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ACHIEVING EU ENERGY TARGETS – IMPACTS OF EVOLUTIONARY AND REVOLUTIONARY TRANSITION PATHS ON POWER SYSTEMS

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ABSTRACT

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Achieving EU energy targets – Impacts of evolutionary and revolutionary transition paths on power systems

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Ambitious energy targets set by EU put pressures to increase share of renewable electricity supply in this and next decades and therefore, some EU member countries have boosted increasing renewable energy generation capacity by implementing subsidy schemes on national level. In this study, two different change approaches to increase renewable energy supply and increase self-sufficiency of supply are assessed with respect to their impacts on power system, electricity market and electricity generation costs in Finland.

It is obtained that the current electricity generation costs are high compared to opportunities of earnings from present-day investor's perspective. In addition, the growth expectations of consumptions and the price forecasts do not stimulate investing in new generation capacity.

Revolutionary transition path is driven by administrative and political interventions to achieve the energy targets. Evolutionary transition path is driven by market-based mechanisms, such as market itself and emission trading scheme. It is obtained in this study that in the revolutionary transition path operation of market-based mechanisms is distorted to some extent and it is likely that this path requires providing more public financial resources compared to evolutionary transition path. In the evolutionary transition path the energy targets are not achieved as quickly but market-based mechanisms function better and investment environment endures more stable compared to revolutionary transition path.

TIIVISTELMÄ

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Aino-Mari Keskinen

EU:n energiatavoitteiden saavuttaminen – Evoluutionaarisen ja revoluutionaarisen muutoksen vaikutukset sähkövoimajärjestelmässä

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EU:n asettamat kunnianhimoiset energiatavoitteet aiheuttavat paineita lisätä uusiutuvan sähköenergian tuotantoa tällä ja seuraavilla vuosikymmenillä ja osa EU:n jäsenmaista on tukenut uusiutuvan tuotantokapasiteetin lisäämistä erilaisten tukiaisten avulla kansallisella tasolla. Tässä työssä tarkastellaan kahden erilaisen muutosstrategian, revoluutionaarisen ja evoluutionaarisen muutospolun, vaikutuksia Suomen sähköjärjestelmään ja sähkömarkkinoihin sekä sähkön tuotantokustannuksiin tarkoituksena lisätä uusiutuvan energian tuotantoa ja sähkön tuotannon omavaraisuutta.

Nykytilanteen tarkastelussa havaitaan, että investoijan näkökulmasta nykyiset sähkön tuotantokustannukset ovat korkeat ansaintamahdollisuuksiin nähden. Lisäksi sähkön kulutuksen kasvunäkymät ja hintaennusteet eivät kannusta tällä hetkellä investoimaan uuteen tuotantokapasiteettiin.

Revoluutionarista muutospolkua energiatavoitteiden saavuttamiseksi ohjaavat pääsääntöisesti poliittiset toimenpiteet. Evoluutionaarista muutospolkua ohjaavat enemmän markkinaehtoiset mekanismit, kuten markkinaehtoisuus itsessään sekä päästökauppajärjestelmä. Työssä havaitaan, että revoluutionaarisessa polussa markkinaehtoisten mekanismien toiminta häiriintyy ainakin jossain määrin ja oletettavaa on että tämä polku vaatii enemmän taloudellista julkista tukea evoluutionaariseen polkuun verrattuna. Evoluutionaarisessa polussa taas energiatavoitteita ei saavuteta oletettavasti yhtä nopeasti, mutta markkinaehtoiset mekanismit toimivat paremmin ja investointiympäristö säilyy vakaampana.

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Aino-Mari Keskinen

CONTENTS

ABREVIATIONS AND SYMBOLS

AC	Alternating current
AMR	Automatic Meter Reading
Bio SNG	Bio-based Synthetic Natural Gas
CCS	Carbon capture and storage
CO2	Carbon dioxide
CHP	Combined heat and power
DC	Direct current
GHG	Greenhouse gas
ECCP	European Climate Change Programme
EU	European Union
EU ETS	European Union Emission Trading Scheme
EV	Electric Vehicle
FIP	Feed-in premium
FIT	Feed-in tariff
FLH	Full-load operation hours
IEA	International energy agency
IPCC	Intergovernmental Panel on Climate Change
IVO	Imatran Voima, former electricity supply company
LCOE	Levelized cost of electricity
LDC	Load duration curve
LNG	Liquefied Natural Gas
LO1&2	Loviisa 1&2, Nuclear power plant
LTS	Large technical system approach
NEA	Nuclear Energy Agency

OEDC	Organisation for Economic Cooperation and Development
OL1&2	Olkiluoto 1&2, Nuclear power plant
OL3	Olkiluoto 3, Nuclear power plant
OPEC	Organization of the Petroleum Exporting Countries
PVO	Pohjolan voima, electricity supply company
RES	European Union renewable energy directive
RLDC	Residual load duration curve
SIS	Sectorial innovation system
SNM	Strategic niche management approach
SO2	Sulphur oxide
TGC	Tradable green certificate
TIS	Technological innovation system
TSO	Transmission system operator
TVO	Teollisuuden voima Oyj, electricity supply company
UNFCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
VRE	Variable renewable energy
VTT	Technical Research Centre of Finland

1 INTRODUCTION

The climate change is one of the major current global challenges nowadays and the reason behind it is considered to be the greenhouse gas (GHG) emissions. History behind international climate change prevention efforts dates back to the late 1980s, when the international community became awaken of the problem. Intergovernmental Panel on Climate Change (IPCC) was established in 1988. In the year 1990 IPPC claimed that the climate change was a threat and these lead to adopt the United Nations Framework Convention on Climate Change (UNFCC). This convention divided the countries into Annex I countries, which were industrialized countries, and Non-Annex I countries, which were mainly developing countries. Annex I countries adopted policies to stabilize their emissions, which were not yet legally binding. Couple of years later, UNFCC launched Kyoto protocol, which included binding reduction targets for GHG emissions and introduced three alternate mechanisms countries to implement. (Brohé, et al., 2009, pp. 60-65)

The energy sector is one of the major sources of GHG emissions and the emission reduction objectives touch especially this industry. In many countries, including Finland, the energy policies' target was realizing reliable, secure and affordable energy before adopting Kyoto protocol and now the focus was shifted to reducing GHG emissions, (Negro, et al., 2012, pp. 3836-3837).

European Union (EU) is one of the largest economies in the world and it consumes around 20% of the world's energy, (European Commission, 2012, pp. 5-7). It has been the one of the global first movers to respond the climate challenge and has set regulative directives and implemented European Union Emission Trading Scheme (EU ETS) as a mechanism of Kyoto protocol to reduce GHG emissions. EU has very few reserves of its own and it relies on oil and gas imports and increasing the self-sufficiency is also an objective. Traditional major suppliers of oil and gas imports are Russia, Norway, OPEC countries, but there are some emerging suppliers such as Eastern Mediterranean countries, Iraq and Caspian Sea countries, (European Commission, 2012, pp. 5-7).

The EU member states are free to realize their energy policies within the framework of EU legislation. In practice, EU sets the obligations to the member states in terms of objectives and decides the internal electricity market model and emission trading system. In addition to emission reduction targets, other energy policy aspects of EU are to maintain the economic competitiveness, secure the energy supply and sustainability as well as a common internal electricity market, (European Commission, 2012, p. 4)

The renewable energy sources, such as bioenergy, wind power and solar power are often seen as solutions to meet the international climate change challenges and decrease the dependency on energy imports from outside of the union as well as a way create new “green” jobs. Therefore, subsidizing these technologies on a national level is seen as an attractive way to reach the targets in many countries. For example, Germany and Spain have been the first movers in EU to meet the targets and have deployed massive volumes of variable energy technologies into their electrical power systems, mainly by subsidizing them. In these countries the share of renewable electricity generation has increased, but it has led to increasing costs of electricity, overcapacity of the production and massive support schemes, but their GHG emissions have not decreased as expected.

Overcoming the initial problem, to reduce GHG emissions, is not as straightforward as policy makers see it. Wind and solar power are variable renewables (VREs) meaning that their production pattern is intermittent. The major challenge when deploying intermittent technologies is that the variability must be compensated somehow. Alone these technologies cannot fulfill the demand and substitute the conventional dispatchable technologies.

Finland is one of the second movers meeting the regulative targets of EU and actions to reach the ambitious targets have been minor so far, even though there are subsidies available and the public interest towards energy issues has been rising. However, the Finnish electricity production industry must meet the regulative targets set be EU, which are reducing GHG emissions to and increasing renewable electricity generation.

In Finland, share of renewable electricity supply is one of the highest proportions in the EU because of hydro power and utilization of bio-based fuels in the thermal generation, but the European Union Renewable energy directive (RES) has set a target to increase renewable energy supply further, (Finnish Energy Industries, 2014b). The general objectives of RES directive are cutting GHG emissions 40% compared to 1990 levels and achieving 38% share of renewable energy. In addition to RES directive, another motivation to increase renewable energy supply is improving self-sufficiency of supply. As mentioned, EU relies highly on energy imports and the ongoing crisis in Eastern Europe can be seen as increased the motivation recently to reduce energy imports.

In the case of electricity, the renewable share should be higher than 38% and European Commission (2013, p. 6) proposes to achieving 45% renewable electricity supply by 2030 to meet the general objectives. The benefits of increasing the renewables in the electricity supply are possibility transmit the energy efficiently even over long distances if the infrastructure exists and allowing centralized generation with high efficiency. The main challenge is poor storability of electricity, which makes it a special case compared to other goods such as fuels. Therefore, this study focuses on increasing share of renewable electricity supply and power system transition.

1.1 Rationale behind the study

The renewables have caused revolutionary transition in the electricity supply driven by political decisions in many countries. In Europe the member countries of EU have implemented a variety of support schemes to boost the development and deployment of renewables on national level. In some countries this has led to innovations and technology development, but in some countries the support schemes have caused distortions the electricity markets and the initial intention the cut GHG emissions have not been successful as thought.

As mentioned, Finland has been realizing a second-mover strategy in meeting the regulatory targets to increase the share of renewable electricity supply. At the moment, the majority of the renewable electricity sources are hydro power and biomass, which is mainly from the wood-processing residuals, (Finnish Energy Industries, 2014b). In the recent years the share of annual renewable electricity has varied between 25% and 32% in Finland, (Statistics Finland, 2013). In Finland the yearly varying hydro power reservoirs cause the substantial fluctuation of this share. Furthermore, the electricity consumption in Finland is featured with the high demand of heating and lighting required for 9 months in a year and existence of energy intensive industry, which consumes around 50% of the electricity and is also a substantial electricity supplier, (Ministry of the Environment & Statistics Finland, 2013, p. 37).

The wind power and solar power deployment to the power system has been minor so far. Finland implemented the current feed-in tariff available for maximum 2500 MW of renewable energy in 2011 and before that the major instrument to support renewable technologies was tax exemptions, (Kitzing, et al., 2012, p. 196). If the majority of the power plants affiliated to the current feed-in tariff were wind power plants, the annual renewable energy production would increase approximately 5,5 TWh with the operation hours 2200 h/a. This amount equals to approximately 6% of the present electricity consumption of Finland.

The current feed-in tariff may not be a sufficient support to increase renewable generation substantially and meet the target of 45% renewable electricity consumption. The purpose of this study is to assess how the current energy industry could reach this target and how the different policy interventions influence to the electricity markets, energy prices and electricity supply industry and its dynamics.

1.2 Research questions

In this study, the focus is on the electricity supply industry and how it should move to the regulatory 45% renewables target. The two alternate change approaches assessed are evolutionary and revolutionary transition paths and also consider the economic consequences of transitions. Therefore, the research question is following.

> *What are the estimated future levels of electricity generation cost of considered production types when the regulatory targets are reached through evolutionary and revolutionary paths in chosen spatial domain?*

In order to approach the topic*, levelized cost of electricity (LCOE)* is applied to assess the cost level, the electricity supply industry is illustrated as *an innovation system* and *roadmaps* are generated to describe the alternate paths. Therefore, the secondary research questions of the study are following.

> *What is the influence of input parameters in the LCOE calculations?*

> *What is the state of the present energy innovation system in chosen spatial domain and how it affects the current electricity generation cost level from the perspective of investors?*

> *What are the differences in the development of innovation system between the evolutionary transition path and revolutionary transition path?*

> *What kind of control mechanisms are required in order to reach the regulative EU energy targets and what are the side effects of them on the electricity markets and the future LCOE levels?*

1.3 Methodology

Aim of this thesis is to perform a comparative case study based on mainly inductive research approach. Definition of a comparative case study is a research project where small number of cases in their real life context is selected and the results obtained are assessed in qualitative manner. Furthermore, this case study is practice-oriented in order to contribute knowledge for practitioner who has responsibility for real-life situation. (Dul & Hak, 2008, pp. 3-4, 217)

In this case study qualitative analysis is supplemented by quantitative analysis aspects by applying LCOE assessment. The general structure of the analysis is illustrated in Figure 1.1.

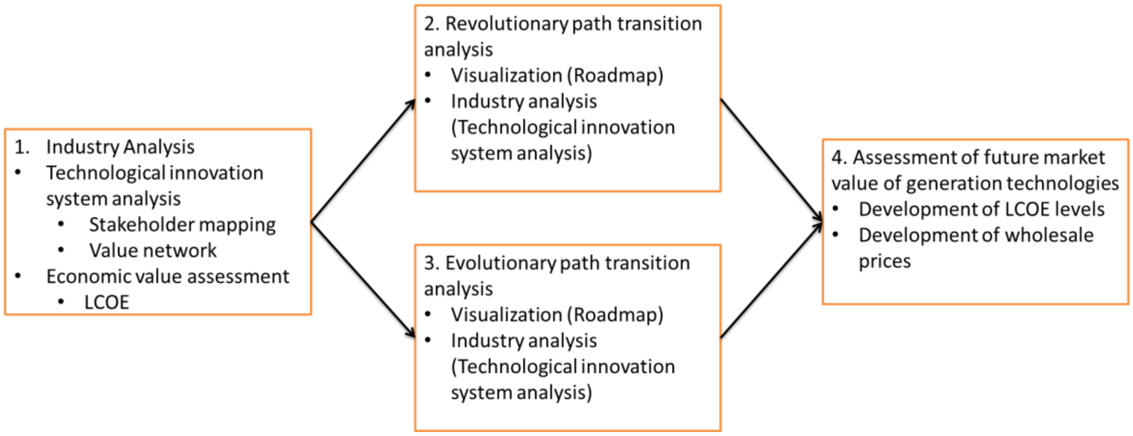


Figure 1.1 Structure of case study analysis.

As seen in Figure 1.1, the technological innovation system analysis and LCOE assessment are performed to compare the current situation with considered transition paths. Analysis in steps 2 and 3 seen in Figure 1.1 are attempted to perform in as uniform manner as possible in order to make transition paths more comparable. In addition to tools applied in step 1 seen in Figure 1.1, technology roadmaps are applied mainly to visualize the transition paths and distinguish the activities in transition to a number of layers. The tools mentioned here and their applications are introduced in Chapter 3. Finally, the development of market value of generation technologies is both transition paths are viewed by considering the development of LCOE levels and wholesale prices in step 4.

The data applied in this case is gained from literature references, internet documents and discussion with experts. Alternately, interactive methods, such as workshops or Delphi surveys with industry experts and relevant stakeholders, could have been used in the innovation system analysis and creating roadmaps in order to make them more credible and higher quality, but due to limited resources they are not applied in this study.

2 BACKGROUND OF THE CASE STUDY

The case study of this thesis considers the Finnish power system as a part of Nordic power system. This section introduces the Nordic power system in Chapter 2.1 and discusses the main characteristics of electricity supply and consumption in Finland in Chapter 2.2. A brief history of Finnish power system is given in Chapter 2.3 in order to understand the situation better and finally, a common business model of electricity supply industry in Finland called “Mankala” principle is introduced in Chapter 2.4.

2.1 Nordic power system

The Finnish power system is a part of Nordic Power system together with Sweden, Norway and Denmark and in addition there are DC connections from Estonia and Russia to Finland. Each country in the Nordic power system has its own electricity generation structure illustrated in Figure 2.1.

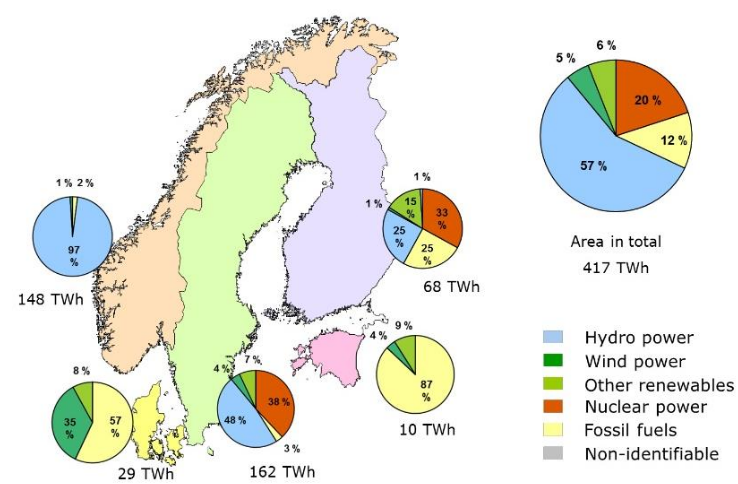


Figure 2.1 Electricity supply in the Nordic power system. (Finnish Energy Industries, 2014b, p. 18)

The main benefit of diverse generation structure is that it allows very cost-optimal plant dispatch, (Syri, et al., 2013, p. 249). As seen in Figure 2.1, there are substantial hydro power resources especially in Norway, but also in Finland

and Sweden. Finland and Sweden both have nuclear power production and Denmark has significant wind power capacity. The remaining power is generated by other renewables and fossil fuels.

2.2 Electricity supply and demand

In Finland, annual electricity consumption has been 82…87 TWh in recent years, (Finnish Energy Industries, 2014b, pp. 2). The electricity supply by sources and by suppliers and the electricity consumption by sectors can be seen in Figure 2.2.

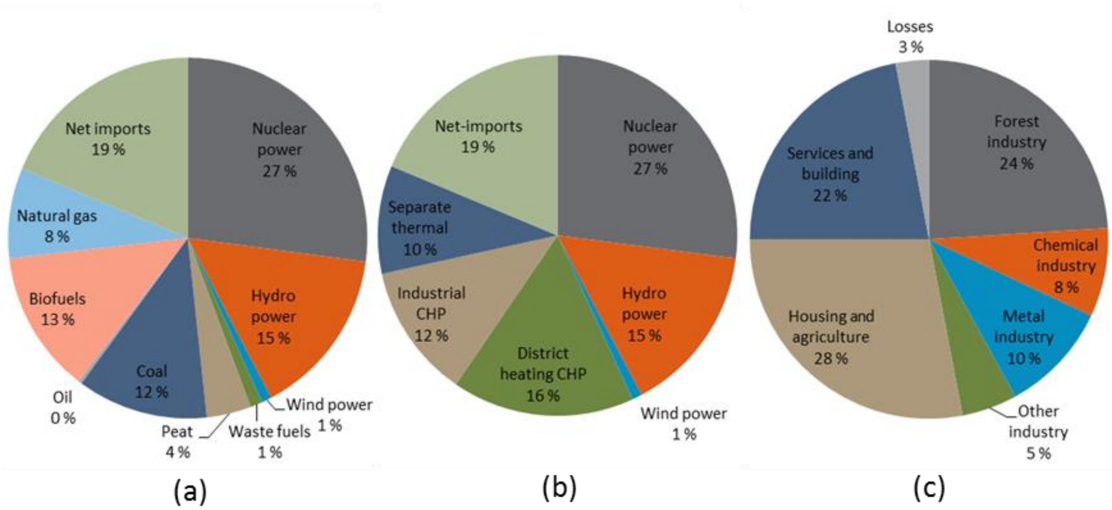


Figure 2.2 Electricity supply by sources (a), suppliers (b) and electricity consumption by sectors (c) in 2013. (Finnish Energy Industries, 2014b, pp. 5, 8-9)

As seen in Figure 2.2 (a) and (b), the majority of the generated electricity in Finland is thermal power, nuclear power or hydro power. The majority of the generated thermal power is Combined Heat and Power (CHP) produced in co-generation process with district heating heat or industrial heat. A substantial share of supplied electricity is imported as seen in Figures 2.2 (a) and (b). The net-imports come mainly from Sweden and Russia, (Finnish Energy Industries, 2014b, p. 13).

Industrial sector consumes around 50% of the total electricity consumption as seen in Figure 2.2 (c). Housing and agriculture sectors consumes around a quarter of the total consumption and services and building sectors around quarter. The most substantial industrial consumer is the forest industry, which is also substantial electricity supplier through its co-generation processes, (Finnish Energy Industries, 2014b, p. 7).

In 2013, the total generation capacity in the Finnish power system was around 16 500 MW (Jäppinen, 2014, p. 9), while the capacity available during peak load period was around 13 300 MW, (Statistics Finland, 2013, Table 3.5). The peak-demand is often used to determine the needed electricity supply capacity and capacity available during peak load period is determined by concerning the capacity credits of generation units. The highest peak-load demand in Finland so far occurred in winter 2011 when the demand was almost 15 000 MWh/h momentarily, (Fingrid Oyj, 2014a, p.2). In Finland, the peak-load demand has been covered in recent years partly by imports from neighboring countries and thus scarcity of domestic capacity has not become a problem, (Fingrid Oyj, 2014b, p. 3).

On average, the electricity supply capacity in Finland is fairly old and it is expected that a substantial proportion of electricity generation capacity will be decommissioned by 2030, (Confederation of Finnish industries & Finnish Energy Industries, 2009, p. 21). In the recent years some of the flexible conventional condensing capacity has left the market already and it is expected that further 1700 MW conventional condensing capacity will be decommissioned by 2020, (Jäppinen, 2014, p. 9). Meanwhile, it is expected that energy consumption increases moderately in Finland and according to some estimates the annual electricity consumption in 2030 would be around 100-111 TWh, (Finnish Energy Industries, 2009, p. 21). Also the peak-load demand is expected to increase. The estimated development of existing and pending electricity supply capacity and peak-load demand can be seen in Figure 2.3.

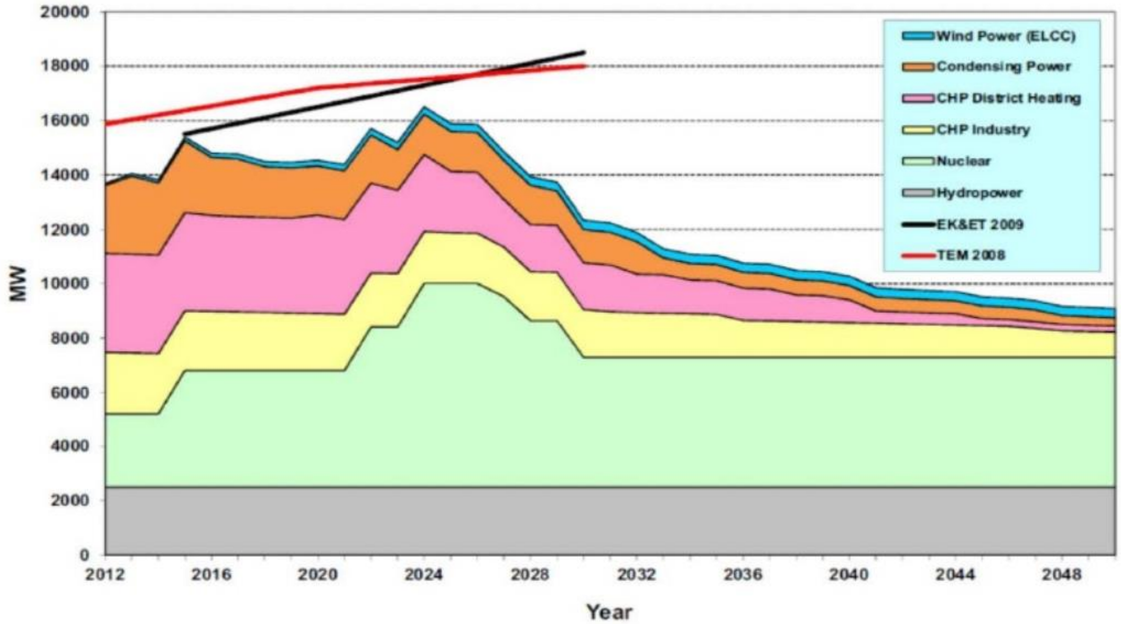


Figure 2.3 Electricity generation capacity and peak load demand development in Finland 2012-2050. (Syri, et al., 2013, p. 253)

Currently there are 4 operating nuclear power plants with total capacity of 2752 MW, (Finnish Energy Industries, 2014a). These plants, Olkiluoto 1&2 (OL1&2) and Loviisa 1&2 (LO1&2) were built in 1977-1982 and it is expected that their capacity will exit from the market in late 2020s or 2030s, (Finnish Energy Industries, 2014a). In addition one nuclear power plant, Olkiluoto 3 is under construct and two plants, Olkiluoto 4 and Hanhikivi 1, have positive decision-in-principles, (STUK, 2014).

Total share of CHP electricity is around 25% of the production portfolio. CHP electricity is produced in industrial processes and district heating power plants. The major fuels of CHP power plants are coal, natural gas and bio fuels while peat has a minor share. The share of biofuel utilization has increased in district heating in 2000s significantly and its share is expected to rise. (Finnish Energy Industries, 2014a; Finnish Energy Industries, 2014b).

Hydro power has production share around 15% and the average production is 13 TWh per year, (Finnish Energy Industries, 2014b). The annual hydro power production is determined by rainfall and water storages and the annual production has varied between 9…17 TWh in the last decade, (Finnish Energy Industries, 2014b). In Finland, the hydro power is mainly run-of-river hydro power with limited possibilities for peak-load utilization, but it can be utilized in short-term power balance maintenance as flexible supply, (ÅF-Consult Ltd, 2012, p. 102). The present hydro power generation capacity is around 3 000 MW and is expected to increase due to capacity increases of current power plants and construction of small-scale hydro power plants, (Finnish Energy Industries, 2014a).

The share of wind power production has increased in the last years, but it still has a very minor share with total capacity of 447 MW, (VTT, 2014) fulfilling only less than 1% of the demand as seen in Figure 2.2 (a) and (b). In the future, it is expected that share of wind power increases substantially.

The main concern currently is sufficiency of flexible electricity supply capacity in the future. As seen in Figure 2.3, the capacity of inflexible nuclear power increases later in this decade and next decade and in addition variable renewable capacity is expected to be deployed to the power system.

2.3 History of the Finnish power system in brief

In the history of Finnish power system, state-owned enterprise Imatran Voima Osakeyhtiö (IVO) has been the single most contributing actor to deploy energy technologies to the power system. IVO was merged with state-owned oil-import and refinery company Neste Oil in 1998 to establish Fortum Oyj. Some years later, Neste Oil was span off from Fortum to an independent company and IVO is still represented by Fortum, whose major shareholder is still the government. In the 20th century, IVO built several major hydro power plants, two nuclear power plants and later has been a forerunner to deploy domestic sources, such as wood and peat in the separate electricity generation and combined heat and power (CHP) generation. Another contributing actor has been Pohjolan Voima Osakeyhtiö (PVO), which was founded in 1940s by eight forest industry companies. Finnish forest industry expanded strongly in 1950s and due to growing consumption begun to take interest into building cogeneration plants. Cogeneration capacity grew especially in the 1960s and 1970s. In the late 1960s Teollisuuden Voima Oy (TVO) was founded by 16 industry and power utility companies, including IVO and PVO, in order to build and generate nuclear power in Finland. (Kara, et al., 2004, pp. 36-41)

PVO and IVO were also contributing actors to build the main grid. In 1997 they sold their transmission grids to the present transmission system operator (TSO) Fingrid Oyj, when the electricity market was deregulated in the Nordic countries. The distribution grid was built by local power utilities in the last century, which were often established by local communities and usually they also built local power plants to produce electricity and heat. District heating systems were implemented in the towns and local utilities and IVO were central actors in building CHP power plants. (Kara, et al., 2004, pp. 37-39)

Finland has been an exporter of energy technologies in the past decades. In the middle of 20th century several machine oriented engineering works were established and therefore, the Finnish machine industry is well developed, (Borup, et al., 2008, pp. 56, 63). The major exporters of energy technologies have been Strömberg, Ahlström, Wärtsilä and Tampella, (Kara, et al., 2004, p. 40).

The main drivers of the development and direction of search in the energy industry has been electrification of the society at first, then during and after the oil crisis in the 1970s increasing the self-sufficiency of supply and nowadays meeting the regulative emission reduction targets, (Hellsmark, 2011, pp. 316-317). It can be argued that ongoing crisis in Easter Europe has emphasized again the importance of self-sufficiency and it can be seen that increasing self-sufficiency is the second most important driver of electricity supply industry at the moment.

2.4 Mankala principle

In Finland, so-called “Mankala” principle has been a common business model in electricity supply business since 1930s. In this business model a number of companies needing electricity, such as consumers and retailers, found a company to build and operate power plants together. This common company sells the electricity for its shareholders by cost price and shareholders fund the company's investment and operational costs. (Syri, et al., 2013, p. 251)

Mankala principle originates from energy demand of forest industry companies, but nowadays the shareholders are representatives of other industries, local utilities and municipalities, (Syri, et al., 2013, p. 251-252). Substantial share of Finnish electricity is generated in Mankala companies; for example 40% of generated electricity in Finland was produced under Mankala principle in 2012, (EPV, et al., 2013, p. 5). For example TVO and PVO are working under Mankala business model.

3 THEORY

The chosen topic is approached by using theories and tools related to *innovation systems*, *transition pathways* and *economic evaluations* of energy technologies. First, innovation system theories are applied to analyze the current situation. Then the transition pathways theories are applied and the transition is illustrated by using *Technology roadmaps*. The economic evaluations are applied in order to assess the attractiveness of investments for generation capacity.

This section introduces the theories applied in the analysis. Chapter 3.1 introduces the innovation systems and the framework applied in analysis. Chapter 3.2 discusses the typology of transition pathways that are relevant to understand in the roadmapping process and introduces the Technology roadmaps. Chapter 3.3 introduces first the basic principles of the electricity markets in the Nordic power system and then chapter 3.4 focuses on economic evaluation of the energy technologies.

3.1 Innovation system

Innovations can be seen as prerequisite in order to meet the regulatory targets in this case. Definition of an innovation is not only about converting knowledge into products and services, but also putting them into real use, (Johnson, et al., 2011, p. 187). Traditionally innovation process is seen as linear R&D process including research, development, demonstration and diffusion stages, which are relying on the internal resources of an organisation, (Johnson, et al., 2011, pp. 187-194). Nowadays, the innovation process is seen as more complex, multiple-actor process, where these stages are interlinked by feedback loops within the innovation system, (Grübler, et al., 2012, p. 1675). Furthermore, idea of open innovation as a process of knowledge import and export has been adopted by organisations, (Johnson, et al., 2011, p. 191).

The concept of an innovation system, which is applied in this case study, is grounded on *actor-network theory (ANT),* which was originally developed to bring together social sciences and natural sciences. According to the ANT, the actors are individuals, organisations, objects or artefacts, who have certain importance in the network, which describes the relations between the actors and which are never purely technical or purely social. The ANT is based on three basic principles: *agnosticism* as impartiality towards the actors, *generalized symmetry* offering an explanation for conflicting viewpoints between different actors and *free association* as abandonment of distinctions between technical, natural or social elements. The heterogeneous network of actors is reconfigured in *translation* processes. Translation can be seen as source of innovations in the ANT defined as means of entities giving roles to others. Callon (1986, pp. 202-211) distinguishes the translation into four moments of translation: problematization when the actors become aware of a problem, interessement when the actors get motivated driven by some incentive, enrollment as structuration of new roles and mobilization when the enrolled actors act translate the network. Therefore, it can be argued that the reconfigurations of the networks are sources of innovation in the ANT. (Tatnall & Gilding, 1999, pp. 957-960)

The ANT approach helps to understand the emergence of innovations and in addition to technical aspects, it considers also the social aspects. However, the ANT is very generic theory and it does not provide a comprehensive tool or method to describe or illustrate the innovation. Therefore, the innovation system concept is applied rather than ANT.

The concept of *innovation system* includes the complex process of multiple *actors*, which are connected through *networks* and work under a set of *institutions* as rules of the game. The actors, networks and institutions are considered as structural components of the innovation system. The components contribute towards a common purpose by its activities and operations, which are defined as *functions*. An innovation system is not a deliberate construct but an analytical tool, which is applied in order to illustrate the innovation process. The actors of the innovation system do not always share the same goal and tensions usually occur. (Bergek, et al., 2008, pp. 407-409)

3.1.1 Levels of innovation system

Innovation system can be described on different levels, such as national, regional or sectoral, (Geels, 2004, pp. 897-899). In this study, the level of sectoral system is adequate. In the sectoral level there are approaches, such as sectoral innovation system (SIS) itself, technological innovation system (TIS) and large technical systems (LTS) approaches.

The SIS is defined as a group of actors that develops products and generates and utilizes products in some field and the actors are connected through collaboration and interaction or through competition. The technological innovation system (TIS) is a group of actors in networks working under a set of institutions to generate, diffuse and apply technology in a very specific field. In the TIS approach, the knowledge and competence flow is central and it is more narrow approach than in the SIS approach. (Geels, 2004, pp. 897-898)

The LTS approach considers the material aspects as they are important in the innovation systems where for example the infrastructure plays significant role and the physical artifacts are defined as structural components of the innovation system in addition to actors, networks and institutions, (Geels, 2004, p. 898). In this study the TIS approach is applied, since it is most suitable when the analyzed technology field is very specific.

3.1.2 Framework of Technological innovation system analysis

Bergek, et al. (2008, p. 441) provides a step-by-step approach to analyze the TIS illustrated in Figure 3.1.

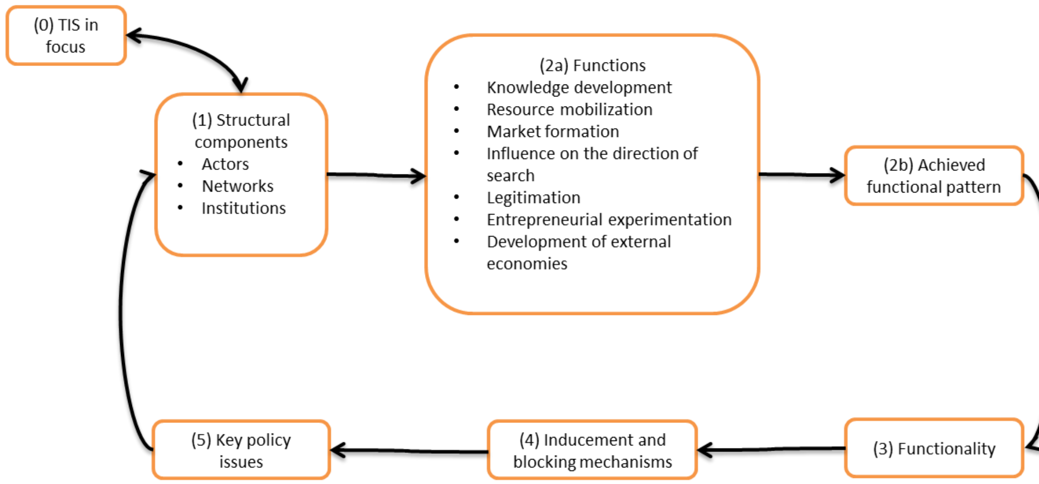


Figure 3.1 Framework of TIS analysis. (Bergek, et al., 2008, p. 411).

As seen in Figure 3.1, in addition to defining the structural components and analyzing the functions, the framework assesses the functional pattern and functionality as well as determines inducement and blocking mechanisms and key policy issues.

Different innovation system frameworks and papers distinguish the functions of the TIS slightly varying and often the functions are partly overlapping. As shown in Figure 3.1, Bergek, et al. (2008, p. 411) introduces seven functions, which are explained in Table 3.1.

Table 3.1 Functions of the TIS. (Bergek, et al., 2008, pp. 414-419; Hekkert, et al., 2011, p. 10; Grübler, et al., 2012, pp. 1689-1690)

Function	Description	Indicators
Knowledge development and diffusion	Breadth and depth of the knowledge base of innovation system. How the knowledge is diffused and combined.	Bibliometrics, R&D projects, Number of professors, Number of Patents, Assessments by managers and others, Learning curves
Influence on the direction of search	Incentives and pressures for the innovation system to develop.	Beliefs in growth potential, incentives from factor or product prices, extent of regulatory pressures, articulation of interest by leading customer
Entrepreneurial experimentation	Innovation system probes for new technologies and applications.	Number of entrants, Number of different types of applications, Breadth of technologies used.
Market formation	Existence of market places, Market Demand, Price and development level of technology.	Quantitative data on market size and customer groups. Qualitative data on actors, standards and purchasing processes.
Legitimation	Social acceptance in accordance with relevant institutions.	
Resource mobilization	Innovation system's ability to mobilize competences, financial capital and complementary assets.	Volume of capital, Volume of seed and venture capital, Volume/Quality of human resources, Complementary assets
Development of positive externalities	Pecuniary and non-pecuniary utilities as positive external economies.	

