimentation	direction
8	Breadth of Hydrogen Techs	From a Danish interviewee I was told that HFCs can be used for transport, storage and as uninterrupted power supply in industry. Are there other avenues being explored in Germany?	Knowledge Development and Diffusion; Resource Mobilization	Change in complementary assets
9	Drivers	What are the drivers behind exploring hydrogen technologies?	Entrepreneurial Experimentation	Who has the competitive advantage for storage solutions?
10	Fuel Cells	What kind of fuel cell research is NIP looking at?	Legitimation; Market formation	
11	Institutional Stimuli	Are there any institutional stimuli that play a role in the funding? Eg. FITs or EU ETS	Knowledge Development and Diffusion	Cost reduction of emerging tech
12	Hydrogen for Storage	What are your views on hydrogen technologies as one of the options for storage of excess electricity?	Knowledge Development and Diffusion	
13	Comparison	How does Hydrogen compare with other technologies eg. batteries for transport, flywheels, pumped hydro, capacitors for storage?	Market Formation; Resource Mobilization; Development of Positive Externalities	Batteries are more energy efficient in conversion; biofuels require minor changes in existing engines/distribution infrastructure
14	Germany vs. Sweden (or Denmark)	These economic drivers to legitimation of emerging technologies are an aspect that I would like to cover as well, especially since in Germany there are public-private partnerships for hydrogen and fuel cell R&D and roll outs, whereas the situation is quite different in Sweden. Why do you think that is?	Knowledge development and diffusion; Entrepreneurial Experimentation; Legitimation; Development of Positive Externalities	Vattenfall credited it to nuclear industry reaction and energy intensive industry
15	Optional question	What do you think about smart grids?	Legitimation; Resource Mobilization	Optional question

Appendix 7

Sample Interview Protocol 4

Organization: Vattenfall

Name and Designation: Nilsson, Mats. A. N. (b. 1965) received a Master of Science degree in Natural Resource Economics at the university of Alaska Fairbanks (1994) and the PhD degree in Economics from Luleå University of Technology (2000). He has worked with the Swedish Competition authority as well as the Swedish Electricity regulator. Presently he is an Economist at Vattenfall AB, Strategy (2005- present) where his main concern is demand and macroeconomic development. His topics of research include empirical electricity market research, and institutional and competition research within natural resource markets.

Interview Date and Place: 5th April, Stockholm.

S. No.	Topic Area	Question	Framework Function Being Addressed	Context (if required)
1	Wind Power as an RES	What does Vattenfall think of wind power as a renewable source of energy for the future?	Knowledge Development and Diffusion	Knowledge base for wind
2	Investment in Wind Power	There have been several new wind projects in Sweden (Forsmark) and Denmark (Klim). Why is there a belief in the growth potential of wind power? What do you think as an economist? Anything to do with EU ETS?	Influence on direction of search	EU ETS and fee system for nitrogen oxide in Sweden are environmental policy instruments that impacted Vf's operational and financial position.
3	Wind's ancillary services in Sweden	What are the nature of interactions between Vattenfall and the Swedish Energy Agency? Has there been articulation of demand for wind energy and ancillary services (like storage)?	Legitimation; Influence on direction of search	Demand being formed, political strength
4	Wind's ancillary services in Denmark	What are the nature of interactions between Vattenfall and the Danish Energy Agency? Has there been articulation of demand for wind energy and ancillary services (like storage)?	Legitimation; Influence on direction of search	Demand being formed, political strength
5	EEP	Is there concern about the effect of excess electricity production from wind power? Is it viewed as an actual problem? If yes, problem in which aspect?	Influence on direction of search	Complementary products/services being looked at

6	Broader mitigation of EEP	Are the ways that the problem of excess electricity can be managed being looked at?	Entrepreneurial Experimentation	Applied knowledge formation, R&D direction
7	Electricity Markets and Negative Pricing	How does energy arbitrage in Nord Pool Spot get affected by excess electricity? Do you think mitigation solutions would help in better pricing?	Knowledge Development and Diffusion; Resource Mobilization	Change in complementary assets
8	Mitigation of EEP: Storage	Is Storage of excess electricity being looked at as a potential solution?	Entrepreneurial Experimentation	Who has the competitive advantage for storage solutions?
9	Institutional Stimuli for wind	What do you think of the Electricity Certificate System in Sweden, and the FITs in Denmark?	Legitimation; Market formation	
10	Institutional Stimuli for wind	Are institutional stimuli like the FITs and ECS good for a wind market?	Knowledge Development and Diffusion	
11	Institutional Stimuli for storage	Can these institutional stimuli be extended to ancillary services associated with wind power?	Market Formation; Resource Mobilization; Development of Positive Externalities	
12	Policies for and investment in devices	You mentioned in your emails that “costly policies that lead to negative prices and high volatility will be abandoned due to the deep and rather long recession in Europe. Makes more sense to invest in devices with short payback period”. Could you elaborate on these policies and the devices you deem appropriate in the context of the recession?	Legitimation; Resource Mobilization	Batteries may be come up as a better alternative in his answer for devices. No clue about what ‘costly policies’ entail.
13	Hydrogen for Storage	What are your views on hydrogen technologies as one of the options for storage of excess electricity? Are these devices where investment seems lucrative?	Knowledge Development and Diffusion	This may be outside his area of expertise but the question must be asked.
14	Germany vs. Sweden (or Denmark)	These economic drivers to legitimation of emerging technologies are an aspect that I would like to cover as well, especially since in Germany there are public-private partnerships for hydrogen and fuel cell R&D and roll outs, whereas the situation is quite different in	Knowledge development and diffusion; Entrepreneurial Experimentation; Legitimation;	If Berlin interviews with NOW/CEP/NIP happen, more questions can be

