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Abstract

The objective of this study is to calculate the cost-effective production of non-fossil energies in the Swedish electricity system, considering external effects and uncertainty. The study includes eight non-fossil energy sources in Sweden. For each energy source a unique marginal cost function is assessed, including production costs, external cost and uncertainty based on data from previous studies and publications. Four different models are created: A standard model excluding externalities, a model including externalities, a probabilistic model excluding externalities and a probabilistic model including externalities. The results show that the cost-effective mix of 150TWh is achieved at a total production cost of 58.3 billion SEK. The model finds the cost of externalities to be 7.1 billion SEK and the cost of uncertainty to about 1.7 billion SEK respectively. In all four models, large-scale hydro, nuclear power and onshore wind are included to their full capacity. None of the models have solar PV and wave energy as part of the cost-effective mix. Biomass, offshore wind and small scale hydro are included to a varying extent in the different models. When comparing the results of the four different models the differences in outcome are rather small. However, there are a number of significant findings that may contribute to guidelines for Swedish policy making. Among the discussed implications are: The most effective way to drive down total electricity cost, the role of solar PV incentives and the cost associated with a decommissioning of nuclear power.

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APPENDIX

1. Introduction

When it comes to the Swedish energy sector, everyone in this country seem to have an opinion. The energy sector has been the arena for countless political controversies, like the battle over Vindelälven 1962 and the Nuclear referendum in 1980 (SCB, 2016; ViEF, 2009; Strålsäkerhetsmyndigheten, 2016). Ambitions to decommission nuclear, battle climate change and adherence to EU legislation have over the years pulled the energy system in different directions.

Today, we are getting closer to a crossroad where some big decisions for our energy system need to be made. The Swedish system for subsidies and fees is growing increasingly complex and our nuclear and hydro facilities are getting older and maintenance costs are increasing as safety regulations become stricter (Elforsk, 2014; Naturvårdsverket, 2016; Vattenfall, 2016). Political pressure to act has mounted since our neighboring countries have chosen different paths, with Germany ceasing all nuclear power production while Finland is one of the few countries in the world that builds a new nuclear plant (World Nuclear Association, 2016). In addition, recent global environmental agreements like Paris 2015 have resulted in more tangible actions affecting the power sector (United Nations, 2016). For instance, it is likely that the EU ETS will extend after 2020 and that additional environmental fees will be applied which may have an imminent impact on the Swedish electricity market. In February 2016 the Swedish Government announced a commission to clarify the future abilities of the Swedish electricity production, further indicating that the issue of electricity planning is more relevant than ever (Energikommissionen, 2016).

The Swedish electricity mix currently consists of about 42.5% hydro, 41.1% nuclear, 7.6% wind and 8.8% CHP (bio and peat) (Svensk Energi, 2016; Svensk Energi, 2015). Although this energy generation is largely CO_2 neutral that does not mean there is no negative externalities that impacts our society. Neither does it mean that the money spent on subsidizing certain energy sources are spent wisely. The lack of research on externalities in the Swedish energy production is one of the most striking shortcomings of the current body of research.

If we include all external effects from each type of energy, how would that change the way we look upon our different energy sources? Will nuclear remain competitive if the issues of nuclear waste and risk of meltdown were reflected in the price? Are we wasting taxpayer’s money in subsidizing energy sources that might even have a negative environmental impact? Hopefully this study can add a few bricks to the foundation to move forward with the big questions for our energy system.

1.1 Objective

The main objective of this study is to calculate cost-effective Swedish electricity production, considering external effects and uncertainty. In other words, to calculate costs and energy mix that achieve a certain electricity production at the lowest total cost under different combinations of production costs, external effects and uncertainty. The aim of this research is therefore to answer the following questions:

1) What is the total costs and optimal mix of non-fossil energies that reach a certain total electricity production at the lowest cost when considering both production cost and negative externalities?
2) How does this mix and the total cost change when assessing the uncertainty of electricity production?

1.2 Limitations

This study rests upon some assumptions that will set manageable limitations to this model. Firstly, all production costs are presented excluding governmental subsidies and regulations, to stress a cost efficient solution. Secondly, we assume a static model that will take production costs, external costs and technology levels as given. Consequently, the capacity limits applied in the model may appear tight, but the static model should approximately represent the current conditions in electricity production. A flexibility of about six percent is added to allow for new combinations of energy sources to occur, while further sensitivity analyses will test the impact of large investments in different energy sources.

1.3 Methodology

The study is based on an operational research (OR) which fits analyses with a clear question but where the answer is complex and depends on many different conditions and constraints. OR aims to mathematically solve a problem within a constructed model, given defined constraints and simplified conditions. This method is common in optimization problems designed with an objective function and where the main purpose is to find better guidance in decision making of complex questions (Winston, 1991). In the case of this study, it means minimizing the total cost of non-fossil energies allowing for all feasible combinations that reaches a certain total electricity production. This problem is solved in the operational program GAMS that can handle multiple variables and multiple constraints (Rosenthal, 2012). GAMS solves cost minimization problems based on the inserted values, hence this method requires a thorough data selection process. Further sensitivity analyses will help to guide if the data inserted is accurate or not by stressing the robustness of the values.

The study includes eight non-fossil energy sources in Sweden; large-scale hydro, small-scale hydro, nuclear, biomass, solar PV, onshore wind, offshore wind and wave energy. The external costs of each of these energy sources are analyzed using life cycle assessment, LCA, meaning that all external effects from cradle to grave are included.

1.4 Disposition

The main part of this study focuses on building a foundation for the resulting analysis. Section 2 frames the scientific foundation in a literature review followed by the theoretical foundation in Section 3, explaining the cost minimization problem with associated constraints. Section 4 focuses on the electricity production in Sweden creating an understanding for the research questions. Section 5 gives a description of the data selection for production costs, capacity limits, external costs and probabilistic constraints. This section is quite detailed but essential for further interpretations of results, which is described in Section 6. Result is divided into three parts, first; the answer to the main research question, hence the optimal combination of non-fossils energies, second; the effect of a probabilistic constraint, in other words, the answer to the sub-question, and third; sensitivity analyses in order to test the robustness of the results. In addition, discussions of results are presented in Section 7.1, discussions on implications of the study in Section 7.2 and summarizing conclusion is given in Section 8.

2. Literature review

Several studies have investigated the optimal combination of energies but used different framings, restrictions and methods, therefore obtaining different types of answers (Budhischak et al., 2012; Hart and Jacobson, 2011; Schmidt et al., 2015; Lund 2005; Vidal-Amaro et al. 2015; Aryanpur and Shafiei, 2015). The application addressed in this study has not been found in previous studies, in other words cost-minimization including a LCA of external effects for non-fossil energies. The question doesn't seem to be relevant in most current electricity systems, in which most systems still are struggling with high direct external impacts from fossil production.

Budischak et al. (2012) use a cost minimization model to solve the optimal combination of offshore wind, onshore wind, solar PV and electrochemical storage in the eastern United States. The study builds on four years of hourly simulations of metrological conditions and electricity demand. The data is modelled with three storage technologies and two different cost scenarios; 2008 and 2030, where the latter scenario should represent a more mature industry with decreasing technology costs. Furthermore, the model applies three levels of coverage requirements for the share of renewables in electricity production; 30%, 90% and 99.9% of the total hours produced, and fossils used as backup in all cases. Offshore wind, inland wind and solar PV have its own maximum production based on actual resource limits. Each simulation seeks the optimum combination of energy production for all values between zero and the maximum. The costs for renewables are calculated based on production costs excluding subsidies. For fossil fuels the cost of externalities[1] is also included. Results show that the higher the share of renewables, the higher the diversity of renewable inputs. For example, when the share of renewable is 30%, the demand can be supplied only by using the cheapest option; inland wind. Budischak et al. (2012) also find that the most cost-efficient scenario is a 90% share of renewable, calculated with the 2030 technological cost. If using the technological cost of 2008 instead, 30% share renewables is the least costly option. In the 90% scenario the capacity of inland wind is more than twice as big as the capacity of fossil, implying that energy security can be achieved regardless of peeling fossil back-ups. Worth noticing is that PV is only cost-efficient in the 99.9% scenario.

Aryanpur and Shafiei (2015) examine the optimal distribution of renewable electricity technologies in Iran during the period 2015 to 2045. The study tries to assess the technology solution with the lowest cost by modelling 11 different resources including geothermal, wind, hydro, biomass and solar. The problem is solved by minimizing the total cost under technical, economic and environmental constraints that define the viable combinations. These calculations include environmental damage, general costs and emission costs. Aryanpur and Shafiei (2015) model three potential scenarios; business as usual, "deployment" and "green deployment". The latter two have increasing fossil fuel prices and two levels of carbon tax, a higher for "green development" and a lower for "development". The scenarios apply a share of renewable of 15%, 37% and 45% respectively and the remaining energy production is mostly covered by natural gas. Hydro is kept relative constant in all three cases, while wind is exponentially increasing in both deployment and green deployment from 2020. Same pattern is seen for solar PV but the expansion starts in 2035. Biomass takes a small share in 2030.

Hart and Jacobson (2011) models different combinations of low-cost and low-CO_2 with the aim to reduce emissions by 80% in the energy generation portfolio of California. The study is based on a deterministic optimization model, followed by Monte Carlo Simulations. The cost minimization problem is calculated based on the total annual cost of generation (during 2005-2006), including all production costs but excluding externalities, while low-CO_2 is simply the minimized carbon emissions. The aim is to find the optimal combinations (low-cost and low-CO2) of wind, centralized solar thermal, rooftop PV, hydro, geothermal and natural gas. Findings suggest that the optimal low-cost mix consists

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[1] For coal they used Epstein et al. study in where externalities are; mining, transport, combustion products and climate change. For other fuels are figures from the EU report "ExternalE" used, where costs related to human health, crop output, ecosystem, climate change etc. are monetarized.

of 60% natural gas, 25% hydro, 10% geothermal and 5% wind. For low-CO_2 applies; 50% wind, 25% hydro, 15% geothermal and 10% solar. In the 2050 scenario the estimated cost of CO_2 is higher which affects the share of natural gas in the low-cost model. Hart and Johnson (2011) recommend to maintain the size of hydro and geothermal capacities and instead make expansions in both solar and wind to achieve the target.

Schmidt et al. (2015) aim to find combinations of solar PV, hydro, wind and thermal that minimizes greenhouse emissions while ensuring the drastically increasing demand in Brazil. They created an optimization model that can handle energy balancing with different capacities in different regions and variable generation. The model also allows for storage of up to 24 hours to balance the variations in sub-daily productions of PV, wind and hydro. Using time-series data Schmidt et al. (2015) models the minimum share of thermal power in the Brazilian electricity system in order to minimize emissions. Their suggestion is a combination of 50% hydro, 37% PV and 9% wind and 4% thermal power. The proposal uses hydro as a secure baseload while wind and PV is uses to stabilize a fluctuating demand. Further findings are that an expansion of hydro will not reduce the need for thermal backup and expanding PV is to favor before wind in terms of stabilizing total output.

Lund (2005) works with an input/output model of the Danish electricity system where he tries to minimize the excess production when integrating solar PV, wind and wave power. The study examines the internal optimal share of PV, wind and wave and advises that 50% of the renewable resources should come from onshore wind power. However, the optimal mix of PV and wave power is contingent to the share of renewables in the total energy production. For cases where renewables represent less than 20% of total electricity inputs, the mix should contain 40% of PV and 10% of wave power. For cases where renewables represent more than 80% of total electricity inputs, the mix should instead be 20% PV and 30% wave power.

Vidal-Amaro et al. (2015) investigate the optimal combination to meet the renewable targets in the Mexican electricity system. The targets are set to 35% renewable by 2024, 40% by 2035 and 50% by 2050 respectively. Vidal-Amaro et al. (2015) set up a minimization problem with respect to the total mix capacity, solving for a solution of biomass, wind and solar power. Three scenarios: HighRES-LowBio, HighRES-MidBio and HighRES-HighBio are compared and the results show that the lowest total capacity is achieved with HighRES-HighBio. Further conclusions suggested that mixing wind with solar PV of 1-15GW, gave the highest reduction of fossil use. Beyond that level, impacts are small and also smaller for single resource than for a mix.

Budischak et al. (2012) is the most relevant literature for the purpose of this study and the single study found focusing on a pure cost minimization problem. The most important feature of this study is to investigate the optimal mixture of energies when external costs are included in the calculations. However, Budischak et al. (2012) only include externalities for fossils which causes a gap between the basic assumptions of their study and the assumptions of this one. The fact that Budischak et al. (2012) don’t include hydro in the optimization will further distinguish their results from the results of this study. Yet, only a few studies (Hart and Jacobson, 2011, Schmidt et al., 2015 and Aryanpur and Shafiei, 2015) include hydro in the optimization problem. Sweden has access to storable hydro power which is a big advantage when it comes to achieve fossil free electricity systems to a low cost.

Although several studies calculate for the optimal combination of energies, the differences in methods and settings (Sims et al., 2003 and Delucchi and Jacobson, 2011) will lead to different answers. The particular question of this study, regarding the Swedish electricity system and accounting for externalities, is nowhere to be found in previous literature.

3. Theory

The study aims to solve a cost minimization problem for the non-fossil energy combination that reach a certain total electricity production of the lowest cost. This is examined through three different models, creating a step wise assessment of the problem. The first model represents the standard scenario, simulating production costs of electricity generation. The second model is extended with an additional cost function for externalities, in order to internalize the cost of environmental damage. This model is the main contribution of this study and seeks the socially optimal solution to the cost minimization problem. The last model is an attempt to capture the uncertain supply by intermittent electricity sources. The model used to correspond to this problem is a probabilistic model with probabilistic constraint on total electricity production instead of the deterministic limits used in model one and two.

The basic model minimizes the cost of the input resource, denoted E_i, that can be produced through different energy sources, i=1…, n. The problem is constrained by two restrictions that limit the number of solution to only the feasible. One constraint controls for that the sum of energy production of all i:s should at least meet a certain level. The other constraint controls for production limitations of i, which may differ among i's. This restriction is set based on the physically possible production achieved from energy source i.

The problem can be written as:

$$\min_{Ei} C = \sum_i C^i\left(E^i\right) \qquad s.t. \sum_i E^i \geq E \quad and \quad E^i \leq \bar{E}^i \tag{1}$$

The Lagrangian equation follows:

$$L = \sum_i C^i(E^i) + \lambda\left(\sum_i E^i - E\right) + \sum_i \alpha_i(\bar{E}^i - E^i) \tag{2}$$

Solving for E^i we get:

$$\frac{\partial L}{\partial E^i} = \frac{\partial C^i}{\partial E^i} + \lambda - \alpha_i = 0 \tag{3}$$

Which can be rewritten as:

$$MC^i = \alpha_i - \lambda \tag{4}$$

This implies that the optimal solution depends on the Lagrangian multipliers of energy production. Without any capacity restrictions, all marginal costs are equal to each other in optimum, but when including capacity constraints for i:s, the marginal cost increases with the size of α_i. The capacity constraint can therefore be seen as a cost that affects the total and marginal cost of reaching the target. As Figure 1 shows, the optimal solution changes from Q* to Q', which is reached to a higher cost. The increase in cost is represented as the shaded area and the subarea of each E, represents the increased value in marginal cost. Hence, when $\alpha i<0$ total cost can decrease from a marginal increase in the capacity of energy source i.

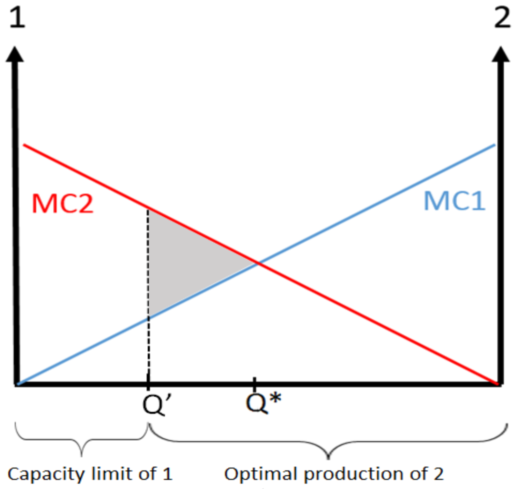

Figure 1. Cost-effective combination of two inputs; 1 and 2 including capacity constraint

Heretofore, the model has treated the optimal mix of energies based on production cost and capacity limits. In order to find a socially optimal solution, the model is extended by an additional cost function for each externality, $C^{ir}(E^i)$, where r; r=1…, k externalities. The new cost function *C* shows the cost of externalities and will be the sum of all external impacts caused by energy production of resource i and recalculated to monetary values plus the production cost.

Our decision problem in mathematical terms becomes:

$$\min_{Ei} C = \sum_i \sum_r C^{ir}(E^i) + c^i(E^i) \qquad s.t. \sum_i E^i \geq E \quad and \quad E^i \leq \bar{E}^i \tag{5}$$

The Lagrangian equation follows:

$$L = \sum_i \sum_r C^{ir}(E^i) + c^i(E^i) + \beta\left(\sum_i E^i - E\right) + \sum_i \alpha_i(\bar{E}^i - E^i) \tag{6}$$

Solving for E^i we get:

$$\frac{\partial L}{\partial E^i} = \sum_r \frac{\partial C^{ir}}{\partial E^i} + \frac{\partial c^i}{\partial E^i} + \beta - \propto_i = 0 \tag{7}$$

Which can be rewritten as:

$$\sum MC^{ir} + MC^i = \alpha_i - \beta \tag{8}$$

The first order condition of E^i includes the summed cost of externalities caused by energy source i. This will push the marginal cost curve upwards, hence find a relatively more expensive solution than the solution suggested in problem (1). This is exemplified in Figure 2, where the new optimal solution Q’ is found to a higher cost. The figure shows a case of two inputs where only input 1 is causing external effects, creating a shift in MC1. Input 1 is also constrained by the capacity restriction but unlike Figure 1, this constraint does not interfere with the solution Q’. This is due to that the effect of external costs is taking over the effect of the capacity limit. The solution Q’, finds a cost-effective combination where the two inputs contributes significantly different to production.