Originally, the framework of TIS was developed for policy makers and researchers to identify policy issues and set process goals, (Bergek, et al., 2008, p. 408). The framework does not just analyze the industry that the study focuses, but notices the supply and user side and the society around the innovation system as well as considers the functionality. It also makes the innovation systems more comparable and it can be applied both for the TIS in development stage and TIS in very mature stage. Furthermore, the innovation system analysis helps to point out the strengths, weaknesses and potential blocking mechanism that affect the transition.

3.2 Dynamic multi-level perspective on system innovations

In order to understand the transition of an innovation system, a framework of a dynamic multi-level perspective on system innovations is introduced in Figure 3.2.

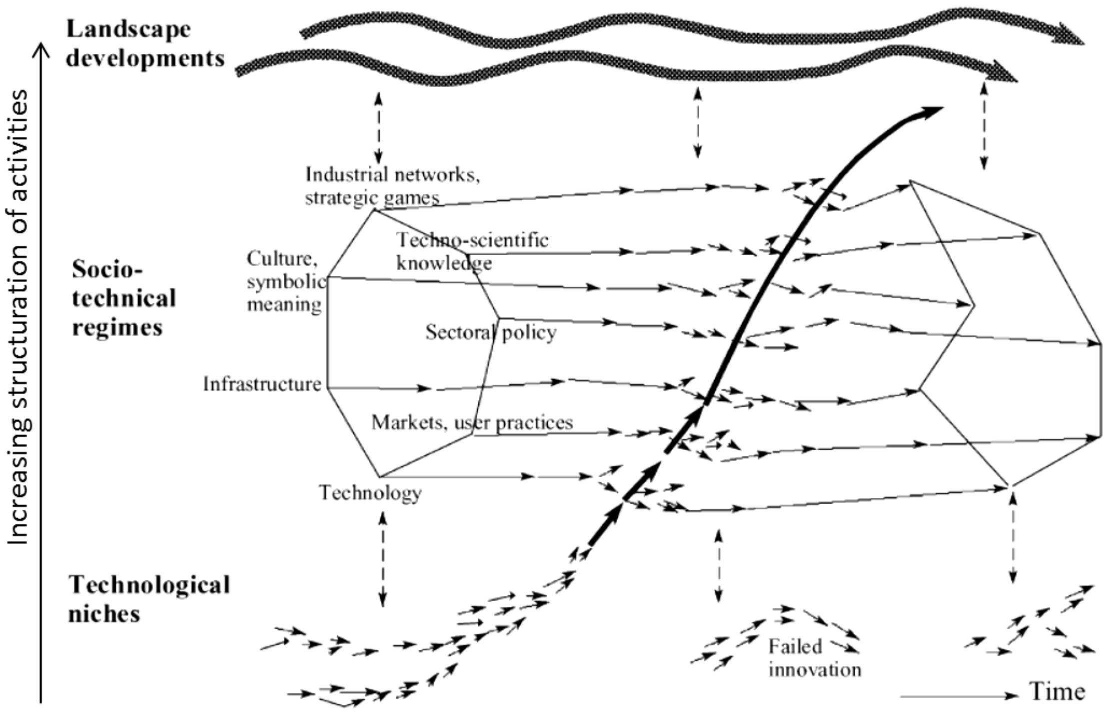


Figure 3.2 Dynamic multi-level perspective of technological transitions, (Geels, 2002, p. 1263). The dash lines in the figure illustrate the pressures that different levels put each other.

The dynamic multi-level perspective on system innovations is based on the socio-technical system theory, which can be seen as another illustration of an innovation system. This framework is closely related on the innovation system theories by introducing three different levels seen in Figure 3.2: socio-technical landscape, socio-technical regime and niche level, (Markard & Truffer, 2008, p. 603).

The three level of the multi-level perspective are described by Geels (2004, pp. 910-915) as follows.

- *The socio-technical landscape* is the macro-level of the multi-level perspective, which is the wider environment of the system. It has stronger structuration of activities and it cannot be changed directly by actors.
- *The socio-technical regime* is the meso-level of the system, which is not as stabilized as the socio-technical landscape. This level can be seen as a set-of science, technology, economy, politics and culture, which have their own development lines as trajectories that are interacting.

- The level *of niche-innovations* as the micro-level is the place where the actors deviate from the rules and practice in the existing regimes. All niche-innovations do not fit to the existing regime and eventually they will die. Some niche-innovations break through and they will be adopted by the socio-technical regime.

The dynamic multi-level perspective theory provides very general framework to analyze the transitions and for example the spatial domain is not determined in this perspective. However, it does not provide a comprehensive framework for the analysis and it is up to user's decision to define for example the regime and regime shift. It also emphasizes radical innovations in the niche level and it seems that the innovations come outside from the stabilized socio-technical regime. However, this is not the case, since the innovations can also take place in the socio-technical regime.

3.2.1 Stability of the existing system

The rules and regimes, actors and organisations as well as socio-technical systems themselves are the drivers of stability. Existing cognitive, normative and regulative rules as institutions are often reproduced and they guide perceptions and actions. Furthermore, the alignment between the institutions promotes stability. Actors and organisations are interacting thought networks, where "organizational deep structure" stems the organisations and commitments and vested interests of organisations drive further the stability of the system. (Geels, 2004, pp. 910-911)

Socio-technical systems themselves can be drivers of the stability. Existing material structures or technical systems are not easy to abandon and the components of the system are interdependent, meaning that they complete each other and the interdependencies are certain kind of inertia in the system. In terms of economic considerations, the transition of the socio-technical system often destroys the executed investments. The existing technologies have certain competitiveness level gained by learning-by-doing and learning-by-using as well as better economies of scales compared to immature technologies. (Geels, 2004, p. 910)

The drivers of stability and entrenchment of the existing regimes of the system can be seen as *lock-ins*. The niche-innovations must overcome the lock-ins, if the niche-innovation actors wish that the niche-innovations are adopted by the existing regime. (Schot & Geels, 2008, pp. 542, 545)

3.2.2 Transitions of the socio-technical system

The transitions of the socio-technical systems are result of interactions between the three levels. As illustrated in Figure 3.2, the changes at the socio-technical landscape put pressure on the socio-technical regime and the destabilization of the regime opens windows for new opportunities and the increasing internal momentum on the niche-innovation level interacts with the socio-technical regime, (Geels & Schot, 2007, p. 400). Furthermore, tensions and misalignments are an essential feature of transitions and without them the diffusion of niche-innovations is less likely, (Geels, 2004, p. 914).

3.2.3 Typology of transition pathways

Geels and Schot (2007, pp. 405-406) develop a typology of transition pathways by combining *timing of interactions* and *nature of interaction* as criteria. According to this typology the transition pathways are *Transition*, *Technological Substitution*, *Reconfiguration* and *De-alignment and re-alignment* illustrated in Figure 3.3. In addition Reproduction process is described as dynamically stable regime, which reproduces itself and only accumulated incremental innovations exist. (Geels & Schot, 2007, pp. 406-415)

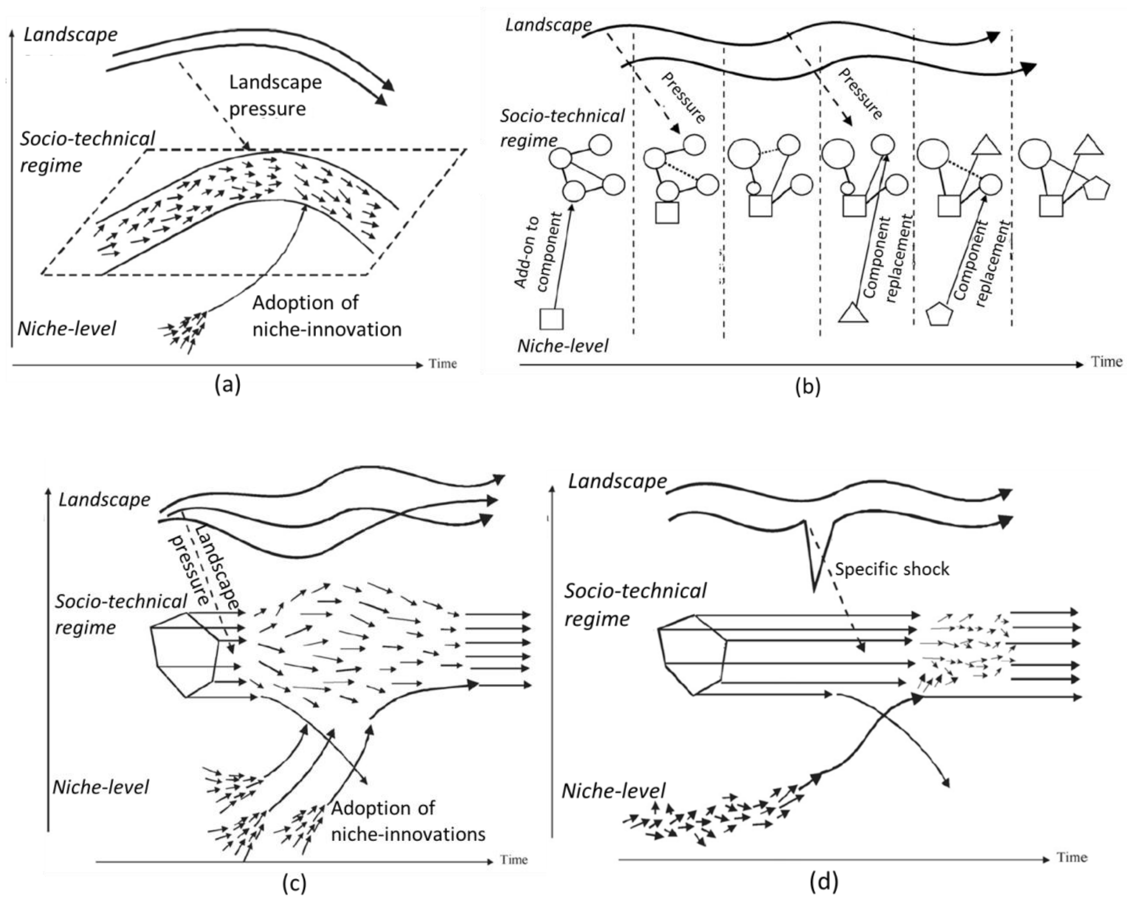


Figure 3.3 Typologies of transformations illustrated by the dynamic-multilevel perspective: (a) Transformation pathway, (b) Reconfiguration pathway, (c) De-alignment and re-alignment pathway, and (d) Technological substitution pathway. (Geels & Schot, 2007, pp. 407,409, 410, 412)

The landscape pressures modify the innovation activities and development path of regime in *the transition pathway* as seen in Figure 3.3 (a), but the activities of the regime actors do not change immediately. Outsiders of the regime may voice their opinion, propose alternatives and develop alternated technologies or practices, which the most viable options may be adopted by the regime. In *the reconfiguration pathway* seen in Figure 3.3 (b) the regime adopts novelties due to landscape pressures and they may lead further changes for example in technology and user-practices. This reconfiguration may open spaces for new adoption of novelties and this pathway is more relevant for a system where several technologies are interplaying. In the both pathways the regimes can be seen crowing out of old regimes, in the transition pathway though gradual adjustments and in the reconfiguration pathway there are substantial sequential changes. (Geels & Schot, 2007, pp. 406-408,411-413)

Both transition types *De-alignment and re-alignment* and *Technological substitution* pathways are caused by avalanche change in the landscape. In the de-alignment and re-alignment pathway seen in Figure 3.3 (c) there is large and sudden divergent change in the socio-technical landscape, which causes problems in the socio-technical regime leading to *erosion* and *de-alignment* of the regime. This often leads to multiple niche-innovations carried out by outsiders and there are no stable rules of the game leading to existence of multiple niche innovations and uncertainty, but eventually some of the niche-innovations will become dominant. In the technological substitution pathway seen in Figure 3.3 (d) there is also a sudden change in the landscape described as *specific shoc*k, which opens windows of opportunities for niche-innovations. The difference between this type and the latter transition is that the niche-innovations have already been developed and they have gathered the internal momentum. The technological substitution pathway has technology-push character, which may lead to plight and downfall of incumbent actors. (Geels & Schot, 2007, pp. 408-411)

The typology of transition pathways introduced in this section is useful in this case, but often the transitions occur in a sequence of transition pathways. In this case the considered transition types are revolutionary transition path representing reconfiguration pathway and evolutionary transition path representing transition path as discussed more detailed in Chapters 5.1 and 6.1.

3.2.4 Strategic Niche Management approach

Schot and Geels (2008, p. 540) introduce a strategic niche management (SNM) approach to understand how successful market niches emerge proposing that niches emerge through collective enactments, not through top-down planning. The technology development can be seen progressing at local niche level and at the global level. At the local level there are single projects carried out by local actors and networks and at this level is a testing place for diffusing and elaborating new ideas. If the local projects are aggregated, the sequence of local projects may create internal momentum and may lead to emerging niches in the global level as seen in Figure 3.4. The sequence of carried projects in the local level, also including the failed ones, leads accumulating into technical trajectories. (Schot & Geels, 2008, pp. 543-544)

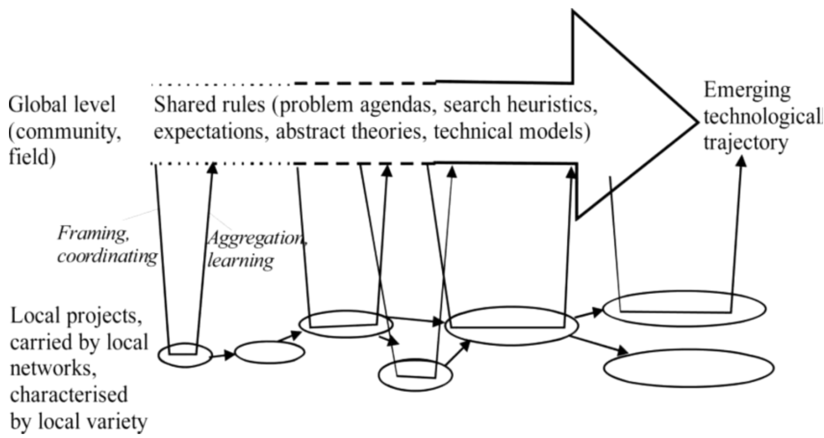


Figure 3.4 Illustration of local level projects and their relation of emerging global level niches leading to emergence of technological trajectories. (Schot & Geels, 2008, p. 544)

The purpose of SNM approach is to help with the challenges of policy issues to nurture niches in transitions. Successful creation of technological niches is distinguished into three different processes: articulation of robust, specific and high-quality expectations and visions, building of broad and deep social networks and learning process at multiple dimensions directing both first-order and second-order learning. However, this is not a straightforward recipe but it includes a number of dilemmas. The dilemmas are for example: flexible visions versus persistent visions, stepwise learning versus big leaps learning, working with incumbent inside actors versus working with outside actors and level of variety of learning and level of protection provided to nurture niche-innovations. (Schot & Geels, 2008, pp. 540-541, 548-549)

3.2.5 Technology roadmapping

The transition of the innovation system is illustrated by applying *technology roadmap* technique in this study. The technology roadmap approach helps to distinct the assumed future activities of an innovation system and its development from the current situation to the vision into a number of layers and to point out the required policy interventions.

Technology roadmapping is a technique to make long-term strategic plans combining technology and product technology aspects with market requirements with respect to timing, (Farrukh, et al., 2003, p. 6). It is not a forecast or prediction tool, but a tool of strategic planning considering the present situation, vision and the gaps between them distinguishing the roadmap into a number of perspectives such as market, infrastructure, technology, science, resources et cetera as seen in Figure 3.5, (Phaal & Muller, 2009, pp. 39-40).

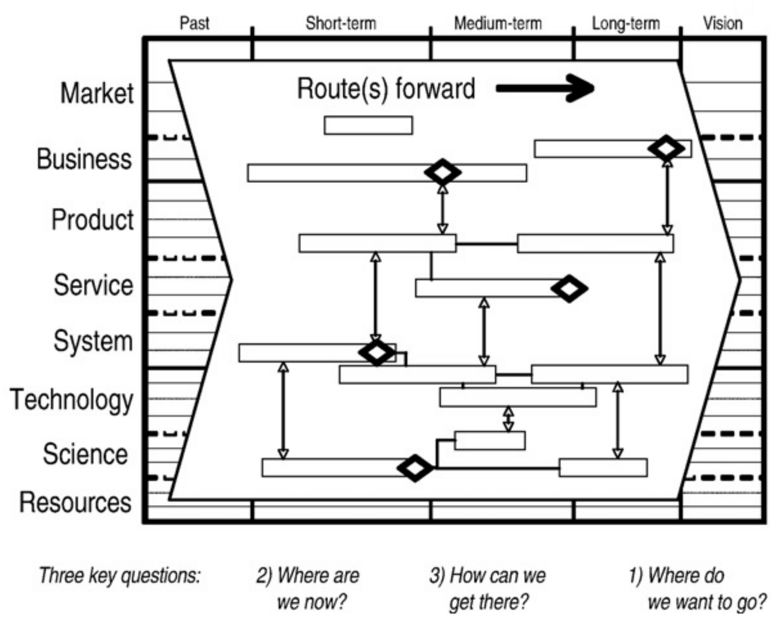


Figure 3.5 The basic architecture of a roadmap. (Phaal & Muller, 2009, p. 40)

The general roadmapping process starts from defining the desired future starting as vision and the determining the present situation and driving forces. Then the required actions achieving the vision are identified and potential risks determined. (Phaal & Muller, 2009, pp. 39-40)

Development of high quality roadmaps would require involvement of stakeholders in workshops or Delphi-surveys, but due to limited resources the stakeholders are not involved in this study, (Phaal & Muller, 2009, p. 41). In this study, the technology roadmaps are used to visualize the transition and a framework to consider different aspects of transition. Usually roadmaps are applied within organizational context, but in this case the roadmap is used in an industrial context. This tool makes the transition paths more comparable and enables more comprehensive discussion of the analyzed transition paths.

3.3 Electricity markets in the Nordic power system

The common Nordic electricity wholesale market was established in the 1990s, when the Nordic countries Denmark, Finland, Norway and Sweden deregulated their markets and introduced free competition allowing power transmission across the borders. Thereafter Baltic countries Estonia, Latvia and Lithuania have joined the common market. (Nord Pool Spot, 2014a)

The day-ahead market Elspot is an auction for trading electricity in the Nordic power system. Elspot is the main trading arena and in Finland 70% of the consumed electricity is traded though Elspot market, (Ministry of Employment and the Economy, 2013a, p. 12). The *system price* for power for each hour is based on the balance between supply and demand meaning that the price is set where the bids for sell price and buy prices are met. Intraday market Elbas is a supplement for Elspot where the power balance is secured against incidents between the closure of Elspot and the delivery. Hence, the power balance is maintained commercially, the available transmission capacity must be considered as well. If there is no sufficient transmission capacity available, the *area prices* for predetermined bidding areas are calculated. In order to support the commercial power balance maintenance, the transmission system operators (TSOs) are buying or contracting strategic reserves as an additional capacity mechanism in Finland, Sweden and Norway, (De Vries & Ramirez, 2012, pp. 6-8). (Nord Pool Spot, 2014a)

In addition to Elspot and Elbas trading, the market participants can conduct bilateral supply contracts in *over-the-counter (OTC)* markets. Market participant can also purchase financial contracts for price hedging and risk management in Nasdaq OMX Commodities, (Nord Pool Spot, 2014a).

3.3.1 Merit-order

The purpose of the day-ahead electricity markets is to find the most cost-efficient set of generation units fulfilling the demand and attain the power balance subject to available transmission capacity. If the transmission capacity is sufficient, the wholesale price of electricity as Elspot price is determined by the variable costs of the last required generation unit needed to fulfill the demand, (Nord Pool Spot, 2014a). This is called merit-order illustrated in Figure 3.6.

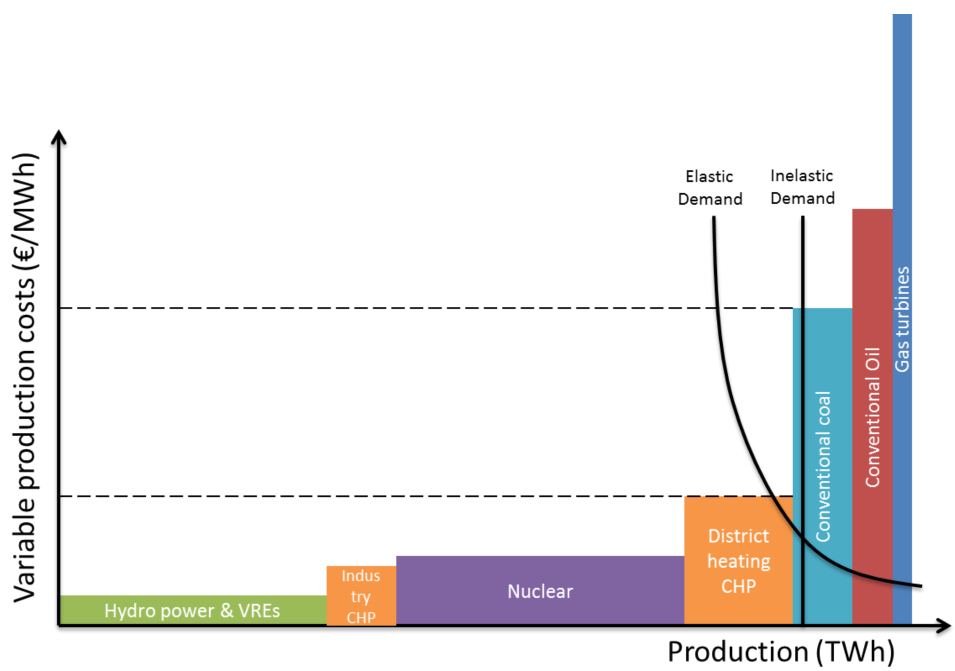


Figure 3.6 Illustrative merit-order curve. In practice, each power generation unit has unique variable costs and the variable costs are not as homogenous as in the figure. (Nord Pool Spot, 2014a)

As seen in Figure 3.6, the market price is determined by the base electricity demand, the demand elasticity and the availability of power plants. The demand diagram is a straight line, if the consumers are not elastic in terms of the wholesale price, and a curve or a sloping line if the consumers are capable and willing to increase and decrease their consumption by wholesale price. As illustrated in Figure 3.6 the market price remains more uniform if the demand is elastic. This means that the consumers avoid consuming in the hours, when the market price is high and they transfer their consumption in terms of time to hours, when the market price is lower.

In the most hours the market price is determined by either the variable costs of CHP production or conventional coal production in the Nordic power system. Availability of dispatchable generation capacity is affected by power plant revisions and outages. The hydro power resources in Finland are limited, but due to short start-up and turn-off times the hydro power plants they be used in the short-term power balance management. The price of imported electricity is usually lower than the variable costs of domestic production and the imports are usually present in the each consumption level. Therefore, the imports fall into same category as the hydro and nuclear power in the merit-order and the costs of importing do not affect the marginal pricing in Finland. (Nord Pool Spot, 2014a)

Intermittent renewable supply falls also into the same category as the hydro power in the merit-order. The proportion of intermittent generation depends greatly of the weather conditions. If the VRE deployment in the power system is substantial, in the windy or sunny hours the intermittent generation affects last required generation unit needed and lowers the market price. This phenomenon is called *merit-order effect,* (Hirth, 2013, p. 219). (Nord Pool Spot, 2014a)

3.3.2 Load duration and residual load duration

In order to illustrate the demand and how it is fulfilled, *a load duration curve* is introduced. In the load duration curve, the electricity consumption hours in a year are ordered from the highest to smallest on the vertical axis. The load duration curve is filled bottom-up by generation types, so that the base-supply is on the bottom and the peak supply is on the top with low operation hours and the flexible supply in between them as shown in Figure 3.7. (Ueckerdt, et al., 2013, p. 69)

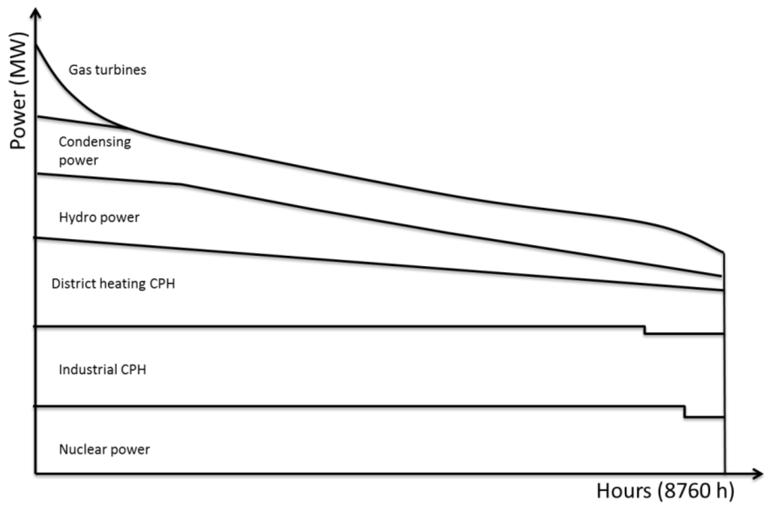


Figure 3.7 Illustrative load duration curve in Finland excluding the net-imports.

As seen in Figure 3.7, nuclear power and CHP power represent the base supply. Hydro power and condensing power are flexible supply and therefore they are located above the base load supply in load duration curve. Gas turbines represent the peak supply.

The load duration curve demonstrates the merit-order of dispatchable technologies with the exception that hydro power generation is flexible supply and it is located between the base supply and peak supply as seen in Figure 3.7. The intermittent generation can be seen as prioritized generation and its effect to load duration curve when the deployment is non-marginal is shown in Figure 3.8 (a). In order to capture challenged by intermittent technologies, *a residual load duration curve* is introduced in Figure 3.8 (b) starting from the highest residual load hour. Residual load in this case denotes the non-intermittent part of the power system. (Ueckerdt, et al., 2013, pp. 63-66)

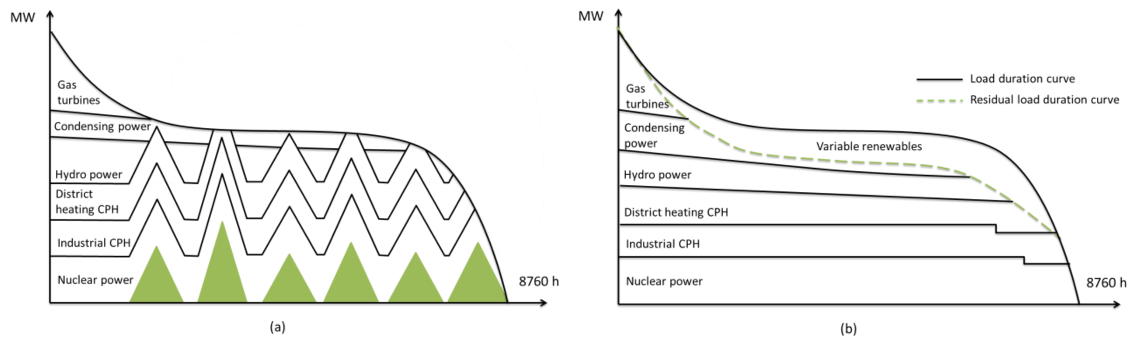


Figure 3.8 Deployment of intermittent technologies to the power system, where green areas represent variable renewable generation. (a) Effect of intermittent generation in terms of the load duration curve considered as primary generation, (Keronen, 2013, p. 48) and (b) introduction of residual load duration curve, (Ueckerdt, et al., 2013, p. 66).

3.4 Economical evaluation of generation technologies

The impacts of generation include economical, environmental and social aspects. In this study, the focus is on economic evaluation, although the social and environmental impacts of generation are very different between the different technologies and the social and environmental aspects affects to investment decisions as well. The economic evaluation of generation technologies should be based on both the costs of generation and the market value, (Hirth, 2013, p. 62). The economic characteristics of electricity are shaped by its physics. It is an intangible good, which cannot be transported or stored efficiently, so it must be transmitted in lines meanwhile keeping the production and consumption at a perfect balance constantly. A paradox is that electricity can be seen as both homogeneous and heterogeneous good, (Hirth, et al., 2014, pp. 4-5).

From the consumer's point of view, the electricity is a homogeneous good and consumer cannot distinguish it by its source. The price that the consumer pays doesn't depend on the source of the electricity meaning that electricity from different generation sources are worth the same. The electricity price and demand vary over time and therefore, the electricity can be seen as homogeneous good only at a certain point of time. (Hirth, et al., 2014, pp. 4-5)

Hirth, et al. (2014, pp. 5-6) argue that the electricity is a heterogeneous good along three dimensions: time, space and lead-time. This heterogeneity is caused by both market design and the technology. The difference between production of homogenous and heterogeneous goods is that for homogenous goods only one production technology is efficient and for heterogeneous goods there exist a set of efficient production technologies, which are required to fulfill the demand. Electricity cannot be stored efficiently and therefore the production and consumption must be balanced constantly. This causes the heterogeneity over time. Transmission over transmission lines, which have limited capacities, is constrained, meaning that electricity is heterogeneous over space. Flexibility of the power plants is constrained, especially in thermal power plants, whose adjustment ability to quickly control the power outputs quickly are limited. This causes heterogeneity over lead-time.

3.4.1 Generation costs

In this study the costs of generation are assessed by *Levelized cost of generation (LCOE)*. LCOE can be calculated by using the following formula

$$LCOE = \frac{\sum_{t}\left((Investment_{t}+O\&M_{t}+Fuel_{t}+Carbon_{t}+Decommissioning_{t})\cdot(1+r)^{-t}\right)}{\sum_{t}(Electricity_{t}\cdot(1+r)^{-t})} \qquad (3.1)$$

where variables indicate

$Investment_{t}$	Investment costs in year t
$O\&M_{t}$	Operation and maintenance costs in year t
$Fuel_{t}$	Fuel costs in year t
$Carbon_{t}$	Carbon costs in year t
$Decommissioning_{t}$	Decommissioning costs in year t
$Electricity_{t}$	Produced electricity in year t
r	Interest rate.

As shown in Equation (3.1), LCOE is a net present value of discounted costs divided by discounted electricity generation. The rationale behind discounting the physical production in the nominator is a consequence of accounting transformation and thus the LCOE indicates the earnings of the production per produced unit. (IEA, 2010, pp. 33-35)

The cost components of LCOE can be distinguished into *fixed costs* and *variable costs*. Fixed costs of energy production include the investment costs, personnel costs, insurances, fuel storing costs and costs of those maintenance, which must be performed regardless the production of a power plant unit. Fixed costs components of in Equation (3.1) are $Investment_t$ and $Decommissioning_t$ as well as fixed $O\&M_t$. Variable costs are determined by produced energy, which are often expressed as full load operation hours. Variable costs consist of fuel costs, CO2 costs, internal energy consumption of the plant, water treatment costs and variable maintenance costs expressed as $Carbon_t$ and $Fuel_t$ as well as variable $O\&M_t$ in Equation (3.1). (Huhtinen, et al., 2008, pp. 317-319)

Furthermore, unit costs of generation are affected by the technology development stage and unit size of a plant. The unit costs of generation tend to decrease when the market diffusion of technology increases, which is demonstrated by *experience curve* or *learning curve.* They have slightly different formulation, but they both measure learning by cost decline in terms of cumulative capacity or cumulative generation, (Lindman & Söderholm, 2012, p. 755). Junginger et al. (2006, pp. 4025-4026) identifies a number of mechanisms influencing the costs: learning-by-searching, learning-by-doing, learning-by-using, learning-by-interacting, upsizing or downsizing and economies of scale. These aspects will be considered when assessing the future generation costs in Chapter 7.

The LCOE itself considers only the costs of generation, but it ignores the heterogeneity aspects of the electricity. In addition to costs that are considered in equation (3.1), some generation costs are caused by *grid costs* related to required investments in the electricity network when either the dispatchable or intermittent generation technologies are deployed into the power system. For variable renewables the applicability of LCOE is limited, if the variable generation is non-marginal. Intermittent generation causes additional *balancing costs* and *backup costs* in the power system due to possible forecast errors of production and their low capacity-credit. Intermittent generation reduces the operation hours of dispatchable generation technologies, which causes *full-load hour reduction costs* in the residual system. Besides, if the intermittent generation must be curtailed when the production exceeds the consumption, the economic benefit of intermittent generation reduces and causes *overproduction costs*. (Ueckerdt, et al., 2013, pp. 65-66)

According to Ueckerdt et al (2013, p. 62) these cost increases are defined together as *integration costs* and together with LCOE they form *System LCOE*. Since the backup costs, full-load hour reduction costs and overproduction costs are related to indirect costs of intermittent generation, they can be seen as *profile costs,* (Ueckerdt, et al., 2013, p. 66). The relation of LCOE and integration costs is illustrated in Figure 3.9.

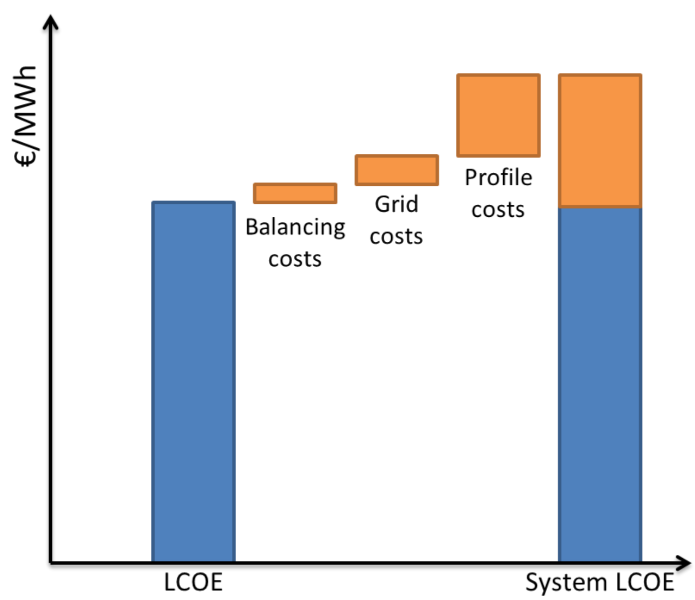


Figure 3.9 LCOE, integration costs and System LCOE. (Ueckerdt, et al., 2013, p. 65)

In this study, the profile costs seen in Figure 3.9 are the most interesting when assessing the benefits of renewable generation technologies. The magnitude of total integration cost depends on the deployment rate of intermittent technologies and the responses of the residual power system. Therefore, the integration costs do not remain the same over the lifetime of intermittent technologies, but the systems response decreases the integration costs.

3.4.2 Market value

Market value of generation determines the earnings that generation units can yield from the market without subsidies. Also market value can be seen as heterogeneous over three dimensions in similar way than electricity as a good. Integration costs diminish the market value of generation and market value can be derived subtracting the integration costs from the base price, which is Elspot price in this case as illustrated in Figure 3.10, (Hirth, 2013, p. 219).

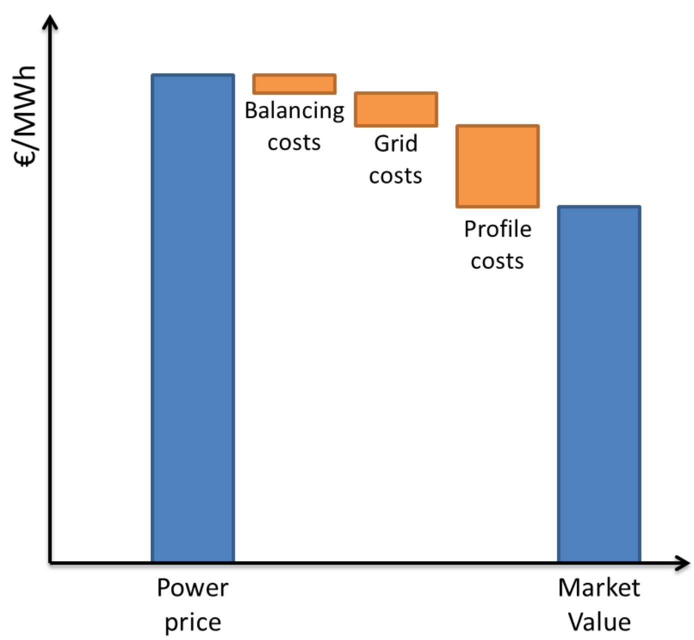


Figure 3.10 Market value of the variable renewable technologies derived from the average power price. (Hirth, 2013, p. 219)

As seen in Figure 3.10, high integration costs reduce the market value of variable renewable technologies.

4 CURRENT STATE OF FINNISH ELECTRICITY SUPPLY INDUSTRY

This section gives the results of the performed analysis related to present situation of electricity supply industry. The section follows the TIS analysis introduced in Chapter 3.1.2 with some additions. The focus of the study is determined in Chapter 4.1. The structural components as actors, networks and institutions are analyzed in Chapters 4.2–4.4 and functions of the innovation system in Chapter 4.5. The process goal is set in Chapter 4.6 and finally, the key policy issues are discussed in Chapter 4.7.

The summary of current situation is given in Chapter 4.8 in a structure that follows the technological roadmap framework. This is done outside the TIS analysis as groundwork for transition analyses given in Chapters 5 and 6.

