

Long-Term Dynamics of Electricity Generation Expansion Optimal Investments for the Next 50 Years

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ABSTRACT

Sustainable development has become the foundation in planning for the future. Nowhere is it more evident than in the energy sector. Re-Conceptualization of the electricity market is currently underway. The latter being unsustainable has attracted a lot of public attention. Debates on its future vary significantly in expectations. However its transition to a fully renewable based one has gathered most of the scientific and public support. Energy Transitions exhibit complex and dynamic behavior. In order to better understand them and close the gap between desired expectations and achieved results, new electricity market models are being build and analyzed.

This thesis will rely on the System Dynamics methodology to build a small model of the electricity market. The model sheds some light on the dynamics of the battle between old non-renewable technologies and new renewable ones. The core interest is in generation expansion planning and its investment strategy. Optimal strategies given the built model are determined relying on a tool called Stochastic Optimization in Policy Space (SOPS). The policies highlight the fact that most investment should be re-allocated from the non-renewable to renewable technologies from the beginning to achieve optimal results on the long run.

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1. INTRODUCTION

Electricity markets are undergoing major changes. Deregulation trend of markets worldwide, rise of renewable sources and increase in public interest about topics such as climate change and energy supply security have altered the behavior of the market and made it more volatile. As a result, new regulatory interventions are being introduced gradually to control for these factors. This in turn has further complicated the market since a blend of regulated and deregulated policies is now at play.

These new developments have pushed the power sector players, private and governmental ones, to rethink and redefine their understanding of the mechanism in which the electricity market operates. Typical static frameworks that modeled monopolistic power markets (production, transmission and distribution) were judged to be obsolete and new market models have been developed that take into consideration the new competitive landscape with multiple producers and retailers.

The interest of governments and private companies in new market models lies in their interest for survival in the constantly changing market. To achieve competitive advantage, the ability to hedge against uncertainties and design strategies to take advantage of the market is of absolute importance and this cannot be done without new and dynamic market models as stated in (Teufel, 2013) and (Olsina, 2005).

Energy Transitions are inherently complex and dynamic. Delays, feedback, non-linearity and uncertainty are staple attributes of such events whether on a local, regional or global level. The System Dynamics (SD) model built in this thesis will portray a simple picture of the dynamics that govern this complex system in an effort to better control its behavior. If properly managed, the outcome will be a quick and smooth transition towards more sustainable sources of energy. These sources are renewable and can meet the ever growing demand for electricity while respecting their natural carrying capacity and meeting the newly drafted environmental regulations.

The prime focus of the model is the long term generation expansion planning problem that arose lately in the market. Over the next 20 years, over 40% of the total world energy investments will be into the power sector, that is over 16 trillion dollars. 58% of the 16 trillion dollars will be into power plant construction (IEA, 2014a). Efforts to better understand and plan capital expenditures in the power sector offer a lot of benefits if proven successful. The end goal is to devise optimal investment strategies to maximize the social

welfare. For this, a tool called Stochastic Optimization in Policy Space (SOPS) along with the modeling software Powersim were utilized.

The model looks at the global expansion planning problem with an aggregated view of the two power sectors of Non-Renewable and Renewable. The Nuclear and hydropower technologies were removed from the non-renewable and renewable sectors respectively. Nuclear technology has been undergoing phasing-out policies in more countries around the world and hydropower has reached maturity and its potential for low cost environmentally friendly option is shrinking. All of the other technologies (Coal, gas, oil, biomass, wind, solar...) were considered when determining the generation capacity and its costs for each of the sectors.

The simulation results show a steady increase in the renewable market share. The increase is achieved through a built in "Premium" factor. This factor aggregates some of the economic incentives such as capital subsidies and feed-in-tariff. It is this premium that is pushing the renewable technologies forward into maturity and eventually unsubsidized commercial viability. The increase in the market share is however not fast enough to meet targets such as the 2 degrees one.

The optimization with the goal of maximizing the social welfare shows a straightforward strategy of re-allocating most if not all of the investments into the renewable sector to achieve optimal long term net benefits. Net benefits take into consideration both the producers and consumers interests.

The model can prove useful for gaining insights into how the market behaves under certain assumptions and scenarios. Hence it is a learning tool for those interested in acquiring some preliminary understanding of the market.

2. BACKGROUND

The basic issue which this thesis tries to discuss, analyze and offer some new insights about is energy management and in particular the electricity generation expansion planning problem. In this section we will try to justify the contemporary relevance of this issue and place the problem in context with the methodology utilized to analyze it.

2.1 Power sector and renewable global investment

Power sector investment has had the larger share of total energy investments (Figure 1).

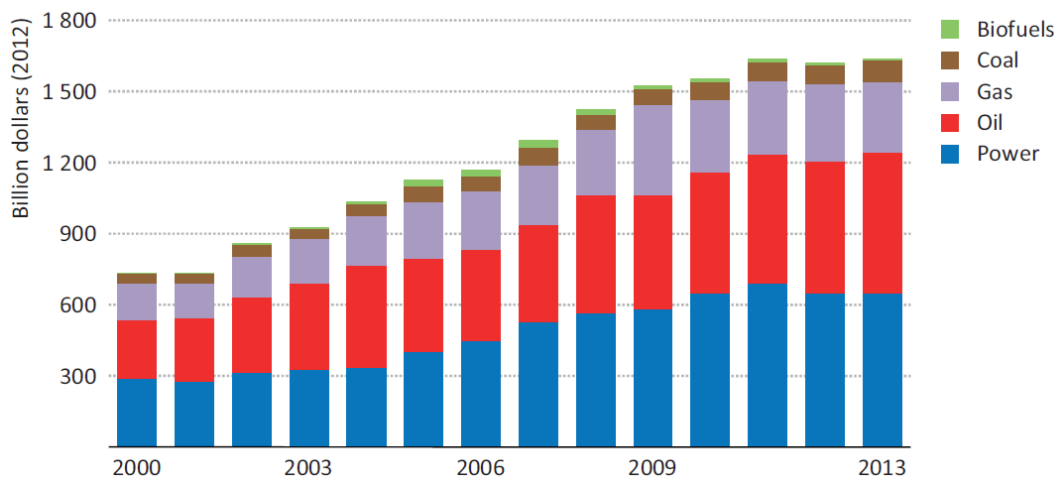


Figure 1: Investments into the power sector taken from (IEA, 2014b)

Renewable sources of energy have been constantly under-invested. Currently it is around 12% of the total energy investments (Figure 2).

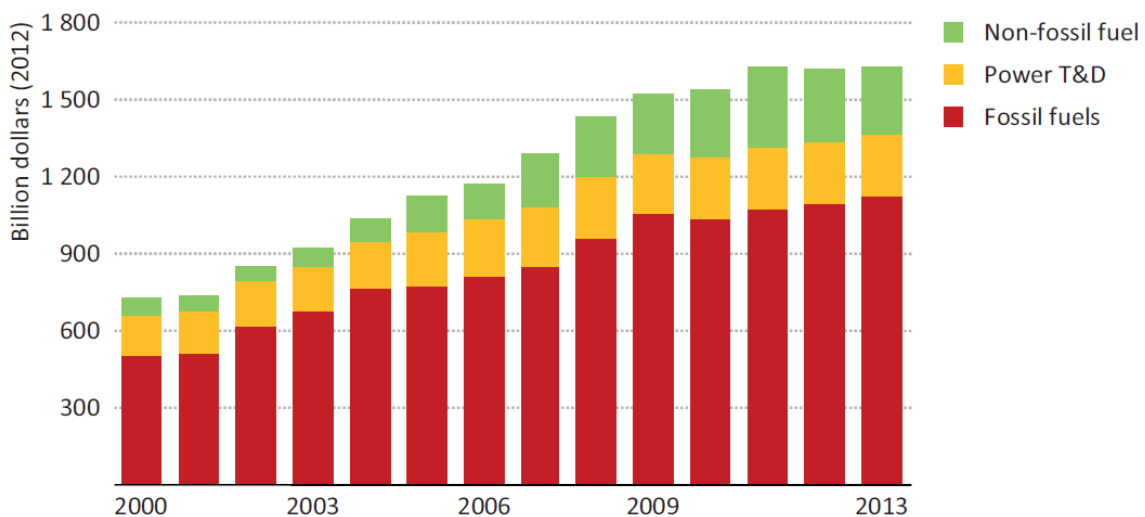


Figure 2: Non-Fossil Fuel Investment taken from (IEA, 2014b)

N.B: "Non-fossil fuel" category in Figure 2 includes all renewable technologies as well as nuclear and bio-fuels.

Power sector will see an influx of 16 trillion dollars of investment over the next 20 years, which is over 40% of the total world energy investments. 58% of these investments will be into power plant construction (IEA, 2014a).

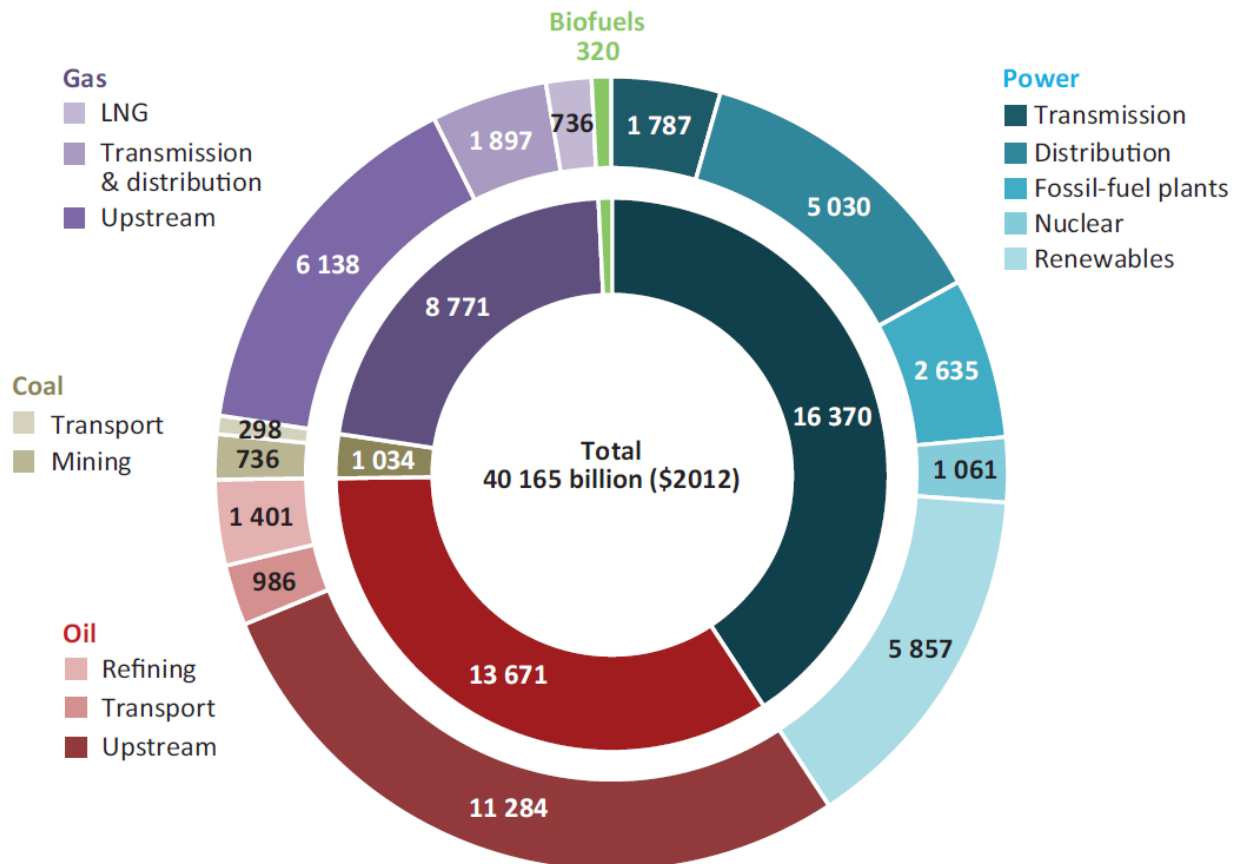


Figure 3: Energy Sector Investments for the next 20 years taken from (IEA, 2014b)

Investments into renewable sources of power generation will amount to 35% over the next 20 years out the total power sector investments (Figure 3). This is too little to catalyze the energy transition and transform the power sector into a sustainable one. Hence the need to focus on the renewable generation expansion investment strategy.

2.2 Power sector sustainable development and uncertainty

Sustainable development has become a planning cornerstone of almost every nation. It has three dimensions: Economical, Social and Environmental. Energy and in particular the electricity sector is a prime subject of recent debates about sustainable development and is undergoing major re-conceptualization of how it works. Investigations are underway for

alternative solutions to transform the electricity sector into a sustainable one. The power sector is unsustainable on all three dimensions (Dominguez, 2008):

- **Economical:** Societies are becoming more consumption oriented and are consuming vast amounts of electricity. This is placing a heavy burden on the power sector which is relying heavily on non-renewable sources which costs are increasing as they are being depleted more quickly causing the prices to increase as well.
- **Social:** 1.6 billion people do not have access to electricity which is considered a basic commodity in other parts of the world. These people are located in mostly poor rural areas. The most viable solution to genuinely improve their lives is to present them with off-grid applications like wind turbines and photovoltaic panels.
- **Environmental:** Pollution and climate change activism are gaining momentum. As more investigation is done, it is becoming clear that the recent surge in fossil fuels usage, mainly in electricity generation, is one of the main contributors and catalyst of climate change.

Energy transition towards renewable sources shows promise in terms of transforming the power sector into a sustainable one. On the long run, transition to renewable sources will drive prices down improving its standing on the economic dimension. When the prices go down, electricity will become more accessible to the less privileged parts of the world. Also, the development of renewable means for electricity generation will make it accessible for everyone to rely on local or regional sources of energy instead of importing expensive foreign ones. With the prices going down as well as tapping into renewable sources of energy in every part of the world, the social standing of the power sector will be greatly improved. And finally, needless to say that transitioning to environmentally friendly sources of energy will improve the environmental standing for an overall boost of the power sector's sustainable development performance.

Many of today's renewable electricity generation technologies face deep uncertainty whether they will survive the battle and reach maturity and large scale unsubsidized commercial adoption. A prerequisite to increase the survival chances of these technologies is initial availability of resources (labor, time and money) to enable active discovery and reduction of the uncertainty that hinder entrepreneurs from investing (Pruyt, 2011). To reduce uncertainty and make the transition smoother, long term analysis has to be done which requires new market models.

2.3 Current analysis approaches and relevance of System Dynamics

Old static frameworks of regulated and monopolistic electricity markets are outdated. New and dynamic models have emerged to study the metamorphosing markets. Three main modeling approaches have been adopted in literature according to (Ventosa et al., 2005) and (Sterman, 1991): Equilibrium models, Optimization models and Simulation models. Within the simulation category there are Agent-Based (AB) models and System Dynamics (SD) models. Both of these approaches are suitable for modeling liberalized electricity markets (Teufel, 2013) and have been widely utilized. This paper will utilize the System Dynamics approach.

With the electricity market experiencing radical changes, our understanding of how it behaves is greatly compromised and "numerical databases" are scarce and incapable of portraying the causalities that govern its behavior (Teufel, 2013). This renders the System Dynamics (SD) methodology suitable for exploring and improving our understanding since SD relies mostly on the "mental database" of modelers involved (Forrester, 1961). These mental databases describe our qualitative cognitive grasp of the real system and can quantitatively portray the many feedback loops that are at play.

The development of the SD model in this paper has followed an iterative process of boundary definition and relationship selection that is typical in simulating a dynamic and complex system such as an electricity market (Vogstad, 2005).

2.4 SD model and its main drivers

With the trend to shift towards liberalized deregulated markets, performance has switched from purely energy supply security and reserve margins to include profitability measures (Kadoya, 2005). This transition has created the generation expansion planning problem (Olsina, 2005). Hence Investments and profitability in the capital intensive power sector play a major role in determining performance.

This paper will focus on the long term expansion planning problem and in particular on determining optimal investment scenarios. The main driver of investments in the model is profitability which in turn is assessed by the ratio of price over levelized costs.

The SD model is built in Powersim software with the end goal of optimizing using a tool called Stochastic Optimization in Policy Space (SOPS). For this, some simplifications that we will discuss later were made along the way to make the model suitable for its intended purpose. However this has not misguided the author to focus purely on reaching the "optimum" solution, rather an effort was made to preserve as much as possible from the system variables and attributes in the final model. Hence the model is a simplified version of

reality yet it still can offer some practical insight both from its structure and behavior as well as from its optimal policies generated by SOPS.

2.5 Optimization and choice of criterion

Optimization was conducted to find the optimal investment track over the next 50 years in both the traditional non-renewable technologies as well as in the new renewable ones. The criterion which we are trying to maximize is the so called social welfare or "Net Society Benefit" as referred to in the model. This criterion was judged to be of pertinence to the model with sound foundation in the field of generation expansion planning. This optimization problem falls under the "decisions and policies" context within the SD optimization field (Graham, 2003).

In centralized markets, performance is determined by energy supply security which in turn is part of the social welfare. Social welfare takes into consideration both producers and consumers surplus. In decentralized markets, profitability has a weight as well when determining performance. Hence in a centralized power market, social welfare would be the natural criterion to maximize for conceptual as well as economic reasons. In the decentralized market, the criterion to maximize could be profits or social welfare. The choice of criterion would greatly influence the optimal investment strategy.

In a perfectly competitive market, investments in a centralized social welfare and a decentralized profit maximization market would be the same (Botterud, 2003). This is because in a perfectly competitive market, the price is set and the players are price takers rather than setters. Hence there would be no feedback from investment to the price, rendering the increase in social welfare the same as that of the increase in profits, which is the increase in producer surplus. As the price feedback which is determined by the price elasticity increases, the difference between the two criteria would increase.

In our model, the market is decentralized and not in a state of perfect competition. Hence there is feedback from investments into price and vice versa. The elasticity is set at '-0.45' which means that the price feedback is moderate and there is some difference between the two criterion options. So, a choice has to be made about which criterion to consider when optimizing in SOPS. The social welfare criterion in our model would produce higher gains than the profit criterion resulting in lower investment threshold. Hence the social welfare is judged to be more appropriate for conceptual as well as economic reasons in our model.

3. MODEL

Having discussed the importance and relevance of the power generation expansion planning problem and the appropriateness of the System Dynamics (SD) methodology to study it, this section will focus on introducing and explaining the SD model developed in this thesis. The model has a long term view of 50 years, from 2015 till 2065, with a time step of 1 year.

The level of details included in the model is rather limited, and this is because we are solely interested in investigating long term behavior as well as because restrictions imposed from the beginning by the prospect of using the tool SOPS. The most important relationships for the long term development of the electricity market, determined following an iterative process of trial and error, are kept in the model even if slightly simplified. Transmission and distribution are not part of the model since they are not interesting to explore on the long run. The result is an SD model of the long term generation expansion planning problem where the profitability determined by price and levelized costs is the main driver of investments.

The model is of a decentralized power market. Therefore it has two decision makers, the renewable and non-renewable ones. Each decision maker aggregates all of the technologies in its respective sector.

The two energy sectors are built almost identically with the same structure. Minor differences, mainly non-renewable resource depletion and renewable premium, will be discussed. Most of the equations are part of the main text since the model explanation was divided into many small parts. Parameter values are naturally different between the two sectors and are listed in Appendix 8.2. The two sectors interact individually with their investment strategies and with each other through the electricity market sector. The electricity market is a simple electricity price formation structure which takes into consideration the supply as well as an exogenous reference demand.

Please note that often the term renewable is shortened to "R" and non-renewable to "NR" in our discussion next.

3.1 Electricity Market Sector

Since our focus is on the long term dynamics, no discrepancy between supply and demand was assumed. So the demand is taken to be the same as the supply. Hence, price formation was determined by supply, an exogenously influenced reference demand stock and a reference market price with no need to include the reserve margin concept. When the supply rises over the reference demand, the electricity unit price will drop and vice versa. Also a

constant long-term price elasticity is introduced to capture some of the feedback that price has on demand. The feedback is not a direct one since supply and demand are the same; however it is through influencing the investments at time (t) which determine supply and demand at (t+1). The equations for the price formation are:

$$\text{Electricity unit price [Billion Dollars/TWh]} = \text{Market Reference Price} \times [(\text{Electricity Supply} \div \text{Reference Demand}) ^ { (1/\text{Demand Price Elasticity}) }] \quad (1)$$

$$\text{Reference Demand [TWh/Year]} = \int_{t=2015}^t \text{Ref Demand Growth Rate} \quad (2)$$

$$\text{Ref Demand Growth Rate [TWh/Year}^2] = \text{Reference Demand} \times \text{Long Run Demand Growth Rate} \quad (3)$$

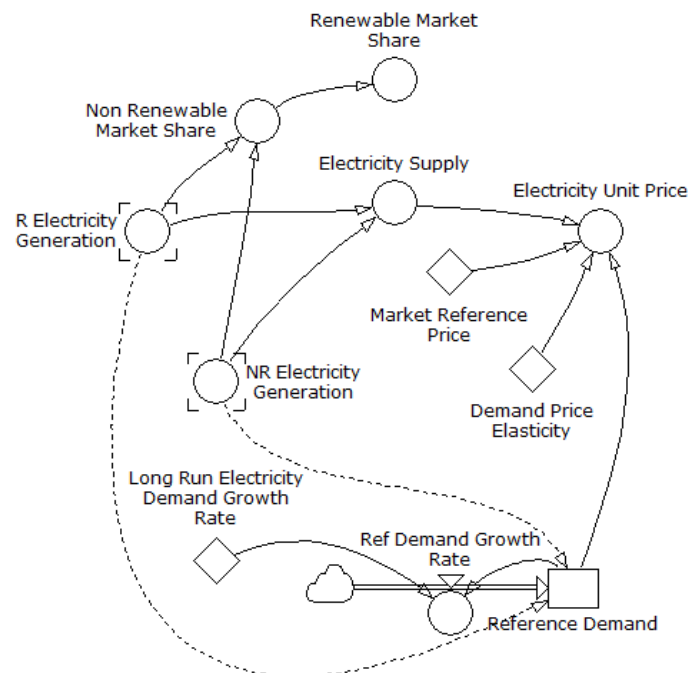


Figure 4: Electricity Demand and Unit Price

The "market reference price", even though being a parameter, is as well determined by the model itself. It is kept as a parameter to avoid the need to add more stocks. The model is run a few times with several values for the reference price until a value is found for which the model would be initialized in equilibrium. By equilibrium, it is not meant constant development over time rather than a smooth one.

Grid and distribution costs are not part of the model hence their costs are not included. Between 30% and 50% of the end customer price is from the grid and distribution costs, so with a generation cost of 8.9 cents/KWh, the final selling price would be in the range of 11.5

cents to 13.4 cents/KWh. This is very similar to the values found in several sources and most importantly in (IEA, 2013).