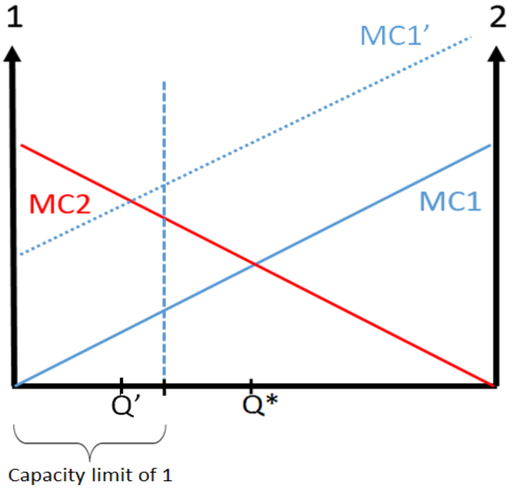

Figure 2. Cost-effective combination of two inputs; 1 and 2 including external cost and capacity constraint

So far, this is the case of a deterministic model. The last step of this study is to turn this model into a probabilistic model in order to deal with uncertain supply. One way of capturing this cost is by adding another restriction to the model, controlling for a minimum acceptance level of energy production. Here, the probability, denoted as γ, will be adjusted.

Our mathematical problem becomes:

$$\min_{Ei} C = \sum_i \sum_r C^{ir}(E^i) + C^i(E^i) \qquad s.t. \;\; \text{prob.}(\sum_i E^i \geq E) \geq \gamma \quad and \quad E^i \leq \bar{E}^i \qquad (9)$$

The probability constraint can be rewritten as:

$$(\frac{\sum_i (\mu^i - E^i)}{\delta} \geq \frac{\sum_i \mu^i - E}{\delta}) \geq \gamma \qquad (10)$$

Hence, the probability of achieving a certain level of energy production is a function of the differences between the average production and production, divided by the standard deviation. This will differ among i:s depending on the reliability of i. For simplicity reasons we let: $\frac{\sum_i (\mu^i - E^i)}{\delta}$ be written as $\O_{\gamma}$. We can then rearrange the equation:

$$\O\gamma \geq \frac{\sum_i \mu^i - E}{\delta} \qquad (11)$$

It is assumed that the standard deviation is the sum of standard deviations from each energy source, and equation (11) can then be written as:

$$\sum_i E^i - \O\gamma \sum_i \delta(E^i) \geq E \qquad (12)$$

The interpretation is then straight forward; the previous sum of energy production is now burdened by the uncertainty of energy production. The more uncertain the delivery performance of i is, the larger is the burden on the production cost. Also, the burden increases with E^i meaning that the effect becomes more evident with greater production volumes. Further, an implication of this restriction is that $\sum_i E^i$ needs to be larger than in previous cases to meet the requirement of the electricity production.

The Lagrangian equation follows:

$$L = \sum_i \left(\sum_r C^{ir}(E^i) + C^i(E^i)\right) + \beta\left(\sum_i E^i - \text{Øɣ} \sum_i \delta(E^i) - E\right) + \sum_i \alpha_i (\bar{E}^i - E^i) \qquad (13)$$

Solving for E^i we get:

$$\frac{\partial L}{\partial E^i} = \sum_r \frac{\partial C^{ir}}{\partial E^i} + \frac{\partial C^i}{\partial E^i} + \beta\left(1 - \text{Øɣ} \frac{\partial \delta^i}{\partial E^i} - \alpha_i\right) = 0 \qquad (14)$$

Which can be rewritten as:

$$\sum MC^{ir} + MC^i = \alpha_i - \beta\left(1 - \text{Øɣ} \frac{\partial \delta^i}{\partial E^i}\right) \qquad (15)$$

Compared to the simplest case, where all marginal costs are equal to each other, the marginal cost is now affected by both the capacity constraint and the probability constraint for i. The probability constraint applies as an extra cost that shifts the marginal cost curve upwards. This is due to the uncertainty effect shown by the $\text{Øɣ} \frac{\partial \delta^i}{\partial E^i}$ in equation (15) and can be seen in Figure 3 where the slope becomes steeper once introducing the probabilistic restriction. It is then assumed that electricity production by energy source 2 is uncertain and that of source 1 is certain. Consequently, a new optimal solution, Q', is found at a higher cost than Q*. The shaded area represents the increase in total cost caused by the restriction, of which each subarea shows the effect on marginal cost for every quantity increase. The size of this cost increase depends on the level of ɣ, production level and the delivery performance of i. Energy sources that are relatively more secure in their delivery performance will therefore have an advantage when introducing this constraint.

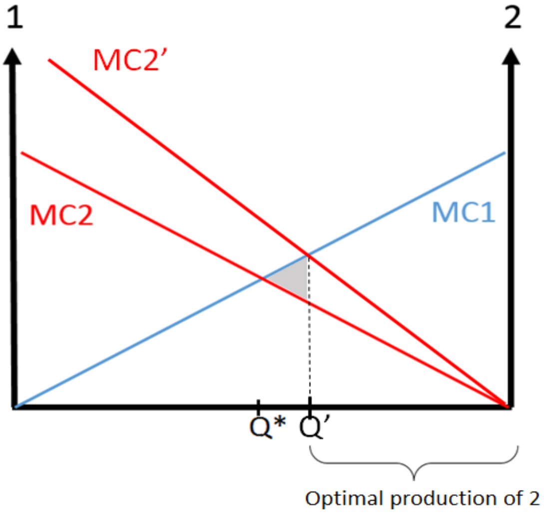

Figure 3. Cost-effective combination of two inputs; 1 and 2 including probabilistic restriction

Allowing for all three adjustments; the capacity constraint, external costs and the probabilistic constraint, the illustration becomes somewhat more complex. Shown in Figure 4 and 5, the marginal costs are first shifted upwards when including the external costs and then tilted into a steeper slope once adding the probabilistic restriction. Figure 4 shows the case where input 1 causes external impacts but no uncertainty, while input 2 is uncertain of a high degree but with no external impacts. The optimal solution then changes from Q*, no constraints, to Q’, with external costs, on to Q’’ with both external costs and probabilistic constraint. Due to the capacity limit, the final feasible solution is found at Q’’’. Figure 5 presents the situation when the additional cost function and the probabilistic constraint are operating simultaneously for both input 1 and input 2, including a capacity constraint for input 1. The shaded triangle in Figure 5 illustrates the increased cost due to the capacity constraint.

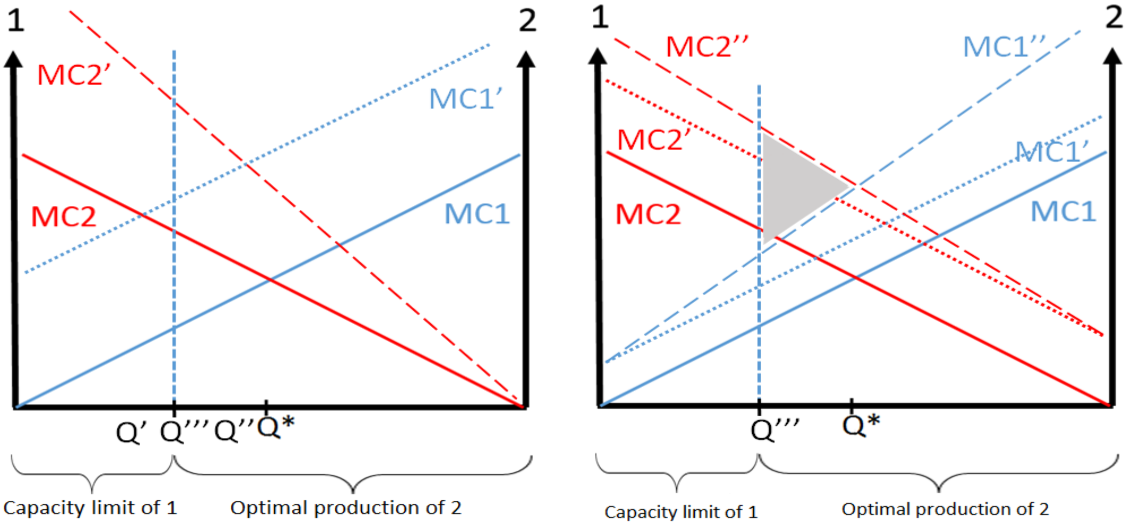

Figure 4 and 5. Cost-effective combination of two inputs; 1 and 2, in the most complex case

4. Energy use in Sweden

Different energy sources have different characteristics of production properties that split them into four categories; baseload, intermittent generation, regulating power and emergency power. Each type serves its own purpose and complement each other to ensure a certain energy demand. The base load produces a stable and constant level of production and is always run to its full capacity. On top of this comes the more flexible regulating power, which can be controlled and regulated with short notice to meet quick changes in demand. Regulating power is also essential to complement the unreliable intermittent generation which is dependent on wind and weather conditions rather than demand for energy (Vattenfall, 2012). In writing, there are no sufficient methods for storing intermittent generation which means that this type of energy needs to be combined with at least one other source of regulating power. Finally, emergency power is typically fossil fuels that can contribute immediately to fluctuating peaks in demand (Vattenfall, 2012). The interaction between these energy categories is essential for the national energy security and to guarantee a reliable supply. This function is fundamental in any economy and is also closely linked to the aspect of self-sufficiency (Vattenfall, 2011). It is therefore important to consider the prospects of domestic supply when investigating the external costs of energy sources. The cost of uncertain supply was expressed in the theoretical Section 3 and will be further described under data description.

The mixture in the Swedish electricity production has the advantage of a high share of non-fossil energies and at the same time has a relatively low degree of uncertainty. This is partly due to the geographical conditions that, makes it possible to provide a large amount of hydro power into the electricity generation. In 2014 the mixture contained of: 42.5% hydro, 41.1% nuclear, 7.6% wind and 8.8% CHP (bio and peat) (Svensk Energi, 2016; Svensk Energi, 2015).

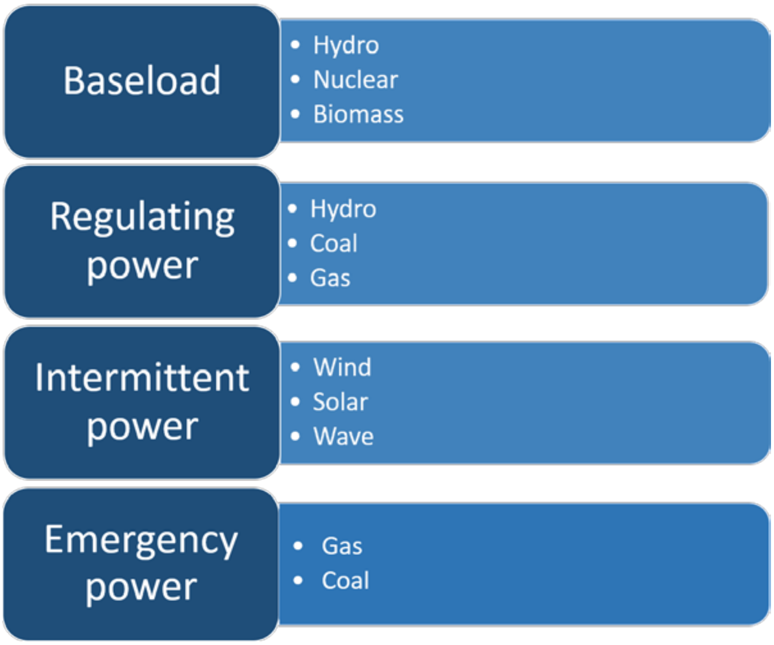

Figure 6. An overview of the Swedish electricity system, preformed based on Vattenfall (2011)

Bioenergy is a terminology used for biofuel, biomass, waste energy and sometimes even peat. In this research *bio, biomass* or *bioenergy* refers to biomass-fired thermal generations and does not include peat combustion. Bioenergy is produced through burning biomass, normally wood chips, in big furnaces. The furnace heats up water that turns into steam and the steam is transferred to a turbine from which electricity is generated. Biomass energy is produced at a stabile paste, and is considered as baseload power (Vattenfall, 2011). In small scale, biomass energy is a reliable source that can meet demand quickly. Due to a big forestry sector Sweden has access to domestic biomass and doesn't need to import biomass today. However, in large fractions, it is harder to guarantee the supply of biomass since the land occupied for biomass production also has an alternative cost in terms of using the land for other purposes. This cost is considered as one of the eminent external effects of biomass (Vattenfall, 2011).

Hydro power is the main electricity source in Sweden and contributes with about 42% of total supply (Energimyndigheten, 2016). Out of this amount about 93% comes from large-scale hydro and 7% from small-scale hydro (Energikommissionen, 2016). The properties of hydro make it possible to store in dams and can therefore be used both as a baseload and as regulating power. The energy is transformed from the potential energy of water into mechanical energy in one or more turbines and is finally converted into electricity (Vattenfall, 2011). Hydro facilities have a life-span of at least fifty years, but the impacts on local ecosystem are more or less eternal regardless of the existence of the facility (Energikommissionen, 2016; Vattenfall, 2011). The loss in local biodiversity is considered the most severe external cost of hydro in this study.

Nuclear power works as a baseload in the Swedish electricity mix, contributing about 41% of the total energy supply (Vattenfall, 2011; Energimyndigheten, 2016). The properties of nuclear make the production stable and reliable and without large emissions. The flexibility is however quite low and thus the reactors are operating at full power at all times. The public and political support for nuclear power has fluctuated drastically over the years, driven by the three big accidents that each time have started big waves of global shutdowns (Strålsäkerhetsmyndigheten, 2016). In between the accidents the public opinion tends to softens based on the advantage of having a relatively unlimited, fossil free and stabile energy source (Vattenfall, 2011). The uncertainty regarding the risk of an accident and radioactive waste is always present in the nuclear debate and is considered as the most crucial external costs in this study.

Nuclear electricity is generated from the enormous heat that is released when splitting nuclei, normally uranium-235. This heat is used to heat up water, that transforms into steam. The steam, in turn, drives a turbine from which the electricity is extracted (Vattenfall, 2011). Uranium is normally mined outside Europe even though Myrviken in Jämtland is considered the third biggest deposits in the world. Myrviken has not been mined for a long time due to the municipal veto and Jämtland is politically dominated by nuclear opponents (LTZ, 2016; Energinyheter, 2016). The fact that Sweden has the possibility to be self-sufficient is however still important once considering the energy security aspect.

Wind power is divided into two sub categories, on-shore and off-shore wind, but the technology is basically the same. Both categories of wind power are reliant of the wind's kinetic energy that pushes the rotor blades of the turbine, creating mechanical energy. The mechanical energy is transmitted into electrical energy in the generator connected to the turbine. This process is sensitive to wind conditions and is therefore categorized as an intermittent source. Obviously, production is not possible if there is no wind, but the windmills are also sensitive to stormy weather and have to be stopped if the wind is too strong. Intermittent sources face a challenge to secure the energy supply, but luckily the wind peaks tend to coincide with peaks in demand which makes the challenge less evident for wind than for solar PV. Other advantages are that wind power doesn't require any fuel nor causes any emissions. In Sweden, wind power was introduced in the early 90s and reached a share of 7.6% of total electricity production in 2014 (Energimyndigheten, 2016).

Solar energy comes in different types of which solar photovoltaic (PV) is the main one and the referred type in this study. Solar PV transforms the energy from solar radiation into electricity and is therefore reliant on the amount of sun hours. This energy transformation is not affected by the size of the absorbance area, meaning that the marginal production is constant (number of kWh/m2 are always the same) but instead affected by the titling of the panels towards the sun (Elforsk, 2007). Since solar PV rely on sun radiation, it doesn't entail fuel in the production, nor causes emissions. However, the technology behind constructing solar panels (and further the recycling) is associated with various external costs that involves quite substantial emissions (Elforsk, 2014).

As an intermittent resource the electricity produced by solar PV needs to be transmitted immediately which challenges the energy security since solar radiation is higher in the summer while the demand peaks in the winter and even in summer there are big variations in sunlight. Further, the amount of sun hours is relatively low in Sweden at 1100 kWh/m^2 compared to sunnier regions like southern United States which yields 2200 kWh/m2/year. Thus, the Swedish production cost is relatively high and has humbled the expansion of solar PV on the Swedish market (Elforsk, 2007). Until 2011 the share of solar energy wasn't measurable in the Electricity Certificate System. In 2014, 11GWh was produced by solar energy which is far less than one percentage (0.0073%) of the total Swedish electricity production (Energimyndigheten, 2016).

Wave energy is a well-known energy source but the actual technology is still in its cradle and the developers have not yet agreed up on the most efficient technical solution. There are some small-scale projects of wave energy but not yet any larger-scale production (Elforsk, 2011). Sweden has sufficient hydrological conditions to introduce wave energy in the electricity mixture, however the production cost has to drop down to the cost of off-shore wind power to be able to compete with other energy sources (Vattenfall, 2010; Elforsk, 2011). Energikommissionen (2016) reached the conclusion that the current technology was too expensive to create incitements for such installations and excluded wave energy from the analysis. This study stays objective until all external costs are added and will include wave energy and its span of suggested costs.