The assessment of value of generation technologies is made in Chapter 4.9. First, the generation costs are assessed by using LCOE approach and then brief view of development of wholesale prices in the past and short-term future is given.

4.1 Focus of the case study

The framework of TIS analysis described in chapter 3.1.2 suggests defining the TIS in focus as the first step of the analysis; choosing the knowledge field, product or product group as the object of the study and the breadth and depth of the study as aggregation level, (Bergek, et al., 2008, p. 411). This study focuses on the industry analysis of electricity supply, which is not only about delivering electricity, but also delivering electricity generation technology and equipment, (Borup, et al., 2008, p. 9). Therefore, the *power generation technologies are chosen as the product group* of the study. All the potential electricity generation technologies are considered as the breath of the study, but the depth of the study does not dig into minor details. *The spatial domain is limited to Finland* in this study.

4.2 Actors

The actors of the TIS can be seen as private persons, organisations or artifacts contributing to the innovation system in accordance with ANT. The most contributing artifacts in this case are the existing technology, infrastructure and natural resources, but this analysis focuses on the organisations and individuals of the TIS. The technologies themselves are structural elements as well as an outputs of the TIS and its existence depends on the actions of the actors, since they develop it and decide whether or not bring it into the TIS, (Hellsmark, 2011, pp. 21-22). Therefore, this analysis focuses on organisations and persons rather than technologies.

In order to understand the relations and power structures of the actors other than technologies, *a value network* and *stakeholder mapping* are applied. The value network is a tool to illustrate the activities of delivering goods or services from the suppliers to the customers and the actors involved to the process, (Johnson, et al., 2011, p. 62). Stakeholder mapping helps to understand the actors' imposed expectations and power to influence the development of TIS by relocating the actors into four categories in *a power/interest matrix*, (Johnson, et al., 2011, p. 91). The value network of the industry is shown in Figure 4.1 and a power/interest matrix in Figure 4.2.

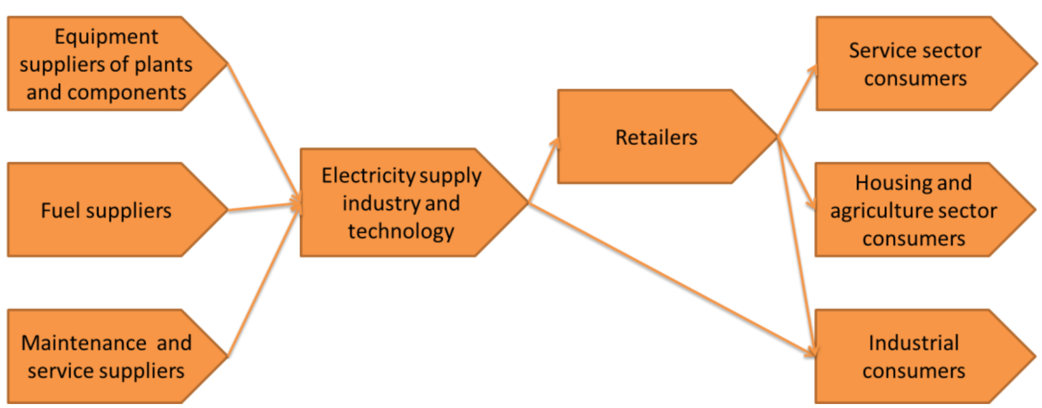


Figure 4.1 Value network of electricity supply industry.

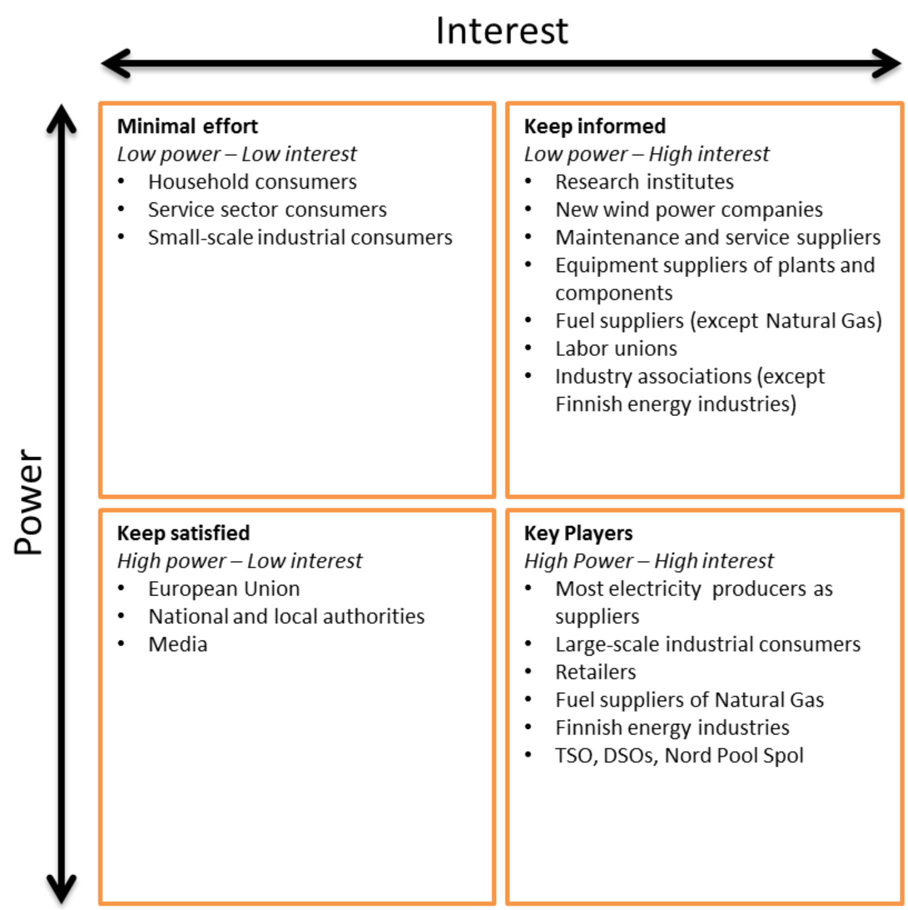


Figure 4.2 The power/interest matrix of electricity supply industry.

The value network illustration in Figure 4.1 shows the position of the electricity supply industry in the value chain and the most important value activities in the network, (Johnson, et al., 2011, pp. 62-63). However, the value network is affected by the surrounding society, such as private persons, industry associations and other unions and political groups. These are not located either to value network or power/interest matrix, but they are discussed in Chapter 4.2.5.

4.2.1 Key players

The main key players in this industry are the most electricity supply companies themselves, large-scale industrial consumers who actively participate to the electricity markets, electricity retailers and those suppliers that are hard to replace to another one. Also actors who provide market place and infrastructure for supply can be seen as key players. These are TSO, DSOs and Nord Pool Spot. As shown in Figure 4.2, key players have high power in the industry as well as high interest.

Local power utilities are holding major share of the electricity production capacity in Finland. The state-owned Fortum can be seen as utility and another large utility is Helsingin Energia owned by the city of Helsinki. Majority of utilities' capacity is district heating CHP capacity, (Energy Authority, 2014). The shareholders of the utilities are mainly local municipalities, which are seeking for stable low-risk returns from the energy business. The utilities are often acting as retailers through their subsidiaries, which can also be seen as the key players of the industry. After the deregulation of the electricity market some new retailers have emerged and it is assumed that the retailers are seeking low-risky returns as well. The retailers are selling the electricity to the household and service sector electricity consumers as well as industrial consumers, which are less active in the electricity market. The consumers are free to choose their retailer, but the retailers decide the pricing principles and the price level of the electricity contracts. The retailers can also decide whether they purchase the electricity from the electricity markets or through over the counter (OTC) markets by concluding bilateral contracts with the producers.

Large-scale industrial consumers have been active to build and operate power plants either by building and operating them alone to fulfill their own heat and electricity demand or by building and operating them together with other consumers in accordance with Mankala principle introduced in Chapter 2.4, (Syri, et al., 2013, p. 251). Industrial consumers are holding mainly industry CHP capacity and some peak load capacity, which they use to fulfill their own demand if the electricity prices are high. The most important players in this category are forest industry companies UPM, Stora Enso, Metsä-Botnia and Metsä Board, (Energy Authority, 2014). They produce electricity and heat in cogeneration processes from wood residuals and black liquor as well as peat and natural gas. It is assumed, that the expectations of this group are low-price electricity and security of supply.

Finnish Energy Industries can be seen as a key player, since it represents most electricity suppliers and is a link between them as an industry association. This association has power to influence to the other actors, such as political groups and research institutions by lobbying and it has also initiated common vision for carbon neutral future.

The fossil fuel suppliers other than natural gas suppliers are available in the market are many. The natural gas is imported from Russia to Finland through natural gas pipe. Therefore, the Russian gas supplier Gazprom has high power and high interest towards the Finnish electricity production industry and it can be seen as a key player at the moment. However, there are initiatives to build terminals for liquefied natural gas (LNG) and it is expected that the power of the Russian gas supplier will decrease in the future.

TSO Fingrid and local DSOs can also be seen in this category, since they provide the infrastructure for electricity supply. Although their operation is highly regulated, they have the power to decide investments for the grid infrastructure. Especially investments for cross-border transmission capacities affecting export opportunities are under control of Fingrid. Nord Pool Spot as stock exchange operates the market place and thus activities and operations of electricity supply industry are affected by Nord Pool Spot. In general, these actors have power to set technical and operational constraints to the electricity supply industry, but since they all operate under high regulation these actors can be seen neutral. Future development of electricity supply industry determines the required measures and investments for the transmission and distribution grids as well as market development. Therefore the interest of these actors towards the electricity supply industry is high.

4.2.2 Keep informed

Most of the actors illustrated in the value network in Figure 4.1 fall into this category, such as suppliers, that can be replaced by other easily and research institutes. Also the small-scale actors producing electricity fall into this category.

Newly established wind power companies, such as Hyötytuuli, Innopower and Tuuliwatti, have deployed wind power by building small-scale wind power farms and they fall into this category due to low power, but high interest. Their power in the electricity supply industry is low at the moment due to relatively low capacity they are holding, but the future development of these companies may change the power relations within the industry. These companies are utilizing the available support schemes and it is assumed that they are seeking for low-risky revenues from their business. At the moment, their revenues are mainly based on the subsidy schemes described detailed in Chapter 4.5.2.

Gas company Gasum Oy and oil company Neste Oil Oyj are the main importer of natural gas and oil in Finland. Gasum operates the gas network in Finland and offers also biogas products. Its major shareholders are the state, Gazprom and Fortum, (Gasum, 2014a). Neste Oil importing oil is also mainly state-owned and it has also collaborated with industrial actors to develop biofuel substitutes for oil in addition to its oil import and refinery business, (Hellsmark, 2011, p. 300). Coal is neither available domestically and it is imported abroad, but there is no single most contributing actor in coal supply. Domestically available biofuels are supplied by several actors. Peat is supplied mainly by Vapo, which also supplies some biofuels, (Vapo Oy, 2014). All of the fuel suppliers can be categorized into low power, but high interest category, except Gazprom, which has high power.

Because of well-developed mechanical industry, especially CHP power plant components and equipment are widely available in the domestic markets, (Borup, et al., 2008, pp. 56-57). There are also several Finnish subcontractors for example in the wind turbine industry. The major domestic suppliers of the energy technologies are Wärtsilä, Finnish subsidiary of ABB, Vacon, Valmet and the Switch. The domestic market may play an important role for these companies in order to make experiments, but they may find partners for experiments abroad as well. Therefore, their interest towards the electricity production industry is high. Power plant components and equipment are also imported to Finland and therefore, the influence power of the component and equipment manufacturer is relatively low.

Maintenance and service providers are often small and medium size private enterprises, but there are also some large multinational enterprises, such as Eltel and Empower, in the markets. The power of these actors is not substantial, but they perform much of the work in the industry and therefore their interest towards the electricity production industry is high.

Research institutes, such as universities and especially VTT Research center, are collaborating with many actors in the industry, not only with the electricity producers, but also power plant suppliers and consumer groups. Their power may not be substantial, but they can be valuable while creating new knowledge. These actors are partly funded by industrial actors and therefore, their interest towards the industry is high.

Labour unions and other contributing associations fall also into this category. In Finland the power of labour unions is in general very high and the labor unions can initiate strikes in order to stop the supply, but since the energy industry is not very labor-intensive, the power of labor unions is assumed to be low in this case.

Other contributing associations, such as Wind Power Association and Small-scale hydropower association act as important links in the TIS, but their power is relatively low. The most contributing industry association after Finnish energy industries is Confederation of Finnish Industries (EK) which has high interest towards electricity supply industry. Confederation of Finnish Industries represents the interests of Finnish business community in the entire private sector.

Confederation of Finnish Industries drives for binding global climate protocols and global GHG allowance prices, consistent and foreseeable energy policy and it wishes to maintain the Finnish cleantech know-how and make the energy technology business the new growth motor, (Confederation of Finnish Industries, 2014). Another aspects of its energy policy are availability of the energy for reasonable price and restraining the climate change in a cost efficient way, (Confederation of Finnish Industries, 2014).

All these actors share high interest towards the electricity supply industry. It is assumed that their expectations towards the industry are predictability and stable business environment.

4.2.3 Keep satisfied

This category includes EU, National and local authorities and Media. This category may not show high interest towards the electricity production industry, but they can be extremely harmful if unsatisfied, (Johnson, et al., 2011, p. 94).

The EU policies affect the Finnish business and industry environment through its legislation. Therefore, gaining the support of EU is important and the electricity supply industry must operate under the institutions set by EU.

Authority actors contributing to the industry are multiple. Finnish Energy Authority is responsible to monitor and implement the regulation and the EU ETS in Finland and it can be seen as a very neutral stakeholder. Authorities admitting the sufficient permissions for the power plants are building inspection authorities in the municipalities, Regional State Administrative Agency allowing the environmental permits if required and the Centre for Economic Development, Transport and the Environment responsible for allowing the permits required if the units are located to the water system and for environmental impact assessments, (Wind power association, 2014). These actors represent the local and national policy making and these actors should be neutral and act consistently as well.

The interest of these actors in this category may not be substantially high, but they have the power stop or inhibit the business of the electricity production industry, if the performance is not met their requirements of this. Media has the power to influence public opinion, since it is extremely effective in transferring knowledge, but its interest to do so may not be very high.

Support organisations, such as banks, venture capitals, innovation and company support organisations and network organisations fall also into this category, since they have the power to decide about the funding, but their interest of the technological outcome may not be high. In this case, the most contributing funding and policy support institute is TEKES Funding Agency for Technology & Innovation, which is hosting several programs. It is working under the Ministry of Employment and Economy and is the main responsible of energy related innovations and technology development. Another contributing institute in this field is Academy of Finland working under Ministry of Education, which is funding the basic research and is the main funder of VTT. Other actors providing funding are EU, IEA and Nordic Energy Research. These organisations execute the public funding and therefore, it is assumed that they influence especially the functions *influence on direction of search* and *resource mobilization*. (Norden, 2014)

4.2.4 Minimal effort

Household, service sector and industrial consumers less active in the electricity market have low power and often low interest towards the electricity production industry. These customers make transactions with the retailers and the DSOs and therefore it can be seen that they do not have direct expectations for the electricity supply industry. However, single persons can contribute to the electricity production industry acting through society actors, which will be discussed in the next section.

4.2.5 Society

Society can be seen as a wild card stakeholder of this industry. It is embodied mainly through political parties, whom mirror the public opinion of private persons having expectations for the industry and its future development. Power of this stakeholder group is based on their ability to transfer knowledge by lobbying and gaining the social acceptance of new technologies.

Traditionally, National Coalition Party (Kokoomus), Center Party (Suomen Keskusta) and Social Democratic Party (SDP) have been the three leading parties in Finland. Finns party (Perussuomalaiset) got boosted in the 2011 election and at the moment it can be seen one of the most contributing parties as well. The objective of Green party (Vihreät) is also considered, since it has a lot to say due to its ideological background. The main objectives and opinions of political parties related to the energy issues are summarized in Table 4.1.

Table 4.1 The interests of the main political parties of Finland.

Party	Main objectives and opinions
National Coalition Party	• Self-sufficiency of energy supply • Creating jobs by local energy supply (Kokoomus, 2014)
Center Party	• Creating new jobs by cleantech • Getting rid of burning coal in the energy production or deploying CCS technologies in order to reach carbon neutral society • Replacing natural gas by biogas slowly • Deploying peat in energy production • Enough electricity production capacity to fulfill the demand of cold winter periods and the demand of the industry • Developing bio-based transportation fuels and electric vehicles (Keskusta, 2014)
Social Democratic Party of Finland	• Affordable energy • Surrendering fossil fuels • Increasing energy efficiency • Active role in the field of cleantech • Subsidies are needed, but they may create unsustainable situation • Removing bottlenecks of investments • No national regulation, neither binding EU energy targets (SDP, 2014)
Green party	• Increasing energy efficiency • Deploying bioenergy from forests, wind power and biofuels • Surrendering nuclear power in a way that does not increase GHG emissions (Green party, 2012)
Finns Party	• Retaining the public ownership of the energy and utility companies • Climate subsidies and policies eat up money (The Finns Party, 2012)

As can be seen in Table 4.1 some parties wish to increase the self-sufficiency and reduce the GHG emission and some parties wish that cleantech would be a new growth motor. The Greens wish to phase the nuclear power. SDP and Finns party think that subsidies for desired technologies may create unsustainable situation. However, as seen in Table 4.1 the range of opinions is wide and the power and interest relations in the field of politics are complex.

The political groups are incumbent and traditional way to affect matters, but unpredictable citizen initiatives and people movements can pop up always. Therefore, gaining social acceptance is extremely important especially when building new power plants.

4.3 Networks

Networks represent the formal and informal relationships of the actors in the innovation system, (Bergek, et al., 2008, p. 413). As seen in the previous chapter, companies are linked espcially by interrelated ownerships in this case. The government and the incumbent actors, such as Fortum, and the industrial electricity suppliers PVO and TVO, are the most central actors in the formal *ownership network*.

Other contributing networks are *buyer-supplier network*, *collaboration network* and *regional networks*. Buyer-supplier networks are illustrated already in the value network in Figure 4.1. The research institutes are the most central actors of the collaboration network. State-funded funding agency TEKES Funding Agency for Technology & Innovation is another central actor in the collaboration network and at the moment it is hosting Cluster for Energy & Environment (CLEEN), which executes development programs with involved companies.

Regional network of the actors exist especially in the cities, where are several companies located along the value network. It can be assumed, that the contributing employers are connected through personal networks formally and informally and the knowledge flows also by this way. For example, in the city of

Vaasa in the western coast of Finland there are several companies located in the field of energy and it can be seen that the regional network is a contributing driver for the success of Vaasa in the field of energy.

To sum up, the networks in the electricity supply industry can be seen quite stable. Furthermore, it can be argued that incumbent actors are most central of the networks.

4.4 Institutions

Institutions are defined as the rules of the game affected by the actors of the TIS. Institutions can be distinguished into regulative institutions as laws and regulations, normative institutions and cognitive institutions either driving change or maintaining stability, (Bergek, et al., 2008, pp. 413-414).

The regulative targets of EU in this case are the most contributing regulative institutions and they are driving change towards GHG emission reduction. They are expressed in directives and EU ETS and they must be adapted to the national legislation. In addition, regulative institutions are also executed by local municipalities, TSOs and technical standards related to electricity supply. Regulative institutions are shaped by policy makers and authorities.

Continuity, predictability and alignment of these institutions are vital in order to support the desired development, (Negro, et al., 2012, pp. 3840-3841). At the moment, the nuclear power decision-in-principals are under public debate and this causes uncertainty for the nuclear power industry, which reflects to the whole industry. Contradictions of the regulative institutions are another problem in Finland. For example in the wind power case, there were structural obstacles, such as regulations not to build wind power plants close to highways, which delayed the wind power deployment when the feed-in tariff was implemented in January 2011. Later on most of these obstacles have been dissolved, but at least the Finnish defense forces are restraining wind power technology deployment due to problems it causes to radar technology in destinations important for the military. (Wind Power Association, 2014)

It is assumed that incumbent actors of the TIS are operating under rigid normative institutions, which has shaped over time during several co-evolution processes. Due to rigidity of normative institutions, these actors can be seen resistant to change radically. Most of these companies, power utilities and industrial electricity producers are committed to GHG emission reduction targets. Their knowledge base is strong in the field they are operating and they prefer to perform actions, which are close to their own knowledge base. For example, some utilities have initialized projects to use biofuels as secondary fuel together with fossil fuels. For these actors, expanding their business for example to wind turbine technologies is not seen attractive enough at the moment.

The cognitive institutions are referred as the culture of the industry and especially legitimation as social acceptance of technologies. The cognitive institutions are strongly shaped by the powerful actors, which are again the incumbent actors of the industry, but they can also be shaped by public opinion through media, associations and private persons as well as politicians. The cognitive institutions are also influenced by society's awareness of environmental impacts of supply. According to the latest Energy Attitude survey, the majority of citizens wish to deploy more renewable energy technologies and decrease the share of coal and oil, but nuclear power clearly shares opinions, (Finnish Energy Industries, 2013). However, in Finland nuclear power is often seen as reliable source of electricity, which also brings benefits, such as increases employment on local level, (Syri, et al., 2013, p. 252). For traditional and existing technologies legitimation is not a problem, but for new technologies gaining the legitimacy may be challenging, (Negro, et al., 2012, p. 3842).

It can be seen that in the field of emerging technologies, the normative and cognitive institutions are still shaping. For example, the newly established wind power companies are small enterprises, which can be seen flexible and growth-oriented. It is expected that these actors will develop further and shape their ways of doing in the future, if their business environment is stable and providential. Also the ongoing research in this field will expand their knowledge base and shape their institutions. Gaining social acceptance for the new technologies is part of the institutional development process and it will be discussed further in Chapter 4.5.6.

4.5 Functions

The functions measure qualitatively how the components of the innovation systems are working out. A comprehensive assessment of the functionality would require involvement of industry experts or key stakeholders and due to limited resources of this study, they are not involved. The following analysis is partly based on diagnostic questions offered by Hekkert, et al., (2011, p. 10) in addition to guidance of Bergek, et al., (2008, pp. 414-419)

As seen in Figure 3.1, the applied framework distinguishes the functions into 7 overlapping categories introduced in Table 3.1. Since the traditional electricity supply industry is in a mature phase in terms of industry life cycle, the focus of this section is on functions *market formation, entrepreneurial experimentation* and *resource mobilization*.

4.5.1 Market formation

Market formation function is affected by the current development phase of the TIS, which are distinguished into nursing, bridging and mature phases, (Bergek, et al., 2008, p. 416). In terms of traditional electricity generation technologies market formation function the current TIS is in mature stage, but in terms of emerging technologies, such as wind and solar power, the function is in bridging stage. This means that only few actors have installed for example wind parks so far and the large-scale market acceleration has not started, although there are several plans and initiations to deploy more renewable technologies to the power system. However, the market formation function for emerging technologies is boosted by the available support schemes described detailed in Chapter 4.5.2

and this support scheme is available for capacity of 2 500 MW and in order to meet the regulative target of 45% of renewable electricity, up to 6800 MW of new generation capacity is required.

4.5.2 Resource mobilization

The development of the TIS requires mobilization of human capital, financial capital and complementary assets to some extent, (Bergek, et al., 2008, p. 417). In case of deploying new energy technologies requires considerable funds and skilled human resources are required in particular, (Jacobsson & Bergek, 2011, p. 50).

In terms of human resources, there are good engineering skills in Finland especially in the field of IT, mechanical industry and offshore technologies. Traditionally, wind and solar power in Finland have never been a contributing energy source, but there are ongoing research projects in the field of these technologies in Finland. Therefore, there are human capabilities in these technologies, but whether these are sufficient and enough in order for TIS to develop to the desired state is another question.

The public financial resources in order for TIS to develop towards the desired state are available through subsidy schemes and investment grants. A target-price feed-in tariff is available in Finland for new wind power plants, new biogas power plants, new wood-fuelled power plants which also produce heat for 12 years. The maximum amount of acceptable capacity in the feed-in tariff subsidy scheme is 2500 MW. In addition, state grants subsidies and grants for investment and research projects as investment grants in the field of renewable energy technologies, (European Commission, 2013). The feed-in tariff comprises the target price, 83,50 €/MWh, but until the end of 2015 the wind power plants receive increased target price of 105,30 €/MWh. For wind, biogas and wood fuel the feed-in tariff comprises less than mean market price of electricity for three months. For timber chip plants the subsidy is determined by the mean-price of emission allowances for three months and the energy tax of peat. (Energy Authority, 2014b)

4.5.3 Entrepreneurial experimentation

Entrepreneurial experimentation is a function in which actors conduct experiments to explore and exploit new opportunities, (Jacobsson & Bergek, 2011, p. 48). In Finland finding a number of actors to be involved in experiments may be a challenge due to number of high power of incumbent actors and relatively low yield opportunities in the electricity markets without support schemes. The capital-intensive energy production companies are often seeking low-risk profits and therefore their willingness to conduct uncertain experiments is low. For example in Finland the wind power parks installed are not very large and solar power deployment is also few on international scale. Also the number of actors conducting experiments is not very high. Therefore, it can be argued that Entrepreneurial experimentation function could be more active in the field of renewable energy technologies.

4.5.4 Knowledge development and diffusion

The knowledge development and diffusion function is often concerned as a central function of the TIS, (Bergek, et al., 2008, p. 414). The broad scope of knowledge development and the extent of its diffusion though the innovation system are prerequisites for the TIS to develop and to be able to establish required supply chains, (Jacobsson & Bergek, 2011, pp. 47-48).

The research institutes are represented in the TIS and they collaborate with the firms through joint R&D programs with the funding provided by Tekes as well as do the basic and less commercialization capable research with the funding of Academy of Finland. Often the joint R&D programs occur between the incumbent actors and therefore this knowledge development can be seen relatively local meaning that the actors are seeking opportunities closer to their previous experiments rather than going for radically unfamiliar areas. It is also assumed that internal R&D efforts of the most actors of TIS are close to their previous practices.

In field of globally emerging technologies, in this case especially in the field of wind and solar power, Finnish energy sector innovation system is following a late-mover strategy. In terms of knowledge development and diffusion, the TIS is able to utilize the knowledge developed by actors outside the spatial domain and thus it is assumed that global knowledge development affects the Finnish energy TIS as well.

4.5.5 Influence on the direction of search

The function influence on the direction of search concerns the incentives and pressures for the organisations to develop the TIS, (Bergek, et al., 2008, p. 415). In this case the incentives, as the available support schemes and emission reduction regulation, exist and the vision of the future of the TIS has been articulated for example by Finnish Energy Industries.

From the actors' perspective, this function is often path-dependent meaning that the actors research efforts are often close to their previous experiments, (Jacobsson & Bergek, 2011, p. 49). Traditionally, wind or solar power technologies have not been contributing energy sources in Finland. On the contrary, utilization of bioenergy sources especially in co-generation processes of the forest industry have played a role in the electricity supply and therefore the incentives to search opportunities there are likely to be stronger.

4.5.6 Legitimation

Legitimation is a function related to social acceptance and compliance with relevant institutions, which is required for the technologies or TIS to overcome its "liability of newness", (Bergek, et al., 2008, pp. 416-417). The development of legitimation function may change the institutions of the TIS, which can further affect the development of the TIS.

In Finland, the traditional power generation technologies have gained their legitimation, but it can be seen that emerging technologies, especially wind power, have not gained fully their social acceptance yet. This is seen as regular public debate of the pros and cons of generation, especially in the wind power case due to their remarkable observability in the landscape. It can be seen that the legitimation of solar power technologies have progressed beyond the wind power, and the extent of public debate is less substantial.

It should noticed that the legitimation may take time and it is an outcome of conscious actions of actors, which often meet resistance from vested interests, (Jacobsson & Bergek, 2011, p. 51). Due to little-developed legitimation of wind power, it can be argued that the actors of the TIS are cautious to search opportunities from these technologies.

4.5.7 Development of positive externalities

Development of positive externalities means the monetary and non-monetary benefits coming out of the TIS development and it is important especially in the growth stage of the TIS, (Bergek, et al., 2008, p. 418). In this case the development of TIS could result improved national security of the electricity supply and emergence of new business opportunities for both new entrants and incumbent actors to manufacture and export technologies in this field.

4.5.8 Achieved functional pattern

The existence of incumbent actors and networks as well as limited experiences in the renewable energy sources other than biomass and their minor deployment to the power system can be seen in the function pattern of the TIS. Especially the function knowledge development and diffusion and influence on the direction of search are strongly influenced by the history, although the aims to reduce GHG emission have been recognized by the actors.

4.6 Assessing the functionality and setting the vision

This section focuses on assessment of the current TIS as the step 4 *Assessing functionality and setting process goals* of the TIS seen in Figure 3.1. Bergek, et al., (2008, pp. 419-420) proposes to determine the phase of development of the TIS distinguishing it into a formative phase and a growth phase. The formative phase is characterized by uncertainty of markets and technologies and the growth phase focuses into large-scale technology diffusion though first bridging markets and then mass markets, (Bergek, et al., 2008, pp. 419-420).

In this case the TIS can be seen to be in the growth phase since the electricity has incumbent role in the society, although there are uncertainties related to the future electricity supply portfolio and the electricity consumption growth in the future. However, in terms of emerging technologies the TIS can be argued to be in the formative phase. Therefore, special attention should be paid for entrepreneurial experimentation function and extensive knowledge development and diffusion in the short-term future if these technologies are expected to be deployed. (Bergek, et al., 2008, pp. 419-420)

In order to identify inducement and blocking mechanisms as well as determine key policy issues in Chapter 4.7, a process goal for the TIS is set as a vision for electricity supply industry in Chapter 4.6.1. In addition, a number of change dimensions needed to support the development is identified in Chapter 4.6.2.

4.6.1 Vision for 2030

The overall target considered in this case study is to deploy renewable energy technologies to the power system so that they would fulfill 45% of the total consumption by 2030, (European Commission, 2014, p. 6). The purpose is that the renewable electricity would replace the fossil generation and increase the self-sufficiency of the electricity supply so that net-imports would be negative. This chapter determines vision for the future electricity supply portfolio and it should be taken into account that the numbers in here are rough estimates and rounded off.

According to some estimates the annual electricity consumption in Finland in 2030 is between 100 and 111 TWh, (Finnish Energy Industries, 2009, p. 21). The consumption of service sector is estimated to increase and the development of Electric Vehicles (EVs) increases further the consumption. The greatest uncertainty of the future consumption is caused by traditional industry and this causes an uncertainty gap of 7 TWh. In this study, it is assumed that *the annual electricity consumption is 102 TWh in 2030* according to base scenario of National energy and climate strategy developed by the Ministry of Employment and the Economy (2013a, p. 36).

The peak load demand in Finland in 2030 has been estimated to be 16 500-18 500 MW, (Confederation of Finnish industries & Finnish Energy Industries, 2009). The peak load demand is linked to adoption of demand responses and the development of general consumption. In this study, it is assumed that *the peak load demand in 2030 is 17 000 MW* in accordance with Partanen et. al (2013, p. 36).

The nuclear power plant commissioning is highly regulated and the future nuclear power capacity depends on the political decisions in the short-term future. The capacity of LO1&2 is expected to exit the market in the 2020s, but OL1&2 and OL3 will probably be operating in 2030 with the current capacities of 2*880 MW and 1*1600 MW, (Syri, et al., 2013, p. 250). According to Energiakolmio Oy (2014, p.7) and Laitinen (2013, pp. 28-29) it is assumed that *the total nuclear power capacity in 2030 is 5000 MW*, which is also applied in this study as an assumption. An annual nuclear power production would be 41 TWh with the operation hours of 8200 h/a corresponding approximately 42% of the consumption.

It has been estimated that there are unbuilt hydro power capacity over 900 MW in Finland, but majority of this capacity is protected from power plant building by legislation and the amount of unprotected unbuilt hydro power capacity is less than 400 MW, (Oy Vesirakentaja Ab, 2008, p. 178). Energiakolmio (2014, p. 8) and Laitinen (2013 p. 29) assume that the hydro power capacity will increase 200 MW by 2030 by building new capacity to water systems that have been already deployed to hydro power generation. In this study, it is assumed that the hydro power capacity will increase 300 MW by 2030 due to power increases in existing plants and building small-scale hydro power and the generation is increased by rainfall increases will due to climate change, (Ministry of Employment and the Economy, 2013a, pp. 38, 149). Therefore, *the annual hydro power generation will increase to 15 TWh* in accordance with the national energy strategy, (Ministry of Employment and the Economy, 2013a, p. 37).

The CHP capacity is expected to remain in the same level than it is nowadays, since it is more attractive technology than separate generation but there are only few potential locations for district heating network expansion and the development of industrial CHP generation is uncertain, (Syri, et al., 2013, p. 253). In the beginning of 2014 the Industrial CHP capacity was 2 600 MW and District heating CHP capacity around 4 200 MW, (Energy Authority, 2014a).

The share of using biofuels in thermal electricity generation in CHP and separate generation plants is expected to increase although the energy consumption and generation of forest industry is not expected to increase. Especially, the utilization of forest converted chips as a result of more careful harvesting of knags and stubs is expected to increase in the electricity generation, (Finnish Energy Industries, 2014a). In 2013 the electricity supply from bio-based sources was 10,7 TWh corresponding 12,8% of the total supply, (Finnish Energy Industries, 2014b, p. 9). There are ambitious plans to increase the share of biofuel utilization in energy production and Ministry of Employment and economy (2013b, p. 23) is striving to replace coal in energy production by mainly bio based fuels by 2025 as well as substitute peat utilization by bio-based fuels. Finnish Energy Industries (2009, p. 22-23) appraised that the coal is part of the production portfolio in 2050 and CCS technologies are developed by then. In this study, the assumption of bio based electricity generation is more restrained and it is assumed that *the electricity generation from bio-based sources increases 6 TWh in 2030* and the total bioenergy-based electricity generation is approximately 17 TWh.

Approximately, the hydro power generation in 2030 is 15 TWh and the bio-fuel based thermal generation 17 TWh, while the required renewable generation is 46 TWh in accordance with the target of 45% renewable energy and the assumed electricity consumption of 102 TWh. The remaining share, *approximately 14 TWh of electricity should be generated by wind and solar*. In this case, only wind power is considered in order to simplify the case study. Generation of this proportion of wind power the required capacity is 6 300 MW, when the full load operation hours are 2200 h/a.

In order to meet the peak load demand of 17 000 MW in 2030, in addition to above mentioned production capacity some additional flexible capacity is required. The capacity of CHP (2600 MW + 4200 MW) and nuclear power (5000 MW) plants can be counted as available in peak load period, but the hydro power capacity is determined in accordance with dry water year. In this study it is assumed that the hydro power capacity available in the peak load period is 2700 MW in 2030, (Statistics Finland, 2013, Table 3.5). Capacity credit of wind power depends on penetration level and when the penetration level is around 40% as in this case the capacity credit has been observed to vary between 5 and 17%, (Holttinen, 2007, p. 105). In this case the capacity credit of wind power is set to 10% and it assumed that 630 MW of wind power capacity is likely available on peak load period in 2030. *Therefore, the requirement of remaining capacity is then approximately1900 MW.*

It is expected that substantial proportion of conventional condensing power will exit the market by 2020. The current conventional condensing generation capacity is 3200 MW and it is assumed that the capacity is 1500 MW in 2020, (Jäppinen, 2014, p. 9). In this study, it is assumed that in 2030 the conventional condensing capacity is 1000 MW and the remaining required 900 MW is gas turbine capacity.

The electricity supply portfolio in 2030 can be seen in Figure 4.3.

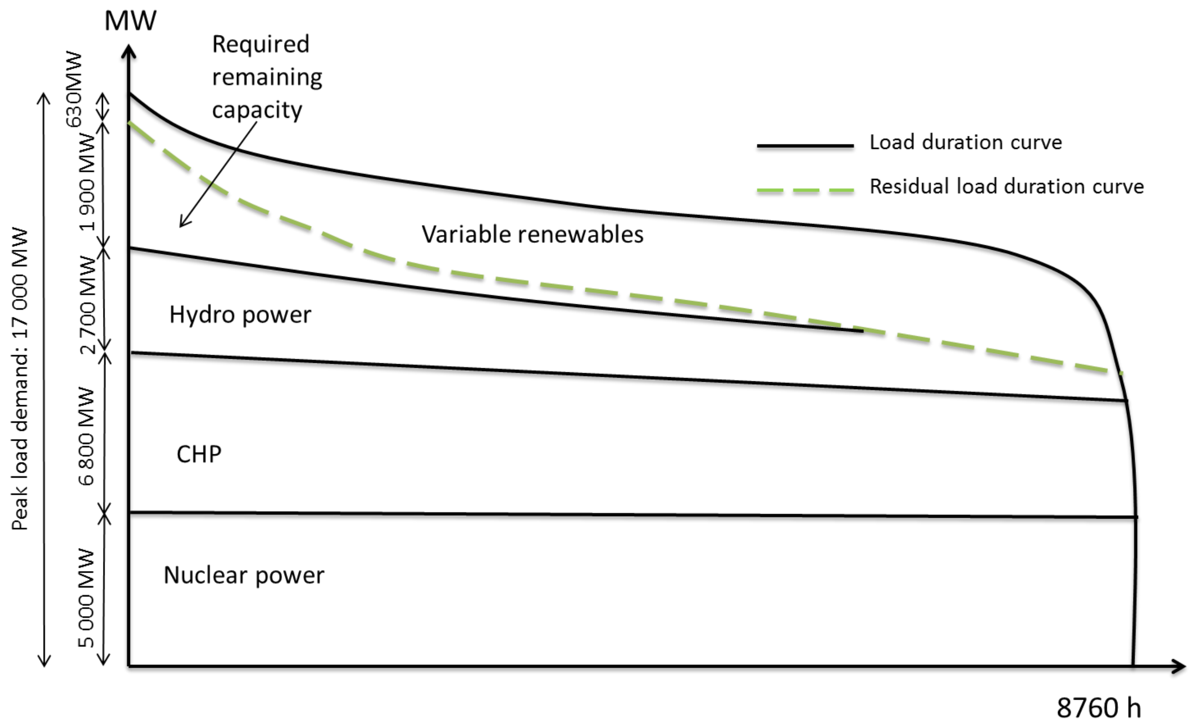


Figure 4.3 Electricity supply in Finland in 2030 illustrated as residual load duration curve.