The long run demand growth rate is placed at 1.5% per year. The rationale behind this value is that the economic growth would dictate the growth in electricity demand and they would have roughly the same value. The economic growth is often placed between 1% and 2% per year, so the mean value of 1.5% is taken. Efficiency improvements have a role in determining the long run electricity demand growth, however it is minimal compared to the economic (i.e. consumption) effect, hence they are neglected.

The price elasticity is set at the value of '-0.45'. Typically commodities have almost inelastic attributes with values close to zero. Electricity being a commodity in some places of the world and a luxury in others, has a price elasticity around '-0.3' (Jamil, 2011). Income elasticity also has an impact on electricity demand. It usually slows down the increase in demand, meaning if supply increases over demand by a certain amount, price will remain higher than if income elasticity was not included. However, to simplify, it is merged with the price elasticity for a final value of '-0.45'.

If there was a gap between supply and demand, meaning if the model took a look at the short to medium term dynamics, the concept of reserve margin would have an impact on price.

Before we move on to the renewable sector explanation, let us quickly discuss the choice of the power units. The model is about the power market, so the units will be in terms of watts. A watt is energy per unit of time (1 watt = 1 Joule/second). The choice is whether the unit will be TW or TWh/Year. Both are basically the same just on different scales:

$$1 \text{ TW} = 1 \text{ TW} \times 8760 \text{ hours/Year} = 8760 \text{ TWh/Year.}$$

Usually supply units are in TW and demand units are in TWh/Year. Supply is represented in the model by the generation capacity stocks to be discussed next and demand is presented by the electricity generation rates also to be discussed next. For simplification and more clarity, both supply and demand will have TWh/Year units.

As for the electricity sectors, the renewable sector is chosen to explain the structure. Any structural differences between the two sectors will be highlighted. A CLD of the renewable sector that visualizes the feedback loops and their stocks is presented in Figure 5. A brief explanation to better understand the CLD:

- The elements in orange are shadow variables of elements from the other sector
- The element in red is the price which is also present in the non-renewable sector
- The element in green represents a structural difference between the two sectors

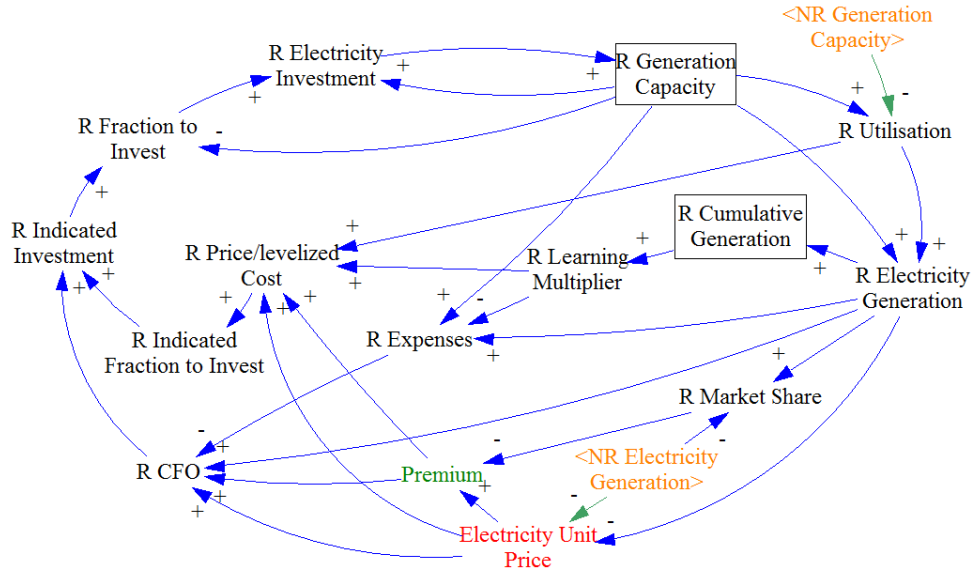


Figure 5: Renewable Sector CLD

Also the stocks and flows model of the renewable sector is presented in Figure 6 for reference. The red arrows in Figure 6 are fake arrows that go into shadow variables. Instead of using graphical functions, each of these shadow variables has a small structure to determine its value. This is to enhance our control over the model as well as for smoother SOPS functioning. For aesthetic reasons, these small structures are moved to the side of the model and will be explained in parallel to the main structure.

3.2 Capacity and cumulative generation

The supply side is restricted to two stocks in each sector which are the generation capacity and the cumulative generation. The generation capacity has an energy investment inflow and capacity depreciation outflow:

$$R \text{ Generation Capacity [TWh/Year]} = \int_{t=2015}^t R \text{ Electricity Inv} - R \text{ Cap Depreciation} \quad (4)$$

Where:

$$R \text{ Electricity Investment [TWh/Year}^2] = R \text{ Generation Capacity} \times R \text{ Fraction to Invest} \quad (5)$$

$$R \text{ Cap Depreciation [TWh/Year}^2] = R \text{ Energy Capacity} \div R \text{ Capacity Life Time} \quad (6)$$

As for the electricity generation, it is determined by the capacity stock and a capacity utilization factor. In addition, a grid loss factor of 10% is introduced to account for the fact that not all generated electricity reaches end users and that some of it is lost in the grid and distribution networks. Later in the policy analysis, randomness will be introduced into the model through the electricity generation, so there is a normal noise factor and switch in equation (8). For now, randomness is switched off and there is no uncertainty in the model.

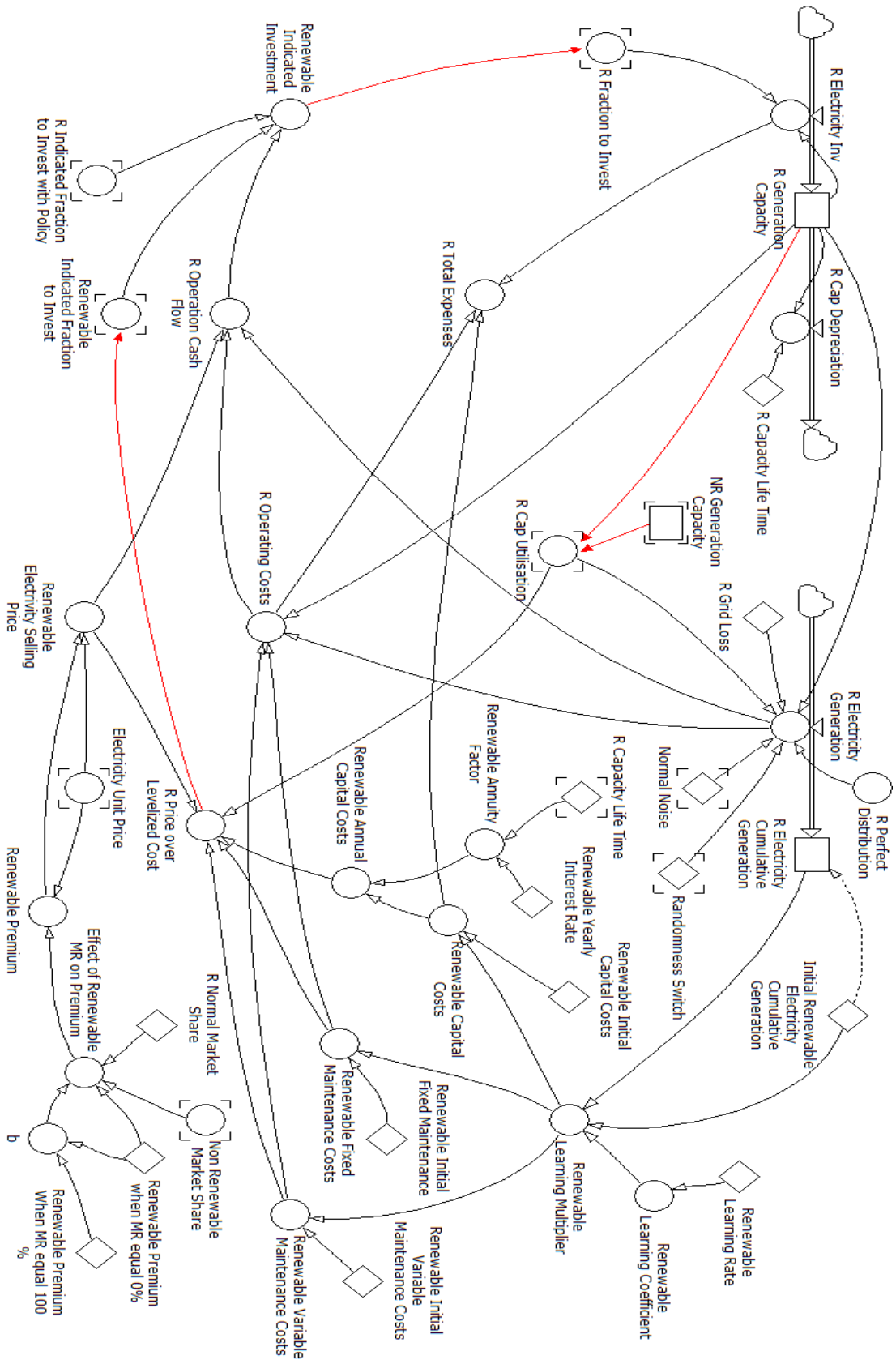


Figure 6: Renewable Sector S&F Model

$$R \text{ Electricity Cumulative Generation [TWh]} = \int_{t=2015}^t R \text{ Electricity Generation} \quad (7)$$

Where:

$$R \text{ Electricity Generation [TWh/Year]} = R \text{ Generation Capacity} * R \text{ Cap Utilization} * (R \text{ Perfect Distribution} - R \text{ Grid Loss}) * \text{MAX}((1 + (\text{Normal Noise} * \text{Randomness Switch})), 0) \quad (8)$$

As for the capacity Utilization, it is determined by a small structure (Figure 7):

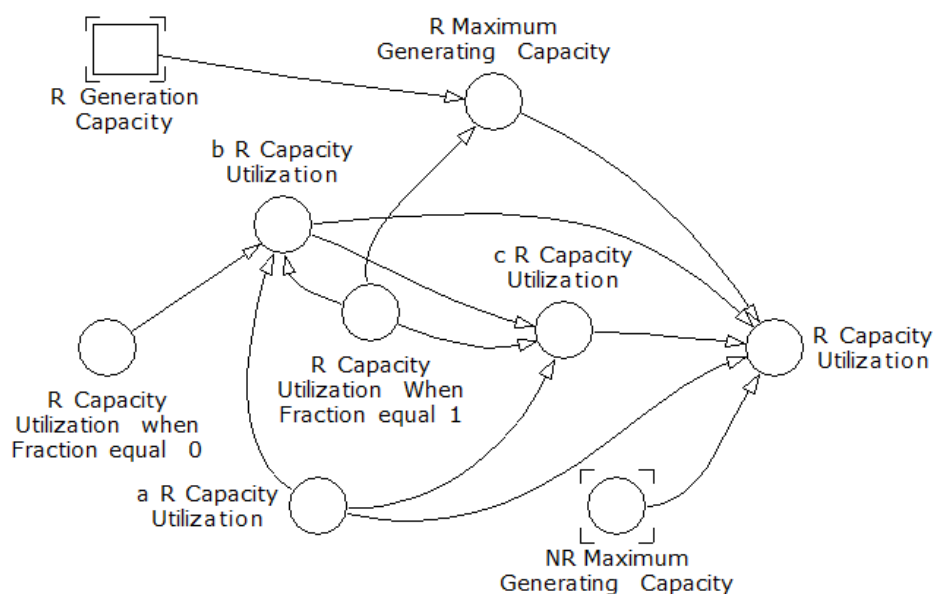


Figure 7: Renewable Capacity Utilization Structure

The structure in Figure 7 basically generates an exponential like curve rather than inserting one in a graphical function. This allows for better control and understanding as well it partially endogenizes the capacity utilization. The utilization is determined based on the two capacity stocks and their maximum generating capacity. As one sector's maximum generating capacity potential increases relative to the other sector, the utilization will increase following an exponential curve. The equation for capacity utilization is of the form $[a \times (b^x) + c]$:

$$R \text{ Capacity utilization [Unitless]} = a R \text{ Capacity Utilization} \times [b R \text{ Capacity Utilization} ^ (R \text{ Maximum Generating Capacity} \div (R \text{ Maximum Generating Capacity} + NR \text{ Maximum Generating Capacity}))] + c R \text{ Capacity Utilization} \quad (9)$$

Please refer to Appendix 8.1.1 for a more detailed view of the capacity utilization. Maximum capacity utilization was taken to be 80% for the non-renewable and 60% for the renewable. This is an aggregation of numbers found in (IEA, 2014b). Renewable technologies due to natural constraints such as limited solar light and wind have lower capacity utilization than that of the non-renewable since the latter is purely dependent on fuel sources. The minimum utilization of each sector was taken to be half of the relative sector's maximum utilization. The structure generates the behavior in Figure 8:

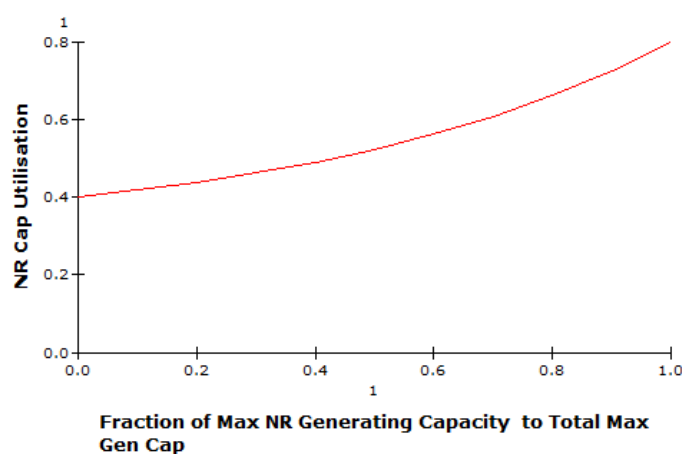


Figure 8: NR Capacity Utilization

The capacity utilization has been simplified to avoid adding more stocks. Ideally operational costs and profitability would have an impact on it. Also, if there was a gap between supply and demand, the gap would have as well an impact on utilization.

3.3 Learning Rates, Resource Depletion and Generation Costs

Technology learning and resource depletion are included in the model to shape how the costs change over time. The values to be presented next were drawn from several sources that the author came across and mainly from (EIA, 2013), (IEA, 2013) and (IEA, 2014b). They represent average aggregate values. Figure 9 represents the Non-Renewable learning, resource depletion and generation costs isolated part of the S&F model. The resource depletion, resource efficiency and fuel costs are a structural difference between the two energy sectors and they are only present in the non-renewable sector, hence in this particular section, the non-renewable part of the model will be illustrated.

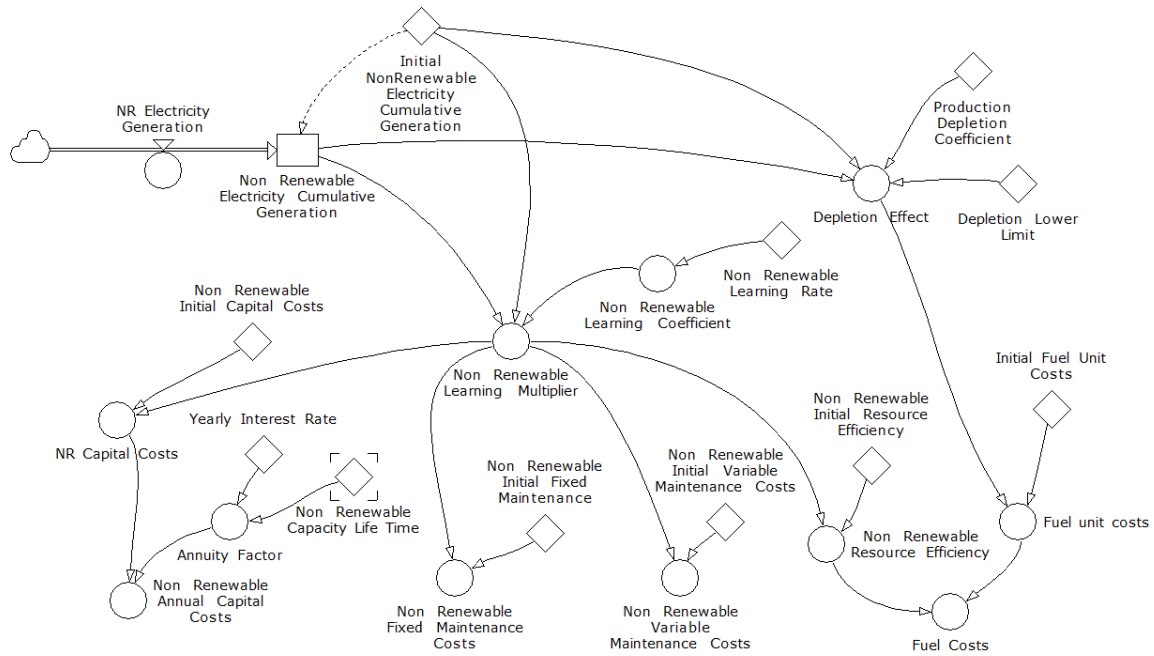


Figure 9: Learning Rate, Resource Depletion and Generation Costs

3.3.1 TECHNOLOGY LEARNING

Learning is an essential part of the model since it deals with the long term dynamics of the market. Learning rates that vary between 10% and 20% are descriptive of most energy technologies (McDonald, 2000). Renewable technologies still have a lot of potential to reduce their costs through learning compared to non-renewable technologies given that they are still far from reaching maturity. Hence 10% learning rate was chosen for the non-renewable and 20% for the renewable. The learning equations are:

$$\text{Non Renewable Learning Multiplier [Unitless]} = (\text{Non Renewable Electricity Cumulative Generation} \div \text{Initial Non Renewable Electricity Cumulative Generation})^{\text{Non Renewable Learning Coefficient}} \quad (10)$$

Where:

$$\text{Non Renewable Learning Coefficient [Unitless]} = \text{Log}(1 - \text{Non Renewable Learning rate}, 2) \quad (11)$$

The values for the initial cumulative generation were iteratively determined based on the initial generation capacity and by observing their resulted output for the learning multiplier.

3.3.2 RESOURCE DEPLETION

Resource depletion, especially in the non-renewable sector also has a large part in determining the dynamics of costs evolution. Non-renewable technologies have exploited their resources to the point where resource availability has become a question to answer and that influences costs. As resources become more scarce costs will increase. For renewable technology, resource availability is in terms of optimal solar farms and wind turbines locations. Since renewable technologies are still pretty young and vastly untapped, resource availability is not a concern and is not included in the model for them.

The depletion effect follows a logarithmic like curve. Here it can be argued that an exponential increase can also portray the depletion effect. In the author's opinion, as the depletion grows more and more, the limit of the depletion effect is reached and it will slow down rather than increase in the long term. The depletion effect equations are:

$$\text{Depletion Effect [Unitless]} = \frac{1}{\text{Depletion Lower Limit} + A} \quad (12)$$

Where:

$$A = \frac{1 - \text{Depletion Lower Limit}}{\left(\frac{\text{Non Renewable Electricity Cumulative Generation}}{\text{Initial Non Renewable Electricity Cumulative Generation}} \right)^{\text{Production Depletion Coefficient}}} \quad [\text{Unitless}] \quad (13)$$

The depletion coefficient translates in a very aggregate way the markets response to resources scarcity. As the depletion coefficient increases, the depletion effect increases and vice versa.

The depletion lower limit translates the limit to which the global community is ready to deplete its non-renewable sources of energy. As the depletion lower limit increases, the depletion effect decreases and vice versa.

3.3.3 GENERATION COSTS

The costs are divided into 4 parts: Capital, Fixed Maintenance, Variable Maintenance and Fuel costs (for the non-renewable only).

- **Capital Costs:** Capital costs are the capital expenditure of commissioning and building new power plants. They are the biggest cost component. Capital Costs are split into two variables: Capital costs [Billion Dollars/(TWh/Year)] incurred when building new power plants and the annual capital costs [Billion Dollars/TWh] used to assess profitability.

$$\text{NR Capital Costs [Billion Dollars/(TWh/Year)]} = \text{Non Renewable Initial Capital Costs} \times \text{Non Renewable Learning Multiplier} \quad (14)$$

$$\text{Non Renewable Annual Capital Costs [Billion Dollars/TWh]} = \text{NR Capital Costs} \div \text{Annuity Factor} \quad (15)$$

$$\text{Annuity Factor [Year]} = (1 - \text{EXP}(-\text{Yearly Interest Rate} \times \text{Non Renewable Capacity Life Time})) \div \text{Yearly Interest Rate} \quad (16)$$

- **Fixed Maintenance Costs:** These costs reflect the maintenance costs which are incurred to keep a power plant in a running condition irrespective of its capacity utilization.

$$\text{Non Renewable Fixed Maintenance Costs [Billion Dollars/TWh]} = \text{Non Renewable Initial Fixed Maintenance} \times \text{Non Renewable Learning Multiplier} \quad (17)$$

- **Variable Maintenance Costs:** These costs reflect the maintenance costs that are incurred when running the power plant. They are linked with the capacity utilization, however in this model they are set as a constant parameter.
- **Fuel Costs:** These costs are only part of the non-renewable sector. These costs are the only one affected by the resource depletion factor as well as the resource efficiency factor. They constitute a sizeable portion of the entire costs. Power plants have different efficiency levels in converting raw sources of energy into electricity (IEA, 2014b), as well as different fuel costs. Average values were plugged in to the model.

$$\text{Fuel Costs [Billion Dollars/TWh]} = \text{Fuel unit costs} \div \text{Non Renewable Resource Efficiency} \quad (18)$$

$$\text{Fuel Unit Costs [Billion Dollars/TWh]} = \text{Initial Fuel Unit Costs} * \text{Depletion Effect} \quad (19)$$

$$\text{Non Renewable Resource Efficiency [Unitless]} = \text{Non Renewable Initial Resource Efficiency} \div \text{Non Renewable Learning Multiplier} \quad (20)$$

3.4 Investment

Profitability is the only driver of the investments for reasons already discussed in the background section. Investments can only be made at the beginning of each year based on a profitability index called "price over levelized cost" which is a ratio of the electricity selling price over the levelized costs. The investment decisions at each of the two sectors were kept to a large extent independent from each other resulting in decentralized decision making which depicts with some realism the competitive electricity market nowadays. This means that an increase (or decrease) in investment in one sector would not necessarily lead to a decrease (or increase) in the other. This is partly inspired by Jay W Forrester statement

(Forrester, 1961): "most industrial systems seem to operate so far from a hypothetical ideal, it is reasonable to hope that system improvements can first be obtained without requiring any compromise. Improving one factor may not require paying a penalty elsewhere."