Wave energy is generated by using the kinetic energy of the wind that creates wave on the upper layer of the ocean. The kinetic energy can be transformed into electricity through different methods but normally contains some kind of oscillation technology, a turbine and a generator. In Sweden one particular technology has been tested, centered around having a buoy floating on the surface that is connected to a generator on the seabed. When the waves hit the buoy, a motion will be transmitted via the connecting rope, down to the generator. It is the motion within the generator that is converted into electricity (Energimyndigheten, 2016). Like wind and Solar PV, this procedure is reliant on weather conditions and is therefore categorized as intermittent generations (Vattenfall, 2011).

5. Data description

To be able to solve the cost-minimization problem, presented in Section 3, the three different models require data for production costs, capacity limits, costs and quantities of externalities and standard deviations to the probabilistic model. The data is obtained from international peer reviewed periodicals and reports from both Swedish and international governmental agencies. To ensure the precision of the cost ranges, the scope of values was further discussed together with several governmental agencies (Energikommissionen, Naturvårdsverket, Energimyndigheten, Energy Information Administration, SBC, Energimarknadsinspektionen), several energy producers or energy suppliers (Vattenfall, Svensk Solenergi, Fortum, Skelekraft, Jämtkraft, Telge, OX2, EON) and some additional actors (SCA, Analysgruppen, Aktea, KPMG). In general, the most recent available data is chosen with the majority of data referring to 2014 due to the time lag in data publication. The final selection summarizes the values that will represent the baseline case where production costs and external costs are added together. To control for under- and overestimations, the full cost range is simulated in various sensitivity analyses to test the robustness of the chosen estimates. These tests are operated for every cost and every energy source, one at the time, to check for effects on total cost, marginal cost and the optimal mix.

All costs are presented in öre/kWh and measured in 2016 SEK based on CPI (SCB, 2016) and currency conversion data (Oanda, 2016). In cases where production and external costs are estimated with different discount rates, the discount rate of 3% will be used as a standard measure, based on the applied discount rate in one of the main sources (Münnich Vass, 2015).

This study assesses the Swedish electricity production and hence Swedish data has priory. However, the accuracy of Swedish data is more relevant in some cases than others. Regarding production cost, only data calculated for Sweden in particular has been considered. This is due to the fact that many contributing factors of production costs are sensitive to geographical location and are of high significance. The external costs are primarily taken from Trafikverket (2015) and the Swedish ASEK values, but are complemented by some European sources based on availability. The same applies for external impacts, where Vattenfall's (2012, 2016) figures are prioritized before other foreign studies.

5.1 Production costs and capacity limits

The production cost is simply the cost to produce a certain amount of energy in Sweden, including capital cost, investments, cost of labor, inputs etc. Similar to Hart and Jacobson (2011), these costs are estimated on a yearly average, which is a simplification in order to create a static model. In practice, the production cost varies quite significantly from hour to hour and day to day for the intermittent sources. The variations are significantly smaller when estimating one year to another, hence justifies the choice of an average production cost in a static analysis. Other variations are due to the difference between new facilities (Elforsk, 2014, 2011, 2007) and existing facilities, where costs of existing facilities are priority. New facilities include higher investment costs and tend therefore to range higher than estimates for existing facilities. This trend is less evident in the case of wind power and solar PV whose technological developments have increased drastically during the last decade.

Production functions are often considered as confidential information and the availability of these data points are scarce. Also, most of the research regarding production costs are made by engineers who tend to calculate marginal cost as constant. Consequently, the final cost functions used in this study are made of a mix of data from different sources resulting in five quadratic functions; biomass, solar PV, small-scale hydro, offshore wind and onshore wind, and three linear functions; large-scale hydro, nuclear and wave energy. All production cost functions are presented in Table 1 with the associated cost range, used in further sensitivity analyses, in Appendix 1.

Energy source	**Marginal production cost**	**Capacity limit**
Biomass	MC=86.4 + 3.82E	1.64
Small-scale hydro	MC=48.2 + 13.32E	5.2
Large-scale hydro	MC=29.1	58.1
Solar PV	MC=170+3.4E	1.3
Nuclear	MC=27.6	62.2
Onshore wind	MC= 61 + 0.6E	12.9
Offshore wind	MC= 85.6 + 0.6E	14.8
Wave	MC=300	3
Total		159.14

Table 1. Marginal production cost functions in öre/kWh, and capacity limits in TWh/year

The cost functions for small scale hydro, onshore wind and solar PV are obtained from Münnich Vass (2015). These cost functions contain one intercept and one quadratic term, calculated based on Green-X (2003) figures for 27 European countries, including Sweden. Münnich Vass (2015) quadratic functions are found to range a bit higher than the static marginal cost functions in other sources of literature (Elforsk, 2014; 2007; Energikommissionen, 2016; Vattenfall, 2010; Energimyndigheten, 2014; Stridh et al., 2013). Therefore, the intercept for solar PV has been corrected downwards, to better fit with other findings. Solar PV show otherwise large variations in the literature, ranging between 93 and 2400 öre/kWh (Münnich Vass, 2015; Elforsk, 2007; 2014, Stridh et al., 2013; Vattenfall, 2010; Energikommissionen, 2016). The latest publications (Stridh et al., 2013; Energikommissionen, 2016; Elforsk, 2014) show a consensus of 93-170 öre/kWh which suggests that Münnich Vass (2015) intercept of 626 öre is probably somewhat overestimated. The compromise is then to use a lower of 170, but keeping the slope from Münnich Vass (2015).

Münnich Vass' (2015) marginal cost function for onshore wind is comparable with, but in the upper range of, the suggested costs in other sources of literature (Energikommissionen, 2016; Vattenfall, 2010; Energimyndigheten, 2014). The submitted cost range is 36-65 öre/kWh but with the emphasis on 45 öre/kWh and upwards due to the underlying assumptions. The consensus of previous literature supports to use Münnich Vass (2015) findings as a baseline cost function for onshore wind. Regarding offshore wind, it is assumed that on- and offshore wind have similar operational costs but different investments cost. Consequently, the production cost of offshore wind is higher than production cost of onshore wind and this is represented by the difference in the two intercepts (Energimyndigheten, 2014, Elforsk, 2014). The intercept for offshore wind is obtained directly from Green-X (2003) estimates of Swedish offshore wind conditions. Green-X (2003) suggests 85.6 öre which is compatible with the static marginal cost range of 87-100 öre/kWh (Energimyndigheten, 2014 and Vattenfall, 2010). The slope suggested by Münnich Vass (2015) for onshore wind is also applied for offshore wind.

The marginal cost function for small-scale hydro is presented by Münnich Vass (2015) and has an intercept of 48.2 öre, similar to Elforsk's (2014) average cost of 55 öre/kWh for new facilities. It is likely that 48.2 öre is too high for existing facilities when comparing with Energikommissionen's (2016) average production cost for large-scale hydro of 29.1 öre/kWh. Therefore, another, lower, intercept is constructed to be used in sensitivity analyses. The lower intercept is found, taking the differences in costs between small-scale and large-scale hydro from Elforsk (2014) and adding that to Energikommissionen's (2016) cost for large-scale hydro. This creates an intercept of 34.5 öre/kWh. Concerning the slope, it is hard to evaluate since no other studies found have published comparable digits. It is however reasonable to think that the slope should be steeper relative to large-scale hydro.

The quadratic cost function for biomass energy has been calculated, using Geijer et al.'s (2009) supply elasticity of 0.55 for wood fuel, the average electricity price in 2014 of 27 öre/kWh (Svensk Energi, 2015) and a quantity of biomass input in electricity production of 1.29 TWh in 2014 (Energimyndigheten, 2016). This equation finds a slope of 3.82 per additional kWh. The intercept then becomes negative since the figures used in the first equation, are market figures which operates under the market conditions where there are large subsides for biomass energy. Therefore, one further correction needs to be made to make this cost function comparable with the other cost functions, expressed without subsidies and other regulations. In Sweden, biomass-fired thermal generators are subsidized by electricity certificates, heat credits and refunds for NO_X payments. Together this amounts to 108.7 öre/kWh when deducted for taxes and fees according to Elforsk (2014). These figures are calculated as an average over the four different sizes of biomass-fired thermal generations presented by Elforsk (2014). Controlling for the subsidies, the intercept for production cost becomes 86.4. Putting this in context, OECD (2010) presented an average cost per kWh of 80 öre while Energikommissionen (2016) suggested a cost of 44.5 öre/kWh.

Large-scale hydro and nuclear are simulated with constant marginal costs, as Trøtscher (2007) suggests. Trøtscher (2007) estimates the marginal cost for new nuclear facilities, while this study investigates the conditions for existing production. Hence, Damsgaard and Edfeldt (2015) and Energikommissionen (2016) are more in line with this study. The two studies, Damsgaard and Edfeldt (2015) and Energikommissionen's (2016), apply slightly different contextual framings, and reach a conclusion of 34.5 and 27.6 öre/kWh respectively. Energikommissionen's (2016) proposal of 27.6 öre/kWh is applied as the reference case, due to the most appealing framing in terms of this study.

Trøtscher (2007) suggests using the weekly spot-price of electricity to determine the marginal cost function of large-scale hydro. In Sweden, the average price of electricity in 2014 was 27 öre/kWh, which matches Energikommissionen's (2016) average total production cost of 29.1 öre/kWh. The production costs for new facilities ranges between 24-46 öre/kWh (Vindkraftsportalen, 2016; SvenskEnergi, 2015; Elforsk, 2014) which, as expected, ranges a bit higher than existing costs. The result from Energikommissionen (2016) will be used as the reference case.

Finally, wave power is an applicable technology but currently not in operation. Therefore, the research for Swedish wave power is very limited and mostly described as a future technology (Elforsk, 2014). Elforsk (2007) made an attempt to evaluate the Swedish potentials for adopting wave power and presents a cost of 150-450 öre/kWh. Elforsk (2014) also refers to global studies where the cost varies between 270-550 öre/kWh. Based on these figures, and the lack of a cost function, this study will use a constant marginal cost of 300 öre/kWh as the baseline case.

Further, Table 1 also presents the baseline capacity limits of the eight energy sources. As can be noted, the capacity limits are set fairly tight to the current production of 150TWh, giving a flexibility of about 6%. This will in deed affect the results, but then again, it is justifiable due to the fact that this is a static model. A static model aims to simulate the current condition, which is given a certain level of production ability. However, the low flexibility will limit the extent of the results and therefore, several sensitivity analyses are made, adjusting the capacity limits one by one for solar PV, on- and offshore wind power, wave energy and biomass and at last, all capacity limits are simultaneously set to their maximum. These estimates are to be found in Appendix 1 and should indicate for a situation where large investments have been made in the different sectors, providing a higher flexibility for energy solutions.

The capacity of hydro is simply the produced Tera Watt hours in 2014 (Energimyndigheten, 2016). Considering Swedish hydro conditions, the vast majority of rivers have already been dammed and the remaining large scale hydro opportunity, Vindelälven, underwent a governmental decision in 1970 that put a moratorium on the exploitation of the river for hydropower production (ViEF, 2009). It is therefore unlikely that any expansion of hydro is likely in the nearest future. The assumption of the capacity limit is supported by Future-E (2008) regarding small-scale hydro but Future-E (2008) finds extension potential of additional 5% for large-scale hydro. However, the assumption of using the production capacity from 2014 remains. The production figure comes with one disadvantage in that it makes no separation of small-scale and large-scale hydro. Therefore, this figure is complemented by subtracting Future-E's (2008) estimation for small-scale hydro capacity, from the total produced quantity presented by Energimyndigheten (2016). This leaves 58.1TWh a year to the large-scale hydro production (63.3TWh minus 5.2TWh).

Nuclear capacity limits are also the obtained from the produced Tera Watt hours in 2014 (Energimyndigheten, 2016). Allowing for the global trends concerning nuclear and the current Swedish law (Strålsäkerhetsmyndigheten, 2016) limiting the amount of reactors to ten, there are no signs that nuclear production will increase in the near future in Sweden. This supports the assumption of using the current capacity of nuclear.

Capacity limits regarding solar PV, biomass, wind and wave energy are set based on the Future-E (2008) study that evaluate the potential extension of energy sources in Sweden by 2020. The restriction of 2020 seems compatible with the previously made assumption that hydro and nuclear production are limited to the current capacities. Setting this restriction, the model allows for a small capacity increase that may help to indicate which type of energy sources are the most compatible. Later, the adjusted capacity limits will reveal the effect of large investments in the different energy sources. However, the capacity limit for onshore wind appears too tight compared to the current conditions (Future-E, 2008; Energimyndigheten; 2016, 2014). Therefore, the assumed possibility of 25% expansion is applied to the current statistics (Future-E, 2008; Energimyndigheten; 2016, 2014).

5.2 External costs

The external cost of electricity production symbolizes all costs that are not included within the production cost and instead are carried by the society. Externalities can both be positive and negative but in general and in this study, focus on the negative externalities. Electricity production causes a large number of externalities of which Li (2005) gives a description of the main ones for hydro, wind, nuclear, biomass and solar. Wave energy lacks research and hence, on recommendation of Elforsk (2010), the social impacts of off-shore wind power are applied to wave energy. The externalities stressed by Li (2005) are used as an indication in data search but are scaled down to include nine different externalities; CO_2, SO_2, NO_X, PM10, land use, noise, waste disposal, depletion of resources and accident. The OR method requires a thorough selection process, since the cost minimization problem simply will be solved based on the inserted values. Therefore, during the process, several externalities have been dropped due to risk of measurement errors. The risk of double counting caused the exclusion of *visual intrusion* and *radiation*, which were interlaced with *land use* and *waste disposal* respectively. The exclusion out of *water supply* was instead due to the lack of a robust scientific founding.

The final costs of externalities in this study are an assortment, selected depending on relevance, availability and timeframe of this study. It should therefore be understood as an attempt to get one step closer the true cost of electricity production, when internalizing the cost of listed externalities. It is, however, not an assessment of the total external impacts of the electricity production and consequently is not comparable with such figures.

CO_2, SO_2, NO_X, PM10 and land use, applies to all eight energy sources and are calculated in a two-step calculation. The first step is treated in this section and evaluates the cost of environmental damage, in terms of cost per unit. The second step tries to allocate the quantity of environmental damage in terms of unit per kilo Watt hour. This step is explained in section 5.3 which ends with an assessment of the two ranges multiplied. The final external costs are expressed in öre/kWh for every energy source and every externality.

The external impacts of energy production are measured from a life cycle assessment, LCA. This means that all emissions from cradle to grave are included. Seen from a life cycle perspective, each kilo Watt hour shows traces of emissions even though electricity production might not. This is mostly due to constructions, mining, transports etc. and concerns all eight resources (Hatch, 2014). In terms of the four types of emissions, CO_2, SO_2, NO_X and *PM10*, the LCA applies to the quantity measurement while for *land use* it is already included in the cost estimate. There are many arguments both why to use LCA and why not to use LCA and it may be considered as a matter of taste. In terms of this study, the comparison of non-fossils becomes rather flat if only direct external impacts are included. Limiting the estimation to the direct impacts, this would give a biased view of the true external impacts of electricity production. The LCA interpretation is applied in the majority of previous literature dealing with external impacts of production of non-fossil energies.

Carbon dioxide, CO_2, is one of the green-house gases causing global warming or climate change. An important feature of green-house gases is that they are global pollutants, meaning that the place of polluting is irrelevant. CO_2 is stored in all plants, living and dead, and is captured in the biosynthesis. When the plants are combusted, the CO_2 is released into the atmosphere. In terms of this study, the main contribution of CO_2 is correlated with construction and transports (Hatch, 2014). The cost of CO_2 is taken from Trafikverket's (2015) ASEK values, which is the shadow price of the Swedish carbon dioxide tax. Trafikverket (2015) estimates this to 1.12 SEK/kg and further recommends 3.62 SEK/kg CO_2 for sensitivity analysis. Previously, the price of Emissions Allowances within the European Trading Scheme, EUA, was a candidate as the price of carbon. Currently, the price for EUA is about 0.048 SEK/kg (EEX, 2016), which ranges outside the suggested interval (IPCC, 2016; Watkiss, 2005; EPA, 2016). Watkiss (2005), summarizes various studies and finds a range between 0.32-1.55 SEK/kg CO_2 for the years of 2010-2020. IPCC (2016) presents estimates from 0.088 to 3.22 SEK/kg CO_2.

Sulfur dioxides, SO_2, is an airborne emission causing acidification of forests and lakes but can also cause negative health effects on the respiratory system. The majority of SO_2 emissions comes from the industrial sector, hence in case of the eight energy sources it is mostly related to the construction process (Hatch, 2014). The cost of SO_2 is taken from Trafikverket's (2015) ASEK value of 28 SEK/kg. The cost is a valuation of individual's willingness to pay and is multiplied with the number of exposed individuals. ASEK value is in line with the Swedish tax of 30 SEK/kg for sulfur airborne emissions but about a fourth of the estimate presented by AEA Technology Environment (2005). AEA Technology Environment (2005) suggests an average external cost of 115 SEK/kg for the European countries, which will represent the upper limit within the sensitivity tests of this study.

Nitrogen oxide, NO_X, is a gas that occurs in all types of combustions in high temperatures. NO_X contributes to various environmental and health effects such as acidification, over-fertilization and respiratory illnesses (Hatch, 2014). Most NO_X emissions in energy production comes from transports in the early production stages (Trafikverket, 2015). As for SO_2, the ASEK (Trafikverket, 2015) NO_X value is an estimation of individual's willingness to pay and is multiplied with the number of exposed individuals, estimated to 83 SEK/kg. Naturvårdsverket (2009) also investigates the willingness to pay for reducing NO_X emissions but focusing on the impacts of acidifications. Naturvårdsverket (2009) found a range between 4 and 70 SEK per reduced kilogram. Within this finding lies the Swedish NO_X charge of 50 SEK/kg airborne emissions (Naturvårdsverket, 2016). AEA Technology Environment (2005) advises the highest value of 85.29 SEK/kg for European NO_X emissions.