The electricity supply in 2030 seen in Figure 4.3 is significantly different compared to current production portfolio seen in Figure 2.2. This change requires changes in other fields, which are defined as *change dimensions* in the following chapter.

4.6.2 Change dimensions

The deployment of substantial proportion of new renewable generation capacity requires changes in the residual power system, transmission and distribution grids as well as demand response, (Keronen, 2013, p. 48). Compared to present situation, the main differences are existence of intermittent generation seen as prioritized supply and more elastic demand. However, the main concern related to large-scale intermittent capacity deployment is maintaining sufficient storing and back-up possibilities in the power system. Nowadays, the most efficient way to store electricity is to store fuels and thus, flexible thermal capacity and incentives to invest into flexible thermal capacity are needed, (ÅF-Consult Ltd, 2012, p. 116).

In order support the development towards the vision, four change dimensions are identified. First, large-scale deployment of intermittent generation capacity requires storing and backup possibilities to complement the supply more than dispatchable technologies. As mentioned, the best way to organize required backup capacity is maintaining flexible thermal capacity in the power system. As seen in illustration in Figure 4.3 (b), the intermittent generation however displaces operation hours of especially conventional condensing power. Therefore, incentives to maintain and invest in flexible generation capacity, which operation hours are lower than nowadays, should be sufficient enough in the future.

In addition to maintaining flexible capacity, other attractive possibility is more active user-side participation in the electricity market as a resource to regulate the power balance, (Laitinen, 2013, p. 113). Nowadays only large-scale industrial users are flexible and are ready to adjust their consumption in terms of wholesale prices and it has been estimated that potential to increase flexibility of power system by implementing demand response opportunities on larger-scale than nowadays is substantial, (Finnish Energy Industries, 2007, pp. 8, 13). Therefore, as second change dimension, there should be sufficient incentives to implement demand response for both retailers and end-users.

Other major change that large-scale deployment of intermittent generation capacity causes is shift of generation locations to areas where may not be sufficient transmission infrastructure available. Nowadays, the power plants, especially CHP plants, are often located close to consumption but it is likely that intermittent renewables will be located to more providential locations in terms of weather conditions and less visible places in terms of landscape. Therefore, as third change dimension, investments for transmission capacity are required to allow both internal and cross-border transmission without development of transmission bottlenecks.

The most dispatchable technologies benefitting higher economies of scales and longer periods of technological learning are more mature than most renewable energy technologies, (Negro, et al., 2012, p. 3841). Thus, renewable energy technologies cannot fully compete with more mature technologies yet and further technology development is essential. As fourth change dimension, there should be sufficient incentives for development of desired technologies.

4.7 Incentives, obstacles and key policy issues of the transition

There are number of issues in the external environment of the TIS that affect the development towards the process goal defined in Chapter 4.6.6. These factors supporting the TIS are called *inducement mechanisms* and the factors hindering the TIS development are called *blocking mechanisms*. Some issues can be seen both blocking and inducement mechanisms at the same time, if they support some functions, but hinder others. In order to strengthen the inducement mechanisms and weaken the blocking mechanism a number of *policy issues* are defined as an outcome of the TIS analysis. The most contributing factors related to this case study are summarized in Figure 4.4. (Bergek, et al., 2008, pp. 420, 423)

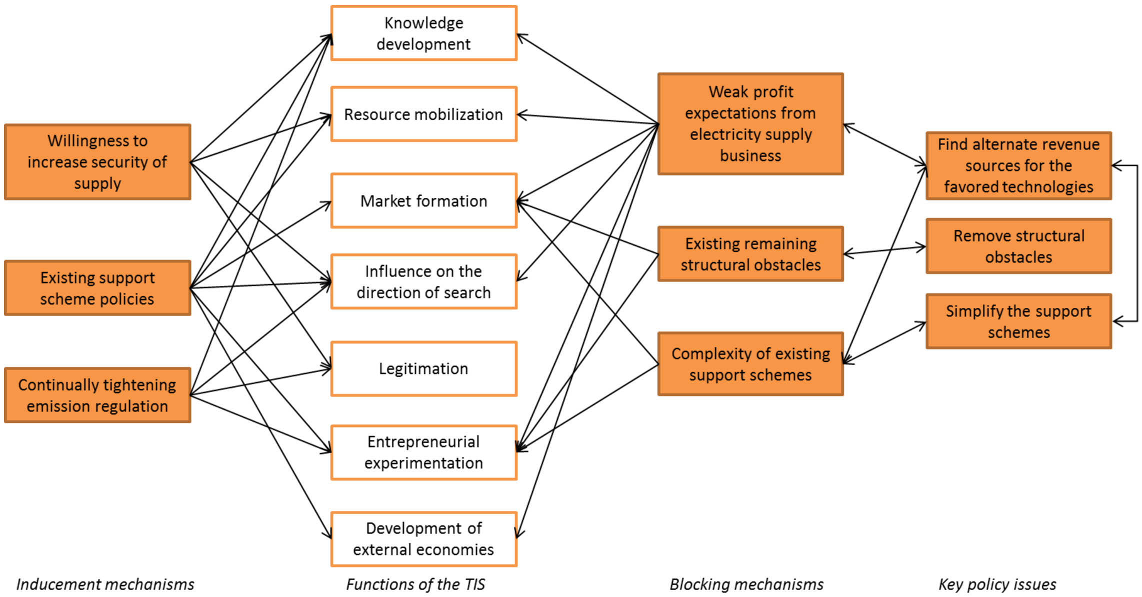


Figure 4.4 The inducement and blocking mechanisms and their relations to functions of the TIS and key policy issues related to this case study.

This section first discusses the inducement mechanisms in Chapter 4.7.1, blocking mechanisms in Chapter 4.7.2 and then defines the key policy issues in Chapter 4.7.3.

4.7.1 Inducement mechanisms

Inducement mechanisms are existing driving forces that support the development towards the process goal. As shown in Figure 4.4, the three most contributing inducement mechanisms of the TIS development identified are willingness to increase self-sufficiency of supply, existing support schemes that provide incentives to invest for renewable capacity and continually tightening emission regulation, which is anticipated to tighten further in the future.

Willingness to increase self-sufficiency of supply has been perhaps the most stable inducement mechanism of Finnish electricity supply industry over the most recent decades. The electricity supply in Finland relies much on imports and renewable energy sources are seen as solutions that improve self-sufficiency of supply.

Support scheme policies can be seen one of the major inducement mechanisms that tend to increase the renewable energy supply by providing financial incentives for investors. However, the support schemes are artificial and shaped by administrative and political decision-making and it can be argued that current complexity of support schemes can be seen as a blocking mechanism discussed in next chapter.

Finally, emission regulation has tightened constantly and it is expected to be tightening further in the short-term future. Therefore, it is likely that renewable as well as CO2 neutral generation capacities are favored also in the future and this factor can be seen as an inducement mechanism to deploy more renewable capacity.

4.7.2 Blocking mechanisms

Blocking mechanisms are existing factors that hinder the development towards the process goal. The most contributing blocking mechanisms identified are weak profit expectations from electricity supply business, existing remaining structural obstacles that obstruct construction of desired technologies and great complexity of existing support schemes as seen in Figure 4.4.

In past years, monthly average wholesale prices in the Nordic electricity market have been less than 50€/MWh with exception of winter moths when higher price speaks have occurred, (Nord Pool Spot , 2014b). Furthermore, it has been estimated that wholesale prices increase slightly in the next decade, but remain in between 35 and 65 €/MWh, (Botnen, 2012, p. 21). Compared to generation costs, which are assessed detailed in Chapter 4.9.2, the opportunities of earnings are low and thus the investment environment does not seem very attractive from investor’s perspective. Therefore, this can be seen as blocking mechanism.

In Finland, it can be argued that structural obstacles preventing or hampering construction of power plants can be seen another contributing blocking mechanism. These are affecting especially the wind power deployment. When the feed-in tariff was implemented in January 2011, there were for example enactments that prevented constructing wind power plants close to highway infrastructure. Afterwards some of the structural obstacles have been removed but still especially restrictions to build wind power in military important destinations related to functionality of radar systems can be seen forming a blocking mechanism. (Wind Power Association, 2014)

The complexity of support schemes that are implemented to be inducement mechanisms can be seen as a contributing blocking mechanism. Within EU in addition to EU ETS, the number of existing support schemes on national levels has increased substantially in this and past decades and most countries apply more than one support scheme simultaneously, (Kitzing, et al., 2012, pp. 196-197). It can be argued that these support mechanisms overlap to some extent weakening the efficiency of efforts and sometimes may even cause contradictions. The support schemes are sometimes affected by political decision making and if short cycles of politics influence the support schemes the short-sightedness may cause further uncertainties.

4.7.3 Other issues

In addition to identified inducement and blocking mechanisms there are number of issues that affect the development of TIS towards the process goal, but are not shown in Figure 4.4. Some of them can be seen both inducement and blocking mechanisms at same time if they strengthen some functions of TIS but weaken others.

Not-in-my-backyard-thinking can be seen as a blocking mechanism to deploy for example onshore wind power, but on the other side it can be seen as an inducement mechanism to develop offshore wind power. European-wide market integration can also be seen as twofold factor; on the other side it opens the opportunities related to electricity exports to Europe and Russia but on the other hand it can be seen as a source of uncertainty related future wholesale prices of electricity, regulation and market practices and investors need to consider also the development of generation capacity and consumption in the neighboring countries.

In general, the public attitude towards nuclear power has been positive in Finland over decades, although there have been minor fluctuations in the public opinion especially after Chernobyl and Fukushima disasters, (Syri, et al., 2013, p. 250). Some industrial actors see that the availability of nuclear power is a premise of affordable energy and national competiveness. Therefore, nuclear power is seen often as more attractive solution to increase self-sufficiency of supply and increase share of CO2-neutral energy instead of renewable energy sources, since it has high reliability. Therefore, nuclear power could be seen as a less-contributing blocking mechanism to some extent.

4.7.4 Key policy issues

It can be seen that the most contributing blocking mechanism is the weak profit expectations from the electricity supply business. Therefore, alternate revenue sources could be added to ensure the deployment of desired technologies. It is also proposed that support schemes should be simplified in order to increase their effectiveness and reduce potential uncertainties caused by possible influences of political decision-making while implementing the support schemes. However, these two key policy issues are interrelated as shown in Figure 4.4 and execution of these successfully at the same time may be challenging. In addition, removing the remaining structural obstacles is suggested as third key policy issue.

4.8 Summary of the current situation

The aim of this section is to summarize the current situation and define the main drivers of the TIS development as groundwork to technology roadmaps in Chapters 5.2 and 6.2. Categories applied in the roadmap illustration are *Market, Infrastructure, Technology, R&D and Science* and *Resources.* Category *Infra-*

structure is further split into two subcategories. Definition of categories is given in Table 4.2.

Table 4.2 Definition of categories and subcategories applied in the technology roadmaps.

Category	Subcategory and explanation
Market	This category refers to identifying trends, drivers and external environment in the present situation. Also the consumption level and magnitude of demand response as well as events in the electricity wholesale markets are included in this category. This category also considers the actors involved in the electricity supply industry.
Infrastructure	***Grid infrastructure*** refers to physical transmission and distribution infrastructure as well as existing automatic meter reader (AMR) infrastructure. Also the power balance maintenance aspects are considered in this category.
	Regulative and legislative structure refers to regulation and legislation structures as well as planning mechanisms of transition.
Technology	This category considers supply portfolio and capacity.
R&D and Science	This category considers the status and patterns of technology development.
Resources	This category refers to Financial and human resources required

In this section, the current situation is discussed considering each subcategory given in Table 4.2.

4.8.1 Market

The main driving force influencing on electricity supply industry is the climate change on global level, which is why the emission regulation is tightening constantly. Furthermore, the increasing prices of fossil fuels, especially oil, are driving efforts to deploy renewable sources and increase energy-efficiency. In the EU level, the corner stones of EU's energy policy can be seen as the major driving forces. These are security of supply, sustainability and competitiveness and EU pursuing towards a common internal electricity market, (Partanen, et al., 2013, p. 8).

Role of the electricity in the societies is getting more important on global level, since it is seen as sustainable, efficient and flexible form of energy, which has a significant role in the transition towards low-carbon societies. Therefore, the electricity consumption is expected to increase, while the total energy consumption decreases in the future. For example, penetration of electric vehicles (EVs) is going to increase the electricity consumption, but the EVs are more energy efficient than combustion engine cars.

On national level, the electricity consumption is not expected to increase as rapidly as before and in the electricity prices have been relatively low in the recent years as discussed in Chapter 4.7. Much of the future consumption depends on future development of energy intensive industries and scale of ongoing industrial restructuration from mass-production towards more service-based production.

The role of demand response in the electricity markets is minor and thus, the demand is not very elastic at the moment. Previously there have not been either facilities or incentives for more active user-side participation to electricity market, but nowadays the facilities exist as will be discussed in Chapter 4.8.2. However, the transition towards active user-side participation requires involvement and initiation of retailers and DSOs and it can be seen that the incentives for their perspective may not be sufficient enough and risks are high.

4.8.2 Grid infrastructure

TSO Fingrid introduced a few year ago an investment program to respond the penetration of 2500 MW wind power according to current support scheme and 2 new nuclear power plants to the Finnish power system. In the recent history, Fingrid has invested to both internal transmission capacity and cross-border capacity. Furthermore, the DC link between Russia and Finland is going to be bidirectional in the short-term future allowing exporting electricity to the Russia. Therefore, the TSO's efforts to respond European wide market integration and deployment of intermittent capacity have started. (Fingrid Oyj, 2014b)

The electricity retailers have initiated some projects to implement demand responses. In Finland the automatic meter readers (AMRs) were installed to most users of electricity by the end of 2013 opening opportunities for demand responses and implementing Smart Grid –concept. Smart Grid –concept is a model of power system, where the consumption load is controlled by the available electricity generation. In the concept the challenges caused by the variability of intermittent technologies are compensated by demand response and storing technologies. (IEA, 2011, pp. 25, 33-34)

4.8.3 Regulative and legislative structures

Emission regulation has been tightening in recent years and thus it is expected that it tightens further. As discussed in Chapter 4.7, in EU there are several overlapping control mechanisms and due to their complexity it can be argued that they are not working as efficiently as they should. It is expected that in the short-term future more decisions are made on global, EU and national levels and it is presumable that emission regulation will tighten further.

4.8.4 Technology

As described in Chapter 2.3, the existing electricity supply portfolio in Finland is fairly old on its average age and substantial proportion of nuclear power and conventional condensing power will be phased out by 2030 due to aging as described. At the moment, there are no other large-scale power plant projects ongoing than OL3, (Vakkilainen, 2014). At the moment it is known that the OL3 will be commissioned by the year 2020 and LO1 and LO2 will be decommissioned in the years 2025-2030. In addition, it expected that 1 or 2 nuclear power plants will be commissioned in years 2020-2025. (Syri, et al., 2013, p. 253)

Some actors have initialized projects to utilize biofuels jointly with fossil fuels in existing thermal power plants and thus increase the share of renewable energy sources. The current capacity of wind and solar power is low and there are only few actors who have increased this capacity mainly by deploying wind power parks mainly consisting of small number of turbines and small-scale solar power sites. However, the public interest towards these technologies is increasing.

This category is expected to meet the most changes in the future. It can be seen that some actors have already responded to landscape pressures by initializing projects for example to utilize biofuels in existing fossil fuel-fired thermal plants. Wind and solar power deployment is minor in Finland at the moment and the installations of wind power consist of small number of turbines and small-scale solar power sites. However, it can be seen that public interest towards especially solar power has increased in recent years.

4.8.5 R&D and Science

On global level, there has been several R&D efforts to develop solutions to supply CO2 neutral or renewable energy as well as to develop carbon capture and storage (CCS) technologies and storing technologies to capture challenges caused by intermittent generation. Wind and solar power technologies are already relatively mature and available commercially widely. CCS technologies are still under development as well as storing technologies excluding pumping power of water reservoirs. As mentioned in Chapter 1.1, Finland has been following a second mover strategy to move to the regulative EU targets and therefore, the knowledge base for example in the field of wind and solar power is mainly based on free-riding and learning from other countries technological innovation systems in accordance with late-mover strategy, (Johnson, et al., 2011, p. 199).

With respect to utilization of bioenergy sources in energy production Finland has been a forerunner, (Borup, et al., 2008, p. 57). Therefore, the knowledge base in this field is strong and the networks between the actors are well-established. However, rationale behind increasing substantial shares of bioenergy sources is twofold, since bioenergy utilization causes GHG emissions although bioenergy is seen as a renewable source. Mainly the forest industry has been utilizing residual bioenergy sources in its co-generation processes traditionally, but the growth expectations of forest industry are weak, (Syri, et al., 2013, p. 254). Procurement of bioenergy sources requires establishing local supply chains to harvest and transport bioenergy, since biomass transportation over long distances is expensive.

4.8.6 Resources

As mentioned in Chapter 4.5.2, there is public financial support available to deploy renewable technologies as feed-in tariff as well as energy aid subsidy for investment and research projects to develop sustainable energy generation solutions, (European Commission, 2013). With respect to human resources, there are human resources with in-depth competences especially in mechanical engineering and bioenergy technologies in Finland, (Borup, et al., 2008, p. 57). However, the most institutes providing technical education are providing education in the field of wind and solar power technologies at least in some extend and there is a number of sub-suppliers of wind power manufactures in Finland, (Borup, et al., 2008, p. 60).

4.9 Economic evaluation of generation technologies

As discussed in Chapter 4.7, the weak profit expectations due to low wholesale prices of electricity and moderate growth forecasts of electricity and other identified blocking mechanisms do not really encourage investing in new electricity generation capacity. The purpose of this section is to assess the economic value of commercially available generation technologies considering both the generation costs and market value as discussed in Chapter 3.4.

The integration costs, which are considerable when the intermittent generation is non-marginal, are not take account in this assessment, since the deployment of those technologies is minor in the Finnish power system. Therefore, the generation costs are assessed by using LCOE procedure. Method and basic assumptions are described in Chapter 4.9.1. More detailed description of the procedure can be found in Appendix II and the applied data in Appendix III. The results are shown in Chapter 4.9.2 and sensitivity analysis for chosen parameters is performed in Chapter 4.9.3. A brief review of the present and future wholesale prices is given in Chapter 4.9.4.

4.9.1 Method and basic assumptions

The calculation method is mainly based on guidance in the report of IEA (2010, pp. 34-45). The main difference in this study is not to apply heat credit for CHP plants. IEA (2010, p. 34) proposes to subtract the value of generated heat from the LCOE and gives a value for generated heat to compensate the fuel and carbon costs of the heat generation in the cogeneration processes. Instead of applying heat credit the costs of co-generation are distinguished in this study by using energy conversion efficiency of cogeneration processes in accordance with benefit sharing method. In this study, national average of this value, 54% is applied, (Gaia Consulting Oy, 2010, p. 12).

Investment expenses are gained from domestic literature references if available, otherwise reference expenses of German power plants are applied. The price level of calculations is set to year 2014 and for data older than from year 2013, the expenses are corrected by building cost index 2,5%/a. Building cost index expresses price development of construction and building costs per year, (Statistics Finland, 2014b). In Germany, workforce in the construction sites comes from the same countries and the actors providing technologies are more or less the same and therefore it can be seen that the expenses in Germany are close to expenses in Finland, (Vakkilainen, 2014). The differences in the costs of unit sizes are not considered in this study due to limited resources. The investment expenses are shared equally over construction period, which vary between 1 and 7 years in accordance with IEA (2010, p. 44), and in calculations the construction period starts in each case in the year 2015.

The fuel costs are derived from fuel price data and electricity conversion efficiencies. The electricity conversion efficiencies for separate generation plants are gained from literature references and the fuel prices from literature references and statistics. The electricity conversion efficiency may vary slightly according to the load and often partial load drive is less efficient than full load drive. However, this fact is ignored in this study due to limited resources.

Carbon costs are derived from CO_2 allowance price, CO_2 coefficient expressing the CO_2 emissions per produced energy unit and electricity conversion efficiency. Present price of CO_2 allowance is approximately 5–6 €/ ton CO_2, (Kost, et al., 2013, p. 15). The price is expected to increase in the future and often a price level of 20-25 €/ton CO_2 is applied in these kind of calculations. Therefore, the price level of 20 €/ton CO_2 is used in this study. Since of carbon can change the position of power plant units in the merit-order, the impact of carbon price to LCOE is assessed in a sensitivity analysis in Chapter 4.9.3.

Operation and maintenance costs are distinguished to variable and fixed costs. As investment costs, they are gained from domestic references if available or alternatively from German references.

The decommissioning costs are ignored for all other power plant types than nuclear power. This is because the power plants often contain valuable materials, which can be sold forward, and thus the decommissioning projects have actually been profitable recently, (Vakkilainen, 2014). In the case of nuclear power, the decommissioning costs are notable and nuclear material waste handling causes additional costs. In Finland, Nuclear waste management fund collects fees from the nuclear power suppliers for the future nuclear waste handling and the fee is included in the operation and maintenance costs of nuclear power generation, (Vakkilainen, et al., 2012, p. 7). Decommissioning of nuclear power plants have not been executed on large scale anywhere and therefore, few data of decommissioning costs is available. In this study, as a reference price of a recently announced joint venture of Babcock and Fluor to decommission 10 old nuclear power sites is applied. Babcock and Fluor made a £7 billion contract of decommissioning 10 oldest nuclear reactors and 2 research sites in the UK, (Financial Times, 2014). The average capacity of old nuclear power plants in UK is 250 MW, (World Nuclear Association, 2013). Converted to the Euros with the currency exchange 0,8262 €/£, the estimated decommissioning cost is 3390 €/kW. This price level does probably not fully correspond to Finnish decommissioning costs since for example the unit sizes of nuclear power plants are different, but it gives an idea of magnitude of decommissioning costs of nuclear power. In this study, it is assumed that the deconstruct work starts 10 years after the last operation year and will last 10 years. Therefore the decommissioning costs are spread over 10 years starting from 10 years after last operation year.

The annual full-load operation hours of a power plant unit determine the proportion of generated electricity in the nominator of Equation (3.1). Thus, full-load operation hours have significant affect to especially capital intensive generation technologies. The full-load operation hours express the operation hours of a power plant unit within a time period, which is in this study one year, if the plant would operate at full capacity. Usually in the LCOE assessment the full-load operation hours are set to be as high as possible. For example in the report of IEA (2010, p. 45) a standard load factor of 85% is applied for all other generation technologies than site-specific renewable technologies meaning that the full-load operation hours are approximately 7500 h/a.

However, such high full-load operation hours can be seen over-optimistic in this case and therefore, the present annual full-load operation hours of Finnish power plants are calculated in Table 4.3.

Table 4.3 Generation capacities, electricity supply and full load operation hours of power plant types in 2013. (Laitinen, 2013, Appendix I; Finnish Energy Industries, 2014b, p. 8; Energy Authority, 2014a)

Plan type	Electricity supply in 2013 (TWh)	Generation capacity in 2013 (MW)	Full-load operation hours in 2013 (h/a)
Nuclear power	22,653	2752	8230
District heating CHP	13,424	3650	3680
Industry CHP	10,068	4200	2400
Conventional condensing	8,390	2340	3590
Wind power	0,839	447	1880
Hydro power	13,424	3000	4470
Net-imports	15,102	-	-
Total	83,9	16389	-

As seen in Table 4.3, the operation hours of thermal power plants are rather low. In the row of separate thermal only the capacity of conventional condensing plants is considered and the capacity of gas turbines is ignored, which would further reduce the operation hours of conventional condensing plants. Therefore, values of full-load operation hours closer to these values are applied in the generation cost assessment and can be seen in Appendix III. The impact of full-load operation hours for LCOE is assessed further in the sensitivity analysis in Chapter 4.9.3. Applied full-load hour value are for hydro power 4200 h/a representing hydro power generation in dry year, for wind 2200 h/a and for solar 1000 h/a representing more global generation levels of wind and solar power.

The applied interest rates in this study are 5% and 10% in accordance with IEA (2010, p. 41). In practice, it should be noted that price of loan is often higher for small and non-incumbent actors and therefore, the interest rate between actors vary, (Vakkilainen, 2014). The interest rate has only impact to investment and decommissioning costs, since the fuel, carbon and operation and maintenance costs can be converted to the form of LCOE directly, (IEA, 2010, p. 59). The costs are discounted to the present moment.

It should be noted that the assumptions in this study are rough estimates and the changes in for example fuel prices are not considered. There are also cost differences between power plants depending on the plant unit size, location and architecture. Also the prices and quality of the fuels affecting to further electricity conversion efficiency may vary even in single generation unit, especially in the bioenergy case. The variation for fossil fuel generation is relatively small compared to bioenergy, since the technology and fuel are more standardized. (Borenstein, 2012, pp. 70-71)

4.9.2 Generation costs

The assessed generation technologies in this study are district heating CHP with variety of fuels, gas-fired power plants and coal- and oil-fired conventional condensing plants and in addition wind power, solar power, hydro power and nuclear power. Separate generation costs from biomass sources are assessed for Bio SNG-fired generation, torrefied biomass generation, when biofuel product is used as a substitute of coal, and three different co-firing techniques: direct co-firing where unprocessed biomass is mixed with fossil fuel, indirect co-firing where gasified biomass is mixed with coal and parallel co-firing where biomass in fired in separate combustor, (Loiri, 2014, pp. 47-51). Industry CHP is not considered in this study, since there is often no rationale to invest for it without need of industrial heat in the production processes.

Obtained results are based on certain assumption and parameters given in previous chapter and in Appendix III. The results of the generation cost assessment for the potential future generation technologies are illustrated in Figures 4.5–4.10.

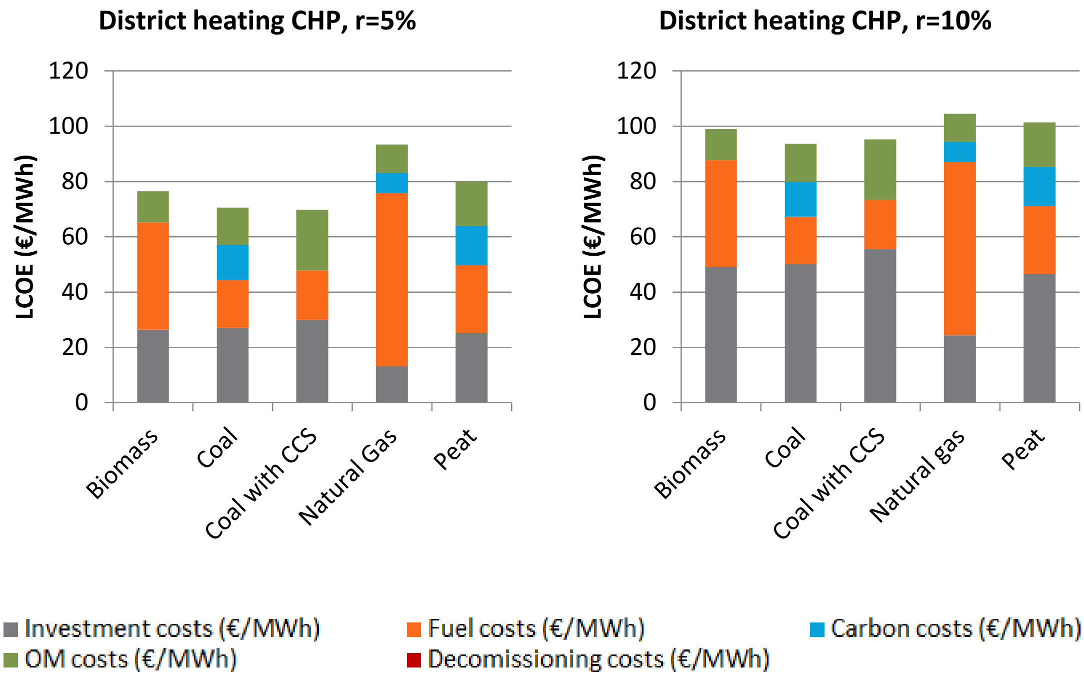


Figure 4.5 LCOE of combined heat and power plants by using biofuels, coal, natural gas and peat as fuel. Parameter *r* corresponds to interest rate and full-load operation hours are 4200 h/a.

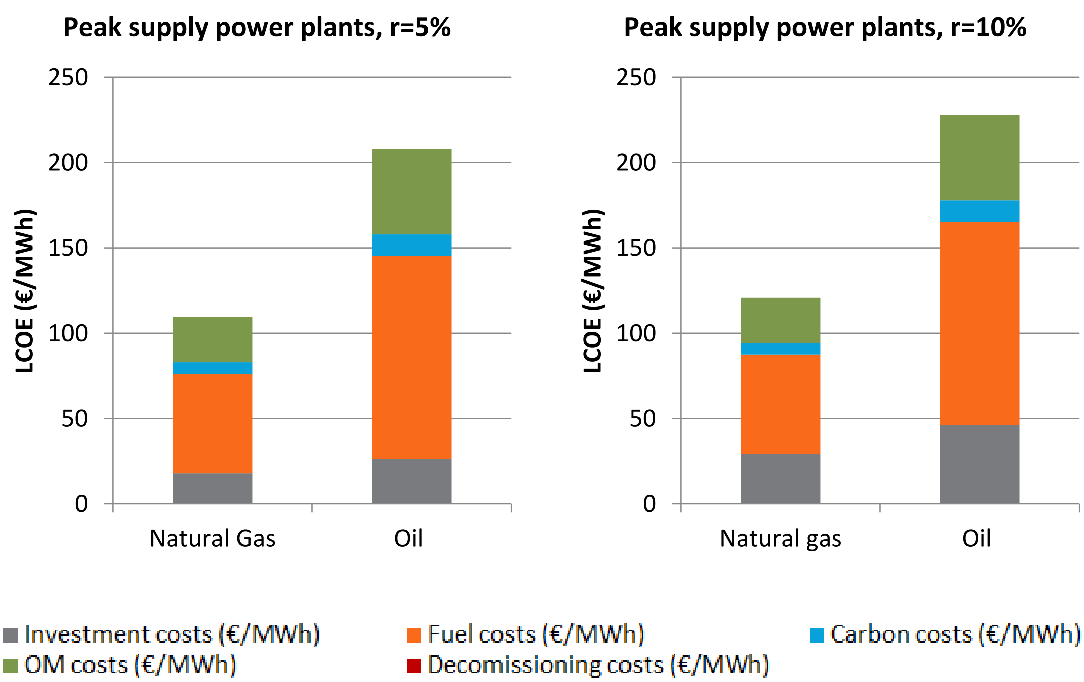


Figure 4.6 LCOE of plants used in peak supply: natural gas-fired gas turbine and oil-fired diesel power plant. Parameter *r* corresponds to interest rate. Full-load operation hours are 1000 h/a for Natural Gas and 500 h/a for Oil.

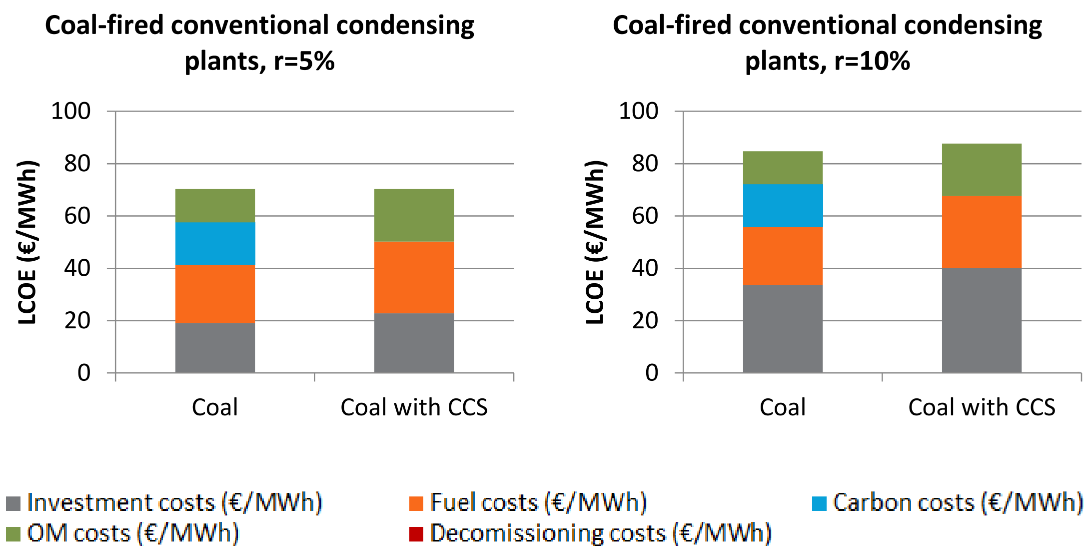


Figure 4.7 LCOE of coal-fired conventional condensing plants. Parameter *r* corresponds to interest rate. Full-load operation hours are 3500 h/a

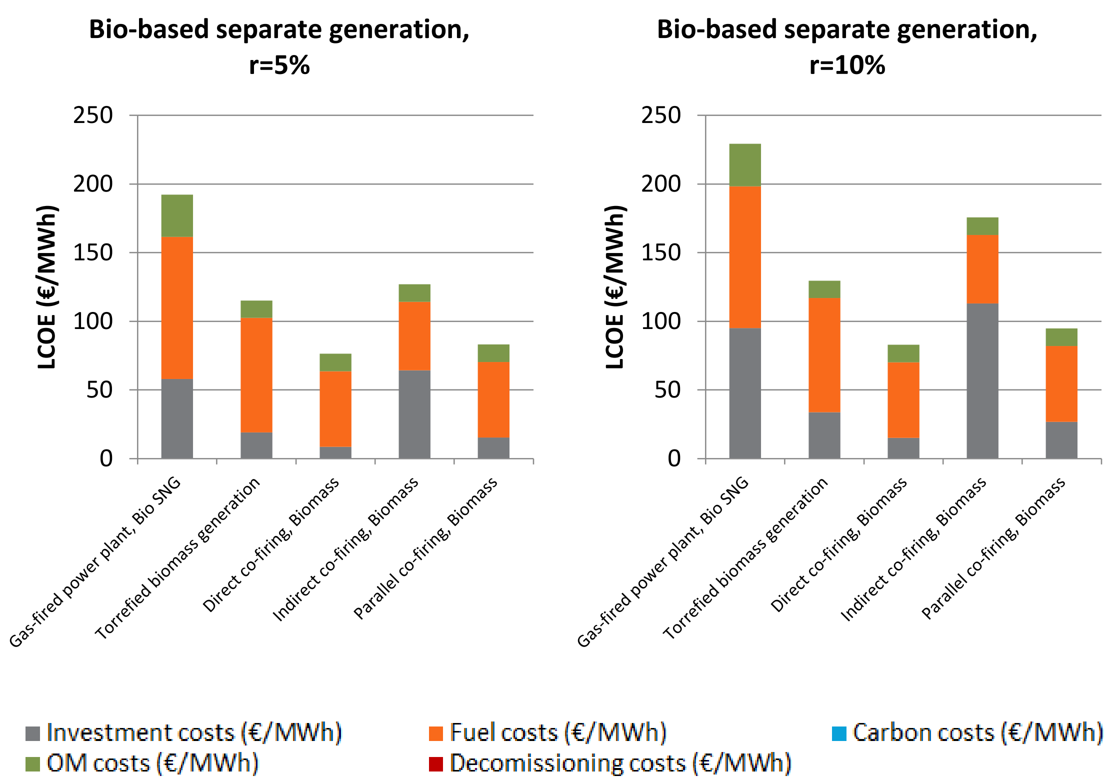


Figure 4.8 LCOE of biomass-based separate generation by using torrefied biomass substituting coal and using biomass in co-firing processes. Parameter *r* corresponds to interest rate. Full-load operation hours are 3500 h/a, except for gas-fired Bio SNG generation they are 4200 h/a since it is assumed that it is used for waste handling.