Figure 10 represents the isolated renewable S&F model for the profitability and investment. Three fake red arrows appear going into shadow variables. These shadow variables each has a small structure which for aesthetic reasons were re-allocated from the main S&F model to the side of it. They will be presented and discussed next.

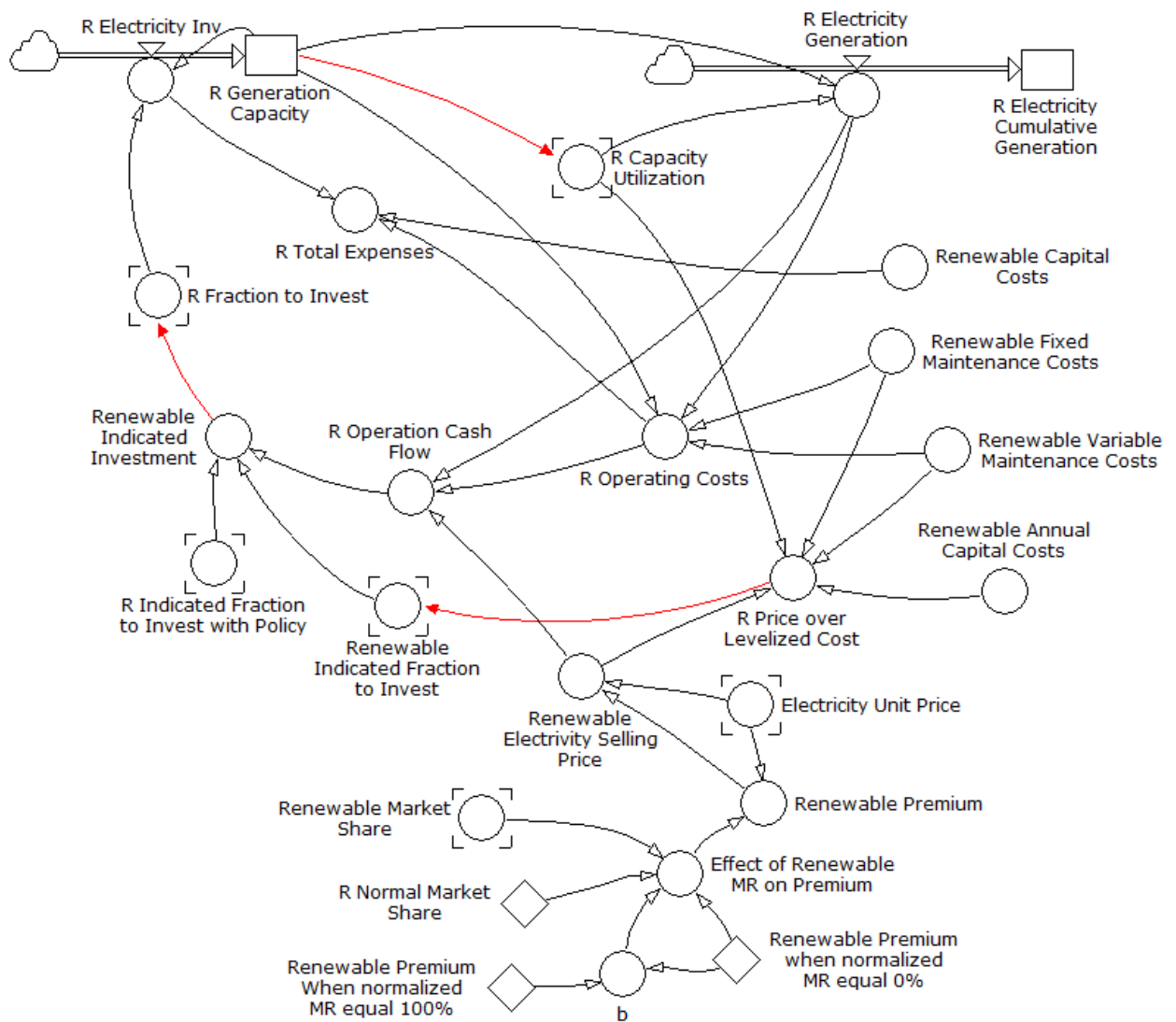


Figure 10: Profitability and Investment

3.4.1 PROFITABILITY ASSESSMENT

Profitability is the only driver of investments. It is assessed by relying on a ratio variable that compares the selling price with the levelized costs. Levelized cost is a common concept used

in the energy management literature to portray costs adjusted for annuity and capacity utilization (Anderson, 2007).

$$\text{R Price over Levelized Cost [Unitless]} = \text{Renewable Electricity Selling Price} \div [(\text{Renewable Annual Capital Costs} + \text{Renewable Fixed Maintenance Costs}) \div \text{R Cap Utilization} + \text{Renewable Variable Maintenance Costs}] \quad (21)$$

Where:

$$\text{Renewable Electricity Selling Price [Billion Dollars/TWh]} = \text{Electricity Unit Price} + \text{Renewable Premium} \quad (22)$$

The renewable premium is a structural difference between the two energy sectors. It is only present in the renewable sector. It accounts for the fact that most renewable technologies have been subsidized as well as sold at a higher price than that of the non-renewable ones. It captures and aggregates the tangible economic incentives utilized by some countries (investment subsidies, feed-in-tariff...) as well as the intangible preference of the public to rely on renewable sources. This factor has a small structure at the lower half of Figure 10.

$$\text{Renewable Premium [B Dollars/TWh]} = \text{Electricity Unit Price} \times \text{Effect of Renewable MR on Premium} \quad (23)$$

Please refer to Appendix 8.1.2 for a more detailed view of the premium structure.

The renewable market is normalized with a "R Normal Market Share" of 50%. The normalized market share allows for the modeler to introduce a preference about how long the premium factor should remain active. If we have a normal market share of 50%, it means when the normalized renewable market shares passes the threshold of 1 (i.e. when renewable MR > 50%), the premium will be negligible.

The "Effect of Renewable MR on Premium" follows an exponential decay as the normalized renewable market share increases. This means that as the renewable market share increases, the premium will decrease rapidly from '1.5' to '0.0001'. Figure 11 illustrates its behavior:

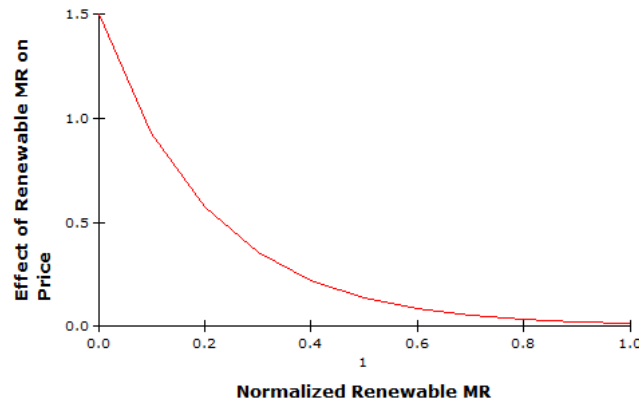


Figure 11: Effect of Renewable MR on Premium

The premium is added to the electricity unit price, meaning when the renewable market share is zero, the renewable selling price would be $(1+1.5) = 2.5$ times that of the electricity unit price. The non-renewable price is always the same as the electricity unit price.

3.4.2 CASH FLOW TO OPERATION (CFO)

In this model, investments were mainly determined by the cash flow to operation. Cash flow to operation (CFO) measures the profits before capital investments are made. Companies usually invest a given percentage relative to their cash flow. As the product becomes more profitable, more of the cash flow will be invested and vice versa. It is possible for a company to invest more than its cash flow, meaning to take debts, if the product is very profitable.

$$\text{R Operation Cash Flow [Billion Dollars/Year]} = \text{R Electricity Generation} \times \text{Renewable Electricity Selling Price} - \text{R Operating Costs} \quad (24)$$

$$\text{R Operating Costs [Billions Dollars/Year]} = \text{Renewable Fixed Maintenance Costs} * \text{R Generation Capacity} + \text{Renewable Variable Maintenance Costs} * \text{R Electricity Generation} \quad (25)$$

For the non-renewable the operating costs would have as well the fuel costs:

$$\text{NR Operating Costs [Billions Dollars/Year]} = \text{Non Renewable Fixed Maintenance Costs} * \text{NR Generation Capacity} + (\text{Non Renewable Variable Maintenance Costs} + \text{Fuel Costs}) * \text{NR Electricity Generation} \quad (26)$$

3.4.3 INDICATED INVESTMENT

Once the profitability is assessed through the "R Price over levelized costs", an indicated fraction to invest is determined. This indicated fraction is an initial number between 0 and

some maximum value that allocates the corresponding portion of the operational cash flow to investments. Indicated Investment has a small structure to the side of the main S&F model presented in Figure 12.

This structure generates an S-shape (logistic growth) curve. As the profitability increases, the indicated fraction to invest increases however more slowly as it gets larger. The profitability index or 'PI' referred to in this structure and its equations is the "R Price over Levelized Costs".

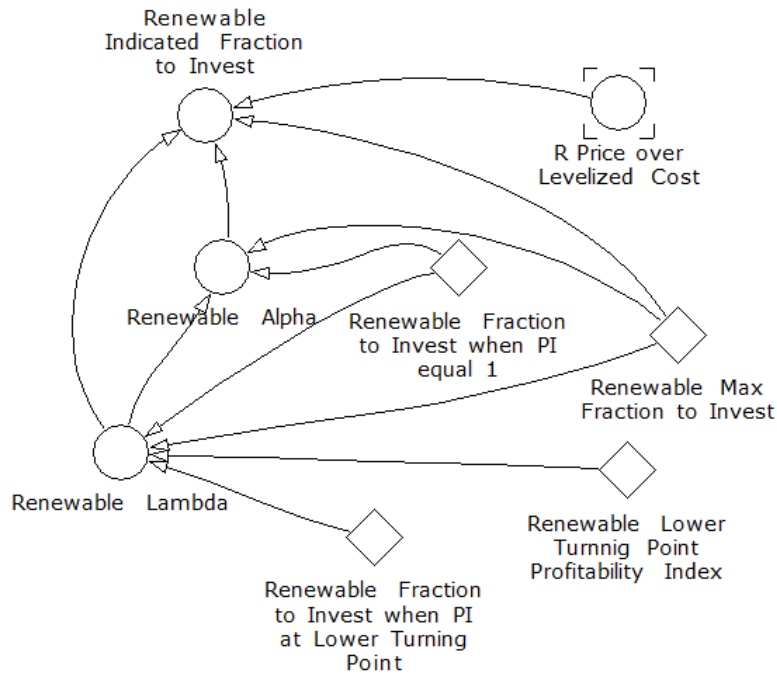


Figure 12: Indicated Fraction to Invest

$$\text{Renewable Indicated Fraction to Invest [Unitless]} = \frac{\text{Renewable Max Fraction to Invest}}{[1 + e^{\lambda \cdot \text{R Price over Levelized Cost} + \alpha}] \quad (27)$$

Please refer to Appendix 8.1.3 for a more detailed view of the Indicated Fraction to Invest structure. This structure generates an S-shape curve like the one in Figure 13:

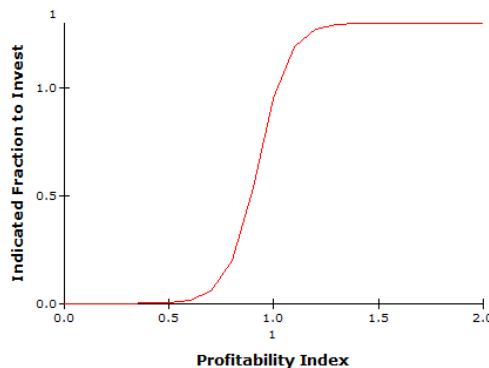


Figure 13: S-Shape Curve of the Indicated Fraction to Invest

The structure allows to better control the output as well as to clarify the modeler preferences about the shape of the curve through the chosen parameter values. After determining the indicated fraction to invest, the indicated investment is found:

$$\text{Renewable Indicated Investment [Billion Dollars/Year]} = R \text{ Operation Cash Flow} \times [\text{Renewable Indicated Fraction to Invest} \times \text{IF}(\text{R Indicated Fraction to Invest with Policy} = 0, 1, 0) + \text{R Indicated Fraction to Invest with Policy}] \quad (28)$$

The "R Indicated Fraction to Invest with Policy" will be discussed in section 5.

3.4.4 FRACTION TO INVEST

After determining an indicated investment, the final investment is determined. Investments are determined in two stages to add a realistic constraint about the feasible capacity increase over 1 year. For example, if the indicated investment results in a 50% capacity increase in 1 year, the fraction to invest would limit it to a more feasible percentage of 32%. The fraction to invest has a small structure presented in Figure 14:

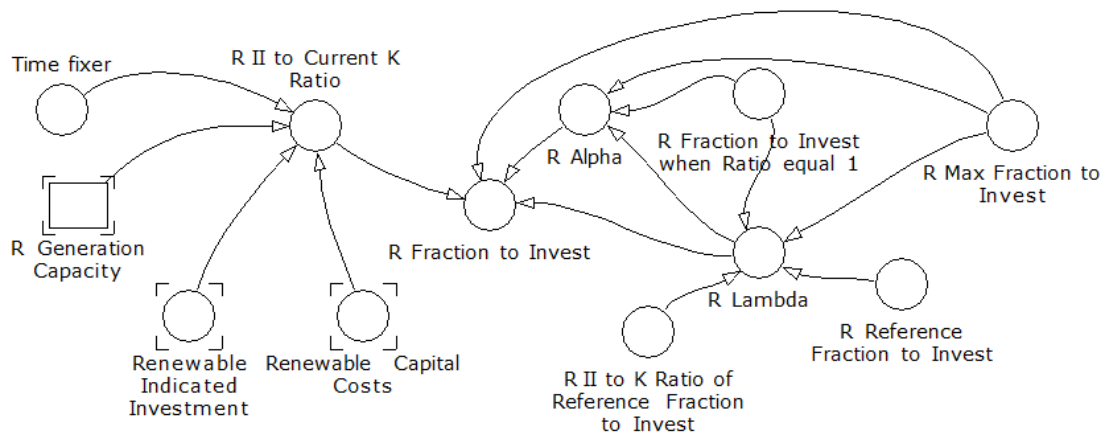


Figure 14: Fraction to Invest

This structure generates an S-Shape curve for the fraction to invest. The rationale behind this structure is that the indicated investment will be compared with the monetary value of the current capacity stock and the ratio of the two will be modified to generate the final fraction to invest. The fraction to invest has a minimum value of zero, meaning it is not possible to decommission a plant early, however it can drop below the depreciation rate decreasing the capacity stock gradually. This helps to avoid wasteful capital investments later on in the case profitability increases for some reason.

$$\text{R Fraction to Invest [1/Year]} = \text{R Max Fraction to Invest} / [1 + E^{\lambda} - (\text{R Lambda} * \text{R II to Current K Ratio} + \text{R Alpha})] \quad (29)$$

Please refer to Appendix 8.1.4 for a more detailed view of the Fraction to Invest structure. The S-Shape generated by this structure is presented in Figure 15:

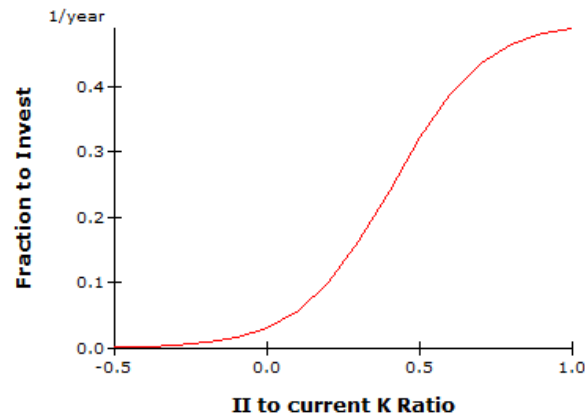


Figure 15: S-Shape curve of the fraction to Invest

Once the fraction to invest is found, the electricity investment flow is determined by:

$$\text{R Electricity Inv [TWh/Year}^2] = \text{R Generation Capacity} \times \text{R Fraction to Invest} \quad (30)$$

3.5 SOPS Criterion

As already discussed, the model is built with the end goal of using SOPS to find optimal investment strategies. Optimization requires a criterion to maximize, and in this model it is referred to as "SOPS Criterion". SOPS functions best when the criterion has values close to '1', so the criterion is a normalized value of the net society benefit. The choice of the criterion is discussed in section 2.5. Figure 16 presents the SOPS criterion structure.

Net society benefit is defined as the difference between benefits and costs adjusted with a long run social discount rate. Benefits and Expenses will be discussed next in section 3.5.1.

$$\text{Net Society Benefit [Billion Dollars/Year]} = \text{Profit} \times \text{EXP} [- \text{Social Discount Rate} * (\text{TIME} - \text{INIT}(\text{TIME}))] \quad (31)$$

Where:

$$\text{Profit [Billion Dollars/Year]} = \text{Supply Benefit} + \text{Renewable Premium Benefit} - \text{R Total Expenses} - \text{NR Total Expenses} \quad (32)$$

$$\text{Social Discount Rate [%/Year]} = 5$$

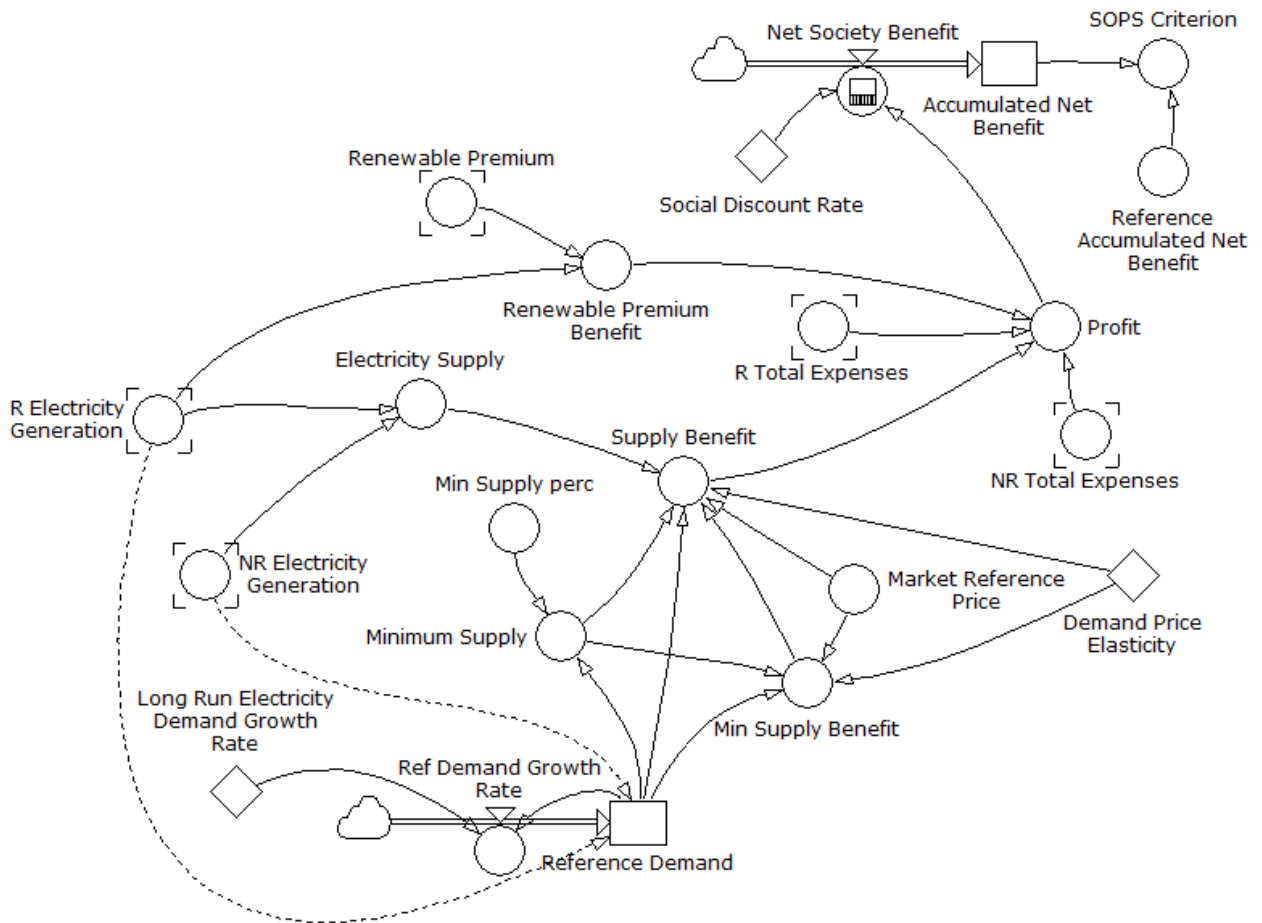


Figure 16: SOPS Criterion

The discount rate value is always open for discussion and can vary significantly depending on the model purpose as well as on the modeler preferences. In literature, it is natural to find values that vary from as little as 1%/Year to as big as 10%/Year. One of the more public disagreements over the discount rate value is between the one set by Professor Nordhaus (Nordhaus, 2008) at 4.1% and the one set by Professor Stern (Stern, 2006) at 1.4%.

A higher discount rate would result in lower social climate change costs on the long run. The choice is always based on many assumptions and is highly dependent on personal beliefs. If the modeler believes in the ability of future generations to handle potential climate change problems, a higher discount rate would be the natural choice. On the contrary, if the modeler thinks that abatement effort should occur sooner than later and more sharply to avoid potential disasters in the future, then a lower discount rate should be chosen.

Given the author's limited knowledge in this highly sensitive topic, he believes that equal weight should be given to economic growth and to our moral responsibility to future generations when determining the social discount rate. We have a moral obligation to future generations to ensure their well-being as best as we can. In order to do so we have to ensure

continued economic growth which would be greatly hindered if sharp abatement measures were taken now. Hence the value of 5% was taken as the reference value. Please note that in section 5.4, scenarios will be run with a 1% discount rate to observe the difference between the two discount rate choices.

3.5.1 BENEFITS AND EXPENSES

Figure 17 illustrates in a simplistic manner the logic behind the calculation of benefits and expenses and consequently that of the profits. The product here is electricity that has a certain selling price for a given quantity. As demand increases, prices drop following the blue price curve. As Supply increases, the expenses rise following the purple expenses curve. They intersect at a point which is the equilibrium price for a given quantity. Consumer surplus is the area under the blue price curve and above the yellow price line. Producer surplus is the area above the purple expenses curve and below the yellow price line.