Particular matter, PM, is describing all suspended solid and liquid particles in the air. This study focuses on PM10, which is a sub group for all particles that fall into the size category of 2.5 µm to 10µm. PM10 circles for serval hours in air and then fall down to the ground as dust. Since the particles are airborne, they are inhaled and cause respiratory related health problems as well as environmental damage. In the case of electricity production, PM10 emissions are often linked to combustion, transportation or construction (Hatch, 2014). Trafikverket's (2015) figures regarding particular matter concerns PM2.5, referring to road traffic, and are specified due to location of emissions. This measurement is not perfectly applicable for the LCA of energy production, neither is the associated cost (Trafikverket, 2015). Instead, the cost of PM10 is obtained from ECOFYS' (2014) estimate of 136 SEK/kg, that corresponds to an average cost of particular matter in Europe including both the health and the environmental effects. The higher limit in the sensitivity analyses is taken from AEA Technology Environment (2005) and the result of 532 SEK/kg for PM2.5, recalculated into PM10 values. European Environmental Agency (2016) multiplies the cost of PM2.5 with 0.6 to get the cost of PM10, this method is applied and gives a value of 320 SEK/kg for PM10.

Land use represents the opportunity cost of using land for other purposes within the time frame of a LCA of each energy resource. This measures the cost of lost biodiversity in the land used in energy production compared to a natural landscape (ECOFYS, 2014). Biodiversity reflects everything from genes to whole ecosystems within a certain area and is generally sensitive to sudden changes. Biodiversity impact is most evident for hydro power and biomass, but it is also noticeable for nuclear, onshore wind and solar PV. Measuring the cost of biodiversity is complex and few studies have attempted the challenge. Trafikverket (2015) chooses not to present any figures for land occupation in their series of ASEK values due to the many uncertainties. The cost of land use in this study is obtained from ECOFYS (2014) that assessed the cost to 0.81 SEK/m^2 a. This is of course a crude simplification, and a more accurate assessment would differentiate the cost, based on the type of environment and opportunity for biological corridors. However, the full valuation of biodiversity is outside the scope of this study.

Noise and visual effects is included in this study to cover one of the more practical external costs of wind power. Noise is normally linked to disturbance of road traffic but also includes the constant, dull sound from wind mills. Apart from the distractions, noise can also cause health impacts, such as insomnia (Trafikverket, 2015). Munksgaard and Larsen (1998) investigated the effects of *noise and visual intrusion* in Denmark. Starting with a willingness to pay analysis for the removal of a windmill, in which the payment would symbolize the monetary value of noise and visual effects. Result shows an average willingness to pay of 0,0565 öre/kWh, 0.02827 öre/kWh for windmills in small windfarms and 0.179 öre/kWh for alone standing mills. Munksgaard and Larsen (1998) continued by testing the results through a hedonic pricing estimation. The external cost of noise and visual effects then became 1.6 öre/kWh, which verifies that the results from the willingness to pay valuation were not overestimated. This conclusion is also in line with ExternE's (1995) suggested interval of 0.0796 to 1.25 öre/kWh and Mirageres (1997) cost of 0.648 öre/kWh. Based on the types of studies and year of publication, this study uses the value of 0.0565 öre/kWh in the baseline case.

Depletion of resources is considered as an external cost in the sense that there is a monetary value to the fact that future generations will not have the ability to enjoy the same opportunities. In this study this applies to uranium used in nuclear power generation. Uranium has a million-fold energy value compared to fossil fuels. Comparing coal with uranium, one-kilogram coal provides 8 kWh while one-kilogram uranium creates 24,000,000 kWh (European Nuclear Society, 2016). ECOFYS (2014) values the external cost of uranium depletion to 0.63 SEK/kg which gives an almost insignificant external cost per kWh, 0.0000026 öre/kWh. ECOFYS (2014) further stresses an own estimate per kWh of 11 öre/kWh but, pari passu, argues that the scarcity of uranium is reflected in the price of uranium, and in practice is zero (World Nuclear Association, 2016). The baseline case will therefore use 0.0000026 öre/kWh.

Waste disposal concerns the external cost of radioactive waste from nuclear production, including the radiation and health aspect. The repository of radioactive waste must guarantee a safe storage of at least 100 000 years, hence the external cost should include the whole time period. This mathematical problem is hard to solve and ExternE (1995) suggests a cost of 0.00000969 öre/kWh for low and intermediate waste disposal and 7.29E-9 öre/kWh for high radiation level waste disposal. It is hard to evaluate if these costs are over- or underestimated due to the enormous uncertainty in such figures. This study has therefore chosen to use a different kind of measurement, namely the charge that Swedish producers pay to the Nuclear Waste Found. In 2016, the charge is 4.2 öre/kWh and aims to cover a secure management of current and future waste disposals, restoration of the land used for power facilities, R&D and insurances (Vattenfall, 2016). This value might be overestimated, but is assumed to bear the external cost of radiation which is presented separately in ExternE (1995) among others.

Accident covers the risk of accidents affecting the public, in contrast to work-related accidents. This external cost applies mainly to nuclear but in smaller scale also to onshore wind. There are different ideas how to measure the cost of an accident and there is no consensus for a unified standard method. The statistical value of life deals with ethnical issues which tears the cost range even wider apart. Comparing nuclear accidents with wind-power accidents, the probability of a nuclear accident is significantly lower, but the consequence of an accident is of course vastly bigger for nuclear than for wind. Since the world "only" experienced three major nuclear accidents in the last 60 years and each one have costed around $100 billion (estimated based on Fukushima 2011) (Financial Times, 2016), it is almost impossible to calculate a true external cost per kwh. The assumptions regarding the probability, the time-frame of recovery, cost of recovery, interest rate and discount rate will therefore distinguish the result. Lévêque (2013) summarizes the probability for another nuclear meltdown between 0,00000027 and 0,0003 based on various literature. In between we find ExternE (1995), that calculates with a probability of 0.00005 for a core meltdown per year. ExternE (1995) then finds a cost range of 0.0026-0.118 öre/kWh. Additional suggestions come from D'haeseleer (2013) with a cost of 0.27-2.75 öre/kWh, Energifakta (2014) stresses 0.1-2.7 öre/kWh and ECOFYS (2014) suggests 0.46 to 3.66öre/kWh. Another way of estimating the risk of an accident is using the nuclear insurance premium. The value of the accident risk then becomes 0.92-1.83 öre/kWh (World Nuclear Association, 2016). The consensus of previous literature is that the figures hold an enormous uncertainty and ranges within the span of 0.0026 to 3.66 öre/kWh. The unweighted average of previous literature is 1.83 öre/kWh and will be the reference case in calculations.

The known number of wind power accidents globally between 1980 and 2015 was 1698, causing a total of 145 fatalities (Boccard, 2015). During the last two decades, the risk of an accident has drastically decreased due to improvements in security through the whole production chain (Boccard, 2015). ExternE (1995) made its calculations in 1995 and found a cost of 0.102 öre/kWh. However, since the early 2000, less than one accident is reckoned per GWyear (Boccard, 2015). Interpreting Boccard (2015) risk assessment for wind power, one can assume that the cost of an accident estimated per kilo Watt hour is insignificantly small and hence could be ignored in such analysis. In this study the ExternE (1995) result will be used in the baseline case and a value of zero based on Boccard's (2015) assessment will be included in the sensitivity analysis.

Externality	Cost/ Unit	Reference
CO_2	1.12 SEK/kg 0.048-3.62	Trafikverket, 2015, IPCC, 2015, 2007, Watkiss, 2005, EPA, 2016 and EEX, 2016
SO_2	27.95 SEK/kg 27.95-115	Trafikverket, 2015 and AEA Technology Environment, 2005
NO_X	82.81 SEK/kg 4-85.29	Trafikverket, 2015, Naturvårdsverket, 2009 and AEA Technology Environment, 2005
PM10	136 SEK/kg 136-320	ECOFYS, 2014 and AEA Technology Environment,2005
Land use	0.81 SEK/m2a	ECOFYS, 2014
Noise	0.0006 SEK/kWh 0.0003-0.016	Munksgaard and Larsson, 1998, ExternE, 1995 and Mirageres, 1997
Depletion of uranium	2.6E-8 SEK/kWh 0-0.11	ECOFYS, 2014 and European Nuclear Society, 2016
Waste disposal	0.042 SEK/kWh 7.29E-11 – 0.042	Vattenfall, 2016 and ExternE, 1995
Wind accident	0.001 SEK/kWh 0-0.001	ExternE, 1995 and Boccard, 2015
Nuclear accident	0.0183 SEK/kWh 0.000026- 0.0366	ECOFYS, 2014, D'haeseleer, 2013, ExternE, 1995 and Energifakta, 2014

Table 2. Description of external costs

5.3 Emission volumes and Land use quantities

The external impacts, like the external costs, are investigated by various studies, creating a range of values for each quantity and each cost (Vattenfall, 2012; IPCC, 2012; Faaij et al., 1998; Nap, 2010; Mann, 1997; Evans et al. 2010; Fthentakis and Chul Kim, 2009; A.K Akella, 2009; Penht, 2006; Sundqvist, 2011; Sheldon and Hadian, 2015; ExternE, 1995, Vattenfall, 2016; Hatch, 2014; Klein, 2013; Alsema, 2006; Stoppato, 2008). The span of quantities is specified in Table 3 in where the chosen baseline cases are highlighted. In cases where no priority exists among the sources, an unweighted average of the results in all listed literature are presented. This average is calculated a bit differently for the CO_2 emissions of solar PV, due to the broad variation in studies. Since a majority of previous studies show a narrower interval of 21-80 g/kWh this is selected for the reference case and outliers are excluded in the calculation on the average (Nap, 2010; Alsema 2006; IPCC, 2012; Stoppato, 2008).

Biomass is commonly considered as carbon neutral, due to the absorbance of carbon in the photosynthesis. However, when adding a life cycle perspective to the estimations, showed in Table 3, the final value becomes positive according to most sources (Vattenfall, 2012, IPCC, 2012 and Nap, 2010) while Mann (1997) instead stresses negative emissions (-410 g/kWh) based on the carbon sink service while growing. The latter argument is criticized by a few authors, including Nap (2010), since Mann (1997) hasn't considered the potential carbon sink of an alternative use of the land occupied by biomass production.

The selected values for land use, highlighted in Table 3, are obtained from Fthentakis and Chul Kims (2009) work on large-scale hydro, onshore wind, solar PV and biomass. The result of large-scale hydro is then applied to small-scale hydro. Several studies (Klein, 2013; Nap, 2010; Sheldon and Hadian, 2015; ExternE, 1995) show other suggestions for one or a few energy sources, but the calculations are based on different assumptions and published in different years which make them less attractive for comparison. Fthentakis and Chul Kim's (2009) findings are slightly modified for onshore wind and for biomass, where land use is excluded from the baseline case. The exclusion regarding onshore wind is based on two assumptions, first, only 1% of the occupied area is land, the rest is air space between the rotor blades, hence the land can still be used for grassing etc. (NAP, 2010). Secondly, several studies (Naturvårdsverket, 2007 and Begrmann et al, 2006) conclude that the effects on biodiversity, mainly bats and birds, may be neglected. The exclusion of land use for biomass is instead based on that the figures presented in Fthentakis and Chul Kim (2009) are concerning willow production, which is a minor part of the Swedish biomass production. The biggest share, 85%, comes from wood chips, a waste product from forestry (Bioenergiportalen, 2016). Since wood chips are a secondary product from the forest industry, it is reasonable to assume that the biodiversity impacts from wood chips-biomass are borne by the forestry sector and not energy production. Hence, the quantity measurement for land use is assumed to be zero at the base line case but is let to vary up to 0.489 m^2/kWh in the sensitivity analysis.

Regarding offshore wind, there is not enough research on the impact of seabed occupation. Some studies (Naturvårdsverket, 2010) even claim that the impact is positive since the foundation of a windmill creates an artificial reef that can affect marine life positively. Based on the contradictions in the findings and the narrow range of research, this external cost has been excluded for both off-shore wind and wave energy.

Hydro energy is probably not perfectly compatible with the measurement m^2/kWh and the true impacts on the local environment might be underestimated. A solid measurement hasn't been found that seems in line with the mainstream criticism against hydro energy. One attempt is made in 2002 by Sundqvist (2002) who investigated the willingness to pay an extra amount on the electricity bill to reduce the impacts on the local biodiversity. The finding suggests an average willingness to pay of 2 öre/kWh which marked up becomes 2.31 öre/kWh. This cost is criticized by Vattenfall (2011) for being too low, however, it is a hundredfold the summed values from ExternE (1995) for forest and agricultural impacts.

Energy source	**CO2** g/kWh	**SOx** g/kWh	**NOx** g/kWh	**PM10** g/kWh	**Land Use** m^2/kWh
Biomass	**16**[A] 16-74[B] 24[C] 15-52[D] -410[E] 30-40[F] 37[G]	0.01-0.17[C] 0.04-0.94[D] **0.028**[A]	0.06-2.57[C] 0.29-0.82[D] **0.68**[A]	0.36-0.488[C] Ave. **0.424**	0.36-0.488[D] 0.489[H] **0**
Hydro$_{SMALL\text{-}SCALE}$	9[I] **5**[A] 3[J]	0.03[I] 0.028[J] ave. **0.029**	0.07[I] 0.49[J] Ave. **0.6**	**0.031**[J]	0.00235[H] **2.31** öre/kWh[K]
Hydro$_{LARGE\text{-}SCALE}$	3.6-11.6[I] 4-14[B] 10[J] ave. **8.9**	0.009-0.024[I] 0.017[J] **0.002[A]**	0.003-0.006[I] 0.036[J] **0.004[A]**	**0.036[J]**	0.00235[H] 0.122[D] 0.001803[L] In öre/kWh; 0.012[M] **2.31**[K]
Nuclear	**3**[N] 5[A]	0.02-0.026[O] **0.03**[A]	**0.025[A]** 0.033-0.045[O]	**0.005-0.011**[o]	**0.000029** [H] 0.0065[D]
Wind$_{ONSHORE}$	**11[N]** 15[A] 7-9[I] 9.1[M] 2-29[D] 10.2[J]	0.02-0.09[I] 0.087[M] 0.022-0.028[O] 0.0395[J] **0.026[A]**	0.02-0.06[I] 0.036[M] 0.025-0.031[O] 0.0311[J] **0.027[A]**	0.012-0.018[o] 0.042[J] Ave. **0.029**	0.00276 [H] **0**
Wind$_{OFFSHORE}$	**11[A]** 9.1[M] 2-29[D] 8.9[J]	**0.035**[J] 0.087[M] 0.02-0.09[I]	**0.021**[J] 0.036[M] 0.02-0.06[I]	**0.011**[J]	**0**

Solar PV	98-167[I] 25-35[Q] 30-80[B] 21-54[D] 42[R] 99[J] Ave. **50**	0.2-0.34[I] 0.073-0.215[D] 0.288[J] Ave. **0.282**	0.18-0.3[I] 0.04-0.082[D] 0.034[J] Ave. **0.061**	**0.61**[D] 0.119[J]	**0.00042**[H] 0.00032-0.00053[P]
Wave	**8**[B] 25[D]	**0.035**[J] 0.02-0.09[I]	**0.021**[J] 0.02-0.06[I]	**0.011**[J]	**0**

Table 3. Description of external impacts of energy production

A: Vattenfall, 2012, B: IPCC, 2012, C: Faaij et al., 1998, D: Nap, 2010, E: Mann, 1997, F: Evans et al. 2010, H: Fthentakis and Chul Kim, 2009, I: A.K Akella, 2009, J: Penht, 2006, K: Sundqvist, 2011 L: Sheldon and Hadian, 2015, M: ExternE 1995, N: Vattenfall, 2016, O: Hatch, 2014 P: Klein, 2013, Q: Alsema, 2006, R: Stoppato, 2008

The cost of externalities is multiplied with the level of external impacts, which gives a value expressed in öre/kWh for each energy source and each externality. These costs are presented in Table 4 and the full ranges of cost are to be found in Appendix 2. As described in Section 3, the external cost functions are summed over the number of externalities for each energy source, which are different depending on energy source. This study sums the external cost of CO_2, SO_2, NO_X, *PM10* and *Land use* for all energy sources and additional *noise* and *accident* for wind energies, and *waste disposal*, *accident* and *depletion of resources* for nuclear. The summed cost of externalities can be read at the final line of Table 4 and is the total assessed value of external effects in this study. The external cost then becomes the largest for solar PV, closely follow by biomass. The external effects of solar PV are mainly due to construction and lack of a sufficient recycling process of the materials, while in terms of biomass the actual energy production causes the largest emissions.

Externality	**Biomass**	**Hydro$_{Small}$**	**Hydro$_{Large}$**	**Nuclear**	**Wind$_{ON}$**	**Wind$_{OFF}$**	**Solar**	**Wave**
CO_2	1.792	1.008	0.997	0.336	1.232	1.232	5.6	0.896
SO_2	0.078	0.081	0.006	0.084	0.073	0.099	0.788	0.099
NO_X	5.631	0.491	0.033	0.206	0.224	0.171	0.499	0.171
PM10	5.766	0.422	0.354	0.109	0.389	0.148	8.296	0.148
Land use	0	2.31	2.31	0.002	0	0	0.034	0
Noise					0.057	0.057		
Depletion of resources				0.0000026				
Waste disposal				4.2				
Accident				1.83	0.102			
Total	13.267	4.312	3.7	6.767	2.077	1.707	15.217	1.314

Table 4. External cost of energy production, expressed in öre/kWh

The assessed external costs are then applied to the previously stated production cost to create eight unique cost functions, see Table 5. These cost functions represent the applied version of equation (5) described in Section 3, and hence the cost-minimization problem will be solved on the basis of these functions. By a quick glimpse, it can be noted that this assessment of external impacts does not have a big effect on the total marginal costs. Nuclear, the second cheapest energy source (after large-scale hydro), has the highest relative change in cost of 24%, but is still significantly cheaper than the third cheapest energy source. Already at this point, it is obvious that for low levels of production, large-scale hydro and nuclear power will be the first included energy sources in the optimization problem.