		Sweden. Vattenfall's core markets are these two countries and I would like to understand the differences and comparisons between them.	Development of Positive Externalities	asked.
15	Transport	Vattenfall R&D E-mobility programme aims to increase role of electricity in transport. Plug-in hybrids with Volvo. Is this also a potential use for excess electricity?	Influence on direction of search	Definitely outside his area of expertise; optional question
16	Carbon pricing	I noticed while reading Vattenfall publications that there was an assumption that carbon prices will rise – is this a valid assumption for the future?	Influence on direction of search	Optional question
17	Smart Grids	What are your views on smart grids for integrating wind power generation to deal with demands on electricity networks? Smart grids projects for decentralized production have been mentioned in a few Vattenfall documents. What are these projects?	Entrepreneurial Experimentations; Development of Positive Externalities	Optional question

Appendix 8

Sample transcribed interview 1

Jens Jacobssen

Question – emerging technology involvement. What role do hydrogen and FCs play in today's system and in future decarbonized energy system?

Today – no role. Some other ways eg. natural gas reformed into hydrogen and then used in micro CHP. Part of Danish system, micro heat and elec. Happens in western part of Jutland in DK. Doesn't see a bright future for this technology because it's still fossil fuel based and one of his visions is to get rid of fossil fuels. There are problems with biogas, because if it comes from waste, from farming industry, if you get it from crops – food security angle where the resources are used for fuel instead of food. Rapeseed is used for biomass whereas instead you could grow corn.

Micro CHP running on natural gas are commercially available in Japan and Germany. They get subsidies from both govts. As Its very expensive. German govt wants to deploy this tech.

Hydrogen in Lolland, in wider perspective, we want to build electrolyzing process into the units, so you don't need the grid. It's too expensive to take a grid and have the houses close by the source. With units primary objective is to get rid of oil boilers because they pollute, CO2 emissions etc. whereas with this you solve surplus wind energy problem – 1) elec cheap 2) hydrogen production 3) when elec is expensive you use hydrogen for power and heat.

20th of December 2011, had negative price on elec. Had to pay germany to take their power.

Perspective is to work to commercialize the micro CHP based on hydrogen, but it is years ahead.

Question – H2 tech being used in Lolland is for micro-CHP. Are you looking at H2 storage from wind in Lolland also?

Yes, but is not part of the project. The main aim of project is to demonstrate the FC tech in private houses, which means storage demonstration pro

Only parameter for electrolyzer was cost. Didn't have money to run electrolyzer so went for the cheapest possible one. Energy efficiency wasn't looked at.

Working with electrolyzation process in other projects.

Future – smart grids – make correlation between wind production and energy storage.

Today – elec used for electrolyzation is unknown power source, could be from nuclear.

Question – why H2? Why is there a belief in those techs.

H2 will be one of many ways to store energy in the future. Advances in hydrogen are easy, easy to keep it safe. Alternative could be methanol but it is very poisonous if it leaks, or steam from it. And what is more important, you have to secure it like you do in gasoline. People are afraid of methanol, but aren't of hydrogen.

Depends on pressure for storage of hydrogen. For efficient usage it has to be in liquid form (100 bar or sso).

Hydrogen has bright future in vehicles. 150 kms per day – Evs are fine. But for longer distance cars, buses, lorries etc. want hydrogen, are building hydrogen fuelling stations

Question – same interest in hydrogen in DK+SWE as in GER? Germany on different scale though?

Hydrogen fuelling station in Malmo (though unused since COP15), Copenhagen municipality has strategy for Hvehicles and wants more fuelling stations.

No govt support in DK and SWE.

Norway has hydrogen on agenda.

Question – advocating emerging techs, related to transport and mobility. Does storage fit into all of that, in terms of access to funds, political will when it comes to project.

Political will may be present in DK. Announced funding from govt, EU to H2 projects. Money hasn't been given yet, still applying for it. New energy minister is keen on H2 technology, made visits to demo projects etc. Japanese delegations (After Fukushima, looking for alternatives), Toyko gas have also been interested in the demo.

Retired man living in house is unafraid of hydrogen, comfortable with it, satisfied with working. Older man participated because he wanted his grandchildren to have better energy system.