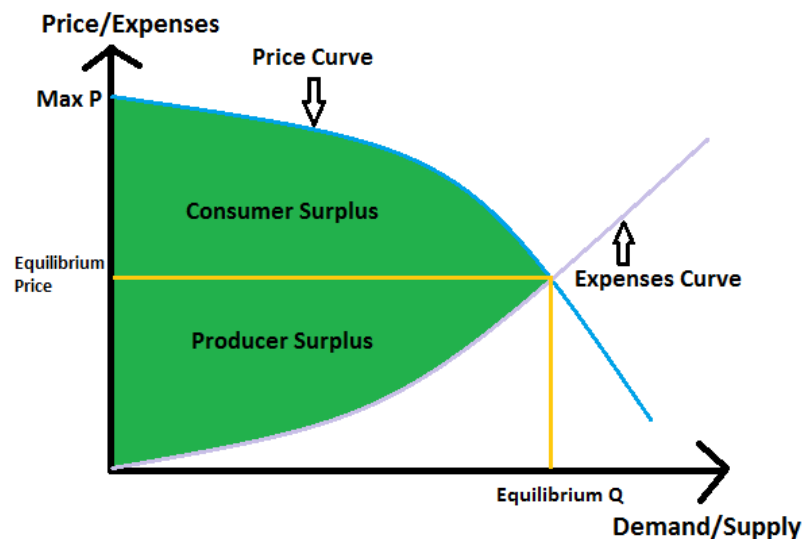


Figure 17: Benefits, Expenses and Profits

Since we are considering the net society benefit as our criterion, both consumer and producer surplus have to be considered resulting in the green area which is the profits. It is this green area that we will try to maximize by using SOPS later on.

To calculate this green area in our model, we simply calculate the entire area under the price curve, i.e. the benefits, and subtract from it the area under the expenses curve, i.e. the expenses. Some modifications were made to this logic in order to calculate the profits in our model and they will be discussed next.

3.5.1.1 BENEFITS CALCULATION

Benefits are split into main categories, the supply benefits and the premium benefit.

Supply Benefits

To calculate the supply benefits we need to find the area under the price curve which requires integration. In Figure 17, there is a maximum price indicated where the price curve meets the y-axis. This is inaccurate, since when the demand/supply asymptotically edges closer to zero, the maximum price would increase to almost infinity. Hence the need to either set a fixed maximum price y-axis value and derive from it a minimum supply x-axis value or vice versa. We chose to set a minimum supply value and derive from it a maximum price.

The minimum supply is set as a percentage of the reference demand. The percentage can be changed to reach a reasonable maximum price value. In our model, the minimum supply was set at 90% of the reference demand. This is plausible since in the electricity market, there will be a 90% or even higher minimum supply target to meet out of the reference demand. This results in a maximum price which is plausible and not too much higher than the market selling price, which is also a realistic portrayal of the electricity market. Since we have now a fixed minimum supply percentage with its maximum price, the integration is split into two parts:

$$\text{Supply Benefit [Billion Dollars/Year]} = \int_0^{S_{min}} P_{max} dS + \int_{S_{min}}^S Price dS \quad (33)$$

In Figure 18, the light blue area would be the max price (i.e. minimum supply) benefit and the dark blue area would be the remainder of the regular price (i.e. regular supply) benefit. The sum of these two areas results in the total supply benefits area.

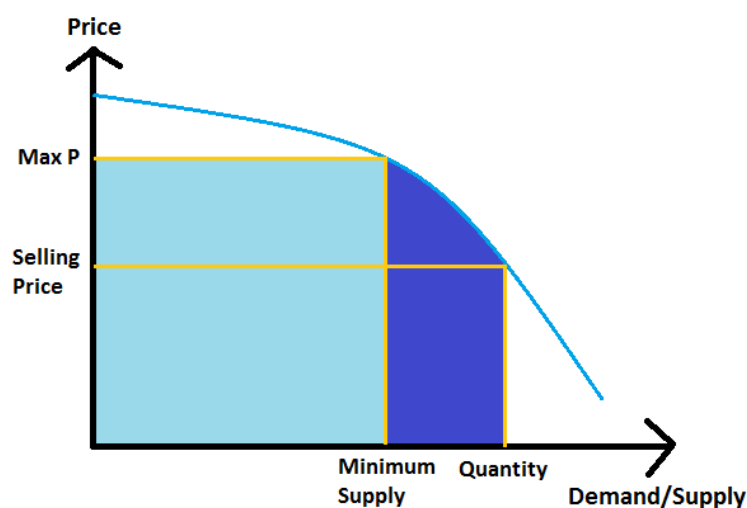


Figure 18: Supply Benefits area under the price curve

The equation for the total supply benefits in the SD model is:

$$\text{Supply Benefit [Billion Dollars/Year]} = \text{Min Supply Benefit} + (\text{Market Reference Price} \times (\text{Electricity Supply} \div \text{Reference Demand})^{(1 + 1 \div \text{Demand Price Elasticity})} \times (1 \div (1 + 1 \div \text{Demand Price Elasticity})) \times \text{Reference Demand}) - (\text{Market Reference Price} \times (\text{Minimum Supply} \div \text{Reference Demand})^{(1 + 1 \div \text{Demand Price Elasticity})} \times (1 \div (1 + 1 \div \text{Demand Price Elasticity})) \times \text{Reference Demand}) \quad (34)$$

Where:

$$\text{Min Supply Benefit [Billion Dollars/Year]} = \text{Market Reference Price} \times (\text{Minimum Supply} \div \text{Reference Demand})^{(1 \div \text{Demand Price Elasticity})} \times \text{Minimum Supply} \quad (35)$$

Premium Benefits

On top of the supply benefits, there is a premium benefit which is from the renewable technologies. This premium reflects the fact that the renewable technologies have a higher selling price and hence more benefits. Its equation is:

$$\text{Renewable Premium Benefit [Billion Dollars/Year]} = \text{Renewable Premium} \times \text{R Electricity Generation} \quad (36)$$

3.5.1.2 EXPENSES CALCULATION

For a given supplied quantity of electricity, there are expenses incurred. They have to be subtracted from the total benefits in order to calculate profits. Figure 19 illustrates the expenses curve and its resulting dark purple expenses area.

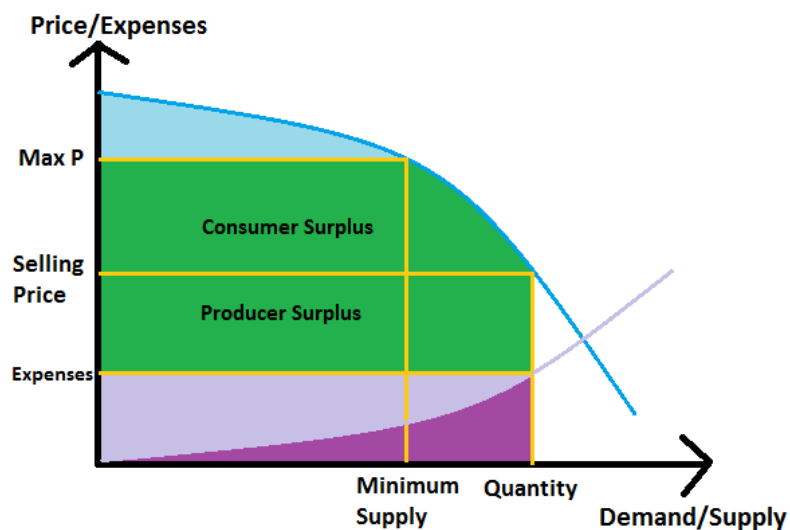


Figure 19: Expenses and Final Profits area

However a simplification was made in the expenses area calculation. To generate an expenses curve in function of the supply is a complicated task and would result in a complex

equation. This is because expenses are divided between operational costs and investment costs and the latter are not directly linked to supply. So the expenses are considered as a constant in function of supply when determining the expenses area. The expenses area is calculated as simply the area under the expenses line for a given supply, meaning it is now the sum of the light and dark purple areas in Figure 19.

$$R \text{ Total Expenses [Billion Dollars/Year]} = R \text{ Operating Costs} + R \text{ Inv} \times R \text{ Capital Costs} \quad (37)$$

$$NR \text{ Total Expenses} = NR \text{ Operating Costs} + NR \text{ Inv} \times NR \text{ Capital Costs} \quad (38)$$

The calculated profit area is shown in green in Figure 19. The light blue and light purple areas were omitted in our calculation for reasons explained before.

3.5.2 SOPS CRITERION

SOPS functions best when its criterion has values close to '1'. So the accumulated net benefit is normalized with a reference one:

$$\text{SOPS Criterion [Unitless]} = \text{Accumulated net benefit} \div \text{reference accumulated net benefit} \quad (39)$$

4. BEHAVIOR TESTING

The constructed model is of a highly aggregated global electricity market. It captures some of the long-term dynamics of the generation expansion problem. The model is not built to replicate historical behavior nor to be applied within a specific region. It is ran from the present (i.e. 2015) 50 years into the future (i.e. 2065). Its objective is to hypothetically simulate and determine optimal investment strategies by utilizing the tool SOPS.

Uncertainty is not part of the model itself and investment decisions are made based on what is perceived as perfectly accurate information. The model is descriptive rather than prescriptive. However uncertainty will be inserted into the model to test the robustness of the optimal policy found in section 5.3.

The model structure was explained in previous sections. Main assumptions and consequent structure simplifications were also discussed. Please note that a strict constraint on the number of stocks, including delays, was set from the beginning since utilizing SOPS was the end goal of this thesis. The model passes validation tests (Barlas, 2006) such as parameter confirmation tests, extreme condition tests and behavior sensitivity tests. Only Sensitivity tests will be briefly discussed next in section 4.3.

4.1 Behavior

The behavior of the model will be briefly presented in this section. The graphs presented next are able to fully summarize the model's behavior.

First let us start with the capacity stocks and their utilization:

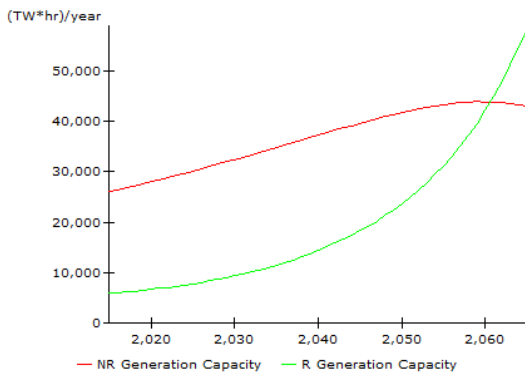


Figure 20: Generation Capacity Stocks

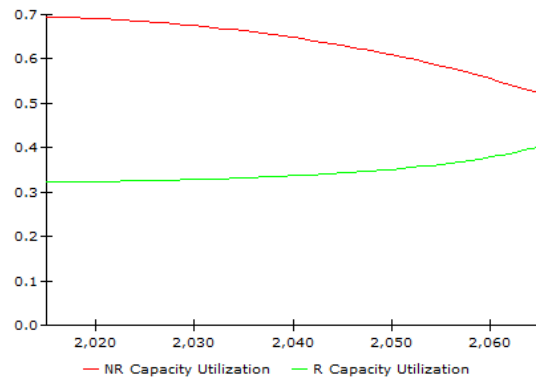


Figure 21: Capacity Utilization

Non Renewable capacity starts at a much higher level than that of the renewable (Figure 20). Both capacity stocks increase however the renewable stock increases at a much faster pace, this is because of the much higher investments seen in Figure 29. Around 2055, the Non renewable capacity stock stops increasing and even decreases a little, meanning the investmenta are no longer able to fully compensate for the capacity depreciation.

The utilization is determined based on the capacity stocks and their maximum potential for generation. So as the renewable capacity stock increases at a faster pace than that of the non renewable, the renewable utilization will increase and the non renewable utilization will decrease as seen in Figure 21. The product of the capacity stocks and their utilization are the electricity generation flows in Figure 22:

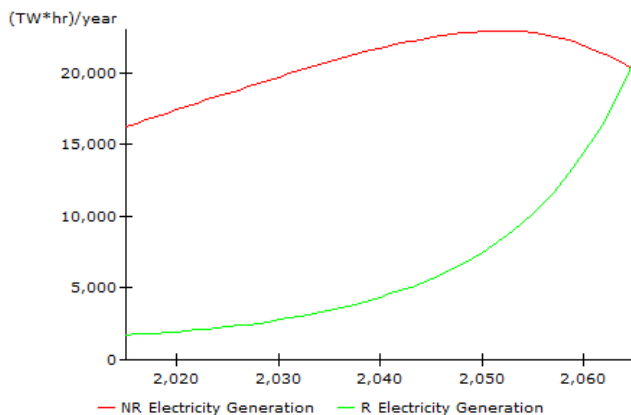


Figure 22: Electricity Generation flows

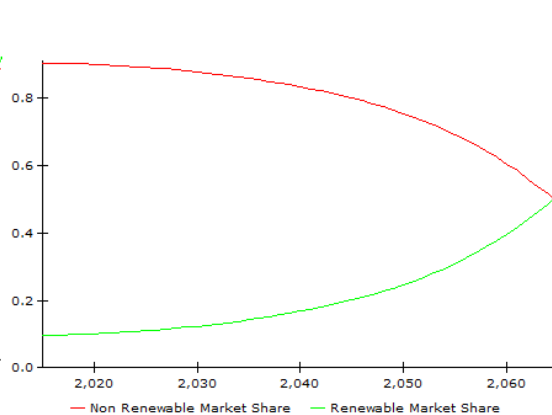


Figure 23: Market Shares

Since the renewable capacity is increasing at a faster pace than that of the non-renewable as well as its utilization is increasing versus a decrease in that of the non-renewable, the renewable generation as a result will increase as well much faster than that of the non-renewable.

Market Shares are directly determined from the generation flows. Since we assume there is no gap between supply and demand, the supply of each sector will be its demand. The market share exhibits the same behavior as that of the generation flows. In 2015, the renewable market share starts at 9.6% and increases to 51% by 2065 (Figure 23).

As the renewable market share increases, its premium will decrease. The premium concept is that people are willing to spend more on renewable sources of energy both for their environmental advantages as well as to increase their market share to reach maturity and commercial viability eventually. In the model, maturity was set at 50% market share, so the premium will become negligible once the renewable market share reaches 50%. Figure 24 shows the development in the selling price for the renewable and the non-renewable. The premium starts very high and increases the renewable selling price over that of the non-renewable by 50%. By 2065, the premium will become almost zero and the renewable selling price will merge with that of the market.

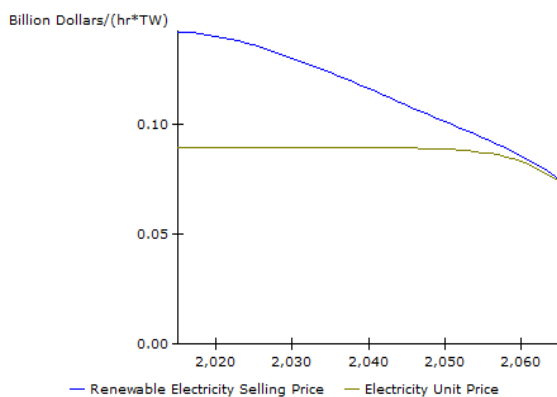


Figure 24: Electricity Selling Price

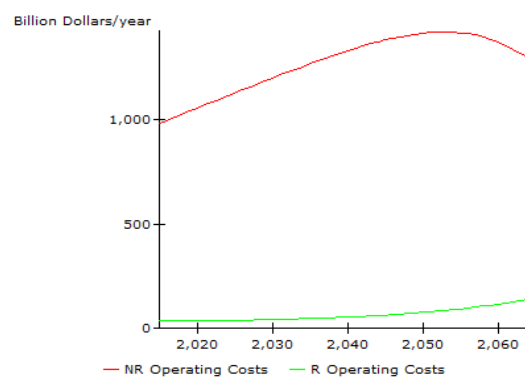


Figure 25: Operating Costs

As the generation increases for both sectors, so will the accumulated generation stocks. This will increase the learning multiplier and the resource depletion in the case of the non-renewable. So the fixed and variable maintenance costs will decrease and the fuel costs will increase. The operating costs are the sum of the fixed and variable maintenance costs plus the fuel costs in the case of the non-renewable. As seen in Figure 25, the non-renewable operating costs are much higher than that of the renewable because of the significant fuel costs. The learning multiplier slows down the increase in operating costs however it is not enough to compensate for all of the increase in generation. So the operating costs will still increase yet at a slower rate than that of the generation flows. In the case of the non-

renewable the increase in costs is much faster than that of the renewable because of the resource depletion effect. However the final cost to generate 1 TWh (Figure 26) showcase a higher renewable cost before it drops below that of the non-renewable as the time passes. This is because the renewable investment costs are much higher than those of the non-renewable which compensates for the difference in operating costs.

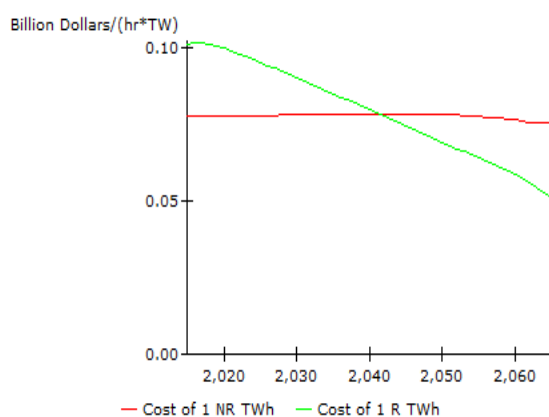


Figure 26: Cost to generate 1 TWh

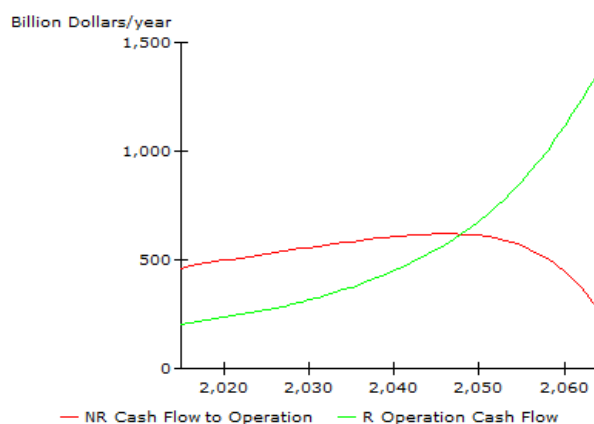


Figure 27: Cash Flows to Operation

Cash Flow to Operation (Figure 27) is the difference between the income from the electricity generated and the operation costs. Electricity generation flows are increasing for both sectors, so the income will increase. However the operating costs are increasing as well as seen in Figure 25. This causes the non-renewable cash flow to increase only slightly before dropping towards the end because of the increasing costs as well as the decrease in the selling price. In the renewable case, the operation cash flow increases very quickly, this is because of the much slower increase in operating costs as well as the much higher selling price because of the premium.

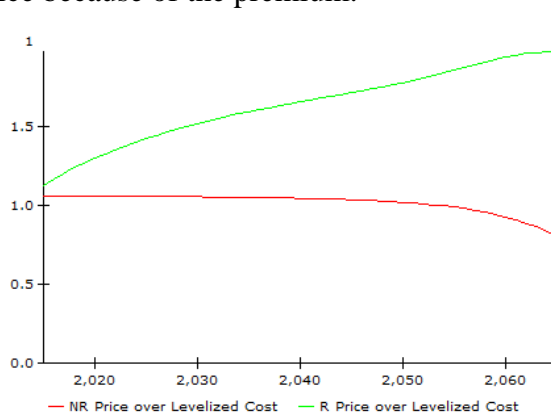


Figure 28: Price over levelized Cost

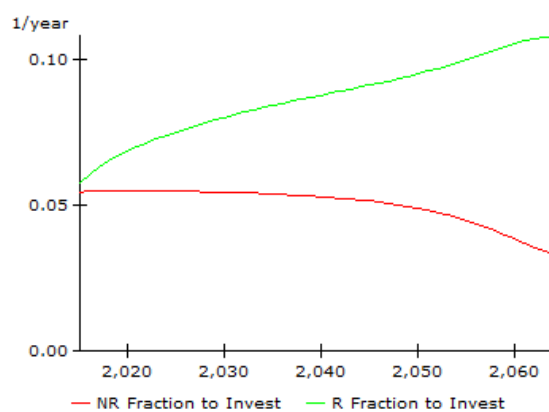


Figure 29: Fraction to Invest

Investments are determined based on a profitability assessment. The profitability measure used is the price over levelized cost (Figure 28). Levelized cost is the sum of all of the costs adjusted for the capacity utilization. If the capacity utilization increases, the levelized cost will drop and vice versa. In the case of the renewable, the fast drop in costs due to a high

learning rate coupled with an increase in utilization results in a fast decrease in levelized costs. The decrease in levelized costs is faster than that of the renewable selling price hence the increasing profitability measure. Renewable technology is able to decrease its costs faster than its gains in market share which is necessary for its sustained success. For the non-renewable, the decrease in costs is counteracted by a decrease in utilization which results in an almost constant levelized cost. Since the price is as well constant, the profitability measure only slightly decreases. However by the end, when the price starts to drop coupled with the strengthening of the resource depletion effect, the price over levelized costs drops.

As seen in Figure 29, the investments have the same behavior as the price over levelized cost. The fraction to invest is determined in two stages. First stage considers the availability of funds for investment. We consider that most of the funds originate from the cash flow to operation, and if the profitability is sufficiently high, the company can take debts and increase its investment. So, in the first stage, an indicated fraction to invest is determined based on the profitability measure as well as the availability of funds from the cash flow to operation. After determining the indicated fraction to invest, it is smoothed and reduced in the second stage. The indicated fraction to invest is compared with the current capacity stock and the consequent increase in capacity is smoothed and reduced down to the final fraction to invest which represents a realistic percentage increase in capacity.

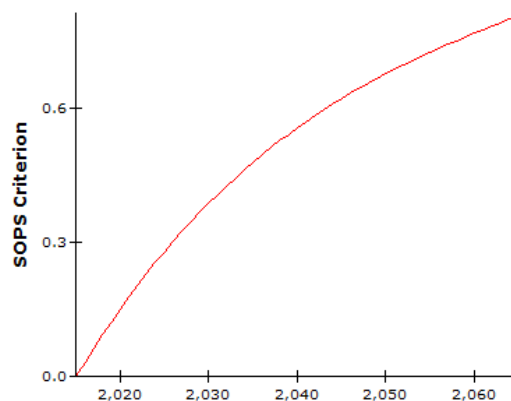


Figure 30: SOPS Criterion

Finally, the SOPS criterion increases from zero until it reaches its maximum of 0.8 at the end of the simulation run (Figure 30). The sops criterion reflects the difference between income and expenses adjusted for the long run with a discount rate. The end goal of the model is to maximize the sops criterion by utilizing the tool SOPS.

4.2 Behavior Analysis and Validation

After discussing the behavior in the previous section, we can conclude that the model produces quite reasonable and realistic results. In this section, discussion will be restricted to the fractions to invest variables and the price formation behavior. The price formation structure in the model is quite simplistic yet its behavior is capable of reflecting the validity of the model given its intended purpose as well as the accuracy of most of its parameters. Price in the model is considered to be an expression of the real price.