Social marginal cost functions

$$MC^{biomass} = 86.4 + 3.82E^{biomass} + 13.267$$

$$MC^{hydro-small} = 48.2 + 13.32E^{hydro-small} + 4.312$$

$$MC^{hydro-large} = 29.1 + 3.7$$

$$MC^{solar} = 170 + 3.4E^{solar} + 15.217$$

$$MC^{nuclear} = 27.6 + 6.767$$

$$MC^{wind-on} = 61 + 0.6E^{wind-on} + 2.077$$

$$MC^{wind-off} = 85.6 + 0.6E^{wind-off} + 1.707$$

$$MC^{wave} = 300 + 1.314$$

Table 5. Social marginal cost functions

5.4 Probabilistic analysis: standard deviation and risk attitude

As shown in Section 3, the risk discount consists of the standard deviation in electricity production and the standard normal for the chosen probability level. The standard deviation in supply of the intermittent resources is calculated by means of the coefficient of variation, which is the standard deviation divided by mean energy production of i. The supply of electricity by large- and small-scale hydro and biomass energy are considered as certain because of their regulating capacity. For hydro and biomass, weather conditions do affect the production to a high extent. Rain and snowfall affects the amount of water in the rivers and weather conditions affect the growth of vegetation. However, extracted over a one-year period and comparing with the completely intermittent resources, this effect is assumed to be neglected. Further, nuclear power is the most reliable energy source in the Swedish electricity system and is therefore not subject to energy uncertainty in this study. This leaves solar PV, on- and offshore wind power and wave energy as uncertain. It should be noted that a static model will not be able to fully assess the true cost of uncertainty since weather conditions may change on an hourly basis and this is far too complex for this type of analysis.

For solar PV the level of insolation hours during one year will decide the range in production, from which the standard deviation is derived. The production is suggested to range between 750-1100 kWh/m2 a year, giving a spreading of 350 and a mean of 925 (Elforsk, 2007). These numbers can be plugged into the span of 4 standard deviations, for the case of a 95% probability, see Appendix 3. The coefficient of variation for solar becomes 0.095 and can the interpreted as the degree of uncertainty.

The weather conditions are a bit more complicated for wind power. A wind mill starts to generate energy at a wind force of 3 m/s but produces the maximum amount of energy around 10-14 m/s. However, in stormy weather, from 25 m/s and stronger, the wind mills have to be stopped due to security reasons. Based on this, wind power can supply energy in 80-90% of the time a given year (Elforsk, 2014). During one year, Elforsk (2014) estimates 2900 full load hours for onshore wind and 3700 hours for offshore wind, on average. Together with the 80-90% production level, it suggests plus minus 5% from the average. The range of full load hours becomes 2755-3045 for onshore wind and 3515-3885 for offshore wind, which gives a coefficient of variation of 0.025 for both on- and offshore wind power, see Appendix 3, due to the same delivery standard. This means that wind power is relatively more reliable than solar energy, which seems reasonable in the Swedish climate. Furthermore, since wave energy lacks founding research, the figures of off-shore will continue to fill the scientific gap and hence 0.025 is applied for the coefficient variation of wave energy.

Standard normal, derived as γ in Section 3, is set to 99% indicating the level of risk aversion. For a one tail test, controlling for a capacity equal or higher than, the corresponding t value is 2.326. Various standard normal are considered in sensitivity analyses, see Figure 13 in Section 6.2

6. Result

The answer to the addressed research question 1) is found in Section 6.1 and the answer to question 2) is enlighten in Section 6.2. Both questions are assessed at a production level of 150 TWh, similar to the current production in Sweden. The sensitivity analyses in Section 6.3 test the robustness of the model by examining how the results vary for adjustments of each parameter.

All simulations are made including and excluding externalities, and presented separately. The aim of a model without externalities is to approximate the Swedish electricity production, however, it should be noticed that the standard model is not an identical replicate of Swedish production. As presented in Section 5, the standard model, hence all models, are founded on cost functions that exclude subsidies and other regulations. Also, the capacity limits for solar PV, biomass, on- and offshore wind and wave energy have been adjusted slightly upwards to create flexibility within the model.

6.1 Cost-effective production of non-fossil energies

The total cost of electricity production in Sweden at a level of 150TWh with and without inclusion of external effects does not change significantly, see Figure 7. The minimum cost amounts to 58.3 billon SEK and that with external costs is 65.4 billion SEK. These estimates are close to production cost as measured in the Swedish national accounts for the electricity sector (including heating and gas) which corresponds to approximately 56.8 billion SEK (SCB, 2016). Comparing the result excluding external costs with the actual cost, the difference of 1.5 billion SEK corresponds to only 2.6% of the total cost. This difference in costs is mainly driven by the slightly different framings of the costs, the increased capacity limit of 6% in the model and the presence of incentives and other regulations in the actual cost. The relatively small difference in total cost together with the relatively similar production mix, indicates that the model works as a quite accurate approximation of the current Swedish situation.

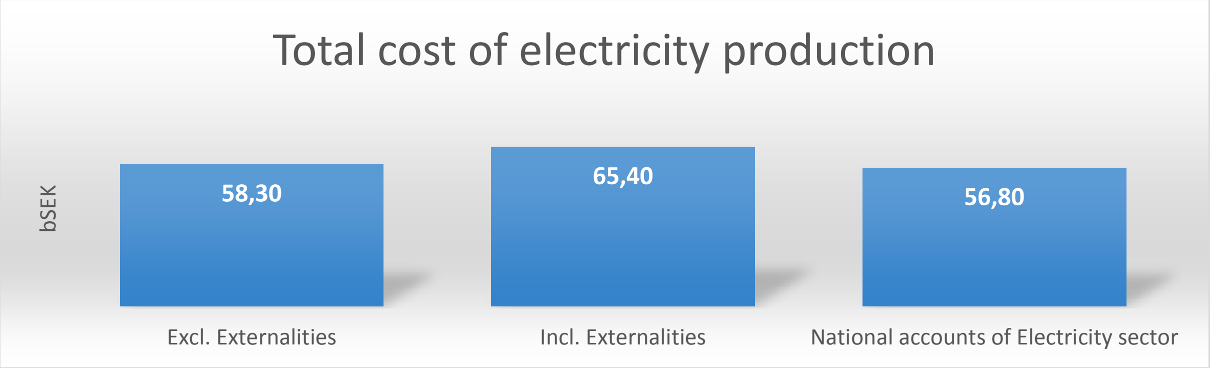

Figure 7. Total cost of electricity production in Sweden at the level of 150TWh, in bSEK

The difference in total cost of the standard model compared to the model including externalities, is about 7 billion SEK. The majority of this cost is today neglected in Swedish production and can be interpreted as the cost of the listed externalities that is currently borne by the society (some taxes cover minor parts of this estimated cost (Elforsk, 2014, Energikommissionen, 2016, Vattenfall, 2016, Naturvårdsverket, 2016)). The change in total cost can be understood in the case presented in Figure 2 (Section 3), where the summed cost of all externalities pushes the marginal cost curve upwards and finds an optimal combination to a higher cost. This is further illustrated in Figure 8, where the gap between the two cost curves represents the additional cost of externalities.

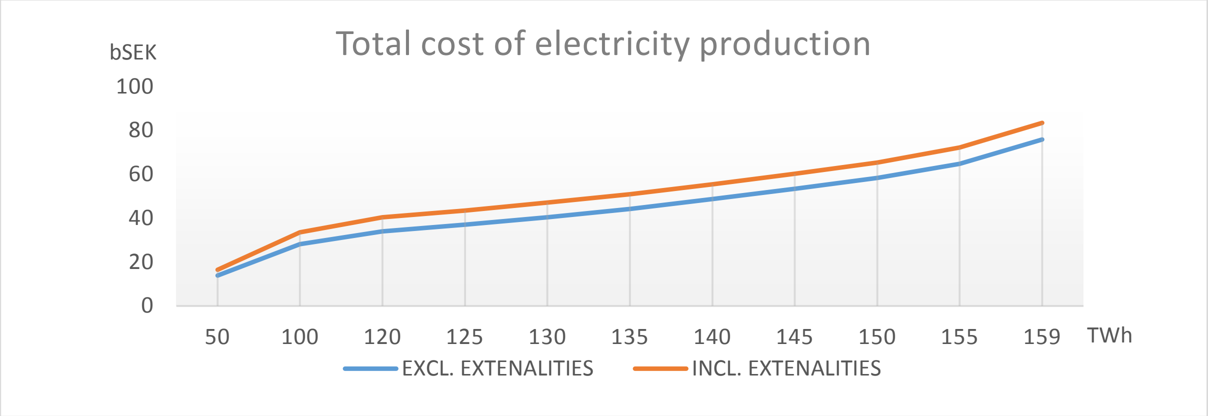

Figure 8. Total cost of electricity production in Sweden, expressed in bSEK

Presented in Table 6, the cost-effective result of the standard model, excluding externalities, shows a mix where biomass, nuclear, large-scale hydro and onshore wind are operated to their full capacities, at a total production of 150 TWh. Offshore wind and small-scale hydro are contributing to the production of a lower proportion while solar PV and wave energy are not part of the mix. Expressed in percentage, the model suggests a combination of; 41.5% nuclear, 38.7% largescale, 1.3% small-scale, 8.8% offshore wind, 8.6% onshore wind and 1.1% biomass energy. Comparing with the actual statistics of 2014; hydro represented 42.5%, nuclear 41.1%, wind 7.6% and CHP (bio and peat) 8.8% (Energimyndigheten, 2016; Svensk Energi, 2015).

The cost-effective result when including externalities is shown in the mix presented in Table 6, or in percentage is about; 41.5% nuclear, 38.7% largescale hydro, 1.3% small-scale hydro, 9.5% offshore wind, 8.6% onshore wind and 0.4% biomass energy. A striking similarity between the suggested mix excluding externalities and the mix including externalities, is that large-scale hydro, nuclear and on-shore wind are operated at their maximum capacities in both cases, and that solar PV and wave energy are not suggested to contribute to the production. The difference between the two cost-effective mixes, is a direct response to the size of external costs presented in Table 4. Biomass generated a relatively high external cost and therefore becomes less attractive in the cost-effective solution once applying the external costs, see Table 6. The opposite happens to offshore wind power which generates relatively low external costs and becomes relatively more attractive in the assessment when externalities are included. Even though the difference is clear it should be noted that the size of these differences are rather small.

Comparing the actual allocation with the cost-effective mixes, the three cases are significantly similar, see Table 6. The main difference is that the cost-effective allocations suggest twice as high share of wind power, instead of the 12 TWh dedicated to other energy sources in the actual mix. The other sources are mainly different types of CHP fueled by bio-energies, apart from biomass, and peat. The actual allocation therefore includes a small share of fossils, in contrast to the non-fossil allocation in this study. Another difference is that a low share of solar PV is present in the actual production mix, due to the large subsidies that makes production profitable. Further, biomass is suggested to produce at a lower level than the actual production when external effects are internalized in the cost.

	Excl. externalities TWh	Incl. externalities TWh	Actual production TWh[1]
Biomass	1.64	0.62	1.29
Solar PV	0	0	0.011
Nuclear	62.2	62.2	62.2
$\text{Hydro}_{\text{Large-scale}}$	58.1	58.1	63.3[2]
$\text{Hydro}_{\text{Small-scale}}$	2.0	1.95	
$\text{Wind}_{\text{Onshore}}$	12.9	12.9	11.2[3]
$\text{Wind}_{\text{Offshore}}$	13.16	14.24	
Wave	0	0	0
Other	-	-	12[4]

Table 6. Cost-effective mix of 150 TWh respectively the actual production

1. Swedish production in 2014 (Energimyndigheten, 2016); 2. Includes both large- and small-scale hydro; 3. Includes both onshore and offshore wind; 4. Mainly different types of CPH (Energimyndigheten, 2016)

The marginal cost of electricity production is quite similar when comparing the two models, which is presented in Figure 9. The marginal cost including external effects ranges just above the marginal cost excluding externalities, and follow the same pattern throughout the production levels. The sharp changes in slopes, illustrate the bordering of capacity limits. Presented in Section 3, the capacity constraint is seen as an extra burden on the marginal cost. The most apparent changes happen at 120.3 TWh and at 150 TWh. At the level of 120.3 TWh, both nuclear and large-scale hydro have reached their capacity limits. Nuclear and large-scale hydro are modeled as linear cost functions as described in Section 5, generating this flat curve in Figure 9. Beyond the level of 150 TWh, more energy sources have reached their capacity limits and solar PV is introduced to the mixture. The introduction of solar PV and finally wave energy, together with the quadratic cost function of small-scale hydro, contribute to the steeper slope.

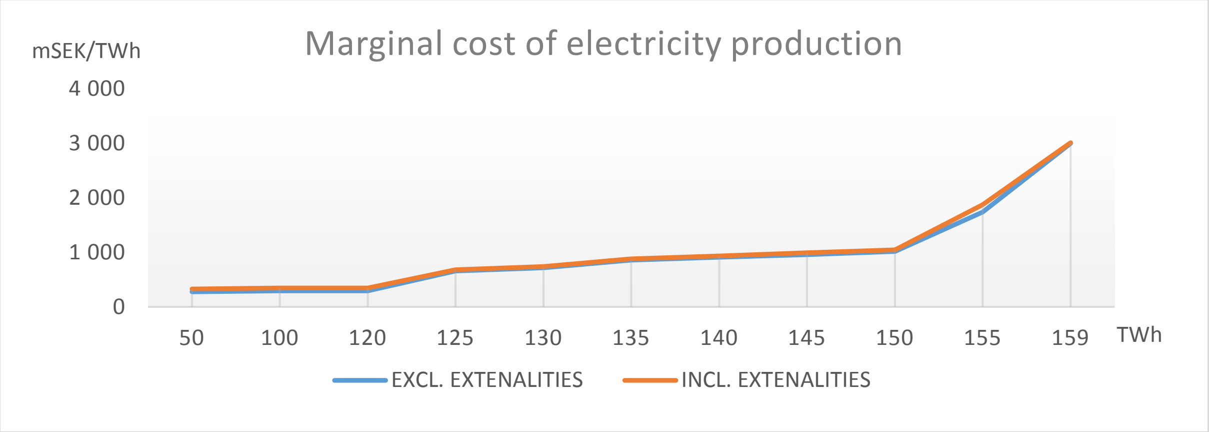

Figure 9. Marginal cost of electricity production in Sweden, in mSEK/TWh

Regarding the mix of different energy sources, the two models follow the same pattern with some adjustments. To begin with, nuclear comes out as the most cost-effective energy in the solution excluding externalities but as the second most cost-effective energy (after large-scale hydro) in the solution including externalities. Large-scale hydro is the second most cost-effective energy in the solution excluding externalities. At the level of 120.3 TWh, both capacity limits are reached and hereafter, the combinations in the two models are notably similar. The next added Tera Watt hour is shared, almost equally, between onshore wind and small-scale hydro. Offshore wind is adding to the production in both models at a level of 135 TWh and biomass adds at the level 136 TWh when excluding externalities and at 146 TWh when including externalities. The delayed introduction of biomass when including externalities is solely due to the increased cost when internalizing its external effects. In both models, biomass, offshore wind and small-scale hydro continues to stepwise increase until the total production reaches 150TWh. Beyond this level, the cost of production increases drastically both in terms of total cost and marginal cost, presented in Figure 8 and Figure 9. Solar PV is first introduced in the production mix in both models at the level 155 TWh. Not until all other 7 resources have reached their capacity limits is wave power suggested in a cost-effective mixture.

6.2 Probabilistic analysis

The second objective of the study is to identify the effect of uncertainty on cost and cost-effective mix of non-fossil energies in the Swedish electricity production. The probability constraint is set to 99% in the baseline simulations, hence a t value of 2.326 derived as ɣ in equation (9). This constraint adds an extra cost on the cost functions, which will further differentiate the cost of uncertain energy sources from certain energy sources. Consequently, when solving for the optimal combination of energies, these higher costs will contribute to a higher total cost of production. Comparing the total costs in Figure 10, the uncertainty within the model is valued to about 1.6 billon SEK excluding externalities and to 1.7 billion SEK including externalities, at a production level of 150TWh. The cost-effective solution when concerning uncertainty in production is achieved to a total cost of 59.9 billion SEK excluding externalities and 67.1 billion SEK including externalities. In addition, considering that the probabilistic constraint only applies to about 18% of the total production, the increase in total cost is quite significant. This implies that the effect of a probabilistic constraint would cause a considerably large impact on total cost in production mixes containing a higher share of uncertain production.