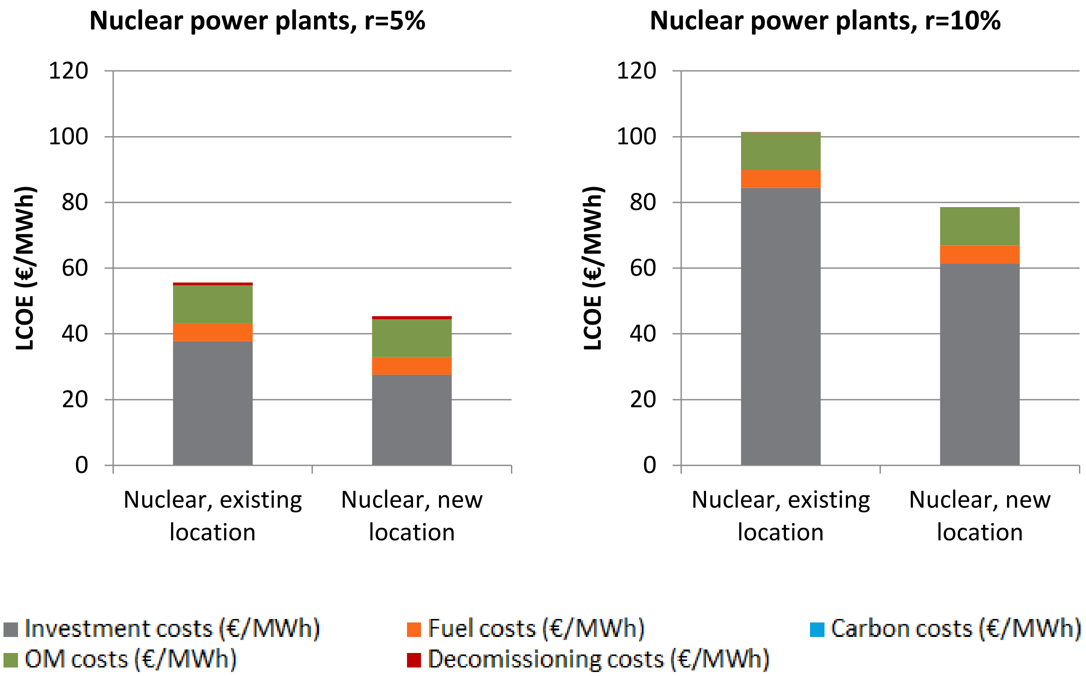


Figure 4.9 LCOE of nuclear power plants. Parameter *r* corresponds to interest rate and full-load operation hours are 8000 h/a.

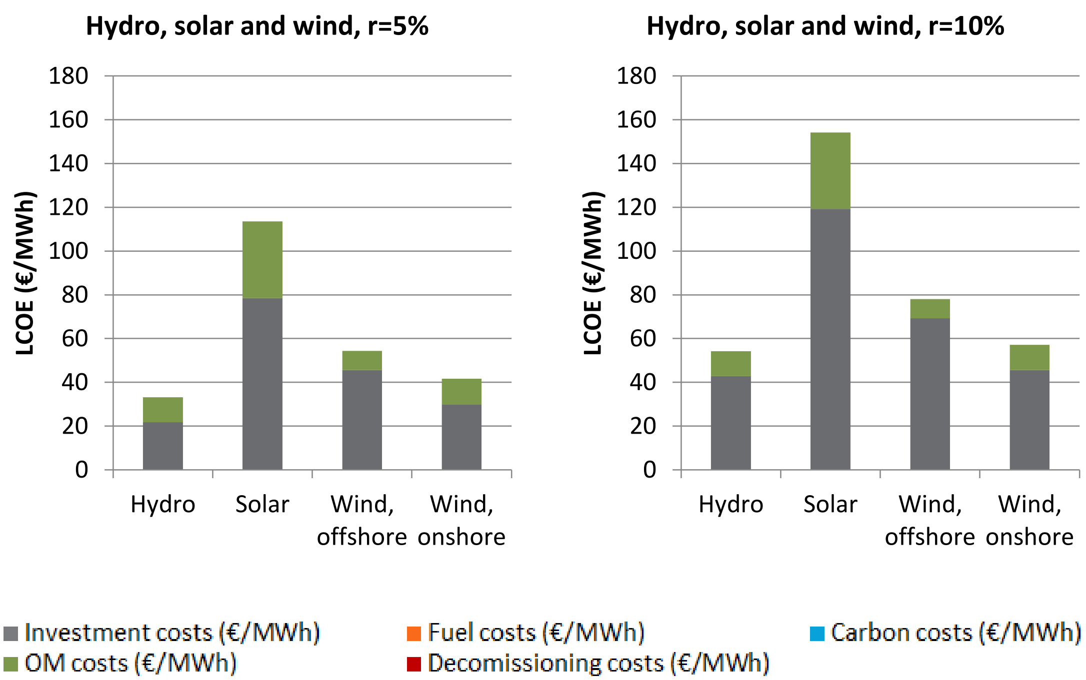


Figure 4.10 LCOE of hydro power, solar power and offshore and onshore wind power. Parameter *r* corresponds to interest rate. Full-load operation hours are 4200 h/a for hydro power, 1000 h/a for solar power and 2200 h/a for wind power.

The costs of CHP generation vary between 70 and 100 €/MWh, when the interest rate is 5%, and between 90 and 110 €/MWh, when the interest rate is 10%, depending on the used fuel as seen in Figure 4.5. The fuel costs are high especially for natural gas and biomass based generation. Peat and coal based generation have high carbon costs. The investment costs are also significant for all CHP plant types.

The generation costs of peak supply generation are high in both cases and they mainly consist of fuel costs as seen in Figure 4.6. The oil-based generation is more expensive due to higher fuel prices of medium and heavy distillates. The investment costs of these technologies are low and thus, the generation costs are not significantly affected by the full-load operation hours.

The difference between coal-fired separate power plants with and without CCS is minor as seen in Figure 4.7. The investment costs are higher in plants with CCS technologies and the efficiency of the plant is slightly lower, but the carbon costs due to purchased emission allowances are higher in the plants without CCS technologies, (Vakkilainen, et al., 2012, p. 7).

The generation costs of biomass-fired separate generation are high in all cases as seen in Figure 4.8. The generation costs of Bio SNG generation are the highest, but since it is assumed that this type is used in waste handling, its full-load hours are set higher. The fuel costs of torrefied biomass generation are approximately triple compared to coal-fired separate generation. The costs of indirect co-firing are significantly higher than costs of direct co-firing and parallel co-firing, which are closer to costs of coal-fired separate generation.

Nuclear power generation costs are not substantially lower compared to other generation technologies due to high capital costs and long length of construction, but lower than the most other technologies especially when the interest rate is lower. Also the applied interest rate affects substantially the generation costs as seen in Figure 4.9. The decommissioning costs can be seen also in the diagrams in Figure 4.9, but because they are discounted to more than 70 years ahead their impact is minor for the overall LCOE.

As seen in Figure 4.10 hydro power has lowest generation costs compared in this case study. However, the locations to increase hydro power generation capacity are limited and thus, the hydro power generation cannot be increased substantially. Solar power has high operation and maintenance costs due to short lifetimes of some components used in solar power technologies, which must be replaced in every 5-10 years, (Vakkilainen, et al., 2012, p. 8). Expenses of solar power have decreased rapidly when the number of solar power installations has increased substantially on global level in the recent years and it is expected that they will decrease further in the short-term future, (Kost, et al., 2013, pp. 18, 25). The generation costs of onshore wind power are cheaper than for example the generation costs of CHP generation or separate generation as can be seen in Figure 4.10 but the challenge related to onshore wind power may be finding suitable locations. The costs of offshore wind power are significantly higher than onshore costs but these are expected to decrease in the future. On offshore locations the weather conditions may be more providential increasing the yielded electricity and furthermore finding suitable locations is likely less challenging. In this calculation, the full-load operation hours of both offshore and onshore wind power were set to 2200 h/a, but in fact the operation hours of offshore wind are likely higher, (Kost)

The fuel and carbon costs are substantial in thermal generation, except in nuclear generation. Therefore, these technologies are vulnerable to fluctuations in fuel prices. The capital costs form substantial share of costs of the most technologies, but especially nuclear and CHP generation and nuclear power are the most capital intensive.

The most literature references indicate the LCOE level of future technologies lower than the results obtained in this study. The reason behind this fact is that in this study, the full-load operation hours of power plants were set to be more moderate as mentioned in Chapter 4.9.1. For example in the report of Vakkilainen et al. (2012, p. 8) the full-load operation hours of electricity generation were set to 8000 h/a for all other power plants than wind power and in the report of IEA (2010, p. 45) a standard load factor of 85% is applied for all other generation technologies than site-specific renewable technologies meaning that the full-load operation hours are approximately 7500 h/a.

4.9.3 Sensitivity analysis

In order to assess how parameters affect the LCOE price level of generation technologies a multi-dimensional sensitivity analysis performed for chosen median-case generation technologies in accordance with IEA (2010, pp. 106-112). The chosen cases for further examination are district heating CHP using biomass or coal as fuel, coal-fired conventional condensing, nuclear power on existing site and natural gas-fired gas turbine. The most interesting parameters chosen for analysis are fuel price, CO2 emission allowance price and full-load operation hours. Since intermittent generation and hydro power are not affected by these costs, they are no considered in this assessment.

Outcome of the multi-dimensional sensitivity analysis is a tornado graph, where impact of ±50% variation in the originally chosen values changed individually is viewed. In the case of fuel and carbon prices, the LCOE level increases if the original value increases the LCOE level increases, and in the case of operation hours the impact is opposite; if the original value increases the LCOE level decreases. Magnitude of the range indicates the impact of parameter to LCOE meaning that larger the range the more significant impact of the parameter. Results of the analysis can be seen in Figures 4.11-4.15. (IEA, 2010, p. 106)

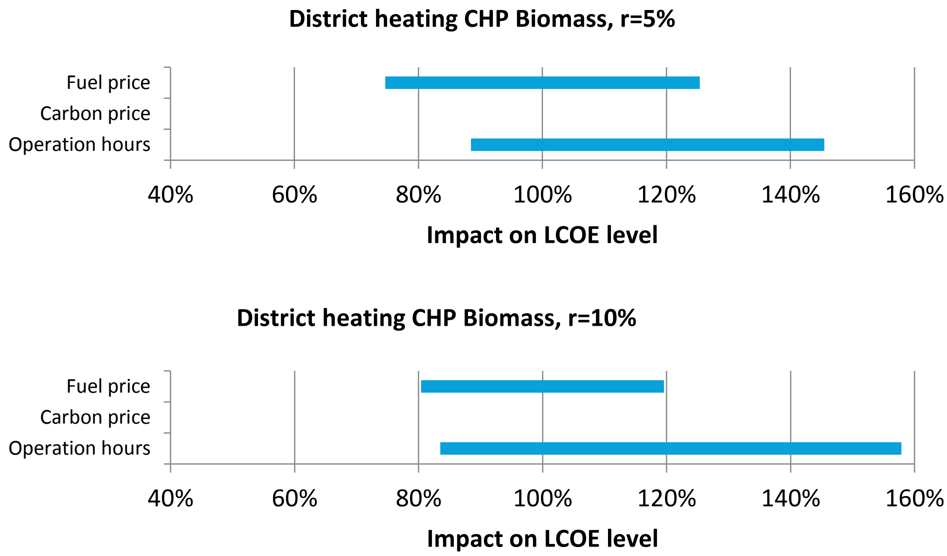


Figure 4.11 Tornado graph of multi-dimensional sensitivity analysis for biomass-fired district heating CHP. Parameter *r* corresponds to interest rate.

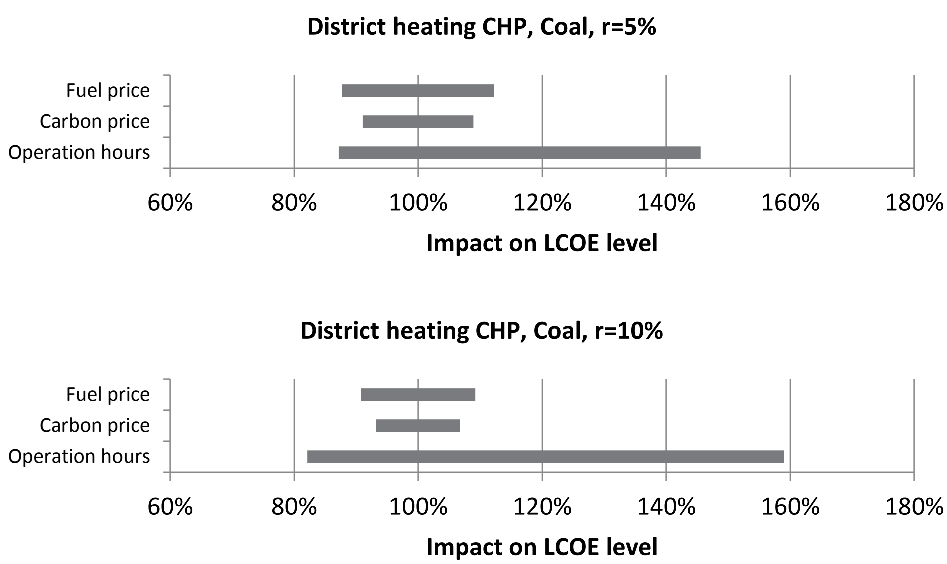


Figure 4.12 Tornado graph of multi-dimensional sensitivity analysis for coal-fired district heating CHP. Parameter *r* corresponds to interest rate.

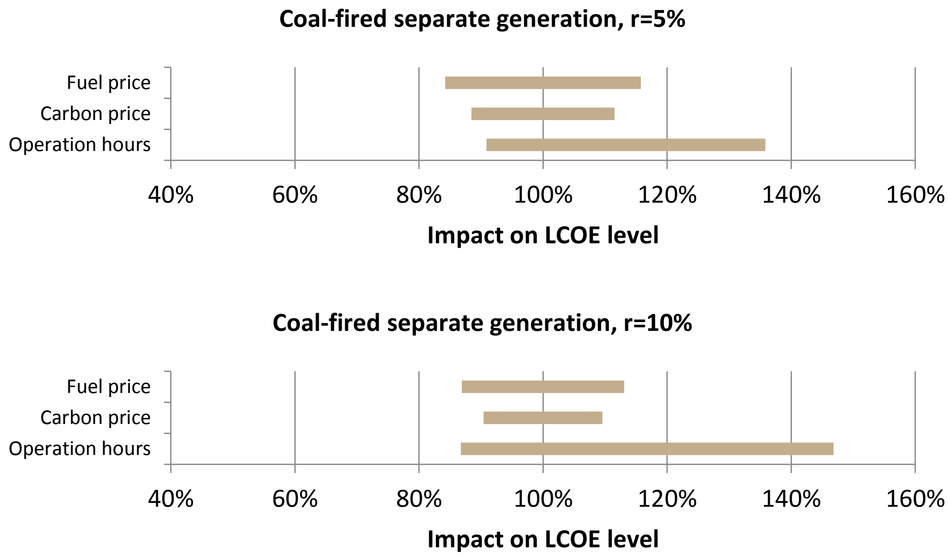


Figure 4.13 Tornado graph of multi-dimensional sensitivity analysis for separate coal-fired conventional condensing generation. Parameter *r* corresponds to interest rate.

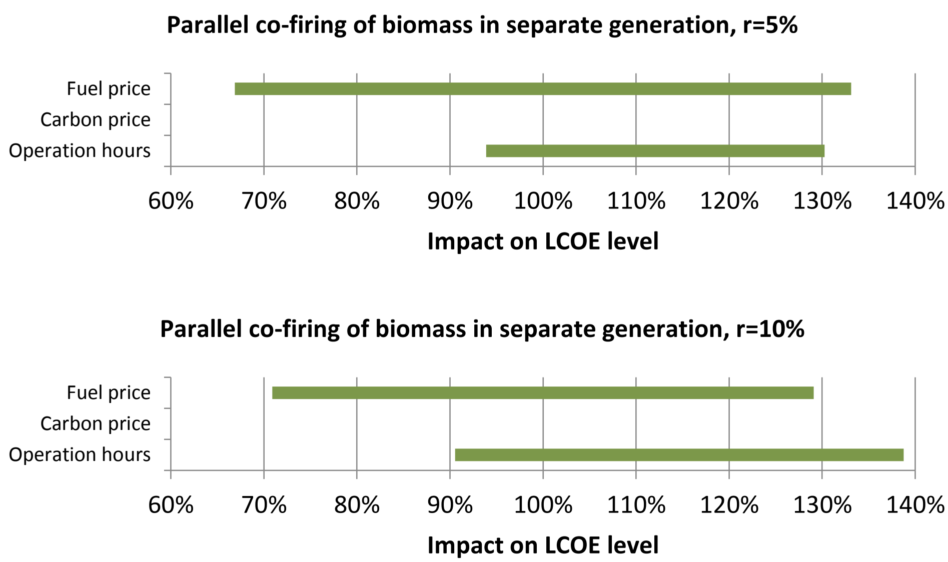


Figure 4.14 Tornado graph of multi-dimensional sensitivity analysis for parallel co-firing of biomass in separate generation. Parameter *r* corresponds to interest rate.

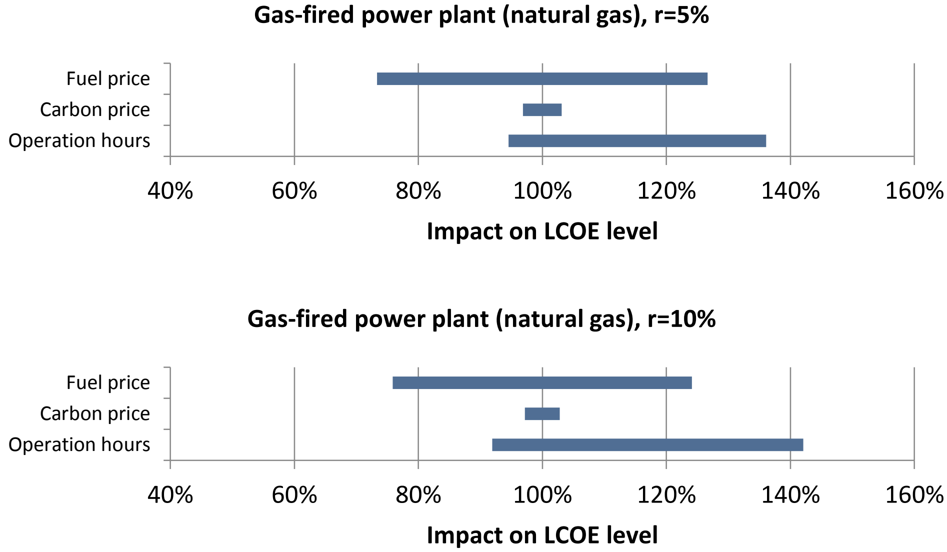


Figure 4.15 Tornado graph of multi-dimensional sensitivity analysis for gas-fired separate generation plant using natural gas. Parameter *r* corresponds to interest rate.

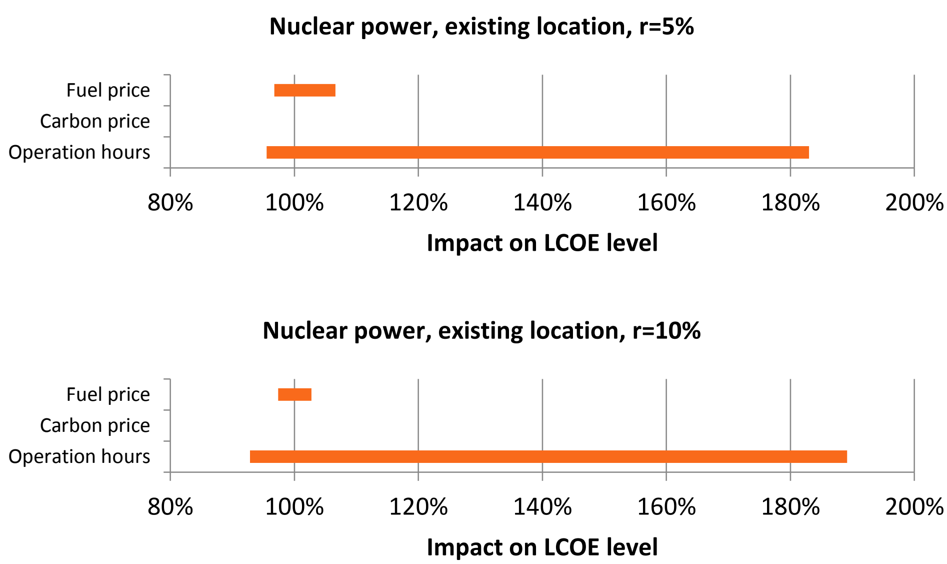


Figure 4.16 Tornado graph of multi-dimensional sensitivity analysis for nuclear power in existing location. As an exception, operation hours of nuclear power are not increased above 8760 h in the analysis. Parameter *r* corresponds to interest rate.

As seen in Figures 4.11-4.13, full-load operation hour change contributes LCOE level more than fuel and carbon prices in the case of capital intensive CHP and conventional condensing generation, but also fuel price and CO2 allowance price changes have impact. The LCOE level of parallel co-firing of biomass in separate generation is substantially affected by both fuel price and full-load operation hour change as shown in Figure 4.14. As seen in Figure 4.15, the costs of gas-fired generation are most affected by the fuel cost changes. Full-load operation hour change contributes also most for nuclear power LCOE level compared to fuel and CO2 allowance prices as seen in Figure 4.16.

4.9.4 Future wholesale prices

The market value of prospective generation technologies is analyzed by making a brief overview of the development of Elspot prices in the recent years and the estimates of the future wholesale prices. The integration costs now and in the short-term future are assumed to be minimal and thus, they are not considered. The monthly Elspot prices between 2004 and 2013 are shown in Figure 4.17.

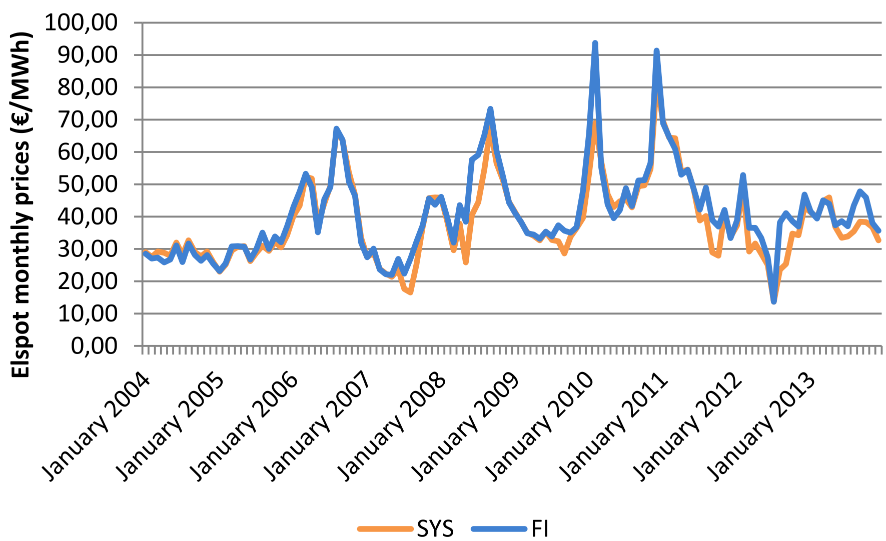


Figure 4.17 Monthly Elspot system prices and area prices in Finland between 2004 and 2005. (Nord Pool Spot , 2014b)

As seen in Figure 4.17, the average monthly Elspot prices, both system prices and Finnish area prices, have varied mainly below 50 €/MWh in last two years. In some winters there have been high temporary price spikes, but otherwise the monthly system price as well as the Finnish area prices have been below 50

€/MWh. The estimates for future price development do not expect substantial increase of wholesale prices in this or next decade. For example, Swedish TSO Svenska Kraftnät (2013, p. 25-27) and Botnen (2012, p. 21) have estimated that in the next decade the electricity wholesale prices are between 33 and 65 €/MWh.

In the other Nordic countries the electricity wholesale price estimates for next decade are close to estimated wholesale prices in Finland. In Baltic countries the wholesale prices are expected to be slightly higher in the next decade, but still less than 70 €/MWh, (Svenska Kraftnät, 2013, p. 25-27). Development of wholesale prices in Russia depends highly on how Russian electricity market and generation capacity develop in the future, (Viljainen, et al., 2013, p. 39). It has been estimated that electricity wholesale prices in Russia may be slightly higher than wholesale prices in Finland in the next decade, but presumably less than 70 €/MWh, (Botnen, 2013, p. 24; Svenska Kraftnät, 2013, p. 31-41).

Compared to calculated LCOE levels, electricity wholesale prices are low. This observation supports the identified blocking mechanism of TIS development considering weak profit opportunities from electricity supply business. Thus it can be seen that investment environment of electricity supply business is not very attractive at the moment and gaining revenues from electricity exports does not seem either very likely.

5 REVOLUTIONARY TRANSITION PATH

This section focuses on Revolutionary transition path and its impacts on power systems. The theoretical background of the transition is discussed in Chapter 5.1 and the transition is visualized and discussed by applying roadmap approach in Chapter 5.2. Development of the innovation system is described in Chapter 5.3 and the lock-ins of the socio-technical regime and their strengths are discussed in Chapter 5.4.

5.1 Background of the revolutionary transition path

Revolutionary transition path of power system has aspects of both *Reconfiguration pathway* and *De-alignment and re-alignment pathway* typologies developed by Geels and Schot (2007, pp. 405-413). Both of these pathways lead to restructuring of the power system though landscape pressures, but the latter pathway is driven by a more uncontrollable event that is a *specific shock* leading to erosion of the socio-technical regime, (Verbong & Geels, 2010, pp. 1217-1218; Geels & Schot, 2007, p. 408). For example, this kind of sudden change of landscape occurred in Japan after the Fukushima nuclear power plant accident in 2011. Before the Fukushima accident, only minor attention was given to renewables in Japan and there were no incentives to increase the share of renewables substantially. The Fukushima accident caused attention shift in the energy policy of Japan due to rising concerns towards nuclear power and led revising the support schemes for renewable energy. (Huenteler, et al., 2012, pp. 6-7)

In this case the considered revolutionary transition path would likely be driven by political decision causing reconfiguration pathway rather than specific shock. The reconfiguration pathway is mainly driven by political dynamism, which causes a landscape change putting pressure to the regime, (Verbong & Geels, 2010, pp. 1217-1218). In this pathway, the regime adopts radical innovations, which are developed in the niches, leading into adjustments of the regime, (Geels & Schot, 2007, p. 411). The changes in the regime are substantial and eventually this will lead to gradual reconfiguration of the architecture of the system, (Verbong & Geels, 2010, p. 1218). The revolutionary transition as reconfiguration pathway is driven by more top-down planning determined by political dynamism, (Verbong & Geels, 2010, p. 1218). This kind of change requires clear articulation of strategic direction and blueprint planning with predefined outcomes, (Kemp, et al., 2007, p. 87).

It can be argued that most of the energy transitions driven by political decisions in Europe have had features of this type of transition. For example in Germany the political decision to crowd out the nuclear power was made after Fukushima which led to large-scale deployment of variable renewables. Germans introduced a transition programme called “Energiewende” in 2010 and legislated it in 2011 to move to low-carbon economy rapidly, (IHS Global GmbH, 2014, p. 1). This has upset the electricity markets to some extent and now Germans are developing sustainable options to meet the challenges of intermittent generation while the generation of coal-fired plants are playing important role in the security of the supply, (IHS Global GmbH, 2014, p. 7). Other examples of transition that have certain features of reconfiguration pathway are the Denmark and Spain, where the renewables were boosted also artificially by subsidies.

The revolutionary transition path from the current situation towards the process goals introduced in Chapter 4.6 requires boosting the innovation system artificially and this transition path can be seen more resource-driven path based on more engineering science knowledge base approach. In this case, a substantial proportion of renewable generation is expected to be deployed sooner than in the evolutionary transition path. Therefore, the uppermost milestone of this transition is to achieve the target of 45% renewable electricity consumption by 2020.

5.2 Visualization of the revolutionary transition path

The revolutionary transition path is visualized by using technology roadmap introduced in Chapter 3.2.5 and distinguishing the layers of the roadmap as described in Chapter 4.8. The general purpose of roadmap is to illustrate the stream from the present situation to the desired future state and help to define required interventions and assumed side-effects and knock-on effects. It should be noted that roadmap is developed for the same focus than the performed industry analysis.

The current situation and known events are shown mainly on the left-hand side of the technology roadmap based on Chapter 4.8. The vision based on Chapter 4.6 is shown mainly on the right-hand side of the technology roadmap. Industry activities as TIS activities, assumed events and required interventions as well as their interlinks and connections to current situation and vision are shown in middle of the roadmap between of present and vision as can be seen in Figure 5.1.

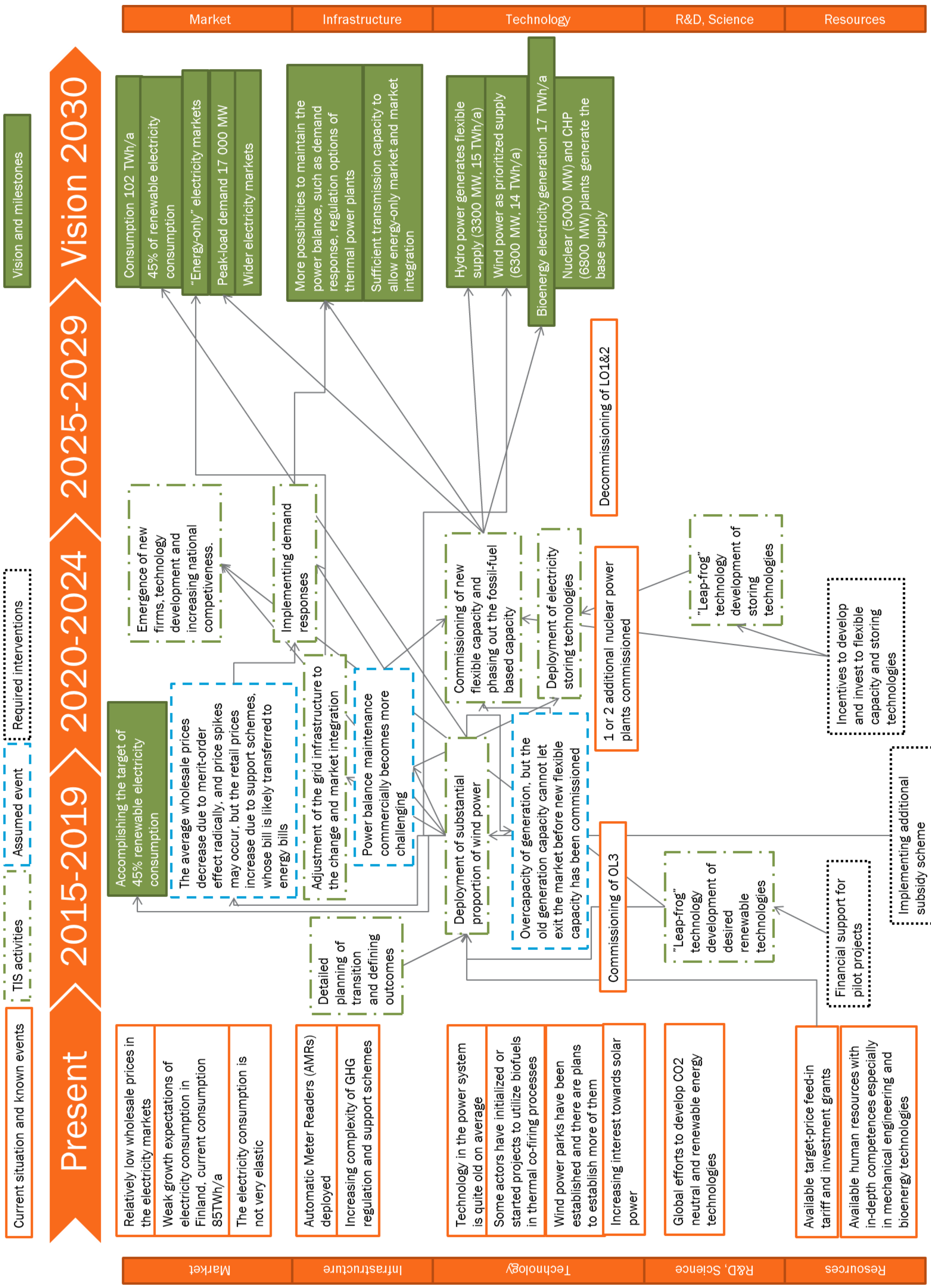


Figure 5.1 Technology roadmap of revolutionary transition path. The timeframe of transition is split into 3 periods: 2015-2019, 2020-2024 and 2025-2029 in the horizontal axis and the events in the roadmap are color-coded explained in the right-side.

As seen in Figure 5.1, the most required interventions to meet the target fast are related to providing financial resources. The technology development and deployment of the desired technologies needs to be boosted artificially, since the current incentives are not presumably sufficient enough as was obtained in Chapter 4.7.

The developed roadmap is discussed in this section by considering each category. It should be noted that the layers of the roadmap are overlapping and each layer is linked to other layers. Since the category *Technology* is expected to meet the most changes, it is discussed first and then other categories in the roadmap illustration are discussed from top to bottom.

5.2.1 Technology

In order to meet the milestone, 45% of renewable consumption, by the year 2020, the development and deployment of the desired technologies is needed to be boosted artificially by implementing some kind of support scheme discussed further in Chapter 5.2.6. Thus, during the first period of the transition, a substantial proportion of new renewable capacity is expected to be deployed to the power system. It is assumed that most of this capacity in this case is wind turbine technology, since its unit sizes in terms of capacity are greater compared to solar power and it does not require establishing local supply chains of the fuels as biomass utilization requires.

As a result, it is likely that there is overcapacity of generation in the electricity market and this affects presumably to flexible thermal generation capacity most by reducing its operation hours significantly. However, due to relatively low capacity credit of wind power, the residual generation capacity is not allowed to exit the market.

Reduced operation hours together with occurred merit-order effect discussed in Chapter 5.2.2 leads to a situation, where new investments or replacement investments are not likely made without subsidizing. Actors may also consider decommissioning of the residual capacity prematurely. Therefore, additional incentives to maintain the current capacity and to build new flexible capacity, which does not increase the GHG emissions, to replace the aging capacity and meet the challenges of intermittent generation are required. For example in Germany, the large-scale deployment of renewable technologies together with crowding out the nuclear power led to utilizing coal-fired thermal plants as flexible capacity and has led to increasing share of coal in the supply portfolio in Germany, (IHS Global GmbH, 2014, p. 12). Therefore, there is a risk that cheap coal-based generation may increase and building CO2 neutral flexible capacity may need to be subsidized. For example, United Kingdom has planned to offer financial support to build new nuclear power capacity in order to ensure the level of the sufficient generation capacity in the future and the British government is justifying the financial support by the unprecedented situation caused by efforts to prevent climate change and maintaining the energy security, (Macalister, 2013). However, the European Commission has started an investigation is impacts to European energy markets and it is unlike that the European Commission will allow these subsidies, (Macalister, 2013).

In addition to introducing financial support to maintain the capacity level, some countries, such as Germany, France and United Kingdom, are considering introducing capacity market mechanisms in this decade to keep the thermal dispatchable capacity in the power system, (Energistyrelsen, 2014, p. 49). In Denmark the ongoing discussion related to introducing the capacity markets are causing uncertainties in the electricity markets and that is why actors are hesitating to invest to the dispatchable capacity and they postpone their investment decisions, (Schröder, 2014).

Due to sudden and large-scale market penetration of intermittent technologies, the need of additional resources to regulate the power balance increases rapidly as mentioned in Chapter 4.6.2. Options are implementing demand response described in Chapter 5.2.2, increasing the possibilities to regulate the thermal generation or development of electricity storing technologies. The electricity storing technologies are still under development, except pumping power. The pumping power requires high heights of hydro fall and finding suitable locations may be a challenge in Finland, (ÅF-Consult Ltd, 2012, p. 94). In addition due to high regulation related to the usage of water resources, process of building pumping power or renovating the existing hydro power plants may be challenging in Finland. Another option would be to add incentives to develop storing options. For example, in Germany the actors have started developing storing options and introduced for example a Power-to-Gas concept, where the surplus electricity is utilized to produce methane, (GTAI, 2014). Additional incentives to develop and deploy these technologies are probably again required, although this technology could gain revenues when it is utilized in the down-regulation when the production exceeds the demand and in up-regulation when the demand exceeds the generation and peak-load hours when the wholesale prices are high.

5.2.2 Market

Due to rapid and large-scale market penetration of generation technologies, which have lower variable costs, it is expected that the wholesale electricity prices will decrease and this is the major issue in this category. More precisely, in the most operation hours, the variable cost for the last required generation form is lower than nowadays and this causes merit-order effect introduced in Chapter 3.3.1.

Although the wholesale prices decrease, it is not likely that the retail prices decrease, since costs caused by implemented support schemes are likely to be charged from the taxes of electricity consumption and the collected taxes are then going to increase. These taxes may be subjected to limited consumer groups, for example excluding the industrial consumers in order to avoid harming their competitiveness. For example, in Germany where the intermittent renewable generation capacity is substantial, the wholesale prices in some operation hours are even negative, but the electricity prices that customer pay have increased faster than in the other countries since the bill of Energiewende is paid by the electricity consumers, (Müller, 2014, p. 12).