4.2.1 FRACTION TO INVEST

The model end goal is to optimize the investment strategies; hence fractions to invest and their behavior (Figure 29) will be discussed because of their significance to the model objective.

The non-renewable sector has already a large capacity stock plus its profitability is decreasing, hence percentage increases in its stock will have to be small and definitely lower than that of the renewable. The renewable sector has a relatively small capacity stock and it is able to realistically increase at a faster rate than non-renewable. By 2065, when renewable market share reaches 51%, its profitability will have reached its maximum level and afterwards it will decrease. So fraction to invest after 2065 will drop, which is excellent behavior since at that time the renewable capacity stock will have grown a lot and hence lower percentage increases can be achieved. So the model is able to generate a good behavior for its intended purpose.

4.2.2 PRICE FORMATION

Price in the model reflects the balance between the increase in supply and that of the reference demand. Also investment and generation costs do not have a direct influence on price which is definitely a simplification of reality. Reference demand is exogenous and is set to increase at a constant 1.5% per year. Electricity demand growth is said to match that of the economic growth or slightly exceed it on the long run. Hence the value of 1.5% seems to be a very good fit since long term economic growth is said to be around 1.3% (Norhaus, 2008) and (Stern, 2006). Please note that in section 4.3.1, randomness by $\pm 50\%$ is introduced to the exogenous growth in reference demand to test the model sensitivity to it. In the long term, demand and supply should be almost equal. Given this logic, the model would be able to replicate reality if it was able to generate an increase in supply to match that of the increase in demand resulting in almost constant real price.

For the first 35 years (i.e. till 2050) the price is almost a constant reflecting a consistent behavior with the logic by which the model was built. After 2050, the price drops. This reflects the increase in the renewable market share with its rapidly decreasing costs. The drop in price should be slower, meaning the model does not capture some of the balancing price loops that gain momentum when the renewable market share starts to increase rapidly. These balancing loops could be an increase in investment and operation costs in both the non-renewable and renewable sectors as the expansion potential shrinks down.

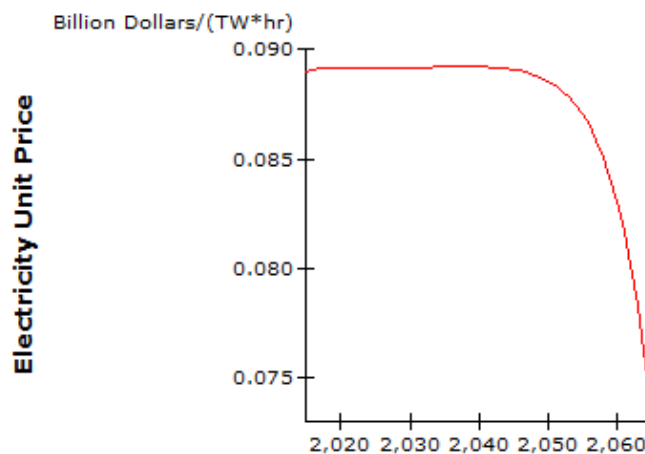


Figure 31: Price Behavior

So the model is omitting some loops that are present in the real market. These missing loops will cause the model to be somewhat sensitive under extreme sensitivity tests to be discussed in section 4.3.2. Hence a choice has to be made whether to add these loops or keep the model as is with a perfectly satisfactory behavior given its purpose.

The model objective is to optimize investment strategies. This led to choose the net society benefit as the criterion to optimize. The criterion calculations were already discussed in section 3.5. Even with the simplistic price formation structure, some simplifications had to be made when calculating the criterion. If additional loops were added, the calculations would be much more complex and additional simplifications would have to be made.

So the choice is between adding more complexity to the model to make it more robust under extreme sensitivity tests, or sacrifice some of its robustness for better and smoother optimization. The choice was to keep the model as is given that it already behaves perfectly given its intended purpose while recognizing its weaknesses.

4.3 Sensitivity Analysis

Sensitivity of the model to its parameters was carefully analyzed. The model is insensitive to most of the parameters, while others the model is sensitive to. Given the limited number of stocks that the model contains with no other delays, it is only natural that it will be sensitive to some parameters.

4.3.1 REFERENCE DEMAND GROWTH RATE

In the previous section, we discussed the price behavior and the model's ability to generate an increase in supply to match that of the exogenous reference demand. Now we will test the model's sensitivity to the important long run reference demand growth rate parameter.

This is done by running the model with the Latin Hypercube sampling method available in the risk analysis window in Powersim. This method allows introducing uncertainty into the model, and in this case into our selected exogenous parameter.

The uncertainty was introduced by changing the parameter from a fixed value across the different runs into a normally distributed parameter that changes values within $\pm 50\%$ of its mean between different runs. Run count was set to 100 which is sufficient to test the sample space of the probability distribution.

The effect of this uncertainty on the model's most important variables was analyzed. Graphs that illustrate 5 different scenarios are shown next:

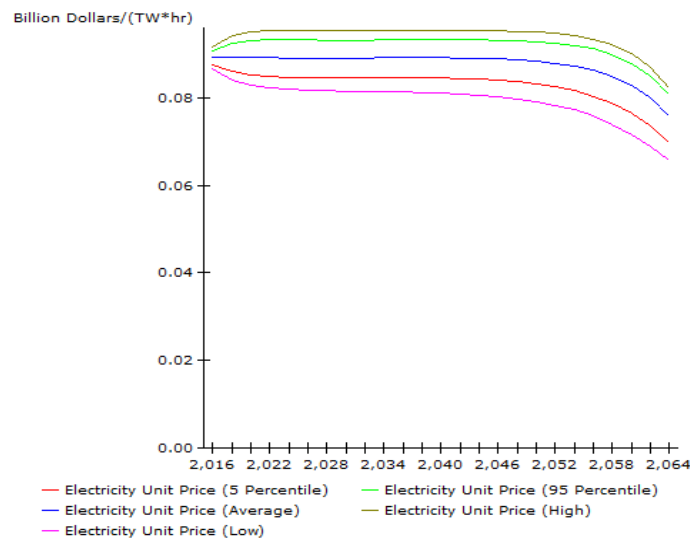


Figure 32: Electricity Unit price Sensitivity to demand growth rate

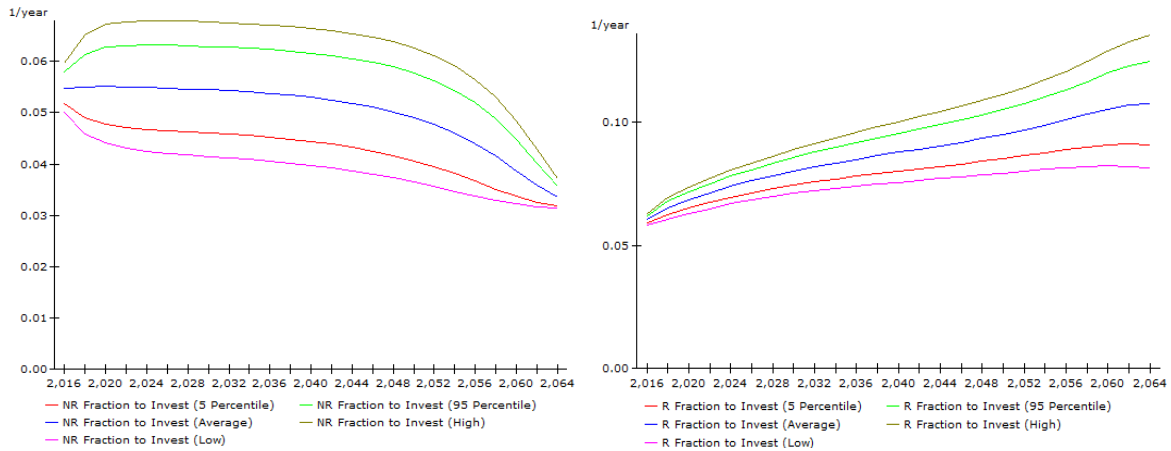


Figure 33: Fractions to Invest sensitivity to Demand Growth Rate

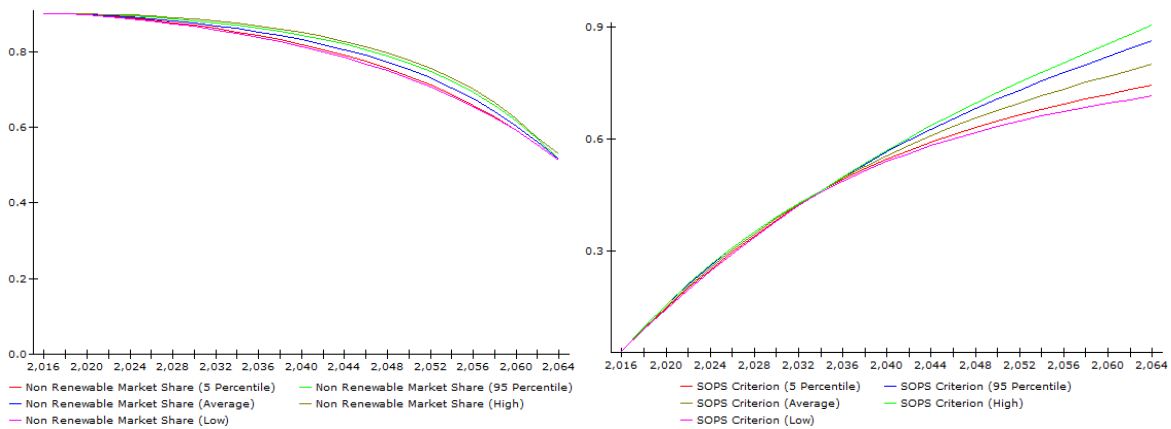


Figure 34: Market Share sensitivity

Figure 35: SOPS Criterion sensitivity

As the graphs show, the model is only slightly sensitive to such a large uncertainty in this important parameter. Hence the model seems to perform well in terms of its intended purpose.

4.3.2 EXTREME SENSITIVITY TESTING

Instead of presenting the sensitivity analysis tests for each of the parameters, a randomness factor was inserted into both electricity generation flows. The generation flows are an ideal sensitivity testing location since they directly influence most of the model. This randomness will amplify any sensitivity that the model has. This can be labeled as extreme sensitivity analysis since it is equivalent to introducing uncertainty to most of the model's parameters simultaneously. Major variables are selected and their simulated results illustrate the model amplified sensitivity to any changes in its parameters.

Model uncertainty is introduced by a Latin Hypercube sampling method with a run count of 100. The randomness factor was a normal variable with a mean of zero and a standard

deviation of '0.1'. This variable is capable of skewing the electricity generation by as much as $\pm 40\%$. This is more than enough to illustrate the model sensitivity to any of its parameters. Equation 8 illustrates how the uncertainty was added into the generation flows equations. Graphs will be presented next that illustrate the model's most important variables behavior and sensitivity under 5 different scenarios, meaning under 5 different randomness values. Each of the scenarios represents indirectly different values for each of the model parameters.

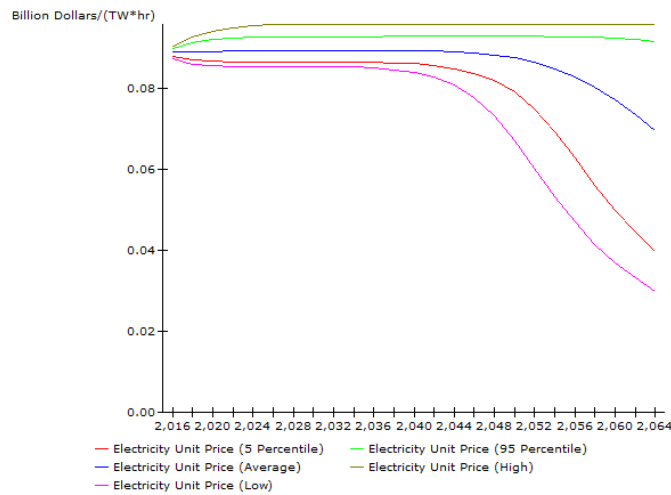


Figure 36: Electricity Unit Price Behavior and Sensitivity

The electricity unit price exhibits a sensitive behavior. As already discussed at the beginning of this section, the model lacks some balancing loops to slow down the decrease in the renewable generation costs. As a result, the price drops rapidly once the renewable technologies reach maturity and their market share starts to increase rapidly. If the renewable market share (Figure 37) varies significantly between scenarios so will the price and vice versa. As we discuss the next variables, it will become clear that the price sensitivity is at the root of all of the rest. Hence by adding additional balancing loops to control for the sharp drop in prices, the model would become quite insensitive even when faced with large uncertainty.

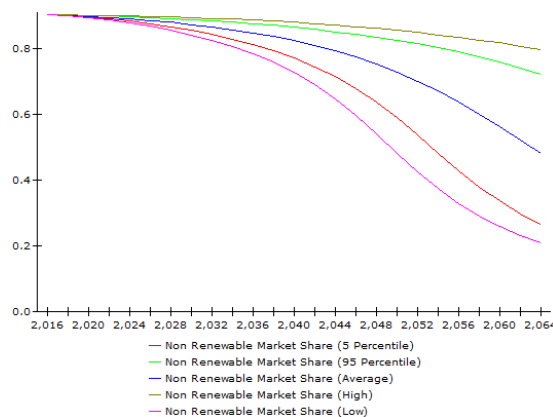


Figure 37: Non Renewable Market Share Behavior and Sensitivity

The non-renewable market share decreases across all scenarios. However the rate of decrease seems to vary a lot between different scenarios. The non-renewable market share is the portion of the non-renewable electricity generation out of the total generation. It is determined by the electricity generation flows, hence the variation. Also it is indirectly dependent on capacity investments, i.e. Fractions to invest in Figure 39. Capacity investments are in turn dependent on the price and expenses. Non-renewable expenses (Figure 38) do not vary a lot since their market share is already quite high, however the electricity unit price seen in Figure 36 varies quite a lot.

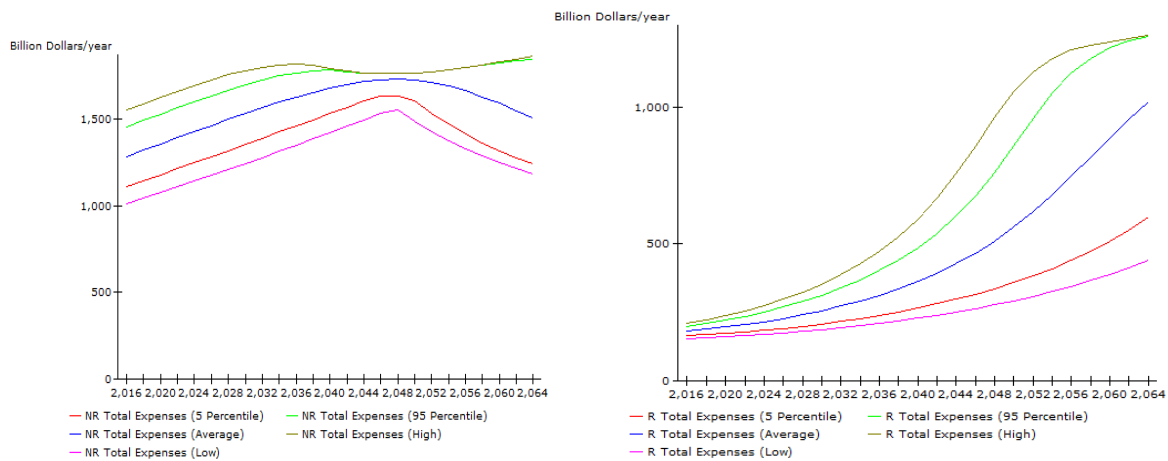


Figure 38: Total Expenses Behavior and Sensitivity

Expenses are dependent on the learning and depletion effects. In the case of the non-renewable, cumulative generation is already quite high so a variation in the generation flow would not cause much of a change in the effects mentioned before. Hence expenses would not vary significantly. On the opposite end, the renewable cumulative generation is quite small and any variation in the generation flows would cause a sizeable change in the learning effect and hence in the expenses.

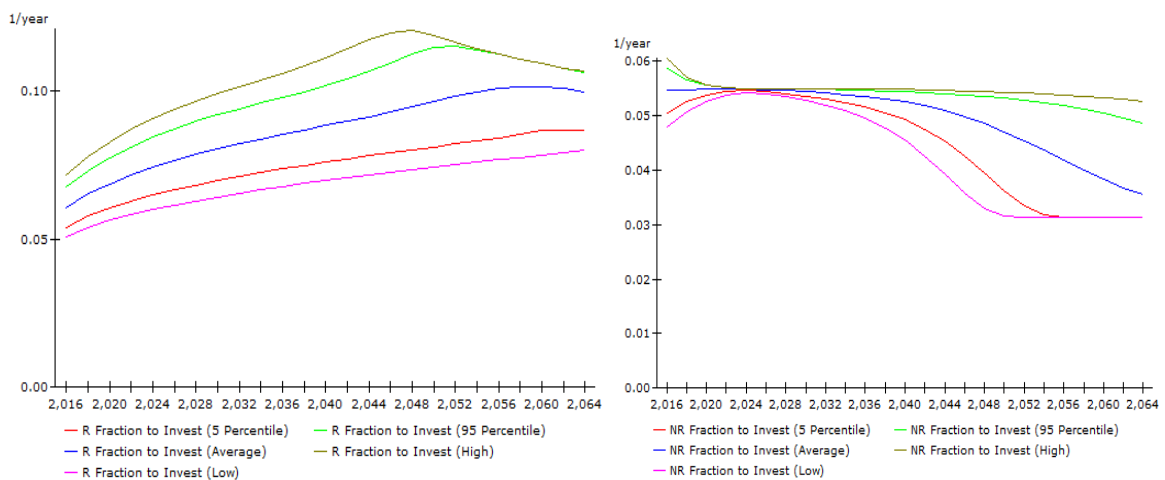


Figure 39: Fractions to Invest Behavior and Sensitivity

Fractions to Invest are among the most important variables in the model. Their result influences significantly the development in the next time step. They are dependent on the profitability ratio "Price over levelized costs". The latter can change from either variation in the price or in the costs. After testing which one of the two elements, i.e. price or costs, contributes more to the variation in the profitability assessment, it is found that by far the price variations (Figure 36) have the bigger impact. Hence the fractions to invest are most sensitive to the price.

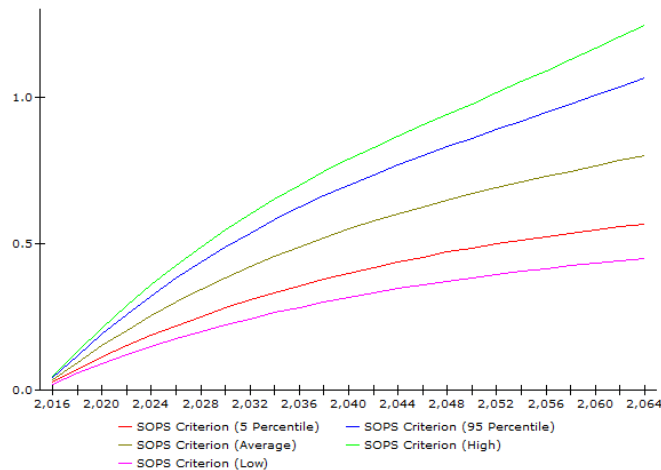


Figure 40: SOPS Criterion Behavior and Sensitivity

The SOPS criterion exhibits the same pattern of development over all of the scenarios. It increases from zero until it reaches its maximum value by the end of the simulation run. The average curve represents roughly the model without any randomness. The SOPS criterion is the end product of almost the entire model since it is determined by the price and expenses of both sectors. The criterion seems to be only mildly sensitive to the randomness, given that there will be up to $\pm 40\%$ variation in each of the electricity generation flows that will in turn affect most of the model, and that it accumulates all of the variations over time.

So, we can conclude that most of the model sensitivity can be traced back to the simplified structure of the price formation. However, the model is built with the primary goal of optimization. Hence a tradeoff has to be made whether to increase the model's complexity for more robustness or keep it at an already satisfactory level for more flexible optimization. The choice was to keep the model with its current structure while recognizing where it lacks in robustness. More so the SOPS criterion used in the optimization proves to be only mildly sensitive even to the most extreme sensitivity testing. Hence the current model structure and its chosen criterion were judged to be valid for the thesis's optimization purposes.

5. POLICY DESIGN AND OPTIMIZATION

Energy transitions follow the typical S-shape technology diffusion curve. They exhibit a non-linear behavior with long delays, hence policies have to be designed within dynamic market models that account for the inherent uncertainty.

After having validated the structure and behavior of the model, we will suggest an optimal investment strategy for the next 50 years to maximize the society's net benefit. This is done by relying on a tool called Stochastic Optimization in Policy Space (SOPS) that works in parallel with the SD modeling software Powersim.

The policies in this thesis are mostly focused on aggregate investment strategies generated by SOPS and not much emphasis was given to particular policies. Still, next is a brief discussion about current policies being implemented by nations worldwide to promote the development of the renewable technologies.

5.1 Current policies discussion

A one sentence to summarize the following policies discussion would be (Sgouridis, 2014): "Switching from an economy based on energy stocks to one based on energy flows requires a social paradigm shift."

Shrinking fossil fuels reserves and recent evidence that supports their negative impact on the environment pushed societies and consequently governments and agencies worldwide to design and apply policies to transform the electricity sector into a sustainable renewable one. When designing new policies, debates about its effectiveness will emerge whether on the specifics or even on the general framework of it.

The electricity sector falls under the energy sector, hence any policy within it will interact with policies on a much wider scale. Energy transitions are not uncommon in the electricity sector. However there is no experience in a transition into a fully sustainable one. To be fully sustainable, it implies that it is in harmony with all the other energy sub-sectors. Past energy transitions were always partial, meaning a primary source of energy, i.e. coal or gas or oil... was substituted in one energy sector yet remained fully present in others. The objective now is a full transition to renewable energy sources and this is unprecedented (Sgouridis, 2014).

Renewable energy sources offer an abundance of supply if properly managed. Current barriers to their diffusion must be removed. Hence policies objective has to be barrier

removal. There are several types of barriers: technical, market, regulatory, social and environmental. The nature of the barriers and their magnitude is specific to either a particular technology, country or region. Government intervention is always seen as a necessity to overcome some if not all of these barriers (Painuly, 2000).

Given that energy transition is such a complex and new concept, investment strategies are often shaped by economic as well as behavioral/non financial factors (Masini, 2013). Bounded rationality has to be considered when studying energy investment choices. Some studies, like (Masini, 2012), have been conducted to examine the structural and behavioral factors that shape investors attitude towards renewable energy investments. A-priori beliefs, personal experience preferences, and risk taking aptitude all affect the type, magnitude, duration and social acceptance of investments into renewable technologies.