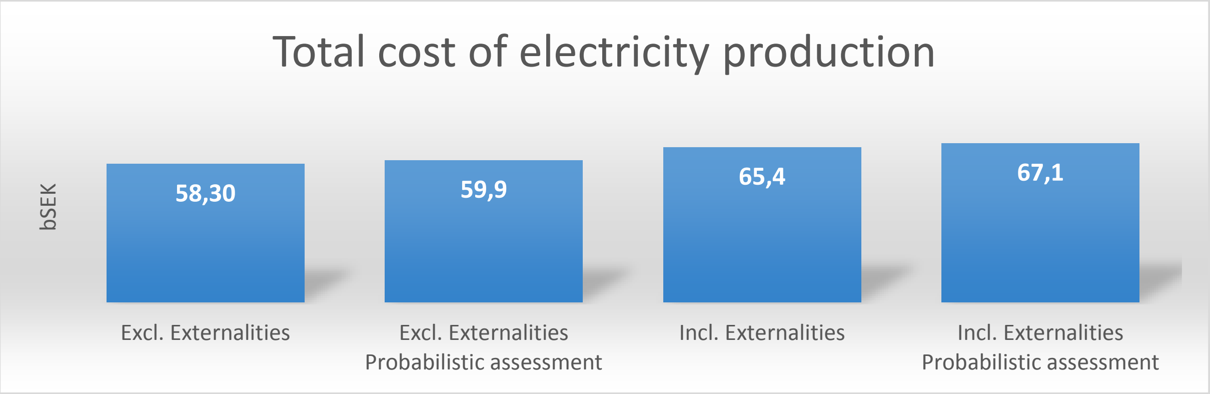

Figure 10. Total cost of electricity production in Sweden at the level of 150 TWh, in bSEK

The costs with probabilistic constraints with and without external effects are presented in Figure 11. Comparing these cost curves with the cost curves in Figure 8, the effect of uncertain supply becomes more noticeable at higher production volumes, which is mathematically explained in Section 3.

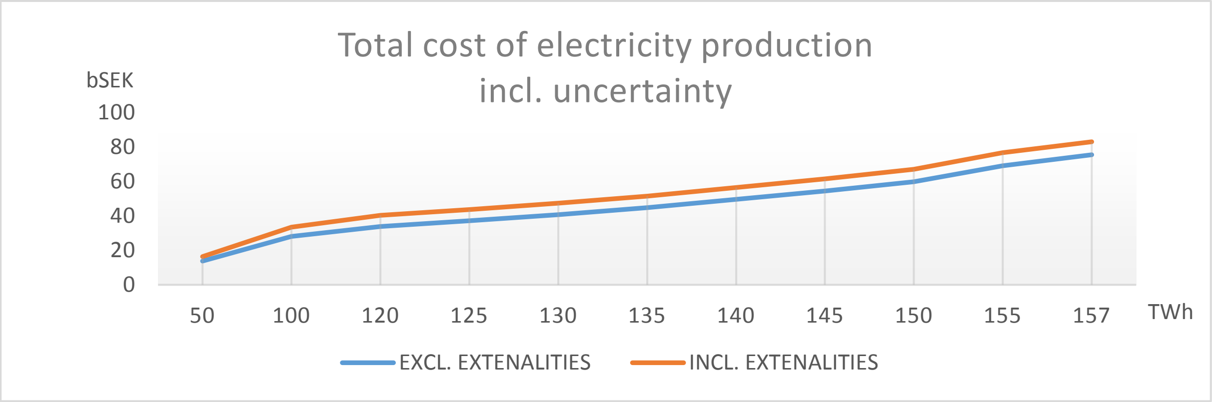

Figure 11. Total cost of electricity production in Sweden calculating for uncertainty, in bSEK

The mixes that correspond to the lowest total costs are presented in Table 7 together with the standard model excluding externalities. The most significant effect of the probabilistic constraint is that a few sources have increased the production at the level of 150 TWh. The increase in total production is a consequent of meeting the probabilistic constraint, and derived in detail in Section 3. It follows that the maximum production capacity declines, illustrated in Figure 11 where production stops at 157 TWh instead of 159.1 TWh. This loss in production might seem insignificant, but corresponds to 1,4% of the current production levels.

	Probabilistic Excl. externalities TWh	Probabilistic Incl. externalities TWh	Reference Excl. externalities TWh[1]
Biomass	1.64	1.53	1.64
Solar PV	0	0	0
Nuclear	62.2	62.2	62.2
Hydro$_{\text{Large-scale}}$	58.1	58.1	58.1
Hydro$_{\text{Small-scale}}$	2.29	2.21	2.0
Wind$_{\text{Onshore}}$	12.9	12.9	12.9
Wind$_{\text{Offshore}}$	14.46	14.66	13.16
Wave	0	0	0

Table 7. Cost-effective mix of 150 TWh when assessing a probabilistic model

The main difference in the results of the probabilistic model in comparison to the deterministic model, is that biomass is considered attractive earlier in the probabilistic models than in the deterministic models due to the relative advantage of being certain. This effect is illustrated in Figure 4 (Section 3), where the effect of a probabilistic constraint overrules the effect of external costs. Comparing the results in Table 6 and Table 7 it is also notable that biomass is relatively more attractive than before, when considering externalities at a level of 150 TWh.

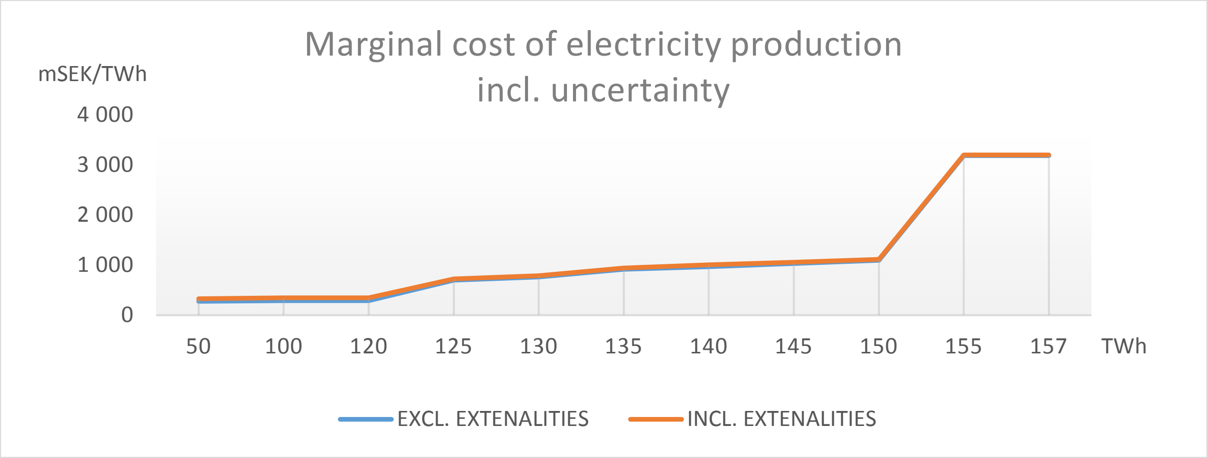

Figure 12. Marginal cost of electricity production in Sweden calculating for uncertainty, mSEK/TWh

Comparing Figure 9 with Figure 12, the effect of a probabilistic constraint on marginal cost does not apply until the production goes beyond 120 TWh and appears stronger as production increases.

Further, the differences in total cost of electricity production when assessing different probability constraints are shown in Figure 13. As predicted in Section 3, the size of ɣ in equation (9) will amplify the effect. A lower requirement eases the stress on total cost, creating a smaller difference between deterministic models and probabilistic models. The opposite applies to a higher probability requirement. When simulating a 99.95% probability requirement, given a t value of 3.291, the total cost reaches 60.6 billion SEK without externalities and 67.9 billion SEK when the cost of externalities is internalized. This further limits the maximum capacity of production at 156.2 TWh instead of the original capacity of 159.1 TWh.

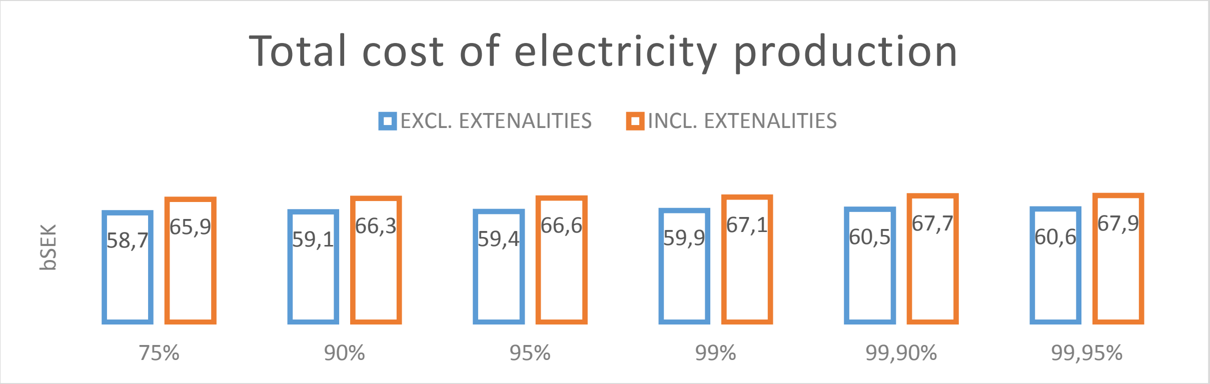

Figure 13. Total cost of electricity production in Sweden at a production level of 150 TWh, calculating for different uncertainty levels, in bSEK

6.3 Sensitivity analysis

The base-line models are followed by 155 different sensitivity analyses to test the robustness of the chosen values. The sensitivity analyses include tests of the minimum and maximum values for all production costs and all external cost, operated one by one. This means that each minimum and maximum value is adjusted one at a time, holding all other values constant on reference case levels. Further simulations are also made by letting the capacity limits increase to the adjusted maximum capacity for biomass, on- and offshore wind, wave energy and solar PV. The production capacity of hydro and nuclear are considered as unchangeable within this study. The data used to specify these simulations are presented in Appendix 1 and Appendix 2.

The sensitivity of the model is traced through changes in the mix, marginal cost and total cost. The tests show that total cost reacts as expected; increases with higher production costs and decreases with lower production costs. The sensitivity analysis that shows the largest effect concerning all three points is the adjusted capacity limit for onshore wind, causing a reduction in total cost of 1.48 billion SEK, presented in Figure 14. This also causes changes in the energy mix, see Appendix 4, and the marginal cost. Apart from the effect of adjusting the capacity of onshore wind, a general conclusion is that the marginal cost is most sensitive to changes in the cost of biomass, small-scale hydro and offshore wind and the total cost responds distinctively to cost changes in nuclear, large-scale hydro and onshore wind.

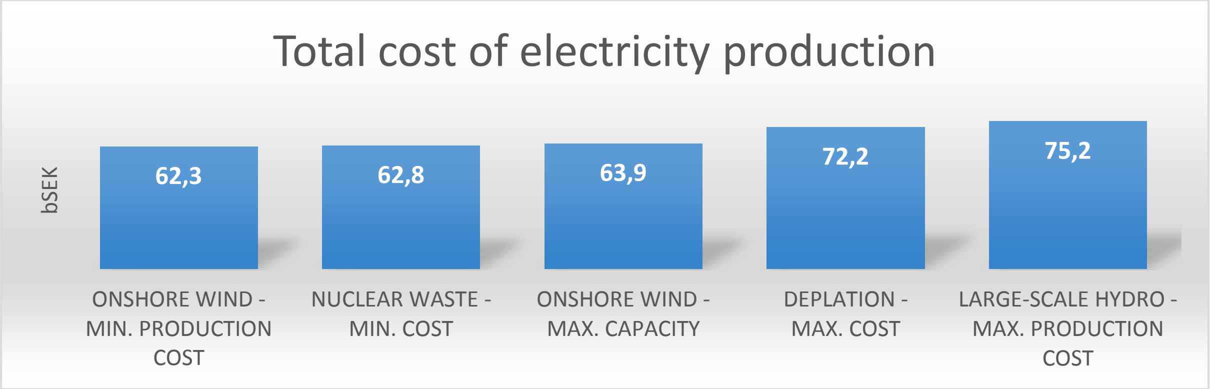

Figure 14. A selection of sensitivity analyses: total cost of electricity production in Sweden at a production level of 150 TWh, in bSEK

The mix of energy sources is relatively insensitive to changes in costs and capacity limits. As stated above, the largest change in mix appears when adjusting the capacity limits for on-shore wind. The cost-effective allocation also reacts when simulating the maximum costs of each of the five environmental effects of biomass. This means that through a relatively small change in cost of biomass, the cost-effective allocation promotes small-scale hydro or offshore wind instead of biomass.

Total cost is most sensitive to changes in minimum and maximum values for the two largest contributors in energy production; nuclear and large-scale hydro. As described in Section 5.3, large-scale hydro and nuclear are the cheapest alternative even at their maximum costs. Large-scale hydro and nuclear will therefore always be operating at full capacity no matter the changes within the model. The highest total cost is found when simulating the maximum production cost of large-scale hydro, shown in Figure 14. The total cost then increases by almost 10 billion SEK, from about 65.4 billion SEK to 75.2 billion SEK, given a production of 150TWh. The second largest increase in total cost, also presented in Figure 14, is caused by an adjustment in the cost of *depletion of resources* for nuclear. When using the maximum cost of depletion, the total cost becomes 72.2 billion SEK, a change of almost 7 billion. The lowest total costs are found when operating the minimum production cost of onshore wind, followed by the minimum cost of *waste disposal* for nuclear and maximum capacity limit of onshore wind. These adjustments change the total cost by minus 3.1, 2.6 and 1.48 billion SEK respectively and are presented in Figure 14, with associated mixes in Appendix 4.

7. Discussion

In this section I will first discuss the inherent weaknesses of the model and hence the limitations of the results. In the next section I will discuss how the results can be used to guide decision makers in energy policy.

7.1 Discussion of results

When comparing the models with and without externalities, the differences in results for total cost and mix are rather small. One obvious reason for this is that the Swedish energy mix, and hence this study, only includes energy sources with small external costs in relation to the total cost. Other energy sources, especially fossil fuels, have significantly higher external cost in relation to production cost. As an example, energy production from coal has a production cost of about 40 öre/kWh (Vattenfall, 2010) and an estimated external cost of 101 öre/kWh, considering CO_2, SO_2 and NO_x (Vattenfall, 2012; Trafikverket 2015). In comparison, onshore wind has a production cost of 61 öre/kWh and an external cost of 2.1 öre/kWh. This means that the cost of coal production increases with about 350% when including external costs while wind power increases with a mere 3.3%. Even for nuclear, the energy source with the highest relative external cost in this study, the cost increase when including externalities is a modest 20%. Given the small relative external cost in the Swedish energy mix, it is quite logical that the model finds similar solutions both with and without externalities. Despite the small differences, the effects that this model identifies can still have a profound impact on the implications for energy policy. This is discussed further in Section 7.2.

Similarly, the effect on total cost and mix from introducing uncertainties in the model is rather small. This is explained by the small share of energy production (18%) that is subject to energy uncertainty in this study.

This study uses OR to find the most cost-effective mix of non-fossil energies. As in any OR, the validity of the results is very much dependent on the reliability and accuracy of the selected data. One can always question the accuracy of data, especially the accuracy of monetary assessments of priceless goods such as biodiversity and human lives. That being said, some of the uncertainty with respect to estimates of production costs and external costs are reduced by using several data sources (Energikommissionen; Naturvårdsverket; Energimyndigheten; SBC; Vattenfall; Energimarknadsinspektionen; Energy Information Administration; SCA; EON; OX2; Svensk Solenergi; Fortum; Skeleftekraft; Jämtkraft; Telge; Analysgruppen; Aktea; KPMG). It is therefore unlikely that the selected costs range outside of the consensus of current body of knowledge.

The results are also limited by the static set up of the model. A dynamic model is significantly harder to construct, both conceptually and mathematically, but holds some clear advantages over a static model. The most obvious advantage is the ability to account for technological development over time. However, a valid dynamic model requires an idea of the technological developments, future demand for electricity and changes in costs etc. From this perspective, it can be more credible to construct a static model and to stress its accuracy by both comparing with the actual Swedish situation and through extensive sensitivity analyses.

Another criticism towards the results in this study is that the external effects applied in this study are a selection out of a large number of externalities. The selection of a few, but not all, external effects underestimates the external cost. The possibility to evaluate the validity and reliability of the external cost data was favored over the risk of underassessments. Considering externalities separately, the comparability between the energy sources improves from clear documentation of each figure. Consequently, it would be easier to expand such a study or to replicate the results. The method of this study responds well to adjustments and the chosen values can easily be replaced or supplemented with more externalities. The contribution is hence not the true social cost of energy production, which is probably nowhere to be found in current literature, but instead a transparent assessment of nine different and relevant externalities in the Swedish electricity production. This choice of method is therefore to the benefit of validity and reliability and leaves the door open for future studies to pursue the search for the true social cost of energy production.

The weaknesses of this study imply suggestions for further studies. The most obvious recommendation is to redo the study as a dynamic analysis, hence including time aspects into the model. The main purpose with this would be to handle technological developments that may shift the different cost functions and therefore the conditions for an optimal mix. Such an analysis would be more mathematically demanding and requires more time then the scope of this study permits.

Another way of expanding the model is to include more information in the optimization model. This can be achieved by either include more energy sources or more types of externalities. Further, companies that hold more accurate information regarding quadratic production cost functions would be able to update the model and redo the simulations for more precise results.

A final idea to continue this study is to investigate the environmental impacts of the Swedish energy mix when linking the energy production closer to neighboring countries like Germany. Once including Germany into the energy system, the effect of reducing net emissions when replacing fossils with non-fossil energies is evident. If expanding the production capacity in Sweden, one could begin to crowd out coal production in Germany with very positive effects on global CO_2 emissions. Munksgaard & Larsen (1998) and Muran & Sherrington (2007) include reduced emission as a positive external cost or so called social benefit in their estimations. Such an aspect of this model would be an interesting twist to the debate.