On the other side, the customers whom are excluded from paying the bill of support schemes can purchase their electricity cheaper than before. Furthermore, the cheaper energy does not encourage to energy efficiency and may lead inefficient energy consumption.

As an outcome of the transition and realized investments, it is presumed that a number of domestic actors will decide to enter the technology development of chosen technology group. That is why it is expected that new industry is going to emerge in the next decade, which can export the technologies and increase the national competiveness further. For example in Denmark, the support schemes boosted domestic wind turbine development in 1970s and led to emergence of Danish wind power industry, which is still one of the major wind power technology exporters in the World, (Garud & Karnøe, 2003, p. 282).

5.2.3 Physical Infrastructure

Deployment of new generation capacity in large-scale is expected to shift the focus points of electricity generation as discussed in Chapter 4.6.2. The current grid infrastructure has been designed to serve the current production capacity and a sudden shift of generation locations requires also rapid investments for the infrastructure. In Germany for example, the grid infrastructure requires a substantial upgrade in this decade due to new locations of the generation, which are no longer following the consumption or the current grid infrastructure, (Müller, 2014, p. 9). In addition to this, the market integration requires further investments to allow more efficient cross-border trading. Therefore, it is expected that the transmission costs increase in this transition path rapidly.

If the infrastructure is unable to meet the challenges caused by the revolutionary transition of generation capacity, it is likely that transmission bottlenecks occur. This means that the grid is unable to transfer the electricity in accordance with merit-order and the system does not allow the most cost-optimal generation, since electricity to meet the consumption must be produced somewhere else.

Furthermore, the large-scale deployment of uncontrollable intermittent generation complicates the commercial power balance maintenance. In power systems, where the balancing options are favorable, this is not a challenge. For example in Denmark, the power balancing relies on Norwegian hydro power reservoirs, (Boeker & van Grondelle, 2011, p. 169). In Finland, the opportunities of short-term power balance maintenance are more limited and therefore, in order to meet the challenges, new flexible generation capacity is required as well as demand response. If the power balance maintenance is unable to meet the challenge, it is expected that the TSO must increase the proportion of strategic reserves, which would increase the share transmission costs in the electricity bills.

It is expected that after the large-scale penetration of intermittent technologies and observation of challenges in power balance maintenance, the willingness to add customer side participation as demand responses is going to increase. In Finland the AMR meters offer the required frames to implement this. Sudden assumed increases in the electricity bills as mentioned in Chapter 5.2.2 would offer sufficient incentives for the consumers to adopt demand response as well as energy efficiency solutions, if there would be an opportunity to affect one’s energy bill. However, the changing customer behavior is complicated process, since single consumers are often acting rationally and their decisions are also driven by other things than money, such as ease-of-use of use and value aspects.

5.2.4 Regulative and legislative structure

In terms of regulation, the revolutionary transition requires developing a clearly articulated transition program with predetermined outcomes. Germany’s Energiewende can be seen as an example of transition program like this. Energiewende includes detailed targets related to GHG emission reductions, energy efficiency, increasing renewable supply and phasing out nuclear power. However, the Energiewende has not been as successful as intended. Although renewable supply has increased, the utilization of coal has increased and the GHG emissions have not decreased as expected. Also the energy prices have increased in Germany as was not supposed. (IHS Global GmbH, 2014, pp. 1-3)

The prices of CO2 emission allowances are expected to increase in the future, since European Commission (2014) is planning to take actions to make EU ETS more efficient control mechanism. Thus, it is expected that in addition to national level support schemes the EU ETS contributes as well the development in the revolutionary transition path.

5.2.5 R&D and Science

The transition like this requires faster and more straightforward technology development called as “leap-frog” approach. In the first period of the transition, the TIS is developing technology in accordance with the pre-defined transition program. This approach is required in this case for both developing renewable energy generation technologies and developing storing options.

Because the investment for the feed-in tariff should also yield other benefits than just increasing the share of renewable energy and self-sufficiency and hence, the implementing the feed-in tariff is often justified by creation of local employment and strengthening national competitiveness, (Schröder, et al., 2011, p. 9052). Since Finland has not been following a first-mover strategy in terms of renewable energy technologies, there is no rationale to support just deployment of renewable energy technologies no more than the available feed-in tariff comprises. Alternately, the feed-in tariff could be targeted to develop renewable energy technologies, which are not yet mature in accordance with differentiation strategy. In Finland, such differentiation strategy could be for example to develop offshore wind power technologies and support their deployment. The offshore wind power technology is not mature technology and in Finland there are actors providing other offshore installations and as Salo and Syri

(2014, p. 344) underrate that there is interest to start developing offshore wind power technologies in Finland. Therefore, the R&D efforts in this transition path are likely targeted to develop technology within relatively narrow scope. The technology development is nurtured artificially and thus, there is a significant risk of getting locked-in to these technologies, (Kemp, et al., 2007, p. 81).

Rapid technology development and succeeding in it may be challenging and risky. Gaining testing experiences within short period of time may be constricted and biased and therefore, the outcome of the efforts may still be immature technologies. Also the search process of opportunities is limited and the scope of research and development activities may be very narrow.

An example of “leap-frog” approach in wind power technology development was seen in the US in between 1970s to 1990s. The actors in the US were developing a radically differing wind turbine design mainly by applying engineering science knowledge and insulating from the practical problems occurring. Implemented subsidies encouraged to invest to the wind power before the functionality of the technology was even proven. When the problems in installed technology emerged, the failed components were just replaced, but finally a large number of wind power plants developed in the US failed. (Garud & Karnøe, 2003, pp. 286-289)

Another example of technology development approach within relatively narrow scope can be seen in Sweden in 1970s and 1980s. The Swedish actors were focusing on research and development of very large wind turbines, meaning the capacity of 2-3 MW per unit due to substantial funding to develop them. Only few large firms decided to enter to the industry, but in Sweden there was no real demand for that technology and also the legitimation was lacking for wind turbines at the time. Therefore, the actors had difficulties to find partners, establish supply chains and find venture capital. In 1985, the level of funding was reduced, but the actors who had entered to the development had difficulties to survive on their own without subsidies and Swedish wind power industry never accelerated. Later on, the Danish and German firms achieved the goal that the

Swedish were pursuing to. Afterwards Sweden has followed a late-mover strategy in terms of wind power deployment, but the deployment of wind power technologies in the Swedish power system has increased in the recent years, (Borup, et al., 2008, p. 72). (Bergek & Jacobsson, 2003, pp. 17-18, 28-29)

Both these examples were subsided generously, but the investments did not pay themselves back as expected. As these examples show, the risks of the "leap-frog" technology development approach are remarkable.

5.2.6 Resources

As perceived from the previous chapters, this transition requires substantial financial incentives to boost the development in accordance with the predefined transition program as discussed in Chapter 5.2.4. It is assumed that during the first period, the boost of technology development requires firstly providing financial support for the pilot projects and then probably an additional operational support scheme. The financial support schemes for pilot projects are one-time investments, but it is assumed that in order to succeed, long-term commitment is required to some extent. An additional operational support scheme in turn requires long-term commitment and the financial support is based on the amount of generation. The options for the operational support scheme could be either a Feed-in tariff (FIT) or a Feed-in premium (FIP). Both of them are usually either guaranteed for fixed period or pre-determined amount of production. In FIT support scheme a target price is determined and the FIT is paid on the top of market price so that the producer receives the target price. In FIP support scheme the producer receives a pre-determined premium in addition to market price. (Kitzing, et al., 2012, p. 194)

Next, the wholesale prices drop due to merit-order effect as discussed in Chapter 5.2.2 and new flexible capacity is required to meet the challenges of intermittent generation and to replace the aging capacity that will exit the market. It is expected that building this capacity requires investment grants as incentives to build new capacity.

With respect to human resources, it is presumed that the transition requires also shift of focus in education to some extent. Thus, the also technical educational institutes need to be involved in the transition.

5.3 Development of the innovation system

As obtained from the previous chapter, the basic architecture innovation system is reconfigured during the revolutionary transition path, (Verbong & Geels, 2010, p. 1218). The development of the innovation system is discussed focusing on structural components in Chapter 5.3.1 and the functions in Chapter 5.3.2. The purpose of this section is to make a brief overview to development of innovation system and future industry dynamics.

5.3.1 Development of structural components of TIS

Geels and Schot (2007, p. 411) argue that the most regime actors in the reconfiguration pathway are likely to survive, but competition and tensions may occur among the technology suppliers. It is assumed that the actors who are capable to initiate large-scale pilot projects are the existing incumbent and relatively strong actors or the actors who have already deployed small-scale wind power parks and these actors are attracted by the financial incentives. Therefore, it is expected that in this transition the existing electricity suppliers are going to expand their business to the wind power and the existing wind power producers are going to grow organically. Some electricity suppliers may also die eventually. Therefore, it is expected that basic architecture of industry providing energy technologies and their sub-suppliers is going to change. The actors providing offshore installations and foreign firms developing also offshore wind power technologies may decide to enter to the TIS attracted by the available subsidies. Also the research institutes are expected to contribute to the development, but their role is going to remain the same in the TIS.

Because the electricity supply industry and the technology development have been boosted artificially by subsidizing, there is a risk that the companies who have entered the market are not able to survive without the support. Then the natural selection process within the industry is disturbed and economic inefficiencies may occur to some extent.

It is expected that the role of electricity consumers is going to become more active in terms of timing and level of consumption, but the power of the consumers is going to remain low. The role of retailers is expected to remain the same, but it is expected that the retailers may be reluctant to implement demand response within short time period, since for them the incentives may not be attractive enough. The role of TSO and DSOs will remain the same, but these actors are forced to invest to the grid infrastructure substantially during the transition. The role of maintenance and service suppliers is expected also to remain the same, but these actors have to adopt new practices to be able to deal with the new production portfolio. The roles of labor unions, authorities, media and EU are expected to remain the same, although the top-down planning becomes more contributing.

As a summary, it is assumed that the most changes in the set of actors and their interest and power relations are going to occur in the groups of electricity supply industry itself and in the equipment suppliers of plants and components. In this transition path, the power of existing incumbent actors who decide to enter the wind power business and the power of growing wind energy suppliers are expected to increase. These actors also become more central actors in the networks of the TIS, especially in the buyer-supplier and collaboration networks.

The regulative institutions of the TIS are going to change and the role of these institutions during this transition path becomes more influential due to top-down planning. It is assumed that the tensions of the institutions will occur in larger extent than in the evolutionary transition path. Gaining the social acceptance for new technologies and subsidies can be a challenge as will be discussed further in Chapter 5.3.2.

5.3.2 Development of functions of TIS

The top-down planning and the provided subsidies are the most contributing factors of the development of the functions. Especially, they have influence on functions *influence on direction of search, knowledge development and diffusion* and *market formation* when extensive *resource mobilization* especially of public funding is going to boost the function *market formation* artificially when the number of installations presumably increases rapidly.

Since the incentives to develop new technology have increased in the very beginning of this transition path and the top-down planning articulates a clear vision, the function *influence on direction of search* will change suddenly. This is why *knowledge development and diffusion* function goes into radically new knowledge fields. Furthermore, success of this function depends on the ability of actors to add and transfer knowledge. The scope of this function is relatively narrow and therefore, there is a significant risk of failure.

Function *Legitimation* is assumed to be most challenging in this transition path. Gaining social acceptance for installing large-scale systems, which in this case study is wind power, is likely to be challenging in Finland, where it can be argued whether the wind power has not yet fully gained it and where nuclear power is often seen as source of more reliable energy as discussed in Chapter 4.7.3.

Development of positive externalities depends on the question whether there are new firms entering to the TIS. If there are, it is likely that the new entrants will resolve uncertainties and strengthen the market formation and when there are more actors it is likely that unexpected innovations emerge, (Bergek, et al., 2008, p. 418). It is argued that number of firms entering to TIS may not be substantial in the revolutionary transition path and therefore, this function may be weak.

The role of entrepreneurial experimentation function in this transition path is minor. Since the incentives are targeted to very narrow technology group and *knowledge development* has a narrow scope, the niches for entrepreneurial experiments are few. Therefore, the variation of experiments and testing of opportunities may be limited and there is a risk that the TIS is going to stagnate to some extent, (Bergek, et al., 2008, p. 416).

5.4 Lock-ins of the socio-technical regime

The revolutionary transition path requires adopting radical innovations that do not fit very well to the existing innovation system, (Negro, et al., 2012, p. 3837). These radical innovations need to overcome lock-ins occurring in the socio-technical regime in order to be adopted by regime actors. Three most contributing lock-ins are defined in this case.

The firms who decide to enter to develop and deploy radically new technologies take a risk when they go for research processes, which are not close to the previous experiments. Thus, these actors are forced to change their perceptions and actions, which will influence the institutions, especially cognitive ones. It is assumed that there are mismatches, contradictions and other institutional problems arising especially in the first steps of the transition. It can be seen that current institutions are more aligned and alignment of institutions promote stability, (Geels, 2004, p. 910). Therefore, potential institutional mismatches can be seen as a certain lock-in.

Second, social acceptance of the existing technologies can be seen as another lock-in. Gaining the legitimation for the public funding required in this case and gaining the legitimation for the new technologies rapidly may form a major barrier for the transition.

Third, the revolutionary transition path may stipulate crowding out the existing technical structure faster than would be natural to some extent. The economies of scale of the existing technologies are higher than the economies of scale of the novelties and the existing technologies complete each other's functionality and these factors promote stability and resistance to change. Therefore, the existing technology can be seen as third major lock-in in the revolutionary transition path.

Overcoming the first lock-in, potential institutional mismatches may be helped by adjusting legislation and changing the focus of technical education rapidly. The lock-in related to social acceptance may be a challenge, since the legitimation process for new technologies often slow and tedious, (Negro, et al., 2012, p. 3842).The third lock-in related to existing technical structure is helped to overcome by providing public financial incentives as discussed in Chapter 5.2.6.

6 EVOLUTIONARY TRANSITION PATH

The Evolutionary transition path is assessed is this section in a similar way than the revolutionary transition path in the previous section. Chapter 6.1 introduces the theoretical background behind the evolutionary transition path. The transition is visualized in Chapter 6.2. The development of the technological innovation system is described in Chapter 6.3 focusing on the structural components and functions and lock-ins are discussed in Chapter 6.4.

6.1 Background of the evolutionary transition path

Evolutionary transition path has certain aspects of especially *Transformation pathway* from the transition typology developed by Geels and Schot (2007, pp. 405-413) introduced in Chapter 3.2.3. In this case the transition needs certain frequent pressures from the landscape and the regime actors respond though cumulative adjustments. Outsiders' role in this transition is important, since they translate the landscape pressure and also develop alternate options in the niche-innovation level. (Geels & Schot, 2007, pp. 406-408)

In this transition path the frequent landscape pressure causes reorientation of the regime, which opens windows of opportunities. Viable alternates that will be adopted by the regime fit with the existing system better than in the revolutionary transition path. However, the basic architecture of the regime is not disrupted and most of the regime actors will survive though the transition. Furthermore, this transition path is more driven by cost-efficiency. The incentives for the deployment of renewable energy technologies to the power system in this kind of transition are more market-based instruments. In addition to market-mechanisms themselves, artificial market-based instruments can be used to guide this kind of transition. These could be for example an efficient emission trading scheme or a green certificate scheme. (Verbong & Geels, 2010, p. 1217)

Development of the Finnish CHP industry can be seen as an example of evolutionary transition path. The first district heating systems were built in 1950s in

Finland and policy makers decided to favor combined heat and power production over condensing generation and use the heat in district heating systems after the oil crises in 1970s. In order to support the development, the public funding was provided to research in this field in the 1970s. The Finnish technology suppliers, such as mechanical industry, benefitted from the available funding and since it had developed together with the Finnish paper and pulp industry, focus of the knowledge development function was not shifted far from their previous experiments. The objective was to enable combustion of wet and heterogeneous domestic energy sources, such as peat and biomass and the research efforts led to experiments with fluidized bed combustion technology. Close cooperation with the energy suppliers and forest industry together with the tight connections to Sweden and well-developed mechanical industry led to wide development of industry providing CHP technologies in Finland. However, the public funding available did not lead to rapid large-scale deployment of CHP technologies to the power system although there was a little spike in the CHP electricity generation development curve in the 1970s, but it lead to development of the industry and more market-based deployment of CHP technologies which continued until the beginning of the 21st century, (Kara, et al., 2004, pp. 74-75). (Hellsmark, 2011, pp. 275-279; Borup, et al., 2008, pp. 57-58)

The evolutionary transition path requires also interpreting a vision and policy interventions in order to ascertain the direction of development. Kemp et al. (2007, p. 87) argue that this kind of goal-oriented transition is a mixture of incrementalism and top-down planning requiring predetermined policy goals, but the development should be coordinated by market-based mechanisms. Compared to the revolutionary path vision, in the evolutionary transition path, the vision should be more flexible and allow stepwise learning process, (Schot & Geels, 2008, p. 549).

Niche-innovations are more essential in this transition path. Schot and Geels (2008, p. 540) argue that successful development of technological niches requires articulation of visions in order to provide the direction to learning process, allowing learning process at multiple dimensions and supporting building process of social networks between the technology actors and relevant stakeholders. Technological niches, which are allow experimentations, do not emerge in this case in a top-down planning, but rather through collective enactments as the pressure form the landscape, (Schot & Geels, 2008, p. 538). In addition to market-base instruments, the niche-innovations can be supported though public R&D funding, but only the most fitting and cost-effective viable options are adopted by the regime, (Verbong & Geels, 2010, p. 1218).

6.2 Visualization of the evolutionary transition path

The events of the transition are distinguished into current situation and known events, TIS activities, assumed events and required interventions as well as vision and milestones in a similar way than in the revolutionary path roadmap in Chapter 5.2. The visualization of the evolutionary transition path by using technology roadmap can be seen in Figure 6.1.

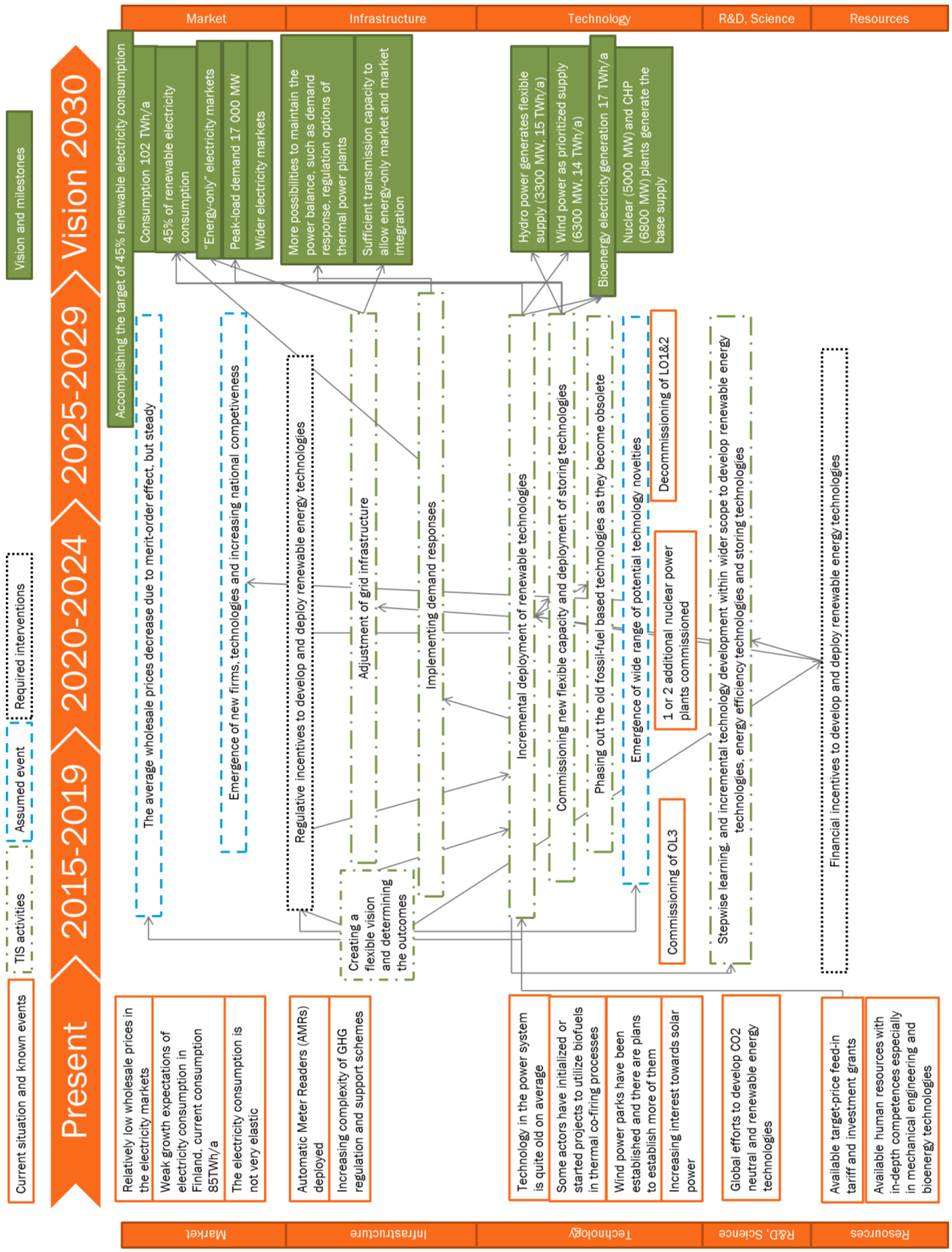


Figure 6.1 Technology roadmap of evolutionary transition path. The timeframe of transition is split into 3 periods: 2015-2019, 2020-2024 and 2025-2029 in the horizontal axis and the events in the roadmap are color-coded explained in the right-side.

As seen in Figure 6.1, the evolutionary transition path includes changes in many fields simultaneously. It is likely, that some artificial interventions are required in order to reach the vision, since it can be seen that current incentives, such as weak profit expectations, do not support the transition towards the target as discussed in Chapter 4.7. In the following chapters, the overlapping layers of the developed roadmap are discussed detailed in similar order than in the revolutionary transition path roadmap in Chapter 5.2. The definition of categories was given in Chapter 4.8.

6.2.1 Technology

The electricity supply portfolio changes from the present portfolio towards the vision introduced in Chapter 4.6 incrementally in this transition path. The renewable generation technologies are deployed gradually and at the same time investments for the new flexible capacity and implementation of demand responses are expected to occur.

One of the main drivers of the change is cost-efficiency in the evolutionary transition path. In addition, it is expected that the regime actors respond to external landscape pressure more likely, such as criticism of environmental groups and social movements, affecting to the electricity supply portfolio and adopted novelties as well. The regime actors adopt novelties developed in the niche-level in this transition path as mentioned based on cost-efficiency. Therefore, the adopted innovations fit presumably better with the existing innovation system and the basic architecture of the regime is not disrupted by adopting radical novelties. (Verbong & Geels, 2010, p. 1217)

In this transition path it is expected that deployment of intermittent renewable technologies is substantial similarly as in the revolutionary transition path, but the deployment is more incremental. The share of bioenergy fuels in the electricity generation is going to increase as well, but due to requirement to establish or expand the supply chains in the biomass harvesting and global development trends, it is assumed that wind and solar power are seen more attractive technologies.

The technology development towards the desired state is guided mainly by applying regulative market-based incentives, such as an efficient emission trading (ETS) scheme or alternatively a tradable green certificate (TGC) scheme as will be discussed detailed in Chapter 6.2.4. Also financial incentives for niche-innovations should be allowed in less extend than in the revolutionary transition path discussed in Chapter 6.2.6. It is expected that there are small-scale demonstration plants in the power system especially in the beginning of the transition and the unit sizes of renewable power plants grow gradually during the transition. It is also assumed that the regime actors are involved in technology development by for example participating to demonstration projects. In addition to boosting the technology development, it can be seen that the regulative incentives implemented incentivize the deployment of flexible carbon-neutral or renewable capacity to the power system. Thus, additional incentives to maintain and stipulate investments in flexible generation capacity are presumably not required.

An example of successful technology development and deployment as an outcome of emission trading scheme (ETS) was seen in the United States starting from 1980s where SO2 emissions in the energy generation were successfully reduced in order to improve air quality and public health and prevent harming the environment. In the US, market based cap and trade mechanism being part of Acid Rain Program started in the 1980s. The mechanism allowed the combustion units to select their own approach to reduce SO2 emissions or alternately the actors were forced to purchase emission allowances. It is assumed that the ETS supported long-term technology development of technologies to reduce SO2 emissions. Between the years 1980 and 2007 the SO2 emissions were reduced gradually from 26 million tons to less than 13 million tons mainly by deploying flue gas desulfurization to the combustion units in the combustion units that were included in the ETS. (US EPA, 2007, pp. 5-6, 10)

6.2.2 Market

The wholesale prices in the electricity markets are expected to decrease as a result of merit-order effect caused by expected market penetration of variable renewable technologies, but more incrementally than in the revolutionary transition path. If there is a more efficient ETS with higher CO2 allowance prices than nowadays, the price of emission allowance is included to the wholesale prices in larger extent in operation hours when the last required generation form is fossil-based generation. Thus, the average wholesale prices may increase in the beginning of the transition. Electricity suppliers generating CO2 neutral electricity have then an opportunity to gain additional revenues. This can be seen as an incentive to invest for renewable or carbon neutral generation capacity. Later on when these investments are presumably made, it is expected that the number of operation hours when the price of emission allowance affects to the wholesale price reduces gradually.

It is likely that one result of support schemes is phasing out of fossil-based generation. Alternately, as happened in Sweden as a result of TGC scheme, the fossil-fuelled thermal power plants can be changed suitable for biofuel generation, (Bergek & Jacobsson, 2010, p. 1259). Phasing out the old electricity supply capacity is likely to cause scarcity of capacity periodically and therefore, there may be price spikes in the hours when the intermittent generation is low, (De Vries & Ramirez, 2012, p. 4). The price spikes in the wholesale prices can be seen as incentives to invest for new flexible capacity and implement demand responses. Therefore, it is important not to impose a price cap for the wholesale electricity prices.

Contrary to the revolutionary transition path, the retail prices of electricity do not increase through increased taxes in the evolutionary transition path. The alternate support schemes discussed detailed in Chapter 6.2.4 are not based on public financing but rather market-based mechanism. The price of emission allowances and the costs of purchasing the green certificates are transferred to the end-user prices through electricity purchasing expenses. For example in the

ETS, the price of emission allowance goes directly to the wholesale prices and is then becomes a part of the retail prices.

The implemented regulative scheme as well as available financial incentives as will be discussed in Chapter 6.2.6 aim to support the technology development in long term. Therefore it is expected that as an outcome of the evolutionary transition path new businesses opportunities emerge and finally there will be new technologies available commercially in the market.

In a case where TGC scheme would be implemented, the scheme would not affect to the wholesale prices in the beginning since the green certificate market is working separately. For example in Sweden, the implemented TGC scheme has faced criticism due to generating extra revenues for already profitable generation units, since the existing renewable capacity was considered as certified capacity in order to ensure the sufficient liquidity of the certificate markets, (Bergek & Jacobsson, 2010, p. 1261). However, the TGC scheme would boost gradually the deployment of renewable and carbon neutral technologies and then the wholesale prices decrease in the electricity markets. The retailers would be obligated to purchase the certificates and this bill would be transferred to the electricity retail prices. For example, the Swedish TGC scheme has increased the electricity bills of electricity customers due to increased payments to purchase certificates, (Bergek & Jacobsson, 2010, pp. 1259-1260).

6.2.3 Physical infrastructure

The grid infrastructure must be adjusted to the change in a similar way than in the revolutionary transition path. Also in this case it is expected that the focus points of generation will shift in similar way than in the revolutionary transition path, but slower and more incrementally. The time scale of grid adjustment is longer and therefore, the transmission costs increase more incrementally.

Demand responses are implemented in this transition path incrementally starting from delimited customer group and narrow scope of applications and then moving to wider customer groups and applications. The prices spikes discussed in Chapter 6.2.2 as well as increasing share of intermittent generation capacity are incentives to implement demand response. Because the timeframe of the implementation in this transition path is longer and therefore gradual adaptation of new user practices is expected to reduce the inertia to change.

6.2.4 Regulative and legislative structure

This transition requires interpreting a clear vision in order to ensure the direction of development. However, the vision should be more flexible than in the revolutionary transition path and allow experiments and variation in the technology development and deployment. The targets of EU and how they have developed can be seen as an example to compare the difference between setting detailed vision and setting more flexible vision. In the very beginning of international climate change efforts, EU set a target to decrease GHG emissions along with other countries in the World, which set a clear direction of the development and the actors in different countries were following this direction. Later in 2007 more detailed vision was introduced as 20-20-20 target and in addition to GHG emission reduction targets it included targets to increase share of renewables and energy efficiency. It can be argued that this new and more detailed vision was confusing for the actors and narrowed down the experimentations in the technology development since the 20-20-20 target pointed out that renewable energy sources were an attractive option to reduce GHG emissions instead of for example deploying carbon capture and storing (CCS) technologies, although for example bioenergy sources are renewable but cause still GHG emissions. Therefore, more flexible vision would support the technology development within wider scope supporting still the overall objective.

The evolutionary transition path requires additional incentives in order to maintain the direction of the development. In this case, the main incentives could be regulative ones, for example an efficient emission trading scheme (ETS) or alternately a tradable green certificate scheme (TGC) on national level. The regulative incentives applied should be more technology-neutral than in the revolutionary transition path and either put an extra price for emitting non-renewable generation or alternately provide additional incomes for renewable generation.

An efficient ETS would put an additional price for fossil-based generation when the suppliers are forced to purchase emission allowances. If the last required generation form to fulfill the demand in the merit-order would be fossil-based generation, the price of emission allowance would affect to the wholesale price increasingly. Thereby the renewable or carbon-neutral generation would gain additional profits by investing to carbon-neutral generation technologies would be more tempting for the market actors. In addition, the suppliers who are able to reduce their emissions for example by deploying CCS technologies can earn savings in the carbon costs or sell their surplus emission allowances.

Existing EU ETS is working inefficiently due to surplus of allowances and influencing it on national level is difficult. The problem has been recognized and European Commission is planning to take actions in order to make the scheme more efficient. Planned actions are for example back-loading of allowances and implementing a market stability reserve. Therefore, it is assumed that EU ETS is guiding the development in the future more efficiently than nowadays. (European Commission, 2014)

Alternately, other long-term national-level support scheme to boost deployment of expressly renewable technologies is a TGC scheme. It is used for example in Sweden and Norway to increase share of renewable energy more incrementally. In this case, the emission trading scheme is considered more favorable regulative incentive than tradable green certificates since it already exists and it is more technology neutral compared to TGC scheme. However, the TGC scheme and its functionality is discussed briefly in the following fragment.

In the TGC scheme, the renewable electricity suppliers can gain additional revenues from an artificial green certificate market in addition to gaining revenues from the electricity markets. This kind of scheme has been implemented for example in Sweden, Norway, Netherlands and UK. It is often argued that the TGC scheme is a cost-efficient policy intervention, which maintains the stability and drive innovation and technology development, (Bergek & Jacobsson, 2010, p. 1256). Schröder et al. (2011, p. 9054) argue that TGCs should be adopted just before technology is fully competitive. Therefore, the support scheme could encourage deployment and development of the technologies, which can receive revenues from the TGC scheme. The principle of the TGC scheme is that the electricity supply is distinguished into certified production and non-certified production, (Schröder, et al., 2011, p. 9054). Certified production in this case could be renewable energy production including also the existing renewable capacity and a certificate is issued per produced electricity unit. The obligated buyers, such as electricity suppliers or retailers, must either purchase or produce certified electricity or buy a certain proportion of certificates from the certificate markets, (Bergek & Jacobsson, 2010, pp. 1255-1256).

It should be noted that both EU ETS and TGC schemes are based on creating an artificial market for CO2 emissions in the first case and certificated electricity in the latter case. Therefore, the design of the artificial market is affected always by political interests and the threat is that the artificial market guides the development to wrong direction and creates unintended economical inefficiencies. These support schemes can also be seen more vulnerable to unexpected events. For example the EU ETS is suffering from over-allocation of emission allowances causing low price of allowance and in addition the national support schemes are weakening the effectiveness of the efforts, (Partanen, et al., 2013, pp. 8-9). Therefore, the EU ETS is not guiding the development as expected. In the UK for example, a TGC scheme called renewables obligation was implemented in 2002 and as a result the renewable deployment increased, but not as expected, (Jacobsson, et al., 2009, p. 2144). The UK scheme supported deployment of mature technologies, mainly wind power, and instead of stimulating innovation on niche-level it stifled the technology development, (Wood & Dow, 2011, p. 2230).

6.2.5 R&D and Science

The technology development in the evolutionary transition path is more based on stepwise learning within wide scope in accordance with the developed vision as discussed in Chapter 6.2.4. The technology development in this transition path is presumably slower compared to the revolutionary transition path, (Schot & Geels, 2008, p. 549). This approach supports the technology development of renewable energy technologies, development of flexible generation technologies and storing technologies.

An example of stepwise learning and technology development of wind turbines was seen in Denmark starting from 1950s. A single Danish engineer developed a wind turbine design in the 1950s and due to pressures caused by the oil crisis in 1970s the design was contextualized again by different actors, for example by a carpenter and a mechanic who tested different materials in the blade design. By 1980 there were in total 10 Danish wind turbine firms, contributing the technology development. Their approach to technology development was very practical and they tended to solve the problems by making practical experiments and some inventions in the development emerged unintentionally. During the development a large amount of new knowledge emerged, which helped to improve the design gradually. As an outcome of the process, one of the still most contributing national wind turbine industries was emerged. (Garud & Karnøe, 2003, pp. 282-283, 285)

As in the Danish example, the landscape pressures open windows of opportunities and therefore it is assumed that the development of novelties in the niche-level is more extensive than in the revolutionary transition path. However, it should be kept in mind that all developed alternates will never accelerate and some of them are likely to die eventually. In turn, the harm caused by unsuccessful technology development occurs on smaller scales and abandonment of failed novelties is more convenient. For example in Germany in the 1970s and 1980s public funding was available to develop small or medium size wind turbines with different designs, (Jacobsson & Bergek, 2011, p. 48). The outcome of the efforts was creation of variety of new technical knowledge and some of it was exploited later commercially, but some of the developed knowledge was not utilized any longer, (Bergek & Jacobsson, 2003, pp. 11-13).

As Schot and Geels (2008, pp. 541-542) stress out that the contribution of networks is an important process in development of successful strategic niches. Therefore, it is assumed the open innovation approach is more dominant in this transition path. The open innovation concept means importing and exporting knowledge and ideas by organisations assuming that deliberate exchange of ideas leads to faster product development and more superior products, (Johnson, et al., 2011, pp. 191-192).

For example in Denmark the collaborative networks and contribution of variety of actors with different backgrounds is seen as an essential factor for the success. Suppliers to build components emerged and most of the actors involved were small or medium sized enterprises. These actors utilized each other's competencies and the knowledge was spread though whole innovation system. In addition, the of early adopters of wind turbines as "owner-users" were essential, since they started organizing regular wind meetings, which were helpful for sharing knowledge and experiences. (Garud & Karnøe, 2003, pp. 285, 288)

Furthermore, it is assumed that the incumbent actors start seeking opportunities close to their previous experiments in the evolutionary transition path and therefore, it assumed that the adopted innovations in this transition path are not as radical as in the revolutionary transition path, (Jacobsson & Bergek, 2011, p. 49). It is assumed that the contribution of existing small and medium sized enterprises as well as new entrants is more important than in the revolutionary transition path especially in the technology development. For example in Germany as a result of public funding available, a large number of actors, both incumbent actors and new entrants, decided to enter the wind power development and contributed to the experiments and already in the middle of 1980s there were almost 15 wind turbine suppliers and several other actors active in the wind power industry in Germany, (Bergek & Jacobsson, 2003, pp. 11-13).

Although the incentives in this transition path allow more flexible technology development within more flexible scope, the design of the regulative support scheme affects the scope of technology development. If the ETS is functioning as intended, the focus will be on developing CO2 neutral generation technologies and developing technologies to reduce CO2 emissions in the existing facilities while if the TGC scheme would be implemented, the actors will likely focus on developing certifiable renewable technologies.

6.2.6 Resources

In this transition path, the niches emerge through collective enactments, but it is assumed that the niches need some nurturing. Therefore financial incentives to develop desired technologies are likely required in addition to regulative incentives discussed in Chapter 6.2.4 and there should be financial support available for selected research and pilot projects However, the extent of available support should be less than in the revolutionary transition path in order to prevent too much protection and avoid creating suboptimal solutions, (Schot & Geels, 2008, p. 549).

Schröder et al. (2011, pp. 9052-9053) argue that financial support for research is the most appropriate when the costs and technological risk of technology development are high, but stress that these kinds of financial incentives cannot stand alone to support the long-term technology development. Therefore, also the regulative incentives are needed together with interpreted vision in order to maintain the direction of development. For example in Germany there was financial support like this available in the 1980s. Some of the supported projects were fruitful, but those who were not were not nurtured further, (Bergek & Jacobsson, 2003, pp. 10-12). Then, the German innovation system did not get locked into unsuccessful solutions.