Costs for micro CHP units

2 problems before micro CHP gets commercial. Costs and better efficiency:

1. FCs in general has lifetime of 20,000 hrs. same materials used in all FCs, HD PEM or whatever. Pan-European project working to prolong lifetime to 40,000 hrs. 40,000 hrs is then competitive with natural gas boilers. Materials, humidification, and other factors being looked at. Different partners looking at different sectors. NL govt ran out of money so is now being headed by NO. half science-half commercial German company, French technical university,
2. A material to replace Pt. Pure Danish project headed by DTU prof, combined univ and industry project.

Mercedes Benz announced a hydrogen vehicle to be commercially available back in 2010, but then changed the announcement to 2013, and now further prolonged it to 2015, then to 2017. It isn't easy.

Question – costs of CHP unit

60,000 DKK is the goal, as it will be competitive with gas boiler.

First unit (at exhibition) – 330,000 DKK

Currently – 130,000 DKK

Still a long way to go.

The price from IRD is more than 130,000 DKK, that is the cost to rent it.

Question – funding?

Some of it comes from Danish micro-CHP governmental project fundings, some of it is their own cost. Project participants include Dong, SEAS-NVE, IRD among other consulting companies. Back in 2006, Danish micro-CHP got 60 million DKK directly under the government., were supposed to end at 2012, but has been prolonged till end of 2013 (hydrogen project demo in Lolland and Jutland).

Objective of project was to penetrate 3 different FC technologies with the aim to get them commercially available through 3 phases. And the 3 tech were (*listen again, 35 minutes*):

1. HC PEM (Lolland)
2. HT PEM (demonstrated in southern part of Lolland) (abandoned due to technical reasons, were unable to make it work)
3. SOFC

Had to move project from sellevorg to vaagh. Sensitive to which kind of natural gas you get. There was a change in the gas delivery to southern part of Jutland a year ago. Bought gas from Germany, which had a little bit more nitrogen in it than Danish gas. FCs and gas boilers in that region had to be readjusted. Decided to move project to Vaaghn where natural gas comes from North Sea.

Question – heat storage in DK more feasible/easier than building up electricity storage?

In future, the Danish energy strategy says in 2050 that 100% of elec shall come from RES. Wind close to 30%. Will run into problems.

There is a joint venture with a German company (eon?)

But no one wants wind in their backyard (NIMBY)

He doesn't see it as black and white – you need both heat and elec storage. If it being used for district heat, heat storage is then number 1. But if you go to rural areas where there is no district heating, elec storage is more feasible. Western Lolland has no district heating at all. They use wooden boilers and oil boilers instead. Houses in Lolland aren't necessarily suited for heat pumps. Rural Danish houses are also not insulated for heat pumps to effectively work. Lolland example applies to the rest of rural Denmark as well. Lolland has focused more on exploring new technologies than looking at energy efficiency in existing buildings.

Question – other alternatives to electricity storage in Denmark being looked at?

At universities yes. Underground storage, magnetic wheels, capacitors etc. these are years ahead, no matter which technology is chosen.

At this point, DK isn't dealing with its excess electricity. They try to avoid complications. EVs, V2G, smart grids,

Question – main drivers to investing in hydrogen?

Personal motivation to get rid of fossil fuels. In societal perspective, batteries for vehicles and for heating in houses is insufficient.

Mercedes hybrid can do 320 km on 1 refuel.

Sweden has more gas refueling stations but is almost impossible to do so in Denmark (not as widespread).

For better deployment of HFC, vehicles, micro CHP, you need better infrastructure, costs to come down, investment, interest etc. the initiatives will come from the industry and there will be joint projects with the university. Funding would be EU funded projects and each government will have its own.

Institutional stimuli role? Only when the product is mature. It is hard to say it's an emerging technology when you are heavily delayed and the technology doesn't work in a stable manner. No one has much of an idea about the timeline for commercial availability. Micro-CHP may have subsidies like in Japan, NL, GE. Danish government wants to get rid of oil boilers, not allowed to install new oil boilers anymore, alternative CHP unit or something else.

Potential exists for both storage and wind-hydrogen system.

Projects in Lolland etc. have been technologically successful, but the owners of the private homes don't understand they are part of this demonstration thing. They just get cheaper electricity, subsidized because if micro CHP isn't running, there is an electric heating device, and then it runs on electric heating which is expensive in DK (2DKK/Kwh). Actual price is 30-40 ore/Kwh. They put a limit on how much the people pay, and the project pays the rest.

32 micro-CHPs in use currently: 5 units in an old folks home (there will be 6), 6 in a former school, a household has 2 units and heat storage, church buildings. No plans to expand since the project ends in 2013. Meeting when they ask for volunteers and of those who volunteered, they did not get enough feasible households. Because those households had heating based on water, whereas oil boiler heating was preferred instead. All CHP units are 1.5kW for heat and 1.5 kW for elec.

Energinet.dk check out.

Appendix 9



Figure 8: Windmills in Skåne

Source: Author, 20th April 2013