7.2 Discussion on implications of this study

This study builds on a static model which limits the extent of the results, but after the extensive sensitivity analyses, it may still contribute to guidelines for policy making. The sensitivity analyses on capacity limits show the effects of an expansion of one or a few energy source in the model. This can be interpreted as a guide for investments in electricity production, indicating which investment that contributes to the largest reduction in total cost. The simulations for minimum production cost may imply a future event of decreased costs due to technological developments. The model suggests that the most efficient way of reducing cost is achieved when either increasing the capacity for onshore wind or pursue investments to lower the cost of nuclear, largescale hydro or onshore wind. Biomass, solar PV and small-scale hydro are all sensitive to changes in costs, meaning that governmental interference could easily effect the usage of these energies. On the other hand, the result from a sensitivity analysis where all energies are operated on their maximum capacity limits, shows that if onshore wind is extended, neither biomass, solar PV nor wave energy are a part of the recommended mix and small-scale hydro and offshore wind are advised to cut production. The favoring of onshore wind can also be seen in Lund (2005) and Aryanpur and Shafiei (2015) described in Section 2.

This reasoning, in line with the findings from Budischak et al. (2012), has specific implications on the expansion of Solar PV in Sweden. If Sweden has the goal to invest in energy efficiency and hence try to reduce the energy use, it would be contra productive to support an expansion of solar PV at the same time. Solar PV is never included in the cost efficient mix in any of the models and shows no sign of economic relevance in the vast majority of sensitivity analysis. Thus, it is hard to justify with economic arguments, that solar investments and energy efficiency investments should simultaneously be supported. It is more likely that solar PV would be crowded out if big investments where made in energy efficiency. If it is a political priority to increase the production of renewable energy in Sweden, it would be far more efficient to support the expansion of wind power. The same argument may apply to the current heavy subsidies on biomass production. However, this study only treats one type out of several types of bioenergy. The full investigation of bioenergy is outside the scope of this study and will be left without adding too much weight to the interpretation.

As a last contribution of this study, several tests have been made to evaluate the role of nuclear in the Swedish energy mix. Nuclear power was suggested as the most cost-effective alternative in the base-case model and as the second most cost-effective alternative when including external costs. Yet, as of today nuclear power has a large part of the public opinion against it and is considered a highly controversial political topic. Using the model, I have attempted to create a simple economic description of the criticism towards nuclear and leave it to the reader, whether to agree or not.

The assessed value of externalities for nuclear sums to about 6.8 öre per produced kWh, far below the suggested total external cost range of 16.3 to 19.9 öre/kWh (ECOFYS, 2014). To stress a higher external cost, one sensitivity analysis tests all external costs at their respective maximum, generating a total external cost of almost 27 öre/kWh for nuclear production. Despite this adjustment, the result still places nuclear as the second most cost-effective option in the cost minimization problem, after large-scale hydro. Taking this test one step further, I adjusted the cost of nuclear accidents upwards until nuclear power begun to lose its market share to the other energy sources. To be able to run this simulation, all capacity limits were set to their maximum levels in order to supply 150TWh. While adjusting the cost of an accident, all other external costs of nuclear remained at their baseline levels.

The result of this analysis shows that it is economically advisable to start reducing the nuclear production when the cost of an accident is valued to 60 öre/kWh. Not until the cost of an accident is set to 101 öre/kWh is nuclear completely excluded out from the energy mix within the model. When including the probabilistic constrain this cost increases to 113 öre/kWh due to the relatively higher cost of wind power.

The implication of this test is that it is economically justifiable to cease nuclear production in Sweden only if one believes that the risk of an accident is valued to more than 1 SEK/kWh. In extension, at this cost and at the current production level, the annual cost of accident risk must be valued to 62.82 billion SEK to legitimize a shutdown. Setting the 62.82 billion SEK into context, the general perception is that a major nuclear accident costs roughly $100 billion (Financial Times, 2016), or 825 billion SEK. Therefore, the probability of an accident in Sweden has to be 1 every 13 years to amount to this cost. To clarify: for nuclear power to be economically uncompetitive, one has to believe that an accident at the scale of Fukushima will happen once every 13 years in Sweden. Another interpretation of this is that the additional amount paid for each kilo Watt hour including external cost could cover for the bill of a major nuclear accident every thirteenth year.

This outcome is based on a static model and is not the most likely outcome if Sweden decided to decommission nuclear production. The most likely scenario is that Sweden increases its imports and that the share of fossil fuel in the production mix rises. Both Germany and Japan replaced the gap in energy production, after their respective nuclear decommission, with large amounts of fossil fuels (World Nuclear Association, 2016; EIA, 2015). Fossil fuel is a cheap alternative to balance the uncertain supply of intermittent sources, but obviously not an environmentally friendly option. The main regulatory power in Sweden today is hydro, but due to its capacity limits it would not be able to regulate the energy system if nuclear is removed. Another option often brought to the table is to combine intermittent production with batteries, however, the technology is still maturing and is not currently available to the extent needed (Luo et al., 2015). Hence, a decommissioning of nuclear would most likely lead to a large increase in the use of fossil fuels in the energy mix.

No matter the alternative to nuclear, the actual cost increase if closing all nuclear power plants will most likely be lower than the assessment of 101 öre/kWh. If not due to fossil fuels or imports, due to technological developments in alternative energy sources. On the other hand, a nuclear accident in any of the Swedish power plants would most likely have a lower bill than Fukushima due to long-running safety and mitigation work that, from an international setting, is at the forefront of nuclear security

(Strålsäkerhetsmyndigheten, 2012). This would in turn affect the interpretation of the associated probability of the risk of an accident.

Such economic assessment may appear irrelevant and inapplicable for nuclear opponents. This study takes no standing whether nuclear decisions should be treated based on ethical or economic arguments, however, there is an ethical discussion to the consequences of ceasing nuclear that often is forgotten. The opportunity cost of ceasing nuclear will be dedicated a section in order to provide a more complete picture. The main thing that needs to be considered is the consequence of shifting the production towards other energy sources. As argued above, it is not appropriate to replace nuclear with only intermittent sources at the same time as fossils would cause huge emissions both locally and globally. Another option is to increase biomass production, but biomass comes with its own ethical and environmental disadvantages. The most severe impact is the consequence of monocrop agriculture, that normally is the case with large-scale bio culture. In Germany the price for energy corn, used in biofuels, is so high that no other cultures may compete (BBSR, 2016; Spiegel, 2016). This is both severe in terms of biodiversity but may also harm the food production. In a global context, small-scale farmers are one of the most vulnerable occupational groups and it is likely that they will be ousted from the market if the demand for bio monocrops increased. Big companies have the budget to shift production after demand and use artificial nutrition in order to make monocrops grow for several seasons, something that would further increase the poverty issues in developing countries.

Even an expansion of intermittent sources may also have negative impacts, based on production materials. Wind mills and solar PV, for example, require solid amounts of raw materials that need to be minded and transported in order to increase electricity production. Mining is often performed in developing countries with poor working conditions and environmental regulations. This impacts the ethical discussion even for considering a nuclear decommissioning in Sweden.

Regardless of the energy source used to replace nuclear power, the total expenditure on electricity production will most likely increase. This may either apply to the private households, in terms of higher electricity prices, or to the Government, in terms of subsidizing the producers for the differences in production cost. In both cases, the most vulnerable in society will suffer the most, since they are the most sensitive to price changes in basic commodities and also the most dependent on governmental outlays, such as health and social care and allowances, which may suffer if large electricity subsidies are paid.

No matter how you approach the problem, decisions within such an important sector will always become complex. This modelling is a mathematical way of illustrating the enormous economic advantage of nuclear power and can be used to understand the actual cost of guaranteeing a consumer 1 kWh when it is demanded.

8. Conclusion

The objective of this study is to identify the cost-effective production of the non-fossil energies in the Swedish electricity system, considering external effects and uncertainty. The study includes eight non-fossil energy sources in Sweden; large-scale hydro, small-scale hydro, nuclear, biomass, solar PV, onshore wind, offshore wind and wave energy. For each energy source a unique marginal cost function is assessed. The costs consist of production costs, excluding subsidies and other governmental instruments, external cost and uncertainty. The external effects are measured in a life cycle assessment of energy production, hence from cradle to grave. Four different models are created in order to solve the cost-minimization problem; a standard model excluding externalities, a model including externalities, a probabilistic model excluding externalities and a probabilistic model including externalities. The cost-effective results are later solved at a production level of 150 TWh, corresponding to the current production in Sweden.

The total production cost of electricity in this model is assessed to 58.3 billion SEK, which is very similar to the actual production cost of 56.8 billion SEK (SCB, 2016). The cost of external effects is to about 7.1 billion SEK generating a total cost of electricity production of 65.4 billion SEK. In addition, the cost of uncertainty is about 1.6 and 1.7 billion SEK, with and without external effects, respectively. In all four models, large-scale hydro, nuclear and onshore wind are included to their full capacity. At the same time, none of these models have solar PV and wave energy as part of the cost-effective mix. Biomass is the energy source that are mostly affected by the internalization of external costs, leaving market share mainly to offshore wind. However, in the model including uncertainty of production, biomass becomes more relevant since offshore wind is burdened with higher costs due to uncertainty in production.

When comparing the results of the four different models the difference in outcome is rather small. This is due the fact that non-fossil fuels have a relatively low external cost in relation to production cost and that only a small share of the production is subject to energy uncertainty in this model.

Despite the small differences in the results, there are a number of findings in this study that can contribute to guidelines for Swedish policy making. Firstly, the study finds that one of the most efficient ways of reducing cost of electricity production is by increasing the capacity for onshore wind. Secondly, solar PV is found to be economically uncompetitive in all four models. Thus, given the assumptions in this model, it is not economically advisable to push for expansion on solar PV. Finally, the model is used to find the cost level at which nuclear becomes economically uncompetitive and it is found that the external cost needed to motivate a full decommissioning is more than 1 SEK/kWh. This roughly corresponds to a Fukushima scale accident happening in Sweden once every 13 years. In all lower cost levels, this model suggests nuclear as a part of the energy mix.

With all math and economics behind us, some attention will be paid to an ethical discussion. The main scientific contribution of this study is to internalize the cost of externalities into a cost minimization problem of electricity production in Sweden. The essential question is however, if this assessment or indeed any monetary assessment of external cost, is an appropriate method. One can argue that monetarizing externalities is a crude simplification of something worth more than money. Consequently, any assessment can be considered underestimating the consequence of environmental damage and may benefit from other assessment techniques than pure economic analysis. However, ever since the environmental conference in Stockholm 1972, major actions to reduce environmental damage only seems to be undertaken when it either affects the developed world or affects business interests (UNEP, 2016). This tells us that a monetary assessment might still be key to get things done in the economic reality of today.

References

AEA Technology Environment. Clean Air for Europe (CAFE) Programme. 2005. “Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas.” March.

Akella, A. K., R. P. Saini, and M. P. Sharma. 2009. “Social, Economical and Environmental Impacts of Renewable Energy Systems.” *Renewable Energy*, Renewable Energy for Sustainable Development in the Asia Pacific Region, 34, no. 2 (February): 390–96. doi:10.1016/j.renene.2008.05.002.

Alsema, E.A.; Wild - Scholten, M.J. de; Fthenakis, V.M. 2006. “Environmental impacts of PV electricity generation - a critical comparison of energy supply options.” ECN Publication ECN-RX--06-016. Presented at the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September.

Aryanpur, V., and E. Shafiei. 2015. “Optimal Deployment of Renewable Electricity Technologies in Iran and Implications for Emissions Reductions.” *Energy* 91 (2015): 882–93. doi:10.1016/j.energy.2015.08.107.

BBSR
Retrieved: 2016-06-11
Search words: “Effects of the extended cultivation of biomass for energy purposes on cultural landscapes”
http://www.bbsr.bund.de/BBSR/EN/

Bergmann, Ariel, Nick Hanley, and Robert Wright. 2006. “Valuing the Attributes of Renewable Energy Investments.” *Energy Policy* 34, no. 9 (June): 1004–14. doi:10.1016/j.enpol.2004.08.035.

Bioenergiportalen.
Retrieved: 2016-04-16
Search words: Biobränslen vår största största energikälla
http://www.bioenergiportalen.se/

Boccard, Nicolas. 2015. “Risk Assessment of Accidents: Wind Power vs. Traditional Energy Sources.” SSRN Scholarly Paper. Rochester, NY: Social Science Research Network, July 15. http://papers.ssrn.com/abstract=2630993.

Budischak, Cory, DeAnna Sewell, Heather Thomson, Leon Mach, Dana E. Veron, and Willett Kempton. 2012. “Cost-Minimized Combinations of Wind Power, Solar Power and Electrochemical Storage, Powering the Grid up to 99.9% of the Time.” *Journal of Power Sources* 225 (1): 60–74. doi:10.1016/j.jpowsour.2012.09.054.

Damsgaard, Niclas and Erica Edfeldt. 2015. “Skatter och subventioner på elmarknaden.” SWECO.

Delucchi, Mark A., and Mark Z. Jacobson. 2011. “Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies.” *Energy Policy* 39, no. 3 (2011): 1170–90. doi:10.1016/j.enpol.2010.11.045.

D’haeseleer, William, D. 2013. “Synthesis on the Economics of Nuclear Energy.” Study for the European Commission, DG Energy. University of Leuven (KU Leuven), Belgium. November 27.

ECOFYS 2014 by order of: European Commission. 2014. “Subsidies and costs of EU energy - An interim report.” Project number: DESNL14583, 10 October.

EEX
Retrieved; 2016-04-06
Search word; Emission Allowances, Spot-market, European Emission allowances
https://www.eex.com/

EIA, U.S Energy Information Administration
Retrieved; 2016-05-31
Search words; Japan, International energy data and analysis
https://www.eia.gov/

Elforsk. 2007. ”Konkurrenskraft för nätansluten solel i Sverige -sett ur kraftföretagens och nätägarnas perspektiv.” Elforsk rapport 07:17.

Elforsk. Per Holmberg, Magnus Andersson, Björn Bolund and Kerstin Strandanger. 2011. ”Wave Power Surveillance study of the development.” Elforsk rapport 11:02. May.

Elforsk. 2014. “El från nya och framtida anläggningar 2014.” Elforsk rapport 14:40. October.

Energifakta, 2014
Retrieved; 2016-02-28
Search word; externa kostnader, systemkostnader
http://energifakta.com/

Energikommissionen. 2016. ”Promemoria om de ekonomiska förutsättningarna för befintlig svensk elproduktion.” Promemoria 2016-03-24.

Energimyndigheten, Energikunskap.
Retrieved 2016-04-19
Search word; Vågkraft
http://www.energikunskap.se/

Energimyndigheten. 2016. “Energiläget i siffror 2016.” Retrieved: 2016-01-29.
http://www.energimyndigheten.se/

Energimyndigheten. 2014. ”Produktionskostnadsbedömning för vindkraft i Sverige.” ER 2014:16. ISSN 1403-1892.

Energinyheter.
Retrieved: 2016-04-07
Search words; Uranbrytning planeras i Sverige
http://www.energinyheter.se/

EPA, United States Environmental Protection Agency
Retrieved: 2016-04-05
Search words; The social cost of carbon
https://www3.epa.gov/

European Environmental Agency.
Retrieved: 2016-04-03
Search words: “EN35 External costs of electricity production”
http://www.eea.europa.eu/

European Nuclear Society
Retrieved: 2016-04-02
Search words; Fuel comparison
https://www.euronuclear.org/

Evans, Annette, Vladimir Strezov, and Tim J. Evans. 2010. “Sustainability Considerations for Electricity Generation from Biomass.” *Renewable and Sustainable Energy Reviews* 14, no. 5 (June): 1419–27. doi:10.1016/j.rser.2010.01.010.

Financial Times
Retrieved: 2016-03-27
Search words; Japan taxpayers foot $100bn bill for Fukushima disaster
https://next.ft.com/

Faaij, André, Berry Meuleman, Wim Turkenburg, Ad van Wijk, Ausilio Bauen, Frank Rosillo-Calle, and David Hall. 1998. “Externalities of Biomass Based Electricity Production Compared with Power Generation from Coal in the Netherlands.” *Biomass and Bioenergy* 14, no. 2 (March 23): 125–47. doi:10.1016/S0961-9534(97)10005-8.

Fthenakis, Vasilis, and Hyung Chul Kim. 2009. “Land Use and Electricity Generation: A Life-Cycle Analysis.” *Renewable and Sustainable Energy Reviews* 13, no. 6–7 (August): 1465–74. doi:10.1016/j.rser.2008.09.017.

Future-E, Gustav Resch, Thomas Faber, Mario Ragwitz, Anne Held, Christian Panzer and Reinhard Haas. 2008. “20% RES by 2020 – a balanced scenario to meet Europe’s renewable energy target.” Intelligent Energy – Europe (IEE), ALTENER Contract no. EIE/06/143/SI2.444285. February.

Geijer, Erik, Göran Bostedt, and Runar Brännlund. 2011. “Damned If You Do, Damned If You Do not—Reduced Climate Impact vs. Sustainable Forests in Sweden.” *Resource and Energy Economics* 33, no. 1 (January): 94–106. doi:10.1016/j.reseneeco.2010.01.004.

Green-X. 2003. “Deriving Optimal Promotion Strategies for Increasing the Share of RES-E in a Dynamic European Electricity Market. Dynamic cost-resource curves- Work Package 1.” Contract No: ENG2-CT-2002-00607. August.