As Schot and Geels (2008, p. 540) argue, the learning process in multiple-dimensions and building the social networks are essential factors of successful creation of strategic niches. For example in the Danish wind turbine development process the impended support scheme required certification of wind turbines through steering process and this requirement increased the interactions between the actors and enhanced the learning in multiple-dimensions, (Garud & Karnøe, 2003, p. 282). Therefore, in addition to support the knowledge development, the financial incentives should support the second-order learning meaning enabling cognitive changes and allow involvement of stakeholders from different backgrounds, (Schot & Geels, 2008, p. 541).

This transition path requires also ensuring that there are sufficient human resources available. Therefore, the focus in education in the technical educational institutes should support the development as well.

6.3 Development of the innovation system

The basic architecture of the innovation system is going to remain the same though the evolutionary transition path, but the landscape pressures and niche-innovations are expected to direct the development towards the vision, (Verbong & Geels, 2010, p. 1217). The development of the structural components of the TIS is discussed in Chapter 6.3.1 and the development of the functions of the TIS in Chapter 6.3.2.

6.3.1 Development of structural components of the TIS

The components of the TIS are changing incrementally though cumulative adjustments in the evolutionary transition path. The pressures from the landscape do not lead to erosion of the regime and most regime actors will survive though the transition, but some of them may die, be merged or taken-over during, (Verbong & Geels, 2010, p. 1217). The role of niche-actors is more contributing in this transition path and they act as front-runners whose activities and practices affect to regime rules, (Geels & Schot, 2007, p. 406). In this transition path, the market-based mechanisms are guiding the development under the interpreted more flexible vision and therefore, the accurate prognostication of the future TIS is more challenging compared to the revolutionary transition path.

In the evolutionary transition path, the renewable energy technologies deployed to the power system would at first be small-scale installations possibly with wide range of variations. These would not disturb the operation of the existing generation portfolio in similar way than in the revolutionary transition path, but due to regulative incentives the polluting generation capacity is phased out. Later, the unit-sizes of installations would increase gradually and presumably the number of variations could decrease.

As mentioned, the role of niche-actors is important in this transition path. They develop novelties by learning and making experiments and are at the forefront of the development. It is expected that their activities and practices will affect the institutions and networks of throughout the TIS and gradually change the regime rules, (Geels & Schot, 2007, p. 406).

The existing incumbent and high-power electricity suppliers and industrial electricity producers adopt the best fitting novelties based on cost-efficiency. It is assumed that they are also contributing the technology development by participating pilot-projects from the beginning of the transition. In the later part of the transition they are more likely to invest to large-scale renewable generation units, for example large-scale wind power parks, biomass gasification and combustion and CCS technologies, (Verbong & Geels, 2010, p. 1217). It is also assumed that also new small-scale electricity suppliers will emerge in the evolutionary transition path.

The role of research institutes may become more central especially in the collaboration network. It is assumed that they contribute in technology development with other actors and support the knowledge diffusion through the TIS.

The retailers may be more motivated to implement demand responses in this transition path due expected growth of price spikes. By doing it gradually, they have also time for learning-by-doing and adopting of new practices and it is likely that they are less resistant to change. However, their power in the TIS is expected to remain the same than nowadays. The electricity consumers’ role becomes more active in this transition path as well, but their power in the TIS may remain low.

As in the revolutionary transition path, the TSO and DSOs are required to invest to the grid infrastructure substantially and the maintenance and service suppliers' role is expected to remain the same, but they must adopt new practices related to new technologies. The role of labor unions, EU, national and local authorities and media are assumed to remain the same. The power of fossil fuel suppliers will decrease further in this transition path, but the power of bioenergy suppliers may increase in the evolutionary transition path.

As a summary, the most changes in the set of actors are expected to occur in the groups of new entrants developing novelties in the niche-level and in the electricity suppliers. The power of current incumbent and strong actors may decrease due to emergence of new small-scale suppliers.

The niche actors influence the most the development of institutions and networks of the TIS. The regulative institutions are affected by implemented regulative incentives, but it is assumed that the cognitive and normative institutions are most shaped by the most successful niche-actors, who also shape the development of networks, especially collaboration and buyer-supplier networks. The development of networks in this transition path is more important than in the revolutionary transition path, since otherwise the diffusion of knowledge through the TIS does not work.

6.3.2 Development of functions of TIS

The interpreted flexible vision and the regulative incentives as well as regime pressures shape especially the function *influence on direction of search*. This function is not changed immediately in the beginning of the transition, but gradually and the niche-actors can be seen as actors who shape this function most.

The scope of *knowledge development* function is wider in the evolutionary transition path and therefore, it is expected that variety of new knowledge emerge.

However, the existing actors will presumably search opportunities close to their previous experiments in accordance with the function *influence on direction of search*, (Jacobsson & Bergek, 2011, p. 49). The pace of this function is slower than in the revolutionary transition path, but more opportunities are likely to pop up. Furthermore, *knowledge diffusion* though the TIS is expected to more extensive due to more active collaboration network.

The function *influence on direction of search* supports also courageous *entrepreneurial experimentations*. The niche-actors are likely to do more small-scale experiments especially if there are sufficient financial incentives for spreading the risk of failure. The incumbent actors are likely to be risk-averse and the financial incentives are important factor to get them involved, (Jacobsson & Bergek, 2011, p. 48). The vibrant experiments reduce the uncertainty, when the developed ideas and knowledge are probed into applications, (Bergek, et al., 2008, pp. 415-416). Some of these experiments are likely to be unsuccessful, but nevertheless they contribute to the *knowledge development.* Furthermore, the number of new firms entering the TIS is likely to be higher in the evolutionary transition path and thus, the function *Development of positive externalities* is expected to be strong.

Speed of *market formation* function is slow in the evolutionary transition path. The incentives support this function, but the function is not boosted artificially as in the revolutionary transition path. Since the transition is boosted more bottom-up approach, it is assumed that the niche-actors developing novelties and deploying small-scale installations communicate actively with relevant stakeholders, (Wood & Dow, 2011, p. 2230). Therefore, social acceptance for new technologies is expected to meet less resistance and the *legitimation* function is smoother, but slower in the evolutionary transition path.

The *resource mobilization* function is not boosted by massive support schemes in the evolutionary transition path, but providing smaller-scale financial incentives for technology development. Due to landscape pressures and interpreted vision to guide the direction of development, it is assumed that there is more private funding available for technology development. *Legitimation* function in the evolutionary transition path supports further the resource mobilization, since it supports the mobilization of additional resources, (Hellsmark, 2011, p. 31).

In Finland, the main challenge may be find sufficient number of actors to be involved both in *knowledge development* and *entrepreneurial experimentation* functions in the whole value chain, (Jacobsson & Bergek, 2011, pp. 47-48). For example this was the problem in the case generating second-generation biofuels in Finland when too few actors were involved conducting experiments, (Jacobsson & Bergek, 2011, p. 48). Another potential challenge may be to ensure the direction of development towards the predetermined vision guided by the market-based mechanisms.

6.4 Lock-ins of the socio-technical regime

The changes that occur in the socio-technical regime, such as in actors, institutions and networks, are more likely to be a continuation from the current situation towards the vision, (Verbong & Geels, 2010, p. 1217). It can be seen that the most contributing lock-ins in the evolutionary transition path are the same than in the revolutionary transition path as discussed in Chapter 5.4. It is assumed that the most contributing lock-ins in this case are also potential institutional mismatches, issues related to social acceptance of new technologies and existing technical structures, (Geels, 2004, pp. 910-911). However, due to incremental nature of transition they form barriers to transition less likely.

In the evolutionary transition path the institutions are more likely to be adjusted gradually in a natural way and it is less likely that are significant mismatches in the institutions. For example, the legislation has better chances to keep track on the technology development and adjust itself before major misalignments emerge.

Since the deployment of new technologies is more incremental, public opinion has more time to adjust the changes and technologies have also more time to gain their social acceptance. It is assumed that when deployment starts from smaller-scale installations, the benefits and positive externalities can be demonstrated for relevant stakeholders more clearly and thus, the social acceptance does not likely form such a significant lock-in than in the revolutionary transition path.

The niche-innovations do not disturb the basic architecture, but the regime pressures aim to phase out the fossil-based generation in the evolutionary transition path, (Verbong & Geels, 2010, p. 1217). Then, the executed investments are not destroyed by crowding out these technologies and the existing material structures and technical systems are not seen a contributing lock-in. The technology development in this transition path has more space for learning-by-doing and learning-by-using and thus, it is likely that the technologies developed in this path have higher economies of scale than in the revolutionary path.

The niche-innovations in this path are not boosted artificially to overcome the lock-ins as in the revolutionary transition path. Therefore, it is assumed that those innovations who manage to overcome the lock-ins are likely to survive without for example subsidy schemes.

7 MARKET VALUE OF GENERATION TECHNOLOGIES IN THE FUTURE

The development of market value of generation technologies is affected by the generation costs and wholesale price development as introduced in Chapter 3.4. Substantial proportion of current dispatchable capacity will exit the market during this and next decades. Due to increasing share of inflexible generation capacity, it is important that investments in especially flexible generation capacity are made. This section aims to analyze how the generation costs of technologies assessed in Chapter 4.9 would develop in the evolutionary transition path and revolutionary transition path.

Chapter 7.1 discusses the generation cost development of intermittent technologies by viewing how different mechanisms of technology development affect the generation costs and how integration costs introduced in Chapter 3.4.1 of variable renewables develop. In Chapter 7.2 generation costs of dispatchable power plants are assessed from present-day investor's perspective. Development of wholesale prices in the alternate transition paths are discussed in Chapter 7.3 by analyzing how merit-order develops in the future. Finally, the findings are discussed in Chapter 7.4.

7.1 Intermittent generation costs

Intermittent generation is seen as prioritized supply and thus its generation costs are mostly affected by the investment, operation and maintenance costs as well as the weather conditions at the site location. In this study, the most interesting case is the development of costs and different technology development mechanisms affecting to cost reduction and development of integration costs. Chapter 7.1.1 focuses on cost development in the revolutionary transition path and Chapter 7.1.2 focuses on evolutionary transition path.

7.1.1 Revolutionary transition path

In the revolutionary transition path, the technology development is boosted by subsidies and therefore, large scale deployment of intermittent technologies is expected to occur by 2020. The subsidies in this case study are targeted for non-competitive intermittent technologies and therefore, the LCOE of these technologies is presumably high, consisting of investment and operation and maintenance costs.

Due to relatively narrow scope of learning-by-searching and little available user feedback during the technology development phase, the generation costs are likely high especially in the beginning of transition. Potential improvements in product design, for example in efficiency or potential life-time extension of technologies may be neglected to some extent in the revolutionary transition path. However, the manufacturing and OM processes are more repetitious in the revolutionary transition path and therefore, the generation costs are expected to decrease due to improved and more efficient manufacturing and OM processes by learning-by-doing and higher economies of scale. Also the upsizing of technology decreases the unit costs of investment decreasing the investment costs in LCOE. (Junginger, et al., 2006, p. 4026)

All integration cost components, grid, balancing and profile costs, introduced in Chapter 3.4 increase substantially especially in the beginning of the transition. The grid costs increase due to required investments for transmission infrastructure as introduced in Chapter 5.2.3 and balancing costs increase because it is expected that forecast errors occur especially in the beginning. However, the power system adopts response mechanisms, such as demand response, and thus, the balancing and profile costs are expected to decrease later during the transition. (Ueckerdt, et al., 2013, pp. 65-67)

The development of LCOE level of intermittent technologies and integration costs in the revolutionary transition path are summarized in Table 7.1.

Table 7.1 Development of integration and LCOE level of deployed new technologies in the revolutionary transition path.

	Deploy-ment	Integration costs			Efficiency	LCOE		Integration costs and LCOE
		Grid	Balancing	Profile		Investment costs	OM costs	
Present	Low	Low	Low	Low		High	High	High LCOE, low integration costs
Present-2019	Substan-tial in-crease	Substan-tial in-crease	Substan-tial in-crease	Substan-tial in-crease	No signifi-cant increase	Remain high, but decrease due to upsizing, higher economies of scale and learn-ing-by-doing	Remain high, but decrease due to learning-by-doing	High LCOE, high integration costs
2020-2024	High	-	Decrease due to adopting response	Decrease due to adopting response	No signifi-cant increase	Decrease	Decrease	Decreasing LCOE, integra-tion costs de-crease at some extent
2025-2029	High	-	Decrease due to adopting response	Decrease due to adopting response	No signifi-cant increase	Decrease	Decrease	Decreasing LCOE, integra-tion costs de-crease at some extent
Vision 2030	High	-	Higher than nowadays	Higher than nowadays	Similar than nowadays or slightly better	Lower than nowadays, but still relatively high	Lower than nowadays	Lower LCOE, but higher integra-tion costs than nowadays

As seen in Table 7.1, compared to current LCOE level of technologies deployed in the revolutionary transition path, the LCOE is expected to be lower finally, but the integration costs are going to be higher than nowadays. Although the technology development has been boosted by subsidizing in this transition path in order to make technology competitive in terms of costs rapidly, it can be seen that developed technology may not achieve as low cost price level than in the evolutionary transition path. The integration costs are at highest straight after intermittent technologies have been deployed, but later they decrease incrementally.

7.1.2 Evolutionary transition path

The deployment of intermittent generation technologies in the evolutionary transition path is incremental and the technology development is more stepwise. In this section the generation costs of those technologies which are developed within the TIS during the evolutionary transition path are assessed assuming that these technologies are intermittent.

It is expected that the generation costs of developing technologies will remain high in the beginning of the transition due to more customized manufacturing of technologies, small unit sizes and lower economies of scale. However, the learning-by-searching and learning-by-using are more extended in this transition path. These allow wider search of opportunities and gaining user feedback from experiments and pilot projects, which presumably lead to continuing improvements in the technology development. Neij (2008, p. 2200) argues that the costs of small modular units decrease more likely than the unit cost of large non-modular units and thus, it is expected that the generation costs will decrease rapidly in this transition path. Furthermore, when the viable alternates are adopted by the regime, the focus of cost reduction is likely to shift from learning-by-searching and -using to learning-by-doing, upsizing and higher economies of scale. Finally, it is assumed that the technologies developed in this transition path are likely to be for example more efficient in terms of electricity conversion efficiency within the theoretical limits and use of materials and have longer technological lifetimes. (Junginger, et al., 2006, p. 4026)

The integration costs increase incrementally in the evolutionary transition path. The grid costs increase as the deployment of intermittent technologies increase. The balance and profile costs increase, but due to incremental adaptation of demand response they do not increase suddenly to high levels.

The development of LCOE level of intermittent technologies and integration costs in the evolutionary transition path is summarized in Table 7.2.

Table 7.2 Development of integration and LCOE level of deployed new technologies in the evolutionary transition path.

	Deploy-ment	Integration costs			Efficiency	Investment costs	OM costs	Integration costs and LCOE
		Grid	Balancing	Profile				
Present	Low	Low	Low	Low		High	High	High LCOE, low integration costs
Present-2019	Moder-ate increase	Moder-ate increase	Moder-ate increase	Moder-ate increase	Low, but rapid increases	Remain high, but decrease due to learning-by-searching, learn-ing-by-using and learning-by-interacting	Decrease	High LCOE, integration costs increase
2020-2024	Increase	Increase	Remain moder-ate, due to adopt-ing response	Increase moder-ately due to adopt-ing response	Increas-ing	Close to competi-tive due to tech-nology develop-ment	Decrease	LCOE decrease, integration costs remain moderate
2025-2029	Increase	Increase	Remain moder-ate, due to adopt-ing response	Remain moder-ate, due to adopt-ing response	Increas-ing	Presumably competitive due to technology development	Decrease	LCOE decrease, integration increase
Vision 2030	High	High	Increased	Increased	Increased signifi-cantly	Low	Low	Low LCOE, in-creased integra-tion costs

As seen in Table 7.2, the LCOE level of technologies developed in this transition path will remain high in the beginning of transition and then start to decrease at some point. The integration costs increase incrementally during the transition, but it is assumed there is simultaneous adaptation of response curbing them. Therefore, the LCOE level of the intermittent technologies in the end of this transition timeframe is expected to be lower than nowadays, but the integration costs will increase at some extent.

7.2 Dispatchable generation costs

Range of dispatchable technologies is wide; there are conventional condensing and CHP technologies used as peak and flexible supply, gas turbines used in peak supply and hydro power, which can be used as flexible or peak load supply depending on storing possibilities. In this section the cost development of these technologies compared to 2014 price level are analyzed.

Generation costs of hydro power are the lowest and it is expected that utilized as much as possible and its use as peak load supply may increase if for example pumping power possibilities are introduced in Finland. The viability of pumping power depends on wholesale price development, since the electricity must be purchased when the wholesale prices are low and supplied when the prices are higher. Thus, especially in the revolutionary transition path it is unlike that use of pumping power is profitable due to low wholesale prices as will be discussed in Chapter 7.3. However, it is unlike that run-of-river hydro power generation costs are going to change substantially in the future.

Nuclear power is located in the front of merit order and therefore, it is expected that nuclear power generation is maximized also in the future, (Nord Pool Spot, 2014a). Furthermore, nuclear power control possibilities are restricted by operational regulations in Finland, which restrict using nuclear power as flexible capacity, the full-load operation hours of nuclear power plants are expected to remain high, (ÅF-Consult Ltd, 2012, p. 20). Therefore, the costs of nuclear power are going to remain in the current level and the fuel costs are remaining low compared to other costs.

Other thermal generation than nuclear power the costs are strongly affected by development of fuel prices and CO2 allowances as well as yielded electricity. The coal prices are going to increase to some extent, but will remain inexpensive compared to other fossil fuel prices. Oil prices are going to increase as previously and use of distillates in electricity generation is feasible only in the peak supply generation. Natural gas prices in the future may remain either in the current price level or increase. The development of natural gas prices depend on utilization potential of shale gas on global level and future development of infrastructure for liquefied natural gas on national level, (Gasum, 2014b). The development of biomass fuels is very local and depends on the primary use of biomass material, but in general no substantial increase is expected compared to current costs. (Kost, et al., 2013, p. 15)

The CO_2 emission allowance prices in EU ETS are expected to increase in this and following decades compared to current price of less than 6 €/t CO_2, (Finnish Energy Industries, 2014a). Kost, et al., (2013, p. 15) estimates that prices are between 17 and 22 €/t CO_2 in 2020 and between 28 and 42 €/t CO_2 in 2030. International Center for Climate Governance (2013, p. 4) anticipated that the CO_2 allowance price will not exceed 20 €/t CO_2 by 2020. A questionary survey made by Thomson Reuters Carbon Point concluded that the CO_2 allowance price would increase 9 €/t CO_2 in 2020, (Finnish Energy Industries, 2014a). However, the carbon costs of generation are expected to be higher than nowadays, but the magnitude of cost increase has great uncertainty and it depends on whether the efforts to stabilize the EU ETS mechanism are successful enough.

In case of capital intensive thermal base and flexible supply, the LCOE level is highly dependent of yielded electricity as was seen in Chapter 4.9.3. Nowadays the district heating CHP or conventional condensing capacity often represents the last required generation to fulfill the demand and thus, this generation may not be needed in the future when the intermittent generation is substantial and nuclear power capacity is likely higher, (Nord Pool Spot, 2014a). Therefore, the operation hours of thermal capacity other than nuclear power is likely to decrease in the future.

The LCOE level as function of full-load operation hours is shown in Figures 7.1-7.3 in order to illustrate how the generation costs increase when the full-load operation hours decrease from the present full-load operation hours shown in Table 4.3. It should be noted that electricity generation in district heating is not determined by the heat demand, since the separate heat generation is possible in the most district heating plants and if the wholesale prices of electricity are low there may not be rationale to generate electricity at all. Thus the full-load operation hours of electricity generation may decrease in district heating CHP plants as well.

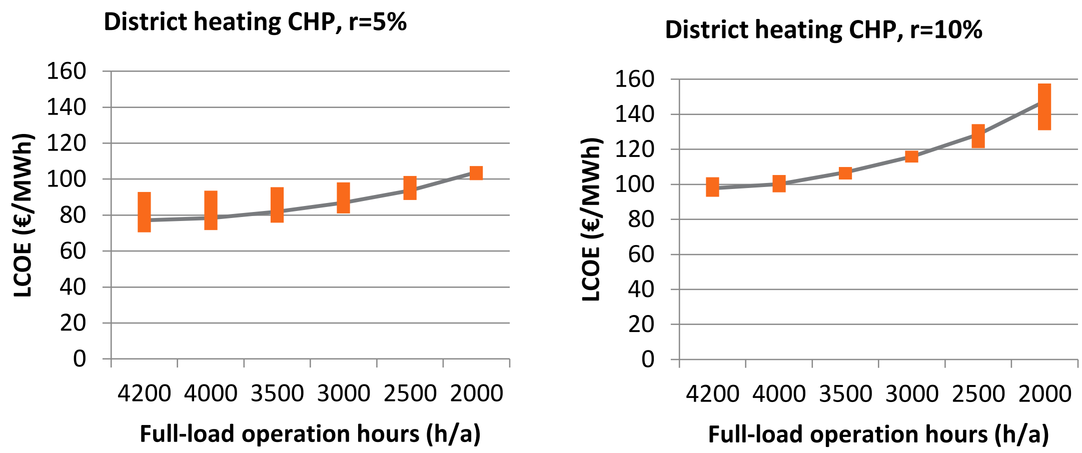


Figure 7.1 Development of LCOE level of district heating generation technologies when the full-load operation hours are reduced. Parameter *r* corresponds to interest rate.

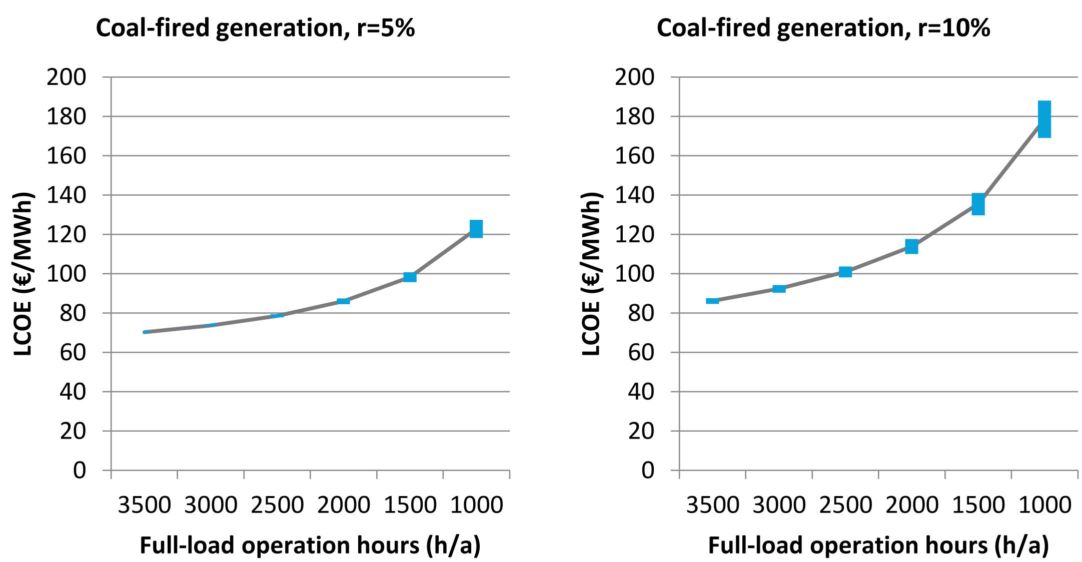


Figure 7.2 Development of LCOE level of coal-fired separate generation technologies when the full-load operation hours are reduced. Parameter *r* corresponds to interest rate.

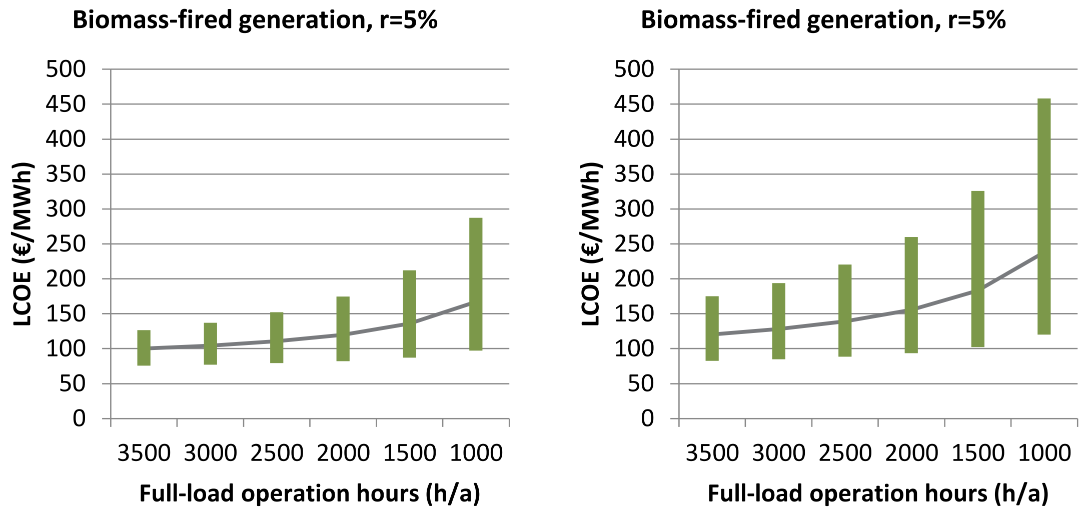


Figure 7.3 Development of LCOE level of biomass-fired separate generation technologies when the full-load operation hours are reduced. Parameter *r* corresponds to interest rate.

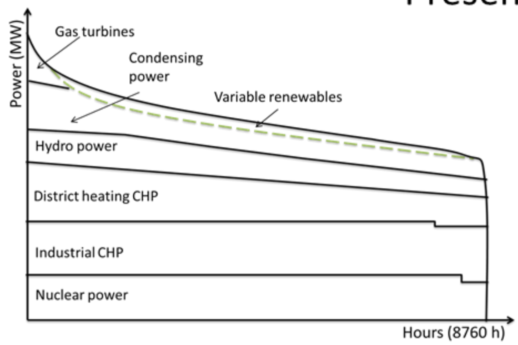
As seen in all Figures 7.1-7.3, the generation costs of considered flexible thermal generation increase substantially when the full-load operation hours are reduced. The timing and magnitude of full-load hour development are different in the alternate transition paths and discussed in following chapters.

7.2.1 Revolutionary transition path

In order to visualize the development of generation capacity in the alternate transitions, illustrative residual load duration curves are constructed. As introduced in Chapter 3.3, the residual load duration curve denotes the non-intermittent generation from the load duration of consumption and qualifies the demand of dispatchable generation capacity.

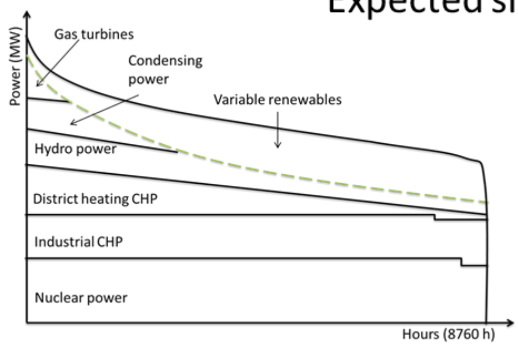
The development of generation portfolio in terms of residual load duration curve in the revolutionary transition path is shown illustration in Figure 7.4.

Present situation



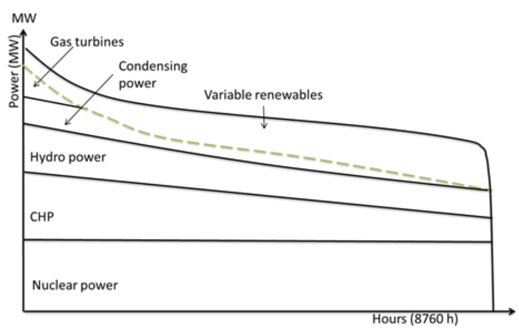
Deployment of variable renewable capacity is minor. Nuclear and CHP capacities represent the base supply, conventional condensing and hydro power represent the flexible supply and peak supply is mainly represented by gas turbines. Net-imports also exists in each consumption level. Demand is mainly inflexible.

Expected situation in 2020



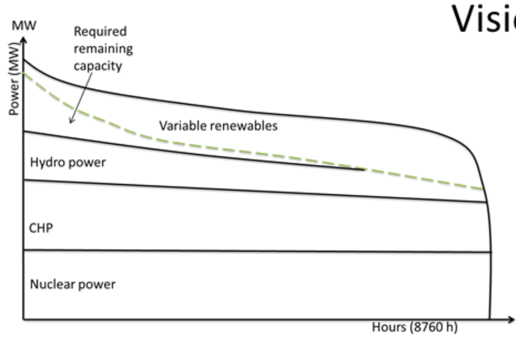
By 2020, substantial proportion of intermittent generation capacity has been deployed to the power system. The residual capacity has likely remained same, although some conventional condensing capacity has left the market and OL3 is likely operating. Demand response is still minor. Operation hours of flexible thermal capacity are likely decreased. Net-imports are decreasing.

Expected situation in 2025



Between 2020 and 2025, the main changes that investments are made for flexible thermal capacity, but their operation hours are still low. Role of demand response in the power balance maintenance is getting more important. Additional new nuclear power plant unit may be operating by 2025 and the nuclear power capacity would be higher than ever. Net-imports are decreasing.

Vision 2030



In 2030, renewables represent 45% of the supply and the net-imports are negative. LO1&2 have been decommissioned and nuclear power capacity has thus decreased. Remaining power generated by hydro power, CHP, conventional condensing plants and gas turbines. Demand response contributes to significant extent in power balance maintenance.

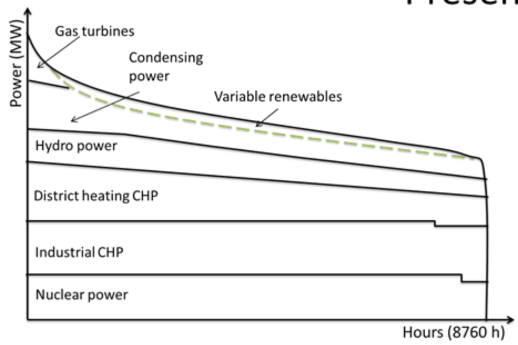
Figure 7.4 Illustration of residual load duration curve development in revolutionary transition path. Green dash-line in the illustrations represents the residual load duration curve.

As seen in Figure 7.4, the substantial deployment of intermittent capacity in the revolutionary transition path declines the operation hours of flexible thermal capacity within short time period, but otherwise the load duration curve is not changed significantly by 2020. Later it can be seen that the load duration curve is adjusted by demand response. In the illustration, it can be seen that especially the yielded electricity in conventional condensing and district heating CHP plants decrease by 2020 and thus, the LCOE level presumably increases from present-day investor’s perspective. There are two factors that affect most to the rapid decline of operation hours that are deployment of intermittent generation capacity and increasing share of nuclear power.

7.2.2 Evolutionary transition path

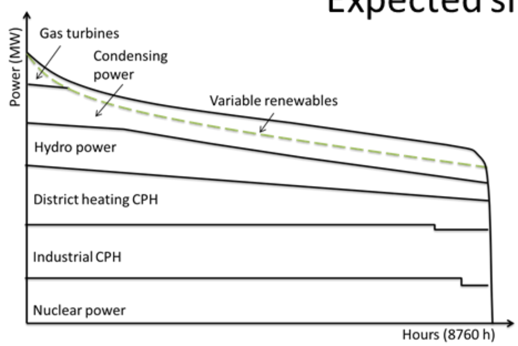
Similar illustration of residual load duration curve development in the evolutionary transition path is shown in Figure 7.5.

Present situation



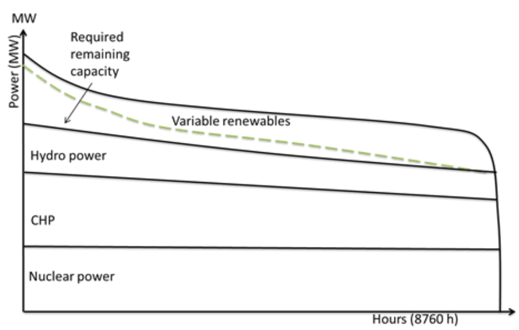
Deployment of variable renewable capacity is minor. Nuclear and CHP capacities represent the base supply, conventional condensing and hydro power represent the flexible supply and peak supply is mainly represented by gas turbines. Net-imports also exists in each consumption level. Demand is mainly inflexible.

Expected situation in 2020



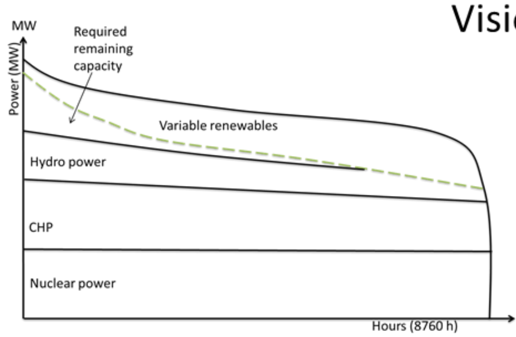
By 2020, the proportion variable renewable capacity has increased and it has declined the operation hours of especially fossil fuel-fired generation due to more efficiently operating EU ETS. The residual capacity has likely remained same, although some conventional condensing capacity has left the market and OL3 is likely operating. The role of demand response is still minor.. Net-imports are decreasing.

Expected situation in 2025



Between 2020 and 2025, the proportion of variable renewable capacity has increased further. There may be scarcity of flexible capacity to some extent and thus, role of demand response in the power balance maintenance is getting more important. Additional new nuclear power plant unit may be operating by 2025 and the nuclear power capacity would be higher than ever. Net-imports are decreasing.

Vision 2030



In 2030, renewables represent 45% of the supply and the net-imports are negative. LO1&2 have been decommissioned and nuclear power capacity has thus decreased. Remaining power generated by hydro power, CHP, conventional condensing plants and gas turbines. Demand response contributes to significant extent in power balance maintenance.

Figure 7.5 Illustration of residual load duration curve development in evolutionary transition path. Green dash- line in the illustrations represents the residual load duration curve.

As seen in Figure 7.5, the share of intermittent capacity increases incrementally in this transition path. Thus the operation hours of flexible thermal capacity does not decline as radically as predicted, however, it is presumed that the operation hours of conventional condensing and district heating CHP are going to decline due to increasing share inflexible capacity. Therefore, the generation costs of flexible thermal capacity are going to increase incrementally and the investments for this capacity do not look very attractive from present-day investor's perspective either in this transition path.

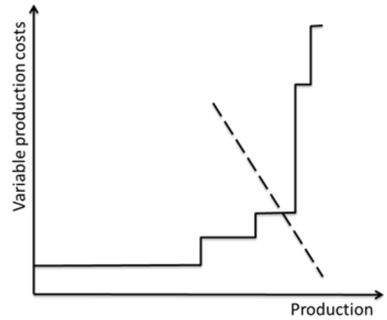
7.3 Wholesale price development

As introduced in Chapter 3.3, the hourly wholesale prices in the Nordic electricity market are determined by the base electricity demand, the demand elasticity and the availability of power plants. Thus, the development of generation capacity affects the development of wholesale prices, which are discussed in Chapter 7.3.1 in terms of revolutionary transition path and in Chapter 7.3.2 in terms of evolutionary transition path.

7.3.1 Revolutionary transition path

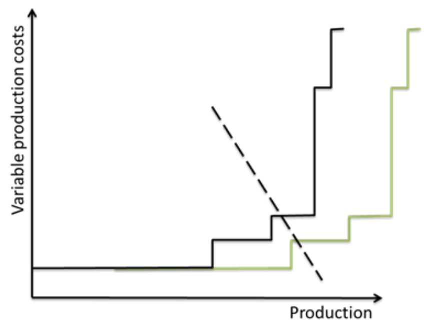
An illustration of merit-order development in the revolutionary transition path is shown in Figure 7.6.

Present situation



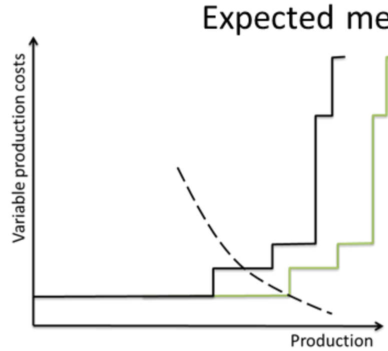
In the most hours the market price is determined by conventional condensing power or district heating CHP in the merit-order. Variable renewable deployment is not significant and thus, merit-order effect does not occur. Demand is not very flexible.

Expected merit order in 2020



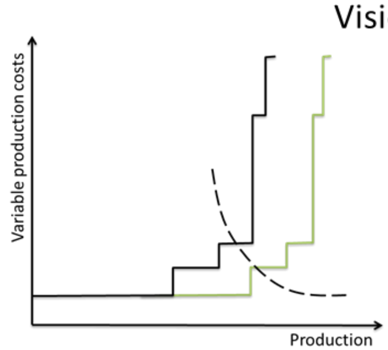
Due to substantial deployment of variable renewable capacity, merit-order effect occurs in hours when the intermittent generation is substantial causing merit-order effect. Also the increasing nuclear power capacity decreases wholesale price, when it is assumed that OL3 is operating. Demand is still quite inflexible.