For the transition to be sustainable, it has to meet specific requirements on all three economic, social and environmental levels. (Sgouridis, 2014) proposes five constraints that must guide the energy transition to ensure its sustainability as well as its success. The five propositions are:

1. The pollution rate must not exceed the assimilative capacity of the ecosystem
2. Renewable energy harvesting and generation must be in harmony with the ecosystem's long run carrying capacity
3. Energy per capita must remain higher than the minimum level necessary to meet society's needs and there should not be at any time shortages in its rate of change
4. Investments into the renewable technologies generation must be fast enough to ensure a sustainable long term energy supply before the non renewable recoverable energy supply is exhausted
5. Consumption in the future and consequently debt issuance must be coupled to energy availability in the future

5.2 Types of Policies

A range of tools and policies are being implemented nowadays to favor the development of renewable technologies. Among these instruments are green certificates, emission quotas, economic incentives, direct regulations and emission taxes (Maribu, 2002).

These policies fall under two different types: Technology-Push and Market-Pull policies (Burer, 2009). Both of these types have to be applied in parallel to ensure a successful

transition. As always, there are debates on which of the two types of policies is the most efficient in meeting transition and mitigation targets.

Technology-push policies focus on developing the technical/supply side of the new sources of energy. This type of policies rely on innovations and breakthroughs to push the renewable sector into maturity.

Market -pull policies on the other hand focus on developing the demand side for the new renewable technologies. This type of policies rely on the fact that demand is essential for the success of any new product, and by increasing demand technological change will follow. Both of these types of policies have to be applied together for the renewable technologies to complete the innovation chain and survive the technology "valley of death" (Grubb, 2004).

(Burer, 2009) is a study in which these two types of polices were assessed through surveys sent to investment professionals. Figures 41 and 42 taken from that study illustrate the rating of the effectiveness of the most common policies under these two types of polices.

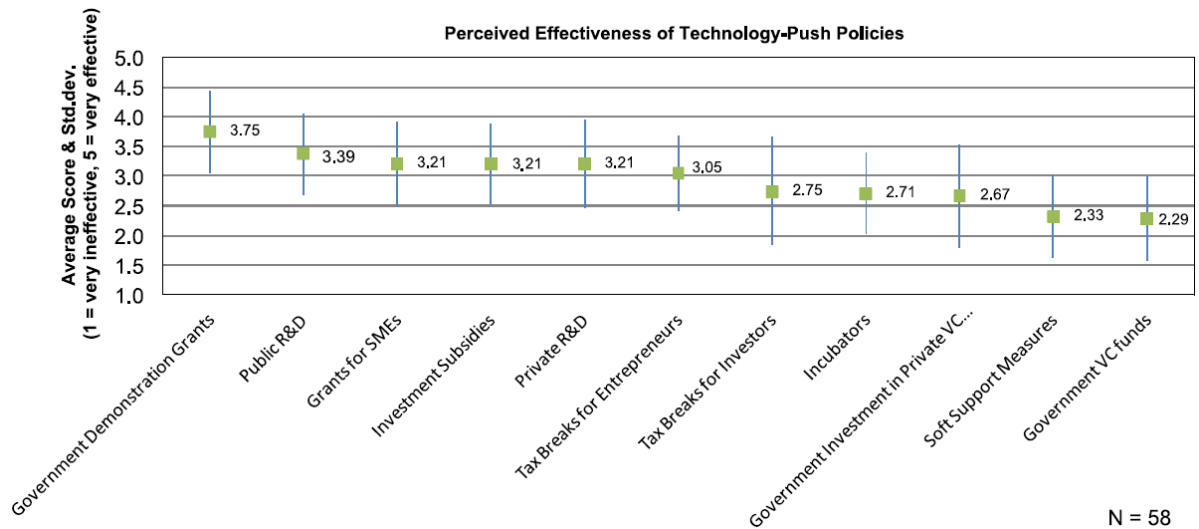


Figure 41: Perceived Effectiveness of Technology-Push Policies from (Burer, 2009)

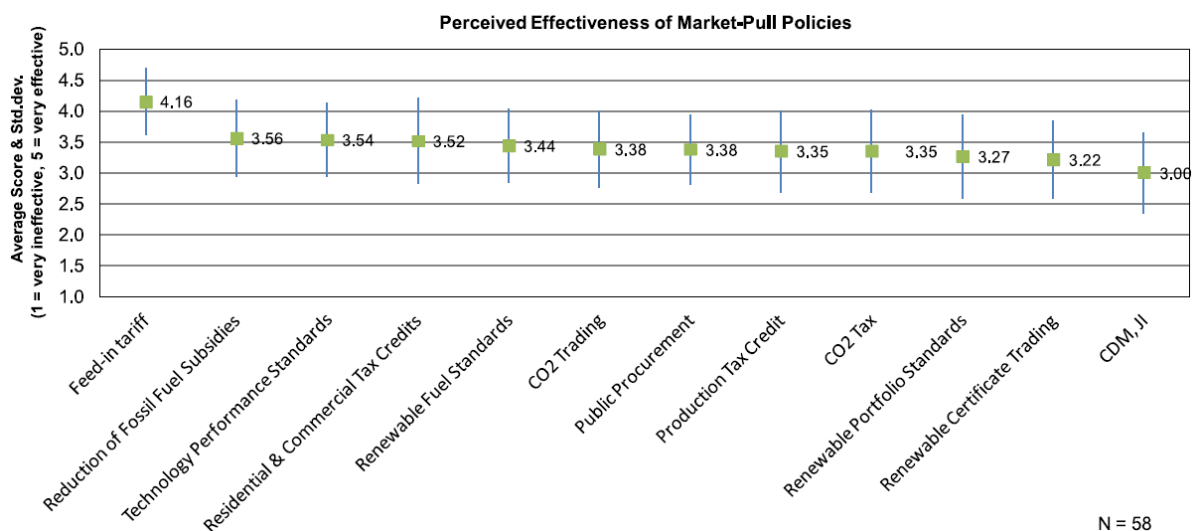


Figure 42: Perceived Effectiveness of Market-Pull Policies from (Burer, 2009)

From Figure 41, Government demonstration grants are perceived as the most effective technology-push policy. This confirms the opinions stated earlier from (Painuly, 2000). Feed-in tariff is perceived as the most effective market-pull policy as seen in Figure 42. This policy generates a guaranteed steady cash flow for the investors which is highly valued.

In this thesis, not much emphasis was placed on one policy option over the others. Instead a built in renewable premium factor was introduced. This factor is an aggregate representation of some of the policies in Figures 41 and 42. GHG emission taxes will be introduced in section 5.4 to briefly explore its impact on the resulting optimal policy.

5.3 Optimal Policy in SOPS and Testing

As already discussed in section 3.4, The model determines the investments in two stages. First stage results in the indicated fraction to invest and the second stage results in the final fraction to invest. SOPS policy insertion point (Figure 43) was chosen at the first stage, i.e. the indicated fractions to invest. This cuts most of the S&F model feedback loops while retaining necessary ones allowing for smooth behavior with the generated optimal policy.

The indicated fraction to invest has a lower limit of zero and an upper limit of '1.3' in the full S&F model. The upper limit is pushed to '2' in SOPS to relax the search space and allow reaching a closer result to the global optimal while still generating feasible policies. One of the scenarios tested in section 5.4 has no constraints to observe the difference in the resulting optimal investment strategies.

For manuals and other applications of optimization by using SOPS please refer to (Moxnes, 2014), (Krakenes, 2005) and (SOPS, 2009).

There are two different types of policies that can be tested in SOPS. One is the grid policy function which results in a flexible non linear policy of ideally all the stocks in the model. The other is the custom policy function which results in a linear constrained policy of all the stocks in the model.

The ideal policy to be found in SOPS would a grid policy function because it offers the more flexible and realistic outcome. However it can handle a maximum of three levels (i.e. stocks) making it not feasible for our model that has five stocks. Nonetheless several grid functions were tested and their results will be discussed later.

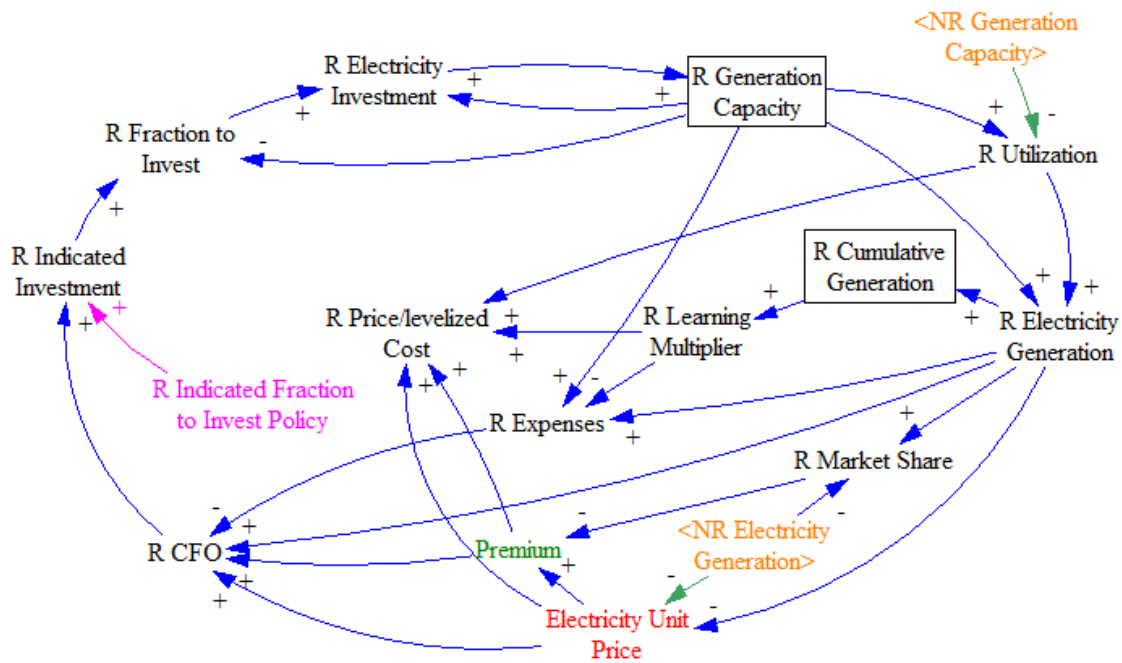


Figure 43: Policy Insertion point CLD

The custom linear policy offers an option for models like ours that have more than three stocks. However being linear, it places a constraint on the policy search in SOPS and the outcome at best would be close to optimal rather than global optimal. For this reason, the optimal linear custom policy will be tested by relying on grid policy functions and more importantly by introducing uncertainty into the model and the policy search.

SOPS was ran with the search count set to '5', eclectic search method and Monte Carlo simulations set to '1'. Also the iteration accuracy for the "SOPS Criterion" was set to '0.00001'. When inserting uncertainty into the model, the search count was set to '1' and Monte Carlo simulations to '100'.

5.3.1 OPTIMAL LINEAR CUSTOM POLICY

Since our model has more than three stocks, a linear custom policy function was chosen to find optimal investment strategies. The structure built in Powersim to be used by SOPS is presented in Figure 44. It is split into two identical parts, one for the non renewable investment and one for the renewable investment.

The custom policy function assigns permanent weights to each of the model's stocks plus a weight independent from the stocks to prevent as much as possible the function from generating illogical results when extrapolating. The weights have to be initialized to values that makes sense, then SOPS will find the optimal combination to maximize the criterion. The equation for the renewable custom policy is:

$$R \text{ Ind Fraction Linear Policy [Unitless]} = SOPSCUSTOMPOLICY(R W + \text{Non Renewable Electricity Cumulative Generation} \times R \text{ non ren cum gen W} + \text{NR Generation Capacity} \times R \text{ non ren gen cap W} + \text{Reference Demand} \times R \text{ ref demand W} + R \text{ Electricity Cumulative Generation} \times R \text{ ren cum gen W} + R \text{ Generation Capacity} \times R \text{ ren gen cap W}) \quad (40)$$

Where the optimal values by SOPS are:

- R W [Unitless] = 0.8607 (0.04468 for the non renewable)
- R non ren cum gen W [1/TWh] = 3.848E-7 (-1.058E-7 for the non renewable)
- R non ren gen cap W [Year/TWh] = 1.007E-5 (8.488E-7 for the non renewable)
- R ref demand W [Year/TWh] = 2.781E-5 (1.593E-6 for the non renewable)
- R ren cum gen W [1/TWh] = 2.922E-7 (4.825E-7 for the non renewable)
- R ren gen cap W [Year/TWh] = 9.132E-7 (2.146E-7 for the non renewable)

The resulting behavior from this optimal linear policy is illustrated in Figures 45 and 46. Indicated fractions to invest for the renewable sector has to be at its maximum level from the beginning, while for the non renewable it has to be zero before increasing gradually later on. The increase in the non renewable indicated fraction to invest is because by 2030 the non renewable cash flow would be negative, so a higher indicated fraction to invest means a lower final fraction to invest as seen in Figure 46.

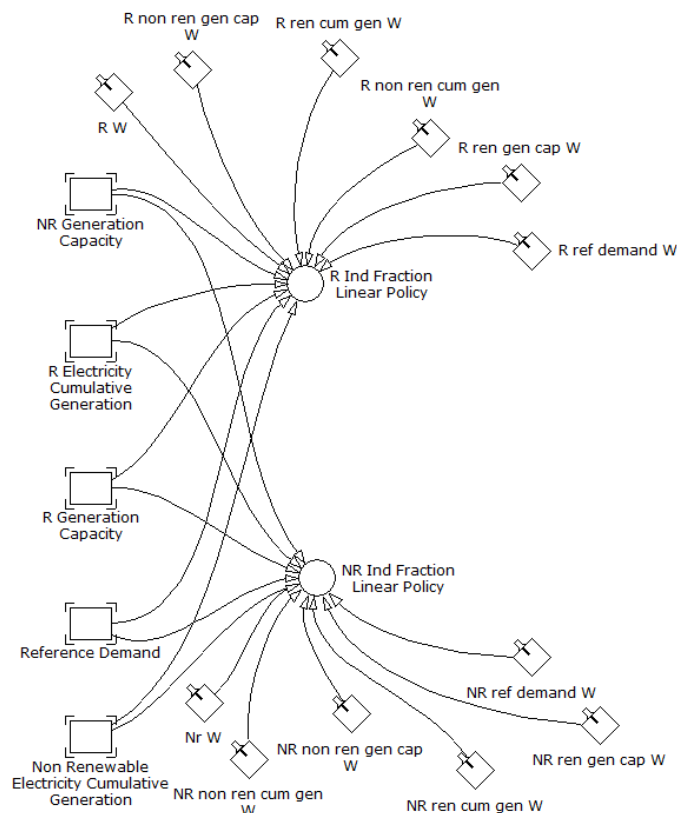


Figure 44: Linear Custom Policy Structure

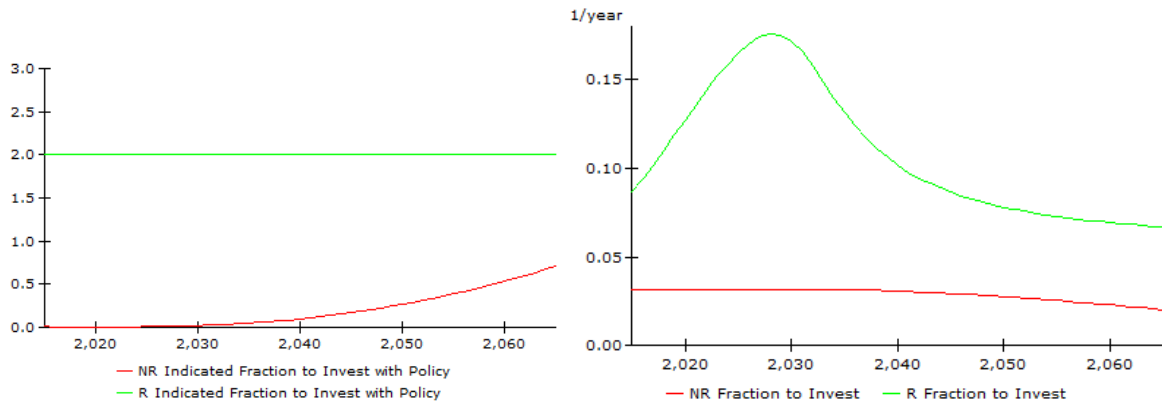


Figure 45: Indicated Fractions to Invest Linear Policy **Figure 46: Fractions to Invest Linear Policy**

The SOPS criterion reaches the value of '0.96' by the end compared to '0.8' with no policy and the renewable market share increases to 93% by 2065 compared to 51% with no policy. The resulting behavior of the fractions to invest is smooth and quite reasonable. The renewable fraction to invest increases gradually to a maximum value of about '0.17' before dropping back down gradually to '0.07' which is feasible in real life.

This optimal linear policy was tested to judge its validity and robustness. This was done by relying on the grid policy function in SOPS and by inserting uncertainty into the model.

5.3.2 GRID POLICY TESTING

Two tests were conducted with the grid policy function. One was a time grid test with only the built in time stock and the other was grid test with the equivalent of all stocks except the reference demand stock.

The grid policy function has as inputs the stocks to be considered in the policy, and for each stock a starting point (Fi) and the step increase or decrease (Delta). In addition, there are a lower and upper limit constraints (Lambda), a grid (Theta) and a dimension parameter for the grid (Rho). Initial values have to be initialized to values that make sense and then SOPS will generate the optimal values. Both of the grids require a grid "variation" value which is higher than zero in the "grid" page in SOPS. This value defines the breadth of the search around the initial grid values. For both grid tests, variation was set to '0.5'.

5.3.2.1 TIME GRID TEST

The time grid structure built in Powersim to be used by SOPS is presented in Figure 47. Same as the linear policy structure, it is split into two identical parts, one for the renewable and the other for the non renewable. There is only one input which is the built in time stock.

This test allows to verify that the behavior of the optimal linear policy is fairly similar to that of an optimal policy which is simply dependent on time. If it is similar, it means that the optimal linear policy is very close to the global optimal.

The optimal time grid policy generated by SOPS has a similar behavior as the optimal linear policy. Meaning investments are to be allocated to the renewable sector and hardly any investments to the non renewable sector. This further validates the optimal linear policy. Figures 48 and 49 illustrate the behavior of the optimal time grid policy.

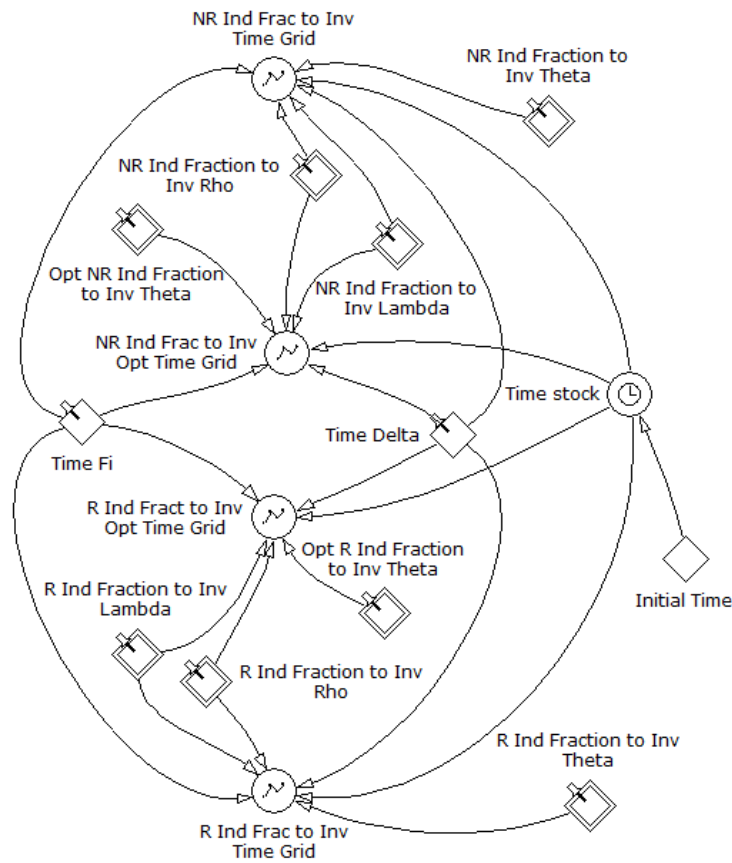


Figure 47: Time Grid Structure

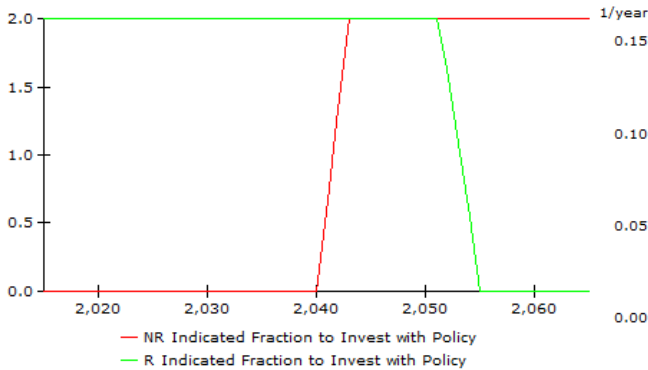


Figure 48: Indicated Fraction to Invest Time Grid

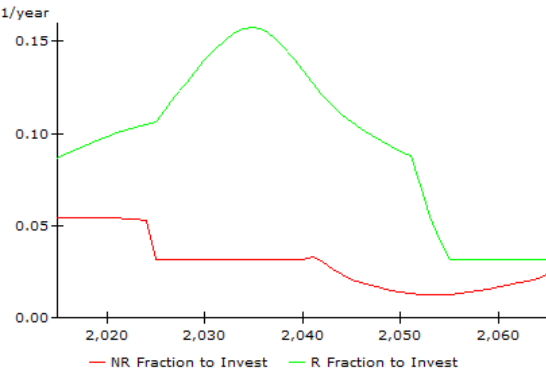


Figure 49: Fraction to Invest Time Grid

5.3.2.2 4 STOCK EQUIVALENT GRID TEST

This test has the same goal as the time grid test. The two capacity stocks were added together, so were the two cumulative generation stocks. The two resulting variables of "Total Generation Capacity" and "Total Cumulative Gen" could be considered as equivalent to 4 stocks.

If the resulting optimal 4 stock equivalent grid policy is similar to that of the linear policy, than the linear policy is close to the global optimal. Its structure is presented in Figure 50.

The optimal grid policy generated by SOPS has a similar behavior (Figures 51 and 52) to the optimal linear policy further validating that the optimal linear policy is close to the global optimum.

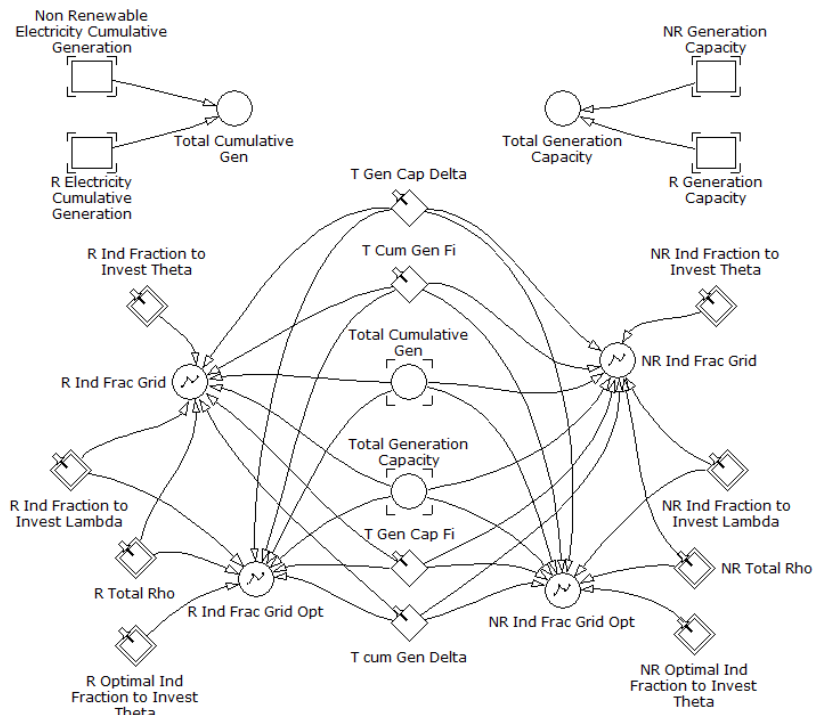


Figure 50: 4 stock equivalent Grid Structure

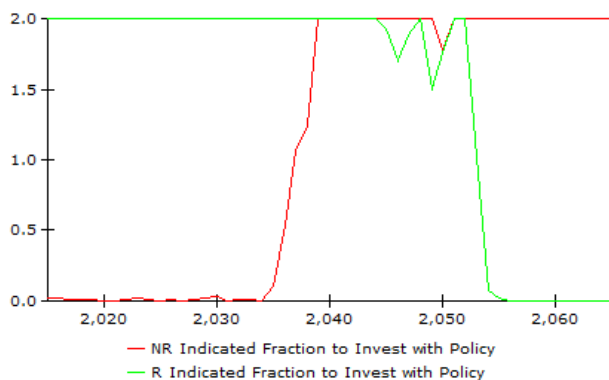


Figure 51: Indicated Fractions to Invest Grid

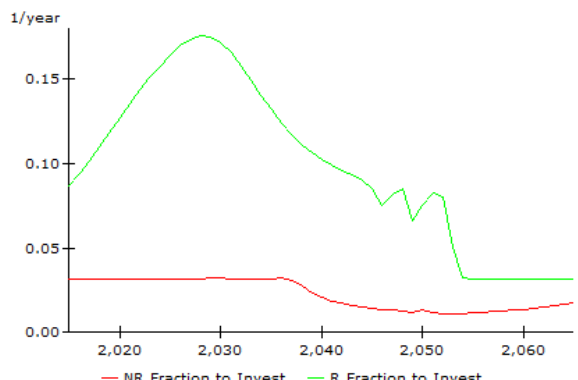


Figure 52: Fractions to Invest Grid

5.3.3 MODEL UNCERTAINTY TESTING

Ideally a Brownian motion structure would have to be added, however that requires an additional stock, so instead a random variable was introduced at each of the electricity generation flows. The uncertainty was modeled by using a variable which has a normally distributed value with a mean of zero and a standard deviation of '0.2'.

This uncertainty was able to change the generations flows by more than $\pm 50\%$ which in turn considerably changes the costs dynamics over time. The noise variable was set as a "series" under the "type" option in the assumptions page in SOPS. This allows for the value to be changed within the same run rather than only between runs. Also the "randomness switch" is switched to '1'.

This uncertainty was ran with the linear policy (Figure 44) with Monte Carlo simulations set to 100 and search count to '1'. If the behavior of the optimal linear policy with uncertainty is averaged out over many different runs, its behavior would be similar to that without uncertainty which confirms the validity of the optimal linear policy found.

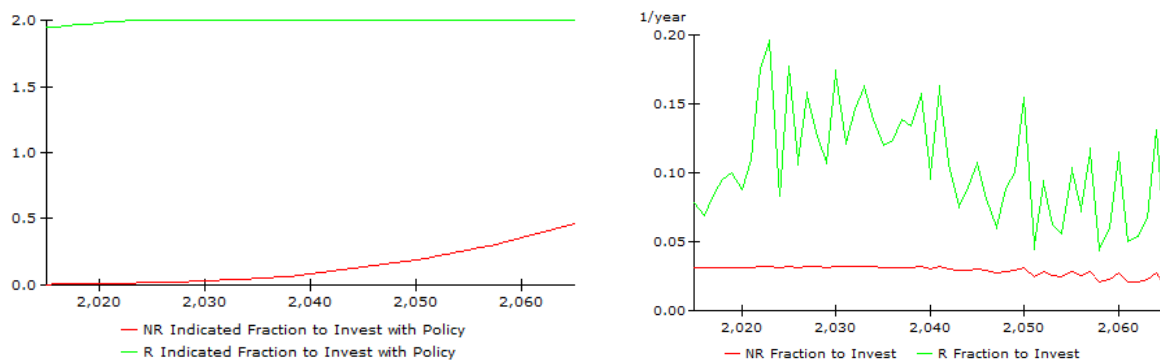


Figure 53: Indicated Fractions to Invest with Uncertainty **Figure 54: Fractions to Invest with Uncertainty**

The behavior shown in Figures 53 and 54 is one example of behavior with uncertainty. Of course it can change when the model is run several times since the noise variable values will change between one run and the next. If ran enough times, like we did by setting the Monte Carlo simulations to '100' in SOPS, the results would be very close to the linear optimal without uncertainty.

All of the optimal results of the different types of policies were inserted in the model for ease of reference. The modeler can switch between the different policies by simply selecting the parameter in question and set it to '1'. For example, if the modeler wants to run the optimal linear policy, then the parameter "Ind Frac Optimal Linear Policy Switch" should be set to '1'. If the modeler wants to run SOPS to find the optimal time grid policy, the parameter "Ind Frac Time Grid Switch" must be set to '1' either in the assumptions page in SOPS or directly in the model.

Special attention must be given if the modeler wishes to run the model with uncertainty. If the modeler wants to run SOPS to find optimal policy, then the "randomness switch" must be set to '1', the "Normal Noise" must be inserted in SOPS as already indicated before and "Ind Frac Linear policy Switch" set to '1' in the assumptions page. If the modeler wants to run the optimal policy with uncertainty, then "randomness switch" must be set to '1', the "Normal Noise" parameter must be changed to an auxiliary variable with a value of Normal (0,0.2) and "Ind Frac Optimal Linear policy with Randomness Switch" set to '1'.

Figure 55 presents the part where the modeler can go and choose between the different policies:

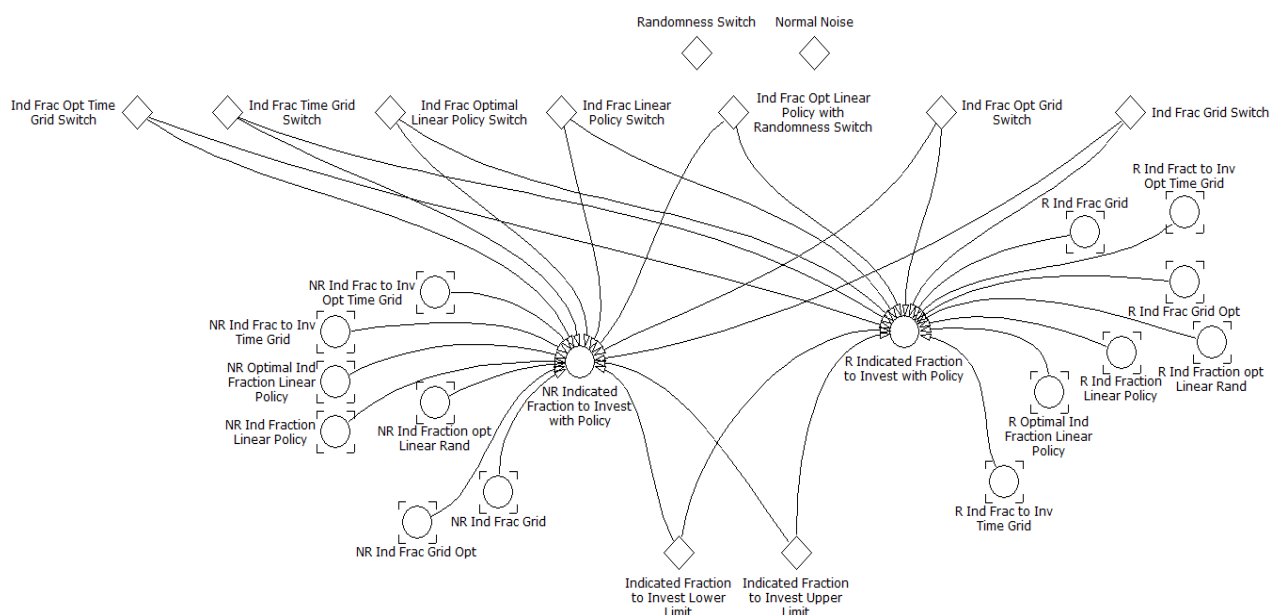


Figure 55: Different Policies and Optimal Results Switches

Table 1 summarizes the SOPS criterion values as well as the final renewable market share for the different policies:

Table 1: SOPS Criterion and Renewable Market Share for Different types of policies

	SOPS Criterion	Renewable Market Share
Optimal Linear Policy	0.96	0.93
Optimal Linear with Uncertainty	0.90	0.92
Optimal Time Grid	0.94	0.87
Optimal Grid	1.01	0.92

SOPS was not able to properly save the files for the "Model with different types of policies". This is most probably because of the "sopscustompolicy" functions. The .sops files do not

open directly, so the .csim file has to be opened and from that file the relevant .sops file has to be opened. Once the .sops file is open, the results in the "optimization" page do not show however all of the assumptions are already set, so by simply clicking on the optimization button, the results will be generated. Please find attached in Appendix 8.3, print screens of the results obtained for all of these policies for your reference.

5.4 Policy Scenarios

Now that we have confirmed that the custom linear policy function is able to generate trustworthy results, different scenarios will be tested with it. Mainly different social discount rates as well as a GHG emissions taxes will be introduced. In total there are 4 different scenarios that can be activated by setting two switches, "High Discount Rate Switch" and "Taxes Switch" to '0' or '1' as presented in Table 2:

Table 2: Different Policy Scenarios Switches Values

	Taxes Switch	High Discount Rate Switch
Policy 11	0	1
Policy 12	0	0
Policy 21	1	1
Policy 22	1	0

In addition to these two switches, the "Ind Frac Linear Policy Switch" has to be switched to '1' as well to run SOPS under the different scenarios. Figure 56 presents the part of the model where the different scenarios can be activated.

To run the model with the optimal results of the different scenarios, the "Optimal SOPS" parameter has to be set to '1' and the "Ind Frac Linear Policy Switch" to '0'.

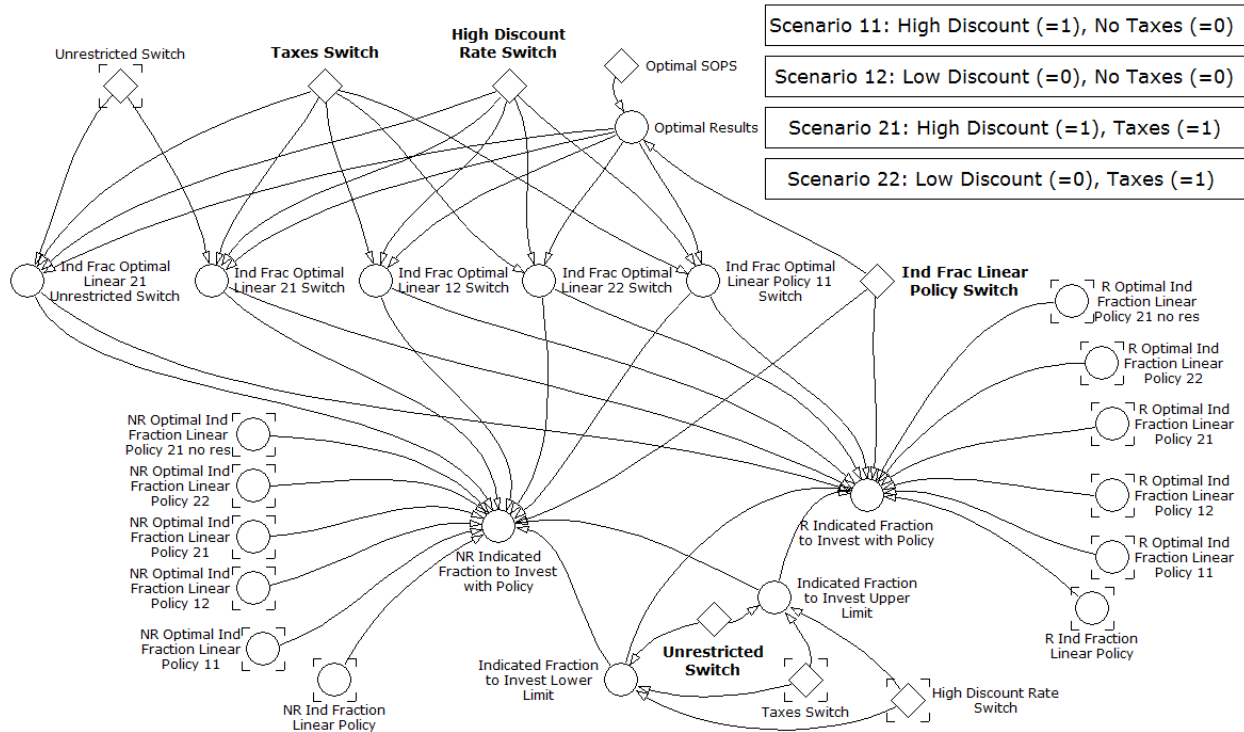


Figure 56: Different Policy Scenarios switches model

5.4.1 DIFFERENT SCENARIOS DISCUSSION

The 4 different scenarios are a combination between different social discount rates with or without GHG emission taxes. The model has a default 5% high social discount rate and no emission taxes, so policy 11 is the same as the optimal linear policy found before.

The social discount rate values were chosen based on the two values proposed by (Nordhaus, 2008) and (Stern, 2006). Nordhaus proposes a value of 4.1% versus 1.4% by Stern. The difference in the values has as origin different beliefs by each of the authors about the severity of the climate change and the responsibility of current generations to mitigate its effects. The choice of the social discount rate is a highly subjective one based on personal beliefs. Hiding it within big models and discussing it as a purely mathematical/economical concept would be misleading.

The two choices to be tested in the model, High with a 5% discount rate and Low with a 1% discount rate, portray the two opposite ends of what most policy makers choose as their discount rates. These two different values were chosen since the author has not had much experience working with climate change mitigation and consequently he still have not formed his own belief about what the rate should be.

If the discount rate is set to 5%/year, then 1 US\$ today in either profit or expenses, is worth only 0.082 US\$ in 50 years. If the discount rate is set to 1%/year, then 1US\$ today is worth 0.95 US\$ in 50 years. Meaning under the high discount rate scenario, in order to maximize society's net benefit on the long term, profits now are valued much more than those in the future and spending/costs must be done in the future rather than now since it is so much cheaper. Under the low discount rate scenario, spending/costs done now will contribute almost equally to the society's net benefit on the long run. A lower discount rate would result in higher net benefits on the long run than with a higher discount rate, however this would depend on how you fundamentally perceive profits in the future versus now.

Marginal Abatement Cost (MAC) curves are commonly utilized in economic investigations of energy transitions and particularly climate change mitigation (Kesicki, 2011). There are several approaches to generate MAC curves and each one has different assumptions. MAC curves are to be treated carefully and careful investigation of their background has to be done before their consideration in policy design.

As for the GHG emission taxes, this policy is selected to be highlighted in parallel to the built in premium factor since it is a straightforward concept. It represents as well the mitigation costs for climate change. It can be either switched on or off. This policy needs an aggregated emission factor (Tonne of CO₂ equivalent/TWh) and a GHG taxes variable (Billion Dollars/ Tonne of CO₂ equivalent). Emission factors for the different types of non renewable generation technologies can be found in (WNA, 2011). The emissions aggregated factor was set to 700000 tonne of CO₂ equivalent/TWh.

Similar to the discount rate different values, there is no single agreed upon level for the mitigation costs. Values differ from as low as 3 US\$/TCO₂ to as high as 95 US\$/TCO₂ (IPCC, 2007). (Stern, 2006) places a value of 61 US\$/TCO₂ in 2015 that drops until it reaches 22 US\$/TCO₂. We chose to place the constant value of 40 US\$/TCO₂ in our model.

The GHG emissions has a structure to be added to the model as shown isolated in Figure 57:

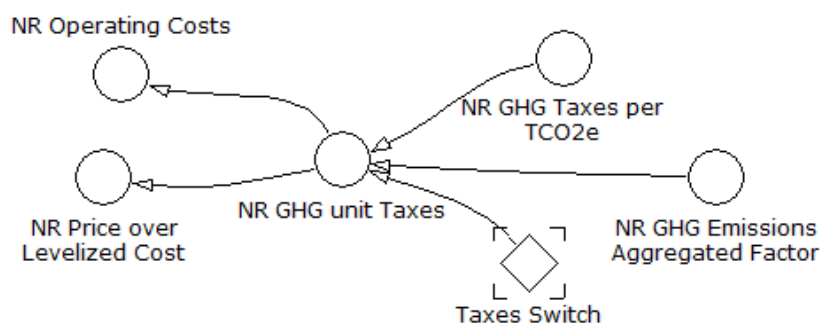


Figure 57: GHG Emissions Taxes Structure

$$\text{NR GHG unit Taxes [Billion Dollars/TWh]} = \text{NR GHG Taxes per TCO}_2\text{e} \times \text{NR GHG Emissions Aggregated Factor} \times \text{Taxes Switch} \quad (41)$$

Where:

$$\text{NR GHG Taxes per TCO}_2\text{e [Billion Dollars/Tonne of CO}_2\text{ equivalent]} = 0.00000004$$

$$\text{NR GHG Emissions Aggregated Factor [Tonne of CO}_2\text{ equivalent/TWh]} = 700000$$

By adding the GHG taxes, the non renewable operating costs and price over levelized cost equations would change to:

$$\text{NR Operating Costs [Billion Dollars/Year]} = (\text{Fuel Costs} + \text{Non Renewable Variable Maintenance Costs} + \text{NR GHG unit Taxes}) \times \text{NR Electricity Generation} + (\text{Non Renewable Fixed Maintenance Costs} \times \text{NR Generation Capacity}) \quad (42)$$

$$\text{NR Price over Levelized Cost [Unitless]} = \text{Electricity Unit Price} \div [\text{Fuel Costs} + (\text{Non Renewable Annual Capital Costs} + \text{Non Renewable Fixed Maintenance Costs}) \div \text{NR Capacity Utilization} + \text{Non Renewable Variable Maintenance Costs} + \text{NR GHG unit Taxes}] \quad (43)$$

5.4.2 RESULTS OF DIFFERENT SCENARIOS

The different scenarios shown in Table 2 were tested in the model. Also an additional scenario was tested. It is similar to policy 21 however with no restrictions in the model when running SOPS. The .sops files are available as well as for your reference. Policy 11 is the same as the optimal linear policy found in section 5.3.1, so its figures are not repeated here. The SOPS files are saved and available for your reference.

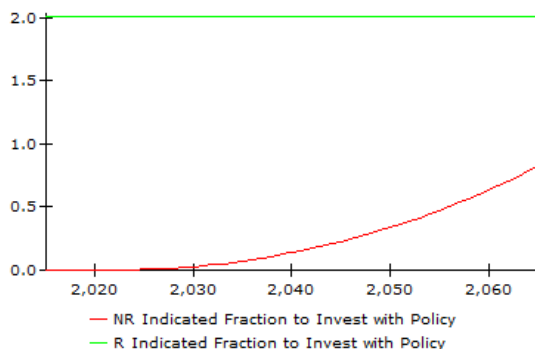


Figure 58: Indicated Fraction to Invest Policy 12

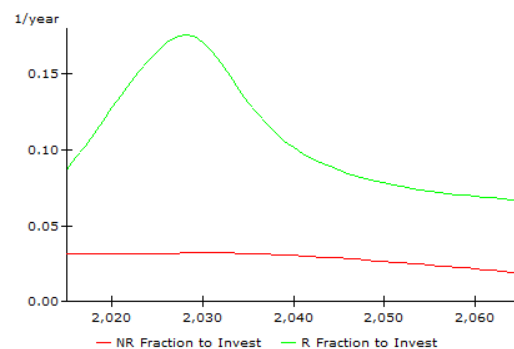


Figure 59: Fraction to Invest Policy 12

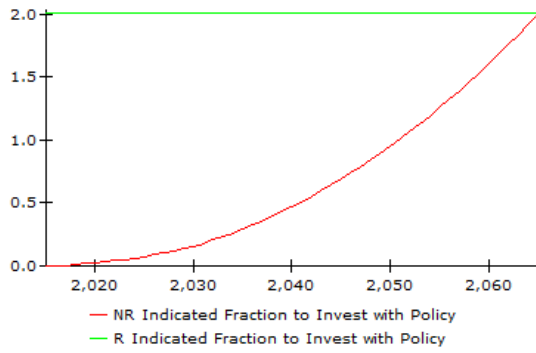


Figure 60: Indicated Fraction to Invest Policy 21

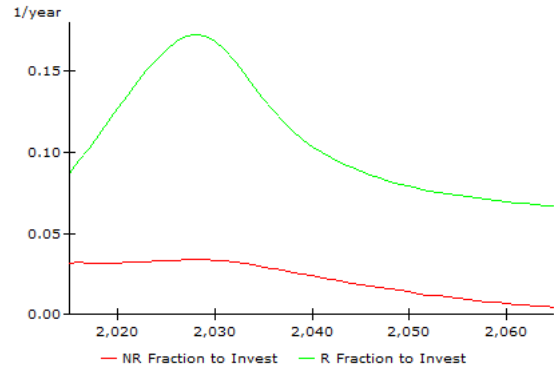


Figure 61: Fraction to Invest Policy 21

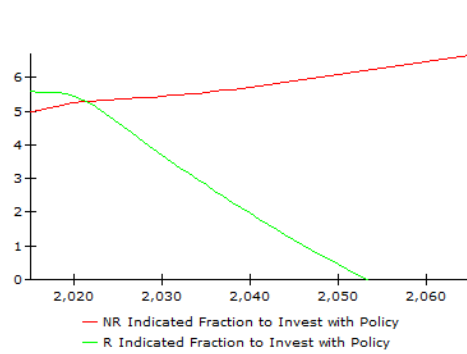


Figure 62: Indicated Fraction to Invest Policy 21 No res

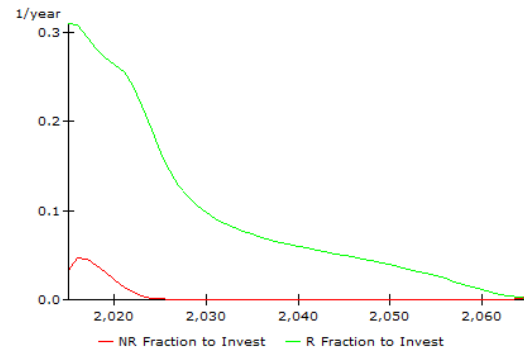


Figure 63: Fraction to Invest Policy 21 No res

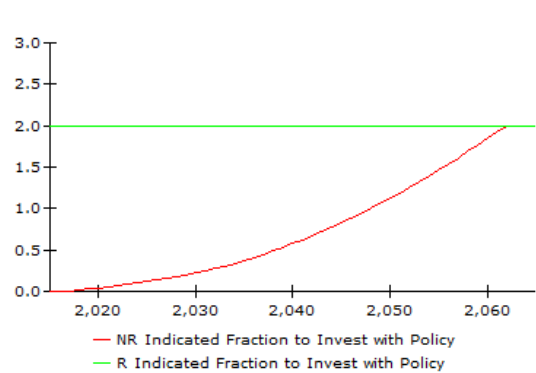


Figure 64: Indicated Fraction to Invest Policy 22

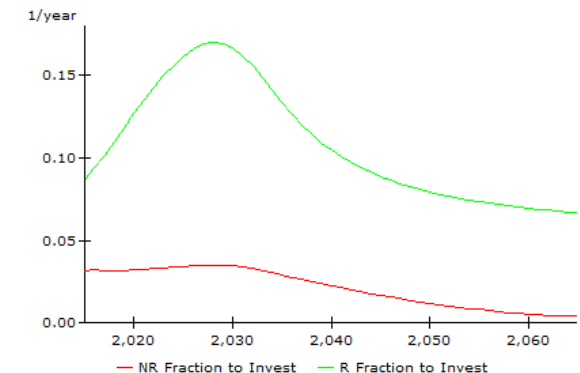


Figure 65: Fraction to Invest Policy 22

Figures 58 to 65 showcases the results of each of the policies when tested in the model. Policy 11 has the same behavior as the one shown earlier in Figures 45 and 46.

The indicated renewable fraction to invest is always at its maximum allowable level of '2' while the non renewable indicated fraction to invest always starts at zero and then increases gradually at different paces between the different polices. The only policy exhibiting a large difference in behavior is the unrestricted policy 21 in Figures 62 and 63.

The renewable fraction to invest has the same behavior across the different policies (except policy 21 unrestricted) since the indicated fraction is as well the same. The non renewable fraction to invest differ slightly in their decrease, where in Policy 12 there is still 3%

investment into non renewable at the end while in the other scenarios it is almost zero. For unrestricted policy 21, the fractions to invest exhibit a more extreme behavior. The renewable fraction to invest starts at above 30% and then decreases to zero by the end. The non renewable fraction to invest starts as usual however it quickly drops to zero by 2025.

The higher the rate of increase in the non renewable indicated fraction to invest, the higher the rate of decrease in the non renewable fraction to invest. This is because higher indicated fractions to invest with negative cash flows leads to lower final fractions to invest.

We can notice that for policies 21 and 22 where taxes are activated, the non renewable indicated fraction to invest rises more quickly leading to a bigger drop in the final fraction to invest. This is because GHG emission will render the non renewable cash flow even smaller and it will drop faster to negative values.

In the case of the unrestricted policy, the behavior is quite extreme. This is because when no realistic constraints are placed to guide the search in SOPS, the result would be simply criterion maximization at the expense of the feasibility of the policy. To maximize the criterion between 2015 and 2065, there would ideally be no investments in both sectors by the end. This is the case in the unrestricted policy.

Table 3 summarizes the SOPS criterion and renewable market share end values for the different scenarios:

Table 3: SOPS Criterion and Renewable Market Share for the different Scenarios

	SOPS Criterion	Renewable Market Share
Policy 11	0.96	0.93
Policy 12	3.02	0.92
Policy 21	0.67	0.95
Policy 21 unrestricted	0.90	0.96
Policy 22	2.64	0.95

As already discussed, the policies with the lower discount rate will generate significantly higher net society benefits, however this does not automatically translate into being better policies because it all comes back to how you judge mitigation efforts should be.

The renewable market share is very close between the different scenarios since it is independent from discount rate choices. With the introduction of non renewable GHG taxes, the renewable market will naturally increase slightly as shown in Table 3. The slight

differences in the market share are a reflection of the slight differences in the investment behavior.

There is no clear measure to assess which policy scenario is best. Policy makers will have to formulate their preferences for the characteristics, i.e. taxes, discount rates, etc..., of their desired power market before being able to discern a more desirable scenario. Also as discussed in section 5.1, a portfolio of different policies has to be applied to increase the odds of a successful transition of the power sector into a sustainable renewable one.

Most of the policies have many barriers to overcome, and it all starts with a change in the mindset of the policy makers as well as society. Typical dependence on the depletion of reliable energy stocks has proven to be myopic thinking at best. Societies instead have to switch to thinking of renewable energy flows which naturally brings with it more uncertainty in the short term yet guaranteed higher benefits on the long run.

6. LIMITATIONS

Most of the model's assumptions and limitations were gradually discussed as the explanation of the model and policies progressed. Two main ideas/limitations are still to share.

6.1 Level of Details in Investment Decision Analysis

Our model has two sectors, Non Renewable and Renewable. Each of the sectors aggregates all of the technologies that fall under its category. This is simplistic yet necessary for the thesis's purpose. Nonetheless, future work must take into consideration that portfolio diversifications, i.e. explicit modeling of different power generation technologies, allows for a more accurate valuation of the different options (Masini, 2013). By adding renewable technologies to a portfolio of non renewable ones, the risk associated with the new technologies would be lower than if assessed on their own, hence investments would be more likely. Also, by diversifying within the renewable portfolio itself, the currently more risky options that may offer the higher profits on the long term would have higher chances to survive (Masini, 2013).

6.2 Level of details in the model's feedback loops

Our model is of a long term power market, hence it only captures long term effects. This is probably simplistic since it assumes that the principle of superposition applies which in turn

assumes that the model is of a linear system. If a model is linear, then the sum of all the short term effects can be simply added up to produce a single long term effect while capturing all of the dynamics involved. For example, a range of short term effects might create a gap between supply and demand that on the long term will be reduced to almost zero. By assuming linearity, these short terms effects can be simply added up and the resulting long term behavior would be balance between supply and demand like we have it in our model. However our model is not linear, hence by doing so we have compromised some of the underlying dynamics of the system. Future work must include short-range effects in order to capture more wholesomely the long term behavior as stated by (Forrester, 1956): "Models, suitable only for long-range prediction, are often used with short-term influences and fluctuations omitted. This is justifiable only if the system is sufficiently linear to permit superposition, an assumption which has not been justified or defended and which is probable untrue. Therefore, the long-range trends are probably very much a function of the short-range behavior of a system."

7. CONCLUSIONS

This thesis has relied on the System Dynamics Methodology to build a small dynamic model of the power market. Current electricity generation technologies rely heavily on fossil fuels which are unsustainable on all three economic, social and environmental levels. Thus, the primary focus was analyzing the generation expansion planning problem and the transition of the power sector into a more sustainable one. The model shows that if current investment behavior stays unchanged, the renewable market share will steadily increase yet not fast enough to meet mitigation targets such as the 2 °C.

Near optimal investment strategies were generated by utilizing the Stochastic Optimization in Policy Space (SOPS) tool. The objective was maximizing the society's net benefits on the long term which takes into consideration both consumer and producer surplus. Optimal scenarios all have in common that most investments should be reallocated to the renewable sector, forgoing short term profits to realize even higher ones on the long run.

The model can prove useful for gaining insights into how the market behaves under certain assumptions and scenarios. Future work must take into consideration the discussed limitations of the current work, mainly by developing a disaggregated model with short term effects included.

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8. APPENDIX

8.1 Explanation of small auxiliary structures

There are no graphical functions in the model, instead small structures were added to generate the same behavior in a partly endogenous.

8.1.1 CAPACITY UTILIZATION

The capacity utilization has a structure shown in Figure 6. It basically generates an exponential like curve. The utilization is determined based on the two capacity stocks and their maximum generating capacity. As one sector's maximum generating capacity potential increases relative to the other sector, the utilization will increase following an exponential curve. The equation for capacity utilization is of the form $[a \times (b^x) + c]$:

R Capacity utilization [Unitless] = $a \times \left[\frac{R \text{ Capacity Utilization} \times (R \text{ Maximum Generating Capacity})}{(R \text{ Maximum Generating Capacity} + NR \text{ Maximum Generating Capacity})} \right]^x + c$

R Maximum Generating Capacity [Unitless] = R Generation Capacity × R Capacity Utilization when Fraction equal 1

NR Maximum Generating Capacity [Unitless] = NR Generation Capacity × NR Capacity Utilization when Fraction equal 1

R Capacity Utilization when Fraction equal 1 [Unitless] = $a \times b + c = 0.6$ (0.8 for the Non-renewable)

R Capacity Utilization when Fraction equal 0 [Unitless] = $a + c = 0.3$ (0.4 for the Non-Renewable)

a R Capacity Utilization [Unitless] = 0.1 (a R Capacity Utilization \neq 0)

b R Capacity Utilization [Unitless] = (R Capacity Utilization When Fraction equal 1 - R Capacity Utilization when Fraction equal 0) \div a R Capacity Utilization + 1

c R Capacity Utilization [Unitless] = R Capacity Utilization When Fraction equal 1 - (a R Capacity Utilization \times b R Capacity Utilization)

The fraction referred to is $X = \left(\frac{R \text{ Maximum Generating Capacity}}{R \text{ Maximum Generating Capacity} + NR \text{ Maximum Generating Capacity}} \right)$.

8.1.2 RENEWABLE PREMIUM

The structure for the renewable premium is shown in the lower half of Figure 10. It is a structural difference between the two energy sectors. It is only present in the renewable sector. It aggregates the tangible economic incentives utilized by some countries (investment subsidies, feed-in-tariff...) as well as the intangible preference of the public to rely on renewable sources.

Renewable Premium [B Dollars/TWh] = Electricity Unit Price \times Effect of Renewable MR on Premium

Where:

Effect of Renewable MR on Premium [Unitless] = $a \times b^x$

When Renewable Market share is 100%, then $X = \frac{\text{Renewable Market Share}}{\text{R Normal Market Share}} = 2$.

When it is 0%, $X = 0$.

So, when the renewable market share is 100%, Effect of Renewable MR on Premium = $a \times b^2$, and $b = \sqrt{\frac{\text{Effect of Renewable MR on Premium when MR 100\%}}{a}}$.

When the renewable market share is 0%, Effect of Renewable MR on Premium = a .

So the equation would be:

Effect of Renewable MR on Premium [Unitless] = $a \times b^x$ = Renewable Premium when MR equal 0% $\times [b^{\wedge} (\text{Renewable Market Share} \div \text{R Normal Market Share})]$

$$b = \sqrt{\text{Renewable Premium When MR equal 100\%} \div \text{Renewable Premium when MR equal 0\%}}$$

Renewable Premium when MR equal 0% [Unitless] = 1.5

R Normal Market Share [Unitless] = 0.5

Renewable Premium when MR equal 100% [Unitless] = 0.0001

The normalized market share allows for the modeler to introduce a preference about how long the premium factor should remain active. If we have a normal market share of 50%, it means when the normalized renewable market shares passes the threshold of 1 (i.e. when renewable MR > 50%), the premium will be negligible.

8.1.3 INDICATED FRACTION TO INVEST

The structure for the Indicated Fraction to Invest is shown in Figure 12. It generates a logistic growth or S-Shape curve. Its equation is:

$$\text{Renewable Indicated Fraction to Invest [Unitless]} = \frac{\text{Max}}{1 + e^{-(\text{Lambda} * X + \alpha)}}$$

X = Profitability Index = PI

So, Renewable Indicated Fraction to Invest = Renewable Max Fraction to Invest $\div [1 + e^{-(\text{Renewable Lambda} \times \text{R Price over Levelized Cost} + \text{Renewable Alpha})}]$

To derive the Lambda and Alpha, we need to set two reference points. We chose to have the points when PI = 1 and when the S-Curve will start to increase rapidly referred to as lower turning point.

$$\text{When PI} = 1, \text{ then: Renewable Indicated Fraction to Invest} = \frac{\text{Max}}{1 + e^{-(\text{Lambda} * 1 + \alpha)}}$$

$$\text{When PI} = \text{Lower Turning Point} = \frac{\text{Max}}{1 + e^{-(\text{Lambda} * \text{Lower Turning Point} + \alpha)}}$$

From these two equations we can derive Lambda and alpha:

Renewable Lambda [Unitless] = $\text{Ln} [(\text{Renewable Fraction to Invest when PI equal 1} \times (\text{Renewable Max Fraction to Invest} - \text{Renewable Fraction to Invest when PI at Lower Turning Point})) \div (\text{Renewable Fraction to Invest when PI at Lower Turning Point} \times (\text{Renewable Max Fraction to Invest} - \text{Renewable Fraction to Invest when PI at Lower Turning Point}))]$

$(\text{Renewable Max Fraction to Invest} - \text{Renewable Fraction to Invest when PI equal 1})) \div (1 - \text{Renewable Lower Turning Point Profitability Index})$

$\text{Renewable Alpha [Unitless]} = \text{Ln} [\text{Renewable Fraction to Invest when PI equal 1} \div (\text{Renewable Max Fraction to Invest} - \text{Renewable Fraction to Invest when PI equal 1})] - \text{Renewable Lambda}$

The parameters are set at:

$\text{Renewable Max Fraction to Invest [Unitless]} = 1.3$

$\text{Renewable Fraction to Invest When PI equal 1 [Unitless]} = 0.85$

$\text{Renewable Fraction to Invest when PI at Lower Turning Point [Unitless]} = 0.2$

$\text{Renewable Lower Turning Point Profitability Index [Unitless]} = 0.8$

8.1.4 FRACTION TO INVEST

This structure generates an S-Shape curve for the fraction to invest. It has the same equation as the Indicated fraction to invest. So Lambda and alpha were derived in the same way. The difference here is that X = R II to Current K Ratio.

The rationale behind this structure and X is that the indicated investment (or II) will be compared with the monetary value of the current capacity stock (or K) and the ratio of the two will be modified to generate the final fraction to invest.

$\text{R Fraction to Invest [1/Year]} = \text{R Max Fraction to Invest} / [1 + E^{\Lambda} - (\text{R Lambda} * \text{R II to Current K Ratio} + \text{R Alpha})]$

Where:

$\text{R Lambda [Unitless]} = \text{Ln} [(\text{R Fraction to Invest when Ratio equal 1} \times (\text{R Max Fraction to Invest} - \text{R Reference Fraction to Invest})) \div (\text{R Reference Fraction to Invest} \times (\text{R Max Fraction to Invest} - \text{R Fraction to Invest when Ratio equal 1}))] \div (1 - \text{R II to K Ratio of Reference Fraction to Invest})$

$\text{R Alpha [Unitless]} = \text{LN}[\text{R Fraction to Invest when Ratio equal 1} \div (\text{R Max Fraction to Invest} - \text{R Fraction to Invest when Ratio equal 1})] - \text{R Lambda}$

$\text{R Max Fraction to Invest [1/Year]} = 0.5$

$\text{R Fraction to Invest when Ratio equal 1 [1/Year]} = 0.49$

$\text{R Reference Fraction to Invest [1/Year]} = 0.04$

$\text{R II to K Ratio of Reference Fraction to Invest [Unitless]} = 0.04$

The reference fraction to invest is the point at which investment would just even out the capacity depreciation. Hence it is '0.04' since the life time is 25 years.

R II to Current K Ratio [Unitless] = Renewable Indicated Investment / (R Generation Capacity \times Renewable Capital Costs \times Time fixer)

The rationale compares a flow like variable which is the indicated investment [Billion Dollars/Year] with the monetary value [Billion Dollars] of a stock which is the generation capacity stock. Hence a constant parameter with a value of '1' was introduced, "Time fixer" [1/Year] to reconcile the units of these two to generate a unitless ratio.

The question here arises whether or not to use the "Renewable Annual Capital Costs" [Billion Dollars/TWh] instead of the "Renewable Capital Costs" [Billion Dollars/(TWh/Year)] to determine the monetary value of the stock. This would relax the need to use the "time fixer". However the concept is to compare the indicated investment which is over time with the monetary value of the already installed capacity stock which is not over time, so the "Renewable annual capital costs" do not fit and would violate the concept. Hence a parameter with a value of '1' is necessary to reconcile the units.

8.2 Parameters

8.2.1 ELECTRICITY MARKET

Market Reference Price [Billion Dollars/TWh] = 0.089 (equal to 8.9 cents/KWh)

Demand Price Elasticity [unitless] = -0.45

Long Run Electricity Demand Growth Rate [1/year] = 0.015

8.2.2 CAPACITY AND CUMULATIVE GENERATION

R Capacity Life Time [Year] = 25 (same for the non-renewable)

R Perfect Distribution [Unitless] = 1

R Grid Loss [Unitless] = 0.1

Normal Noise [Unitless] = 0

Randomness Switch [Unitless] = 0

8.2.3 TECHNOLOGY LEARNING

Non Renewable Learning Rate [Unitless] = 0.1 (0.2 for the renewable)

Initial Non Renewable Electricity Cumulative Generation [TWh] = 963600 (14892 for the R)

8.2.4 RESOURCE DEPLETION

Depletion Lower Limit [Unitless] = 0

Production Depletion Coefficient [Unitless] = 0.2

8.2.5 GENERATION COSTS

- Capital Costs:

Non Renewable Initial Capital Costs [Billion Dollars/(TWh/Year)] = 0.2 (0.4 for the R)

Yearly Interest Rate [%/Year] = 7

- Fixed Maintenance Costs:

Non Renewable Initial Fixed Maintenance Costs [Billion Dollars/TWh] = 0.004 (0.005 for renewable)

- Variable Maintenance Costs:

Non Renewable Variable maintenance Costs [Billion Dollars/TWh] = 0.004 (0.005 for the R)

- Fuel Costs (Only for Non Renewable):

Initial Fuel Costs [Billion Dollars/TWh] = 0.02

Non Renewable Initial Resource Efficiency [Unitless] = 0.4

8.3 SOPS Print screens for Different Policy Types

8.3.1 OPTIMAL LINEAR POLICY

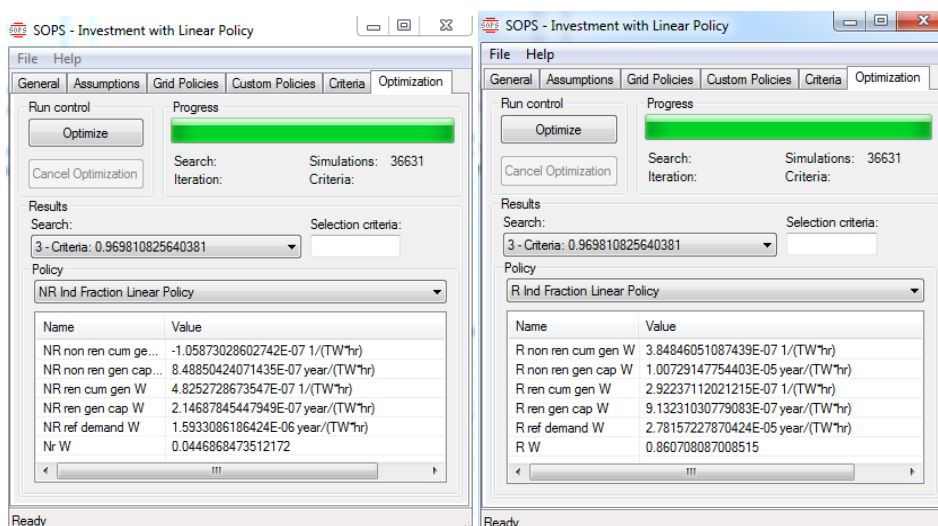


Figure 66: Optimal Linear Policy SOPS Results

8.3.2 OPTIMAL LINEAR POLICY WITH RANDOMNESS

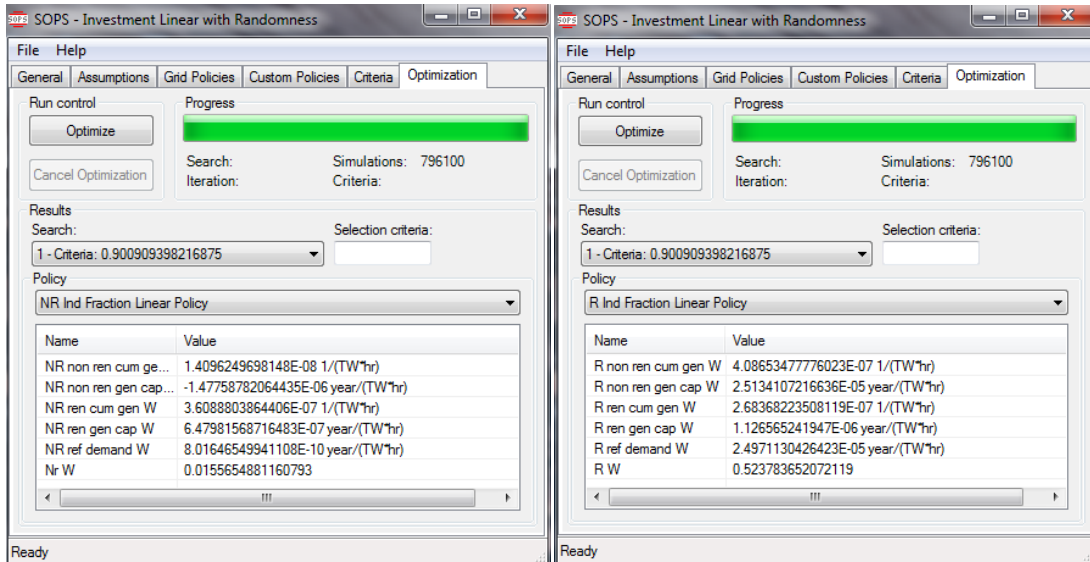


Figure 67: Optimal Linear Policy with Randomness SOPS Results

8.3.3 OPTIMAL TIME GRID POLICY