Hatch. 2014. ”Lifecycle Assessment Literature Review of Nuclear, Wind and Natural Gas Power Generation. Prepared for The Canadian Nuclear Association.” H345621-236-02 Rev. E October 9.

Heide, Dominik, Lueder von Bremen, Martin Greiner, Clemens Hoffmann, Markus Speckmann, and Stefan Bofinger. 2010. “Seasonal Optimal Mix of Wind and Solar Power in a Future, Highly Renewable Europe.” *Renewable Energy* 35, no. 11 (2010): 2483–89. doi:10.1016/j.renene.2010.03.012.

Hart, Elaine K., and Mark Z. Jacobson. 2011. “A Monte Carlo Approach to Generator Portfolio Planning and Carbon Emissions Assessments of Systems with Large Penetrations of Variable Renewables.” *Renewable Energy* 36, no. 8 (2011): 2278–86. doi:10.1016/j.renene.2011.01.015.

IPCC
Retrieved: 2016-03-31
Search words: Publications and data, WG3, Climate Change 2007, Social cost of carbon
https://www.ipcc.ch/

IPCC. 2012.“Renewable Energy Sources and Climate Change Mitigation.” Cambridge University Press 32 Avenue of the Americas, New York, NY 10013-2473, USA.

Klein, Sharon J. W., and Edward S. Rubin. 2013. “Life Cycle Assessment of Greenhouse Gas Emissions, Water and Land Use for Concentrated Solar Power Plants with Different Energy Backup Systems.” *Energy Policy* 63 (December): 935–50. doi:10.1016/j.enpol.2013.08.057.

Klimatupplysningen
Retrieved; 2016-05-31
Search words; Powerwall och ekonomin bakom teslas nya batteri
http://www.klimatupplysningen.se/

Kärki, Janne. 2009. “Biomass utilization in large scale heat & power production”. VTT, Finland. September.

Lévêque, François. 2013. “The risk of a major nuclear accident: calculation and perception of probabilities.” <hal-00795152v2>

Li, Xianguo. 2005. “Diversification and Localization of Energy Systems for Sustainable Development and Energy Security.” *Energy Policy* 33, no. 17 (November): 2237–43. doi:10.1016/j.enpol.2004.05.002.

Lund, H. 2006. “Large-Scale Integration of Optimal Combinations of PV, Wind and Wave Power into the Electricity Supply.” *Renewable Energy* 31, no. 4 (2006): 503–15. doi:10.1016/j.renene.2005.04.008.

Luo, Xing, Jihong Wang, Mark Dooner, and Jonathan Clarke. 2015. “Overview of Current Development in Electrical Energy Storage Technologies and the Application Potential in Power System Operation.” *Applied Energy* 137 (January 1): 511–36. doi:10.1016/j.apenergy.2014.09.081.

LTZ.
Retrieved: 2016-04-07
Search words; Jämtland, Berg, En av världens största uranfyndigheter finns i länet
http://www.ltz.se/

Mann, M., and P. Spath. 1997. “Life Cycle Assessment of a Biomass Gasification Combined-Cycle System.” NREL/TP-430-23076. Golden, Colo.: National Renewable Energy Laboratory.

Mirasgedis, S., and D. Diakoulaki. 1997. “Multicriteria Analysis vs. Externalities Assessment for the Comparative Evaluation of Electricity Generation Systems.” *European Journal of Operational Research* 102, no. 2 (October): 364–79. doi:10.1016/S0377-2217(97)00115-X.

Moran, Dominic, and Chris Sherrington. 2007. “An Economic Assessment of Windfarm Power Generation in Scotland Including Externalities.” *Energy Policy* 35, no. 5 (May): 2811–25. doi:10.1016/j.enpol.2006.10.006.

Munksgaard, Jesper, and Anders Larsen. 1998. “Socio-Economic Assessment of Wind Power—lessons from Denmark.” *Energy Policy* 26, no. 2 (February): 85–93. doi:10.1016/S0301-4215(97)00009-8.

Münnich Vass, Miriam. 2015. “Can Renewable Energies with Learning-by-Doing Compete with Forest Sequestration to Cost-Effectively Meet the EU Carbon Target for 2050?” Rapport. Uppsala, March 16. http://pub.epsilon.slu.se/11905/.

Nap. 2010. ”Electricity from Renewable Resources: Status, Prospects, and Impediments.” Chapter 5, pp. 195-240: Environmental Impacts of Renewable Electricity Generation. The National Academics Press. Washington, D.C.

Naturvårdsverket, Sverker Molander, Helen Ahlborg, Rickard Arvidsson, Linus Hammar, Duncan Kushnir, Are Wallin and Jenny Westerdahl. 2010. ”Förnybara energikällors inverkan på de svenska miljömålen.” Rapport 6391. November.

Naturvårdsverket, Gerda Kinell, Tore Söderqvist och Linus Hasselström. 2009. “Monetära schablonvärden för miljöförändringar.” Rapport 6322. Enveco Miljöekonomi AB. December.

Naturvårdsverket. Ingemar Ahlén, Lothar Bach, Hans J. Baagøe and Jan Pettersson. 2007. ”Fladdermöss och havsbaserade vindkraftverk studerade i södra Skandinavien.” rapport 5748. September.

Naturvårdsverket
Retrieved: 2016-04-01
Search words: Kväveoxidavgiften så fungerar den
https://www.naturvardsverket.se/

Oanda
Retrieved; 2016-03-18, 2016-04-20
Search word; Currency, historical rates, US$, Euro, ECU
https://www.oanda.com/

Organisation for Economic Co-operation and Development (OECD). 2010. “Projected costs of generating electricity.” ISBN 978-92-64-08430-8.

Pehnt, Martin. 2006. “Dynamic Life Cycle Assessment (LCA) of Renewable Energy Technologies.” *Renewable Energy* 31, no. 1 (January): 55–71. doi:10.1016/j.renene.2005.03.002.

SCB
Retrieved; 2016-03-18, 2016-04-20
Search words; Prisomräknaren
http://www.sverigeisiffror.scb.se/

Schmidt, Johannes, Rafael Cancella, and Amaro O. Pereira. 2016. “An Optimal Mix of Solar PV, Wind and Hydro Power for a Low-Carbon Electricity Supply in Brazil.” *Renewable Energy* 85 (2016): 137–47. doi:10.1016/j.renene.2015.06.010.

Sheldon, Seth, Saeed Hadian, and Ory Zik. 2015. “Beyond Carbon: Quantifying Environmental Externalities as Energy for Hydroelectric and Nuclear Power.” *Energy* 84 (May): 36–44. doi:10.1016/j.energy.2015.01.116.

Sims, Ralph E. H., Hans-Holger Rogner, and Ken Gregory. 2003. “Carbon Emission and Mitigation Cost Comparisons between Fossil Fuel, Nuclear and Renewable Energy Resources for Electricity Generation.” *Energy Policy* 31, no. 13 (2003): 1315–26. doi:10.1016/S0301-4215(02)00192-1.

Spiegel
Retrieved; 2016-06-11
Search words: “Corn-Mania: Biogas Boom in Germany Leads to Modern-Day Land Grab”
http://www.spiegel.de/

Stoppato, A. 2008. “Life Cycle Assessment of Photovoltaic Electricity Generation.” *Energy*, 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems ECOS 2006, 33, no. 2 (February): 224–32. doi:10.1016/j.energy.2007.11.012.

Stridh, Bengt, Stefan Yard, David Larsson and Björn Karlsson. 2013. ”PRODUCTION COST OF PV ELECTRICITY IN SWEDEN.” ABB Corporate Research, Mälardalen University, Lund University, Direct Energy. SE-721 78 Västerås.

Strålsäkerhetsmyndigheten
Retrieved; 2016-03-20
Search words: Kärnkraft, historik
http://www.stralsakerhetsmyndigheten.se/

Strålsäkerhetsmyndigheten, Lars Skånberg. 2012. “Utredning avseende den långsiktiga säkerhetsutvecklingen i den svenska kärnkraften och åtgärder med anledning av olyckan i Fukushima.” SSM 2010/1557-10. 31 October.

Sundqvist, Thomas. “Power Generation Choice in the Presence of Environmental Externalities.” Department of Business Administration and Social Sciences, Division of Economics. 2002:26, ISSN: 1402 – 1544. ISRN: LTU - DT - - 02/26 - - SE.

Svensk Energi. 2016. ”Aktuellt kraftläge Sverige Veckorapport.” Vecka 06 8 Feb- 14 Feb år 2016, version: A.

Svensk Energi. 2015. “ELÅRET Verksamheten 2014.” Svensk Energi – Swedenenergy – AB. May.

Timmons, David, Jonathan M. Harris and Brian Roach. 2014. “The Economics of Renewable Energy.” Global Development And Environment Institute, Tufts University.

Trafikverket, 2015. “Samhällsekonomiska principer och kalkylvärden för transportsektorn: ASEK 5.2”. Version 2015-04-01

Trøtscher, Thomas. 2007. “Large-Scale Wind Power Integration in a Hydro-Thermal Power Market.” *103*. https://brage.bibsys.no/xmlui/handle/11250/256564.

UNEP, United Nation of Environmental Program
Retrieved; 2016-05-31
Search words; Declaration of the United Nation Conference on the Human Environment
http://www.unep.org/

United Nations
Retrieved; 2016-05-25
Search words; COP21
http://www.un.org/

Vattenfall
Retrieved: 2016-02-22
Search words; Elcertifikat, Energiskatter, Så fungerar elmarknaden, Ringhals, Produktion och driftläge
http://www.vattenfall.se/sv/

Vattenfall. 2012. ”Livscykelanalys- Vattenfalls elproduktion i Norden.” Vattenfall AB: July.

Vattenfall. 2011. ”Sex energikällor- ett energisystem. Vattenfalls energiportfölj och det europeiska energisystemet.” Vattenfall AB: February.

Vattenfall Research and Development AB, Anna-Maria Wiberg. 2010. “Faktaserien – En jämförelse av elproduktionskostnader.” Published by Analysgruppen, vid Kärnkraftssäkerhet och Utbildning AB; Norrköping, Sweden. Faktaserie year 13, no. 47. June.

Vattenfall, Erik Sparrevik, Henrik Viklands, Peter Bergsten and Linda Harju. 2011. ”Ekologiska effekter och verksamhetspåverkan av förändrade produktionsvillkor i Vattenfalls storskaliga vattenkraftverk.” 27 September.

Vidal-Amaro, Juan José, Poul Alberg Østergaard, and Claudia Sheinbaum-Pardo. 2015. “Optimal Energy Mix for Transitioning from Fossil Fuels to Renewable Energy Sources – The Case of the Mexican Electricity System.” *Applied Energy* 150 (2015): 80–96. doi:10.1016/j.apenergy.2015.03.133.

ViEF, Vindelälvskommunerna ekonomisk förening, Leopold Sjöström. 2009. ”VINDELÄLVEN ETT STEG NÄRMARE SOM VÄRLDSARV.” Press release, 21 April.

Vindkraftsportalen
Retrieved; 2016-02-15
Search word; Framtida produktionskostnader
http://www.vindkraftsportalen.se/

Watkiss, Paul. 2005. “The Social Cost of Carbon.“ Paul Watkiss Associates, UK
https://www.oecd.org/env/cc/37321411.pdf

Winston, Wayne L. 1991. “Operations Research: Applications and Algorithms”. Duxbury Press, Belmont, California.

World Nuclear Association
Retrieved; 2016-04-02, 2016-05-25
Search word; The Economics of Nuclear Power, Liability for Nuclear Damage, Nuclear power in Finland, Nuclear power in Germany
http://www.world-nuclear.org/

APPENDIX 1 – Full intervals of marginal production cost and capacity limit

Energy source	Marginal production cost	Capacity limit
Biomass	(44,5+3,82E) - (86,4 + 3,82E)	1,64- 9,13 [3]
Small-scale hydro	(34,5+13,32E) - (48,2+13,32E)	5,2
Large-scale hydro	29,1 - 46	58,1
Solar PV	(93+3,4E) – (626+3,4E)	1,3 - 30 [2]
Nuclear	27,6 - 34,5	62,2
On-shore wind	(45 + 0,000125E) - (61 + 0,6E)	12,9-88 [4]
Off-shore wind	(85,6 + 0,000125E) - (100 + 0,6E)	14,8 -26,1 [4]
Wave	150-450	3 - < 30 [1]

Table 8. Full intervals of marginal production cost functions, in öre/kWh, and capacity limits, in TWh/year.

1. Elforsk, 2011
2. Elforsk, 2014, Based on the production level in Germany in 2014.
3. Kärki, Janne, 2009. Estimated based on the share of wood fuels in Finland’s electricity production.
4. Energimyndigheten, 2014. Calculated based on production with licenses and production who applied for licenses.

The capacity limits for solar, biomass, wind and wave energy could, in theory, be extended to infinity, imagine solar PV on all rooftops and windmills on all open landscapes and offshore areas. However, this is not likely to happened and therefore are estimates from previous literature applied as the adjusted maximum capacity limits (Elforsk, 2011; 2014; Kärki, 2009; Energimyndigheten, 2014). The obtained values for the adjusted maximum capacity limits is described in table 11. The capacity limits for biomass and solar PV are obtained production levels from neighboring countries that are ahead of Sweden but similar in physical potentials. For biomass, the Finish production volume is used. Finland is both similar in the geographical landscape and considered as the leading country in biomass energy within Europe. The maximum capacity for solar PV corresponds to the German production level, considered as a reachable but high limit, since it is unlikely that Swedish solar production would exceed the German production in the nearest future.

APPENDIX 2 – Full intervals of external costs

	Biomass	Hydro$_{Small}$	Hydro$_{Large}$	Nuclear	Wind$_{ON}$	Wind$_{OFF}$	Solar	Wave
CO^2	0,72-26,788	0,024-4,706	0,017-5,068	0,014-1,81	0,01-10,498	0,01-10,498	0,101-60,454	0,038-9,05
SO$_X$	0,028-10,81	0,078-0,345	0,006-0,276	0,056-0,345	0,056-1,035	0,056-1,035	0,204-3,91	0,056-1,035
NO$_X$	0,024-21,92	0,02-0,597	0,0012-0,307	0,01-0,373	0,008-0,512	0,008-0,512	0,014-2,559	0,008-0,512
PM10	4,896-15,616	0,422-0,992	0,354-0,832	0,068-0,352	0,163-1,344	0,148-0,352	1,618-19,52	0,148-0,352
Land use	0-39,609	0,012-2,31	0,012-2,31	0,002-5,265	0-0,224	0	0,026-0,043	0
Noise					0,028-1,6	0,028-1,6		
Depletion of resources				0-11				
Waste disposal				7,29E-9 - 4,2				
Accident				0,0026 - 3,6	0-0,102			

Table 9. The full range of external cost, described in minimum and maximum values, in öre/kWh

APPENDIX 3 – Deriving the coefficient of variation

$$cov = \frac{\delta^i}{E^i}$$

$$-2std \leq \mu^{solar} \leq 2std$$

$$4std = 350$$

$$\delta^{solar} std = \frac{350}{4}$$

$$\delta^{solar} std = 87{,}5$$

$$cov^{solar} = \frac{\delta^{solar}}{\mu^{solar}} = \frac{87{,}5}{925} = 0{,}095$$

$$-2std \leq \mu^{wind-on} \leq 2std$$

$$4std = 290$$

$$\delta^{wind-on} std = \frac{290}{4}$$

$$\delta^{wind-on} std = 72{,}5$$

$$cov^{wind-on} = \frac{\delta^{wind-on}}{\mu^{wind-on}} = \frac{72{,}5}{2900} = 0{,}025$$

$$-2std \leq \mu^{wind-off} \leq 2std$$

$$4std = 370$$

$$\delta^{wind-off} std = \frac{370}{4}$$

$$\delta^{wind-off} std = 92{,}5$$

$$cov^{wind-off} = \frac{\delta^{wind-off}}{\mu^{wind-off}} = \frac{92{,}5}{3700} = 0{,}025$$

APPENDIX 4 – Results of various sensitivity analyses

	Min. production cost - Onshore wind Incl. externalities TWh	Min. cost Nuclear Waste Incl. externalities TWh	Max. cost Depletion of resources Incl. externalities TWh	Max. production cost – $\text{Hydro}_{\text{LARGE-SCALE}}$ Incl. externalities TWh
BIOMASS	0.618	0.618	0.618	0.618
SOLAR PV	0	0	0	0
NUCLEAR	62.2	62.2	62.2	62.2
$\text{HYDRO}_{\text{LARGE-SCALE}}$	58.1	58.1	58.1	58.1
$\text{HYDRO}_{\text{SMALL-SCALE}}$	1.947	1.947	1.947	1.947
$\text{WIND}_{\text{ONSHORE}}$	12.9	12.9	12.9	12.9
$\text{WIND}_{\text{OFFSHORE}}$	14.235	14.235	14.235	14.235
WAVE	0	0	0	0

Table 10. Cost-effective mix of 150 TWh for various sensitivity analyses

	Max. production cost – Offshore wind Incl. externalities TWh	Max. capacity – Onshore wind Incl. externalities TWh	Max. capacity – All sources Incl. externalities TWh
BIOMASS	1.64	0	0
SOLAR PV	0	0	0
NUCLEAR	62.2	62.2	62.2
$\text{HYDRO}_{\text{LARGE-SCALE}}$	58.1	58.1	58.1
$\text{HYDRO}_{\text{SMALL-SCALE}}$	2.421	1.487	1.487
$\text{WIND}_{\text{ONSHORE}}$	12.9	24.202	24.202
$\text{WIND}_{\text{OFFSHORE}}$	12.739	4.011	4.011
WAVE	0	0	0

Table 11. Cost-effective mix of 150 TWh for various sensitivity analyses