Expected merit order in 2025



Merit-order effect occurs still and wholesale prices remain low especially if nuclear power capacity increases further. Demand becomes more flexible and adopting demand response can be seen as more curve-shaped demand.

Vision 2030



Merit-order effect occurs, but demand has become even more flexible. Due to decommissioning of LO1&2 the wholesale prices will likely increase.

Figure 7.6 Illustrative development of merit-order in the revolutionary transition path. Solid black line represents the merit-order when the intermittent generation is marginal and the green line represents the merit-order when the intermittent generation is substantial. Black dash line represents the demand and intersection of supply and demand curves determines the hourly wholesale price.

As seen in illustration in Figure 7.6, the merit-order effect caused by intermittent generation is expected to occur by 2020 decreasing the average wholesale prices. Also the increasing nuclear power capacity is expected to decrease the wholesale prices further. Later, the demand response is expected to affect the wholesale prices, but in general the wholesale prices are expected to remain low as seen in Figure 7.6.

7.3.2 Evolutionary transition path

Similar illustration of merit-order development in the evolutionary transition path is shown in Figure 7.7.

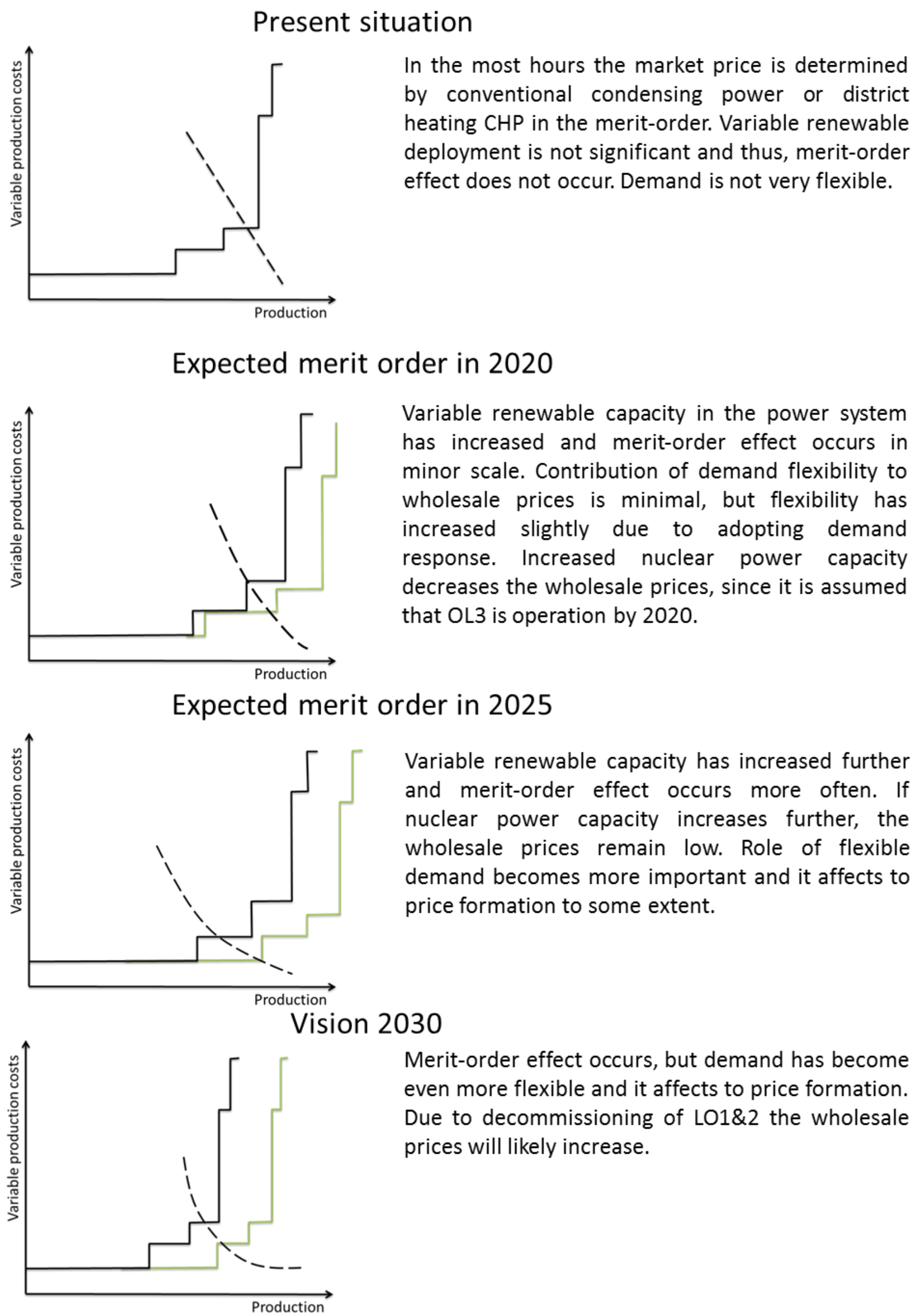


Figure 7.7 Illustrative development of merit-order in the evolutionary transition path. Solid black line represents the merit-order when the intermittent generation is marginal and the green line represents the merit-order when the intermittent generation is substantial. Black dash line represents the demand and intersection of supply and demand curves determines the hourly wholesale price.

As seen in Figure 7.7, the merit-order effect is expected to occur in the evolutionary transition, but in less extent than in the revolutionary transition path. Thus, the wholesale prices are not expected to decrease rapidly, but more incrementally.

7.4 Findings

In general, the development of generation costs of dispatchable generation is affected by development of fuel and emission allowance prices and full-load operation hours. The generation costs of intermittent generation is affected by technology development mechanisms. Technology development mechanisms affect also the generation costs of dispatchable generation, but since those technologies are more mature the cost are not going to decrease as significantly anymore. However, most of the changes in the generation costs are going to occur most likely in the capital-intensive dispatchable generation units.

In the revolutionary transition path, the LCOE level of flexible thermal capacity, which is vital in the power balance management, increases and the wholesale prices are expected to decrease. Therefore, first it is unlike that investments for flexible thermal capacity are going to be executed under current distortions and second it is likely that actors may consider decommissioning existing plants prematurely. Interest to implement capacity remunerative mechanisms is likely to rise during this transition path in order to ensure sufficient revenues for this type of generation.

In the evolutionary transition path the costs of flexible thermal generation are expected to increase gradually and the merit-order effect expected to occur but to less extent than in the revolutionary transition path. From present-day investor’s perspective the investments for flexible thermal capacity are slightly more attractive in the evolutionary transition path than in the revolutionary transition path, but however the profitability of investment projects are still not certain. Furthermore, the full-load operation hour development depends on the penetration of intermittent renewable generation as well as on the development of nuclear power capacity. In this transition path price spikes may occur due to scarcity of generation at some points and thus operation and investments of peak load supply, such as pumping power may be more profitable. Due to these developments these technologies may seem more attractive from present-day investor's perspective.

8 DISCUSSION

The alternate transition paths assessed in this case study demonstrate two extreme example cases and the purpose of the analysis was not to create the future but help to understand the present and tomorrow situations and illustrate the side-effects and knock-on effects of activities interventions to electricity markets. The purpose of this section is to discuss the applicability of applied method and the findings of the case study. The suitability of method and its strengths and weaknesses are discussed in Chapter 8.1 Findings of the case study are discussed in Chapters 8.2-8.5 alongside answering the research questions given in Chapter 1.2. Finally, recommendations are given in Chapter 8.6.

8.1 Methodology implications

This section discusses the applicability of applied methods in case study. The implications of TIS analysis used in industry analysis are discussed in Chapter 8.1.1 and implications of transition analyses and tools applied are reviewed in Chapter 8.1.2. Finally, the economic evaluation method observations are discussed in Chapter 8.1.3.

8.1.1 Industry analysis

Innovation system analysis by applying the framework provided by Bergek, et al., (2008, pp. 410-411) illustrated the dynamics of electricity supply industry and provided a comprehensive picture of present situation. Originally, the TIS was designed to serve researcher and policy makers to assess the functionality of an innovation system and define process goals and policy issues, (Bergek, et al., 2008, p. 408). Advantage of the applying framework is that it aims to address the goodness of the innovation system functionality instead of just defining the structural components and status of functions.

In this case study, the framework served its purpose well although any interactive method involving relevant stakeholders were not applied. However, it should be kept in mind that the outcome of the analysis always depends on analysts' mindset and point of view to some extent.

8.1.2 Transition analyses

The technology roadmap tool is a strategy and planning tool, which can be used at several levels and for various time scales, and was applied in this case study as an illustration tool of the transition analyses, (Phaal & Muller, 2009, p. 39). The difference between the transition paths was seen in the illustrations; the revolutionary transition path is more sequential and the evolutionary transition path the changes are more gradual and simultaneous. In this case study, it was used together with the TIS discussion. The technology roadmap tool classified the activities to layers and pointed out required interventions and possible side-effects. This was supplemented by the discussion of development of innovation system by using the TIS, which illustrated how the dynamics within the industry develop in the alternate transition paths, although only just the development of structural components and functions were considered. Therefore, that applying just roadmaps would not have described the development of dynamics of industry systematically.

Although the dynamic multi-level perspective of technical transition played role only in the background of the analysis, understanding the terms and notion of it were vital in this case study. As mentioned, the problem of multi-level perspective is that it is very general theory and emphasizes the role of niche level. The perspective is rather an illustration tool and thus could not have been standing alone in the analysis.

The most biases in this case study are related to lack of relevant stakeholders' presence due to limited resources. Using some interactive methods would have added value to generating roadmaps, but however it is assumed that conclusions of the case study would have been similar.

In this study, the timeframe of the transition analysis was less than two decades, which represents the schedule of achieving EU energy targets. As Jacobsson & Bergek (2011, p. 43) address, the time scale of technology development from the first experiments to state when the technology has impact on the market is number of decades and in electricity sector the time scale is often unusually long. Therefore, it is less likely that unforeseen radical changes are going to occur within this short timeframe in the electricity supply industry within such short time period and the future is manageably anticipated.

8.1.3 Economic value assessment of technologies

The economic value of generation technologies was viewed by evaluating the generation costs using LCOE method and the wholesale prices of electricity and their development from present-day investor's perspective in order to supplement the qualitative analysis. The generation cost tool LCOE and its assessment supported the qualitative analyses in this study and confirmed the findings of low revenue opportunities from the electricity supply business. However, it should be kept in mind that the outcome of quantitative analysis is always dependent on chosen input values and thus the final result depends on quality of the data. In this study, the data were gained from multiple sources, which can be seen as weak point of the study and data acquisition from less sources would have given more uniform results.

The qualitative analysis method applied in this study does not consider non-pecuniary externalities, such as environmental externalities, comprehensively. As Borenstein (2012, p. 81) addresses all sources of energy have local environmental implications, which are not appeared in the LCOE. These are for example local pollutants affecting the quality of air in thermal generation, low-frequency thumping caused by wind turbines disturbing local inhabitants and changes in ecosystem caused by hydro power constructions, (Borenstein, 2012, pp. 79-81). Environmental implications of CO2 emissions are represented by costs of carbon in the LCOE, which are determined by the emission allowance prices. However, the emission allowance price is based on artificial market and thus the carbon cost does not fully correspond to harm caused by CO2 emissions.

The wholesale price development was discussed by illustrating how merit-order would develop as a knock-on effect of interventions. Any detailed quantitative assessment method was not applied to anticipate the development of future wholesale price development in the both transition paths but the discussion of the development by applying merit-order illustration points out the conclusion. In general, it was anticipated that the average wholesale prices are going to decrease in the future due to merit-order effect but existence and magnitude of price speaks depends on how the generation structure and capacity develops.

In this study only purely economic assessment was considered by using LCOE but according to triple bottom line thinking, there are also environmental and social aspects that affect the investment decision at some extent. These were not considered in this study, but it is assumed that from investor’s perspective the profitability of an investment is the most contributing factor determining if the investment is executed or not.

In general, the LCOE level of future technologies is much depend on technology development activities currently and in the short-term future. Aim of the study was not to forecast the accurate LCOE level in the future, but rather give a foresight of cost development and identify factors affecting into it. Ambiguities related to future limit applicability of LCOE significantly and thus giving exact price tags of future technologies is not feasible. The mechanisms affecting to technology development identified by Junginger, et al., (2006, p. 4026) represented often by experience curve approach do not emphasize the fact that technology development and cost reduction require real actions and efforts. Sometimes it may be implied that technology just evolves over time and fact that something needs to be done to get technology developed may be given less priority.

8.2 Findings of the industry analysis

This section discusses the findings of the performed industry analysis in Chapter 4. It addresses the secondary research question "*What is the state of the present energy innovation system in chosen spatial domain and how it affects the current electricity generation cost level from the perspective of investors?"* The main observation of the industry analysis in Chapter 4 was the weak profit opportunities from the electricity supply business due to relatively low wholesale prices. From present-day investor's perspective the generation costs are high and thus, the profitability of investments is unlike.

It can be argued that reasons leading to the this situation are the structure of existing capacity, which consist of large and fairly old generation units mainly, availability of low-priced imports and which has remained at the more or less same level the past ten years, (Finnish Energy Industries, 2014b, p. 2). It looks that in the future the share of inflexible nuclear power and intermittent capacity is higher. Thus, the main concern is the sufficiency of flexible generation capacity in the future.

Most of the key players in the electricity supply industry in Finland are incumbent actors and they have significant impact on institutions and networks as well as status of current functions. These actors have developed co-evolutionary with the technology and with each other over decades. It can be argued that the power and high economies of scale, these actors as technologies and organisations form a great barrier of entry for prospective new entrants in terms of technologies and organisations.

From the present-day investor's perspective the attractiveness of an investment depends on the price tag of investment, operation and maintenance expenses and future development of fuel prices, emission allowance prices and the opportunities of yielded electricity. As an answer for secondary research question *"What is the influence of input factors in the LCOE calculations?"* the influence of factors depend on role of a generation unit in supply; whether the unit represent base, flexible, peak or prioritized supply and the development. Generation technologies, which represent base and flexible supply, are often capital intensive technologies. Thus, the single most contributing factor of LCOE level is the full-load operation hours, but also the fuel and CO2 allowance prices and their future development affect the costs of generation. For peak supply, the LCOE level of the fuel prices and their development determine the LCOE and utilization of those technologies reasonably requires high momentary wholesale prices. The wind and solar power represent prioritized supply, which generation costs highly depended on investment costs and convenience of weather conditions locally.

8.3 Findings of the transition paths

This section addresses the secondary research questions "*What are the differences in the development of innovation system between the evolutionary transition path and revolutionary transition path?*" and *"What kind of control mechanisms are required in order to reach the regulative EU energy targets and what are the side effects of them on the electricity markets and the future LCOE levels?".* To sum up, the revolutionary transition path is driven by political dynamism and the evolutionary path transition by market-based mechanisms.

The revolutionary transition path requires more detailed top-down planning and policy interventions, which are based on certain assumptions and forecasts. For example, in this case study it is assumed that the annual consumption is going to be 102 TWh in 2030 and in order to fulfill the target of 45% renewable energy, an option would be for example to build 6300 MW wind power capacity. To some extent, it is questionable whether the certain assumptions are fully correct and do the predictions come true. For example, in this case there is a chance that the consumption remains in the current level and then there would be significant excess capacity if the share of wind energy is increased substantially. Furthermore, this transition path may harm the economies of already executed investments. A concern related to revolutionary transition path is losing the benefits of current deregulated energy-only-market. As Verbong and Geels (2010, p. 1218) address, there may be partial return to management philosophy that was contributing before deregulation.

The revolutionary path transition is likely to require substantial artificial boosting of technology development and deployment by implementing additional support scheme. In this case study, effects of implementing a feed-in tariff was discussed. The revolutionary transition path was thus resource-driven and the innovation system develops through reconfigurations. The most contributing side-effects of the revolutionary transition path is the almost immediate merit-order effect decreasing the wholesale prices and the expected displacement of full-load operation hours of flexible supply. Thus, attracting the investors to invest for flexible capacity may be challenging and may require providing additional resources.

Evolutionary transition path is driven by market-based mechanisms and the focus of interventions is on niche-level. In this study, finding comprehensive real-life example cases of evolutionary transition was challenging, since the evolutionary transition path does not contain radical changes to the same extent as revolutionary transition path and thus, the evolutionary transition paths are not often documented as systematically. Therefore, the evolutionary path analysis was more based on certain assumptions. It was obtained that risks of evolutionary path transition occur on a smaller scale and adjustments of direction of development are easier to do. Furthermore, it was seen that market-based mechanisms work more effectively when there are less overlapping mechanisms and the business environment in the evolutionary path transition is more stable. Also the expectations of earnings from investor's perspective look more promising in this transition path although the future capacity development still causes great uncertainty.

In the evolutionary transition path, no substantial additional artificial boosting means are necessarily required. However, the future functionality of EU ETS affects the investment decisions and technology development. Interpreting a clear but still flexible and wide-scope vision is essential also in this transition path in order to ensure the direction of development. The side-effects are minor in this transition path and due to evolutionary nature of the transition, the problems and unexpected issues are presumably resolved before they become unmanageable.

This transition path emphasizes the role of innovations in the niche-level. Therefore, there should be public funding available for development and pilot projects at some extent. Thus, it is more likely that new entrants will entry to the market as electricity suppliers or equipment manufacturers in the evolutionary transition path.

Since the evolutionary transition path is driven by market-based mechanisms and adaptation of novelties is based on cost efficiency, economies of flexible thermal power plants are not disrupted by large-scale deployment of intermittent generation within a short time period. However, the development of nuclear power capacity affects the full load hours of flexible thermal generation and then the generation costs. Therefore, attracting the investors to increase flexible capacity may be a challenge if the nuclear power capacity appears to be growing in the future.

8.4 Findings of assessing the future generation cost level

From present-day investor's perspective the most contributing factors in future of making an investment decision now are the development of fuel prices, development of emission allowance price and development of the surrounding generation capacity and electricity consumption. As an answer for the research question "*What are the estimated future levels of electricity generation production cost of considered production types when the regulatory targets are reached through evolutionary and revolutionary paths in chosen spatial domain?"* the generation cost development depends highly on the development of set of generation technologies in the power system.

The generation costs of intermittent generation are expected to reduce in the future. In the revolutionary transition path, the generation costs are reduced by pursuing mass production, upsizing and higher economies of scale from the beginning. In the evolutionary transition path the generation costs reduce slower in the beginning and there is space for learning-by-searching and learning-by-using leading to for example improved efficiency and longer lifetime of generation technology, which are expected to appear in reduced generation costs. Later the generation costs are presumably reduced by similar mechanisms than in the beginning of the evolutionary transition path; mass production, upsizing and higher economies of scale. Therefore, it can be seen that cost reduction occurs on higher level in the evolutionary path transition finally, but whether the costs are reduced that much within the timeframe of this case study is uncertain.

The flexible thermal generation is expected to experience decreasing operation hours. The development of operation hours depends on timing and magnitude of intermittent capacity deployment. The construction times of intermittent generation sites are only few years and thus large-scale deployment especially in the revolutionary transition path can collapse the economic utilization of flexible thermal generation quickly.

In this study, it was observed that the development of intermittent generation capacity is not necessary the only most contributing factor affecting the cost development of flexible generation capacity. The development of nuclear power capacity affects is another major factor, since in Finland its applicability as flexible supply is limited due to safety terms, (ÅF-Consulting Ltd, 2012, p. 21). Highly capital intensive nuclear power has low variable costs and thus it is located at the front of the merit-order. Therefore, it is reasonable to produce nuclear power as much as possible, without altering the generation to meet short-term fluctuations in the consumption if there is nuclear power capacity in the power system.

From present-day investor’s perspective, it can be argued that prospective investment is faced by risk that revenues gained from generation are not sufficient to cover the generation costs. This is caused by both decreasing wholesale prices and decreasing operation hours, which depend on development of surrounding generation capacity and consumption. The substantial increase of subsidized generation has not only increased the price risk of non-subsidized generation but also added a new type of volume risk for flexible power suppliers that investors need to consider.

8.5 Further findings

In general, it was noticed that the electricity supply business in Finland is concentrated to the large incumbent actors. However, local utilities have played essential role building plants to generate heat and energy locally.

From present-day investor's perspective, the uncertainty related to nuclear power decisions creates uncertainties partly because of its superior unit sizes. For example, the lifetime of flexible thermal generation capacity is a number of decades and from present-day investor's perspective the increasing share of nuclear power in the future would be likely to decrease the operation hours of other generation and therefore, the investors may be hesitant to make investment decisions before the status of future nuclear power has been clarified.

8.6 Recommendations

In the electricity supply business, the lifetimes of technologies and thus investment horizons are often several decades. As was observed in this case study, political and interventions create uncertainties that can easily distort the investment environment in the electricity supply business. In the political decision-making the cycles and planning horizons are short compared to for example technological lifetimes. Therefore, the market-based mechanisms, such as market itself and EU ETS, should be laid off if possible. If some interventions are made for some reason, those should be as consistent and long-sighted as possible and consider the economic, environmental and social consequences in accordance with triple bottom line perspective.

It can be argued that in the case of electricity, the heterogeneous nature of good as introduced in Chapter 3.4 is often not understood very well. The three dimensions of heterogeneity: time, space and lead-time shaped by the physics of electricity, affect the generation and value of it, (Hirth, et al., 2014, p. 29). This means that an efficient set of generation technologies are needed to fulfill the demand and thus, set of base, flexible and peak supply are needed in addition to prioritized supply. This means that for example wind power cannot substitute nuclear power and in order to keep the lights on the generation portfolio cannot consist of only prioritized and inflexible base supply.

The instruments intended to boost technology development and deployment do not often take the heterogeneity aspects into consideration. As Hirth, et al. (2014, p. 30) proposes that if any of the policy instruments are applied, they should better reflect the heterogeneity meaning that they should for example consider the wholesale price fluctuations.

Furthermore, in the EU level, national level and local level there are several interests and objectives related to energy issues. Nowadays from investor's or other actor's perspective no clear priority of objectives can be identified and thus, anticipating the future development is difficult. This causes great uncertainty related to future and therefore it is proposed to pursue towards more clear priority of long-term objectives if possible.

9 CONCLUSIONS

Finland has been following a second mover strategy achieving the ambitious renewable energy targets set by EU. The current inducement mechanisms do not encourage executing the investments for new flexible or renewable capacity. The main reasons behind the situation are low wholesale prices compared to generation costs and moderate growth expectations of electricity consumption in Finland.

The two alternate transition approaches considered in this comparative case study, revolutionary and evolutionary transition paths, demonstrated how the supply portfolio, generation costs and wholesale prices would develop as a result of illustrative actions and interventions. Revolutionary transition path is driven by detailed top-down planning and requires providing substantial financial resources. Furthermore, economic inefficiencies is expected to occur at some extent in the revolutionary transition path due to decreasing wholesale prices caused by merit-order effect and reduced operating hours of flexible generation capacities. Evolutionary transition path is driven by market-base mechanisms, but financial resources should be provided for niche-level to support development and demonstration projects and also a clear, but flexible vision should be interpreted in order to show the direction of development. Less economic inefficiencies are expected to occur in the evolutionary transition path, but the merit-order effect occurs in some extent and generation costs of capital-intensive flexible thermal generation increase presumably due to decreasing operation hours.

Based on the comparative case study, it is deduced that interventions for electricity markets may cause a vicious circle at some extent and thus, any interventions should be avoided to allow undisturbed operation of market-based mechanisms. If any interventions are made for some reason, they should consider the heterogeneity better.

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Sources of gained data for LCOE calculations

Publication	Reference	Invest-ment costs	Opera-tion & Mainte-nance Costs	Fuel prices	Plant efficien-cies	Opera-tion hours	Emission factors
Comparison of elec-tricity generation costs (in Finnish)	Vakkilainen et al. 2012	x	x	x	x	x	
Levelized cost of electricity renewable energy technologies	Kost et al. 2013	x	x	x		x	
Projected Costs of Generating Electricity	IEA 2010	x	x				
Power Plant Engineer-ing (in Finnish)	Huhtinen et al 2008				x		
Publications of Statis-tics Finland	Statistics Finland 2013			x			
Power Plant Register	Energy Author-ity 2014						
Replacing coal with biomass in cogenera-tion using pulverised combustion boilers (in Finnish)	Flyktman et al. 2010			x			
Heat values and efficiencies of fuels, specific CO2 emission coefficients and energy prices (in Finnish)	Motiva 2010						x

Detailed description of LCOE calculations

The LCOE for a power plant is calculated by following formula

$$LCOE = \frac{\sum_t \left((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t) \cdot (1+r)^{-t} \right)}{\sum_t (Electricity_t \cdot (1+r)^{-t})} \qquad (1)$$

where variables indicate

$Investment_t$	Investment costs in year t
$O\&M_t$	Operation and maintenance costs in year t
$Carbon_t$	Carbon costs in year t
$Decommissioning_t$	Decommissioning costs in year t
$Electricity_t$	Produced electricity in year t
r	Interest rate.

LCOE can be decomposed further

$$LCOE = LCOE_{Inv} + LCOE_{Fuel} + LCOE_{Carbon} + LCOE_{FO\&M} + LCOE_{VO\&M} + LCOE_{Decom}, \qquad (2)$$

where variables indicate

$LCOE_{Inv}$	Investment costs
$LCOE_{FO\&M}$	Fixed Operation and maintenance costs
$LCOE_{VO\&M}$	Variable Operation and maintenance costs
$LCOE_{Decom}$	Decommissioning costs.

The investment costs for new power plants are calculated

$$LCOE_{Inv} = \frac{Investmen\ costs \cdot Capacity \cdot \frac{1}{buildingtime} \cdot (\frac{(1+r)^{building\ time} - 1}{r(1+r)^{building\ time}})}{Operation\ hours \cdot Capacity \cdot (\frac{(1+r)^{n+building\ time} - 1}{r(1+r)^{n+building\ time}} - \frac{(1+r)^{building\ time} - 1}{r(1+r)^{building\ time}})}. \quad (3)$$

where the investment expenses are spread over constructing time evenly and then divided by generated electricity starting from finishing the construction time. Parameter *n* corresponds to technical lifetime of a plant.

Fuel costs are calculated

$$LCOE_{Fuel} = \frac{Fuel\ price}{\eta}, \quad (4)$$

where factor η corresponds to the electrical conversion efficiency, which is the plant efficiency for separate production and for CHP plants the conversion efficiency based on benefit sharing method and common value 54% is applied for CHP generation, (Gaia Consulting Oy, 2010, p. 12).

Carbon costs are calculated

$$LCOE_{carbon} = \frac{Carbon\ price \cdot CO2\ cefficient}{\eta}, \quad (5)$$

where η corresponds to the electrical conversion efficiency than in equation (4) and $CO2\ coefficient$ is a factor that gives the CO2 emissions per produced energy.

Operation and Maintenance costs are calculated

$$LCOE_{FO\&M} = \frac{Fixed\ OM\ costs}{Operation\ hours} \tag{6}$$

$$LCOE_{VO\&M} = Variable\ OM\ costs, \tag{7}$$

where $Variable\ OM$ corresponds to the variable operation and maintenance costs and $Fixed\ OM$ corresponds to fixed operation and maintenance costs.

Decommissioning costs are ignored for all other power plants than nuclear. For nuclear power the decommissioning period is set to be 10 years and the decommissioning starts 10 years after the last operation year. It is assumed that the decommissioning costs are spread evenly for the decommissioning period. Therefore, the nuclear power decommissioning costs are calculated

$$LCOE_{Decom} = \frac{\frac{Cost_{Decom}}{10} \cdot \left(\frac{(1+r)^{n+10}-1}{r(1+r)^{n+10}} - \frac{(1+r)^{n}-1}{r(1+r)^{n}}\right)}{Operation\ hours \cdot Capacity \cdot \frac{(1+r)^{n}-1}{r(1+r)^{n}}}, \tag{8}$$

where n corresponds to number of years including construction time and operation period.

Applied data in LCOE calculations

This appendix introduces the applied data in LCOE calculations.

A) Fuel prices in electricity generation and coefficients of CO_2 emissions. (Aleshina & Vakkilainen, 2012, p. 110; Customs, 2014, pp. 2-5; Flyktman, et al., 2011, p. 47; Kost et al., 2013, pp. 39; Motiva, 2010, p. 5; Statistics Finland, 2014; Vakkilainen, et al., 2012, p. 9; Vantaan Energia, 2014)

Fuel	Price (€/MWh)	CO_2 coefficient (t CO_2/MWh)	References
Bio SNG	60,0	0	Flyktman, et al., 2011, p. 47
Biochar	35,0	0	Flyktman, et al., 2011, p. 47
Biofuel	21,0	0	Flyktman, et al., 2011, p. 47
Coal	9,3	0,341	Statistics Finland, 2014; Customs, 2014, p. 3; Motiva, 2010, p. 5
Gas	33,8	0,198	Statistics Finland, 2014; Customs, 2014, p. 3; Motiva, 2010, p. 5
Hydro	0,0	0	
Nuclear	2,0	0	Vakkilainen, et al., 2012, p. 9
Oil	50,0	0,267	Kost, et al., 2013, p. 39; Motiva, 2010, p. 5
Peat	13,3	0,381	Statistics Finland, 2014; Customs, 2014, p. 3; Motiva, 2010, p. 5
Pellet	30,0	0	Flyktman, et al., 2011, p. 47
Residual biofuel	18,0	0	Flyktman, et al., 2011, p. 47
Solar	0,0	0	
Wind	0,0	0	

B) Power plant categories, their electricity conversion efficiencies, technical and economical lifetimes, fixed operation and maintenance costs and investment and decommissioning costs. Data older than from year 2013 is corrected by building cost index 2,5%/a. (Aleshina & Vakkilainen, 2012, p. 108; Financial Times, 2014; Gaia Consulting, 2010, p. 12; Huhtinen, et al., 2008, pp. 21-22, 90; IEA,2010, pp. 59-60; Kost, et al., 2013, pp. 39-40; Loiri, 2014, pp. 47-51; Münster & Meibom, 2011, p. 1616; Vakkilainen et al., 2012, pp. 6-9)

Plant type	Fuel	Lifetime (a)*	Construction time (a)**	Investment cost (€/kW) ****	Decommissioning cost (€/kW)	Electricity conversion efficiency ***	References
District heating CHP	Biomass	40	4	2175	0	54%	Vakkilainen, et al, 2012, p. 9
District heating CHP	Coal	40	4	2226	0	54%	IEA, 2010, p. 63: German 200 MWe plant
District heating CHP with CCS	Coal	40	4	2463	0	52%	Derived from Coal-fired separate production with CCS
District heating CHP	Natural gas	40	4	1082	0	54%	Vakkilainen, et al., 2012, p. 9
District heating CHP	Peat	40	4	2067	0	54%	Vakkilainen, et al., 2012, p. 9
Gas-fired power plants	Bio SNG	30	2	5000	0	58%	Aleshina & Vakkilainen, 2012, p. 108
Gas-fired power plants	Natural gas	30	2	366	0	58%	Münster & Meibom, 2011, p. 1616
Hydro power	Hydro	80	2	2391	0	100%	IEA, 2010, p. 62: Swedish 70 MW plant
Separate electricity production	Coal	40	2	1534	0	42%	Vakkilainen, et al., 2012, p. 9
Separate electricity production with CCS	Coal	40	2	1828	0	34%	Vakkilainen, et al., 2012, p. 9
Separate electricity production	Oil	40	2	300	0	42%	Kost, et al., 2013, p. 39
Separate electricity Production, Torrefied biomass generation	Biochar	40	2	1534	0	42%	Derived from Coal-fired separate electricity generation
Separate electricity Production, Direct co-firing, Biomass	Biofuel	40	2	684	0	38%	Loiri, 2014, p. 47
Separate electricity Production, Indirect co-firing, Biomass	Biofuel	40	2	5147	0	38%	Loiri, 2014, p. 47
Separate electricity Production, Parallel co-firing, Biomass	Biofuel	40	2	1221	0	38%	Loiri, 2014, p. 47
Solar power	Solar	25	1	1700	0	100%	Kost, et al., 2013, p. 39
Nuclear energy, existing location	Nuclear	60	8	5453	3393	37%	Vakkilainen, et al., 2012, p. 9; Financial Times, 2014
Nuclear energy, new location	Nuclear	60	8	3971	3393	37%	Vakkilainen, et al., 2012, p.9; Financial Times, 2014
Wind power , offshore	Wind	25	1	3950	0	100%	Kost, et al., 2013, p. 10
Wind power, onshore	Wind	25	1	1429	0	100%	Kost et al., 2013, p. 10

*) Technical lifetimes from Vakkilainen, et al., 2012, p. 9

**) Constructions time as construction cost profiles from IEA, 2010, p. 44

***) Conversion efficiencies for CHP generation from Gaia Consulting 2010, p. 12

****) Values converted from USD to EUR by applying coefficient 0,68 EUR/USD, if data gained from IEA (2010, p. 38).

C) Operation and maintenance costs of power plant types. Data older than from year 2013 is corrected by building cost index 2,5%/a. (Aleshina & Vakkilainen, 2012, p. 108; Huhtinen, et al., 2008, p. 319; IEA, 2010, p. 60; Kost, et al., 2013, pp. 10-11, 39; Vakkilainen et al., 2012, pp. 6-9)

Plant type	Fuel	Variable OM Costs (€/MWh) *	Fixed OM Costs (€/kW) *	References
District heating CHP	Biomass	2,896	34,7	Vakkilainen, et al., 2012, p. 9
District heating CHP	Coal	8,506	21,2	IEA, 2010, p. 63: German 200 MWe plant
District heating CHP	Coal with CCS	13,878	33,7	Derived from coal fired CHP plant without CCS, coal-fired separate generation plants with CCS and without CCS
District heating CHP	Natural gas	5,033	21,7	Vakkilainen, et al., 2012, p. 9
District heating CHP	Peat	5,511	44,1	Vakkilainen, et al., 2012, p. 9
Gas-fired power plants	Bio SNG	27,316	14,7	Aleshina & Vakkilainen, 2012, p. 109
Gas-fired power plants	Natural gas	4,800	21,7	Vakkilainen, et al., 2012, p. 9
Hydro power	Hydro	11,386	0,0	IEA, 2010, p. 62: Swedish 70 MW plant
Separate electricity production	Coal	6,657	21,0	IEA, 2010, p. 60: German 800 MW plant
Separate electricity production	Coal with CCS	10,566	33,4	IEA, 2010, p. 60, German 740 MW plant
Separate electricity production	Oil	0,000	25,0	Kost, et. al, 2013, p. 39
Separate electricity Production, Torrefied biomass generation	Biochar	6,592	21,0	Derived from coal-fired separate production
Separate electricity Production, Direct co-firing, Biomass	Biofuel	2,896	34,7	Derived from biomass-fired CHP
Separate electricity Production, Indirect co-firing, Biomass	Biofuel	2,896	34,7	Derived from biomass-fired CHP
Separate electricity Production, Parallel co-firing, Biomass	Biofuel	2,896	34,7	Derived from biomass-fired CHP
Solar power	Solar	0,000	35,0	Kost, et al., 2013, p. 11
Nuclear energy	Nuclear, existing location	5,747	46,0	Vakkilainen, et al., 2012, p. 9
Nuclear energy	Nuclear, new location	5,747	46,0	Vakkilainen, et al., 2012, p. 9
Wind power , offshore	Wind	3,719	20,0	Vakkilainen, et al., 2012, p. 9
Wind power, onshore	Wind	6,073	12,3	Vakkilainen, et al., 2012, p. 9

*) Values converted from USD to EUR by applying coefficient 0,68 EUR/USD, if data gained from IEA (2010, p. 38).

D) Expected full-load operation hours of power plant types. (Kost, et al., 2013, p. 13; Vakkilainen, et al., 2012, pp. 8-9)

Type	Fuel	Full load operation hours (h/a)	References
District heating CHP	Biomass	4200	*
District heating CHP	Coal	4200	*
District heating CHP	Coal with CCS	4200	*
District heating CHP	Natural gas	4200	*
District heating CHP	Peat	4200	*
Gas-fired power plants	Bio SNG	2000	*
Gas-fired power plants	Natural gas	2000	*
Hydro power	Hydro	4200	*
Separate electricity production	Coal	3000	*
Separate electricity production	Coal with CCS	3000	*
Separate electricity production	Oil	500	*
Separate electricity Production, Torrefied biomass generation	Biochar	3000	*
Separate electricity Production, Direct co-firing, Biomass	Biofuel	3000	*
Separate electricity Production, Indirect co-firing, Biomass	Biofuel	3000	*
Separate electricity Production, Parallel co-firing, Biomass	Biofuel	3000	*
Solar power	Solar	1000	Kost, et al., 2013, p. 13: North Germany
Nuclear energy	Nuclear	8000	Vakkilainen, et al., 2012, p. 9
Nuclear energy	Nuclear	8000	Vakkilainen, et al., 2012, p. 9
Wind power , offshore	Wind	2200	Vakkilainen, et al., 2012, p. 9
Wind power, onshore	Wind	2200	Vakkilainen, et. al 2012, p. 9

*) Derived from current operation hours, see Table 4.2 in Chapter 4.9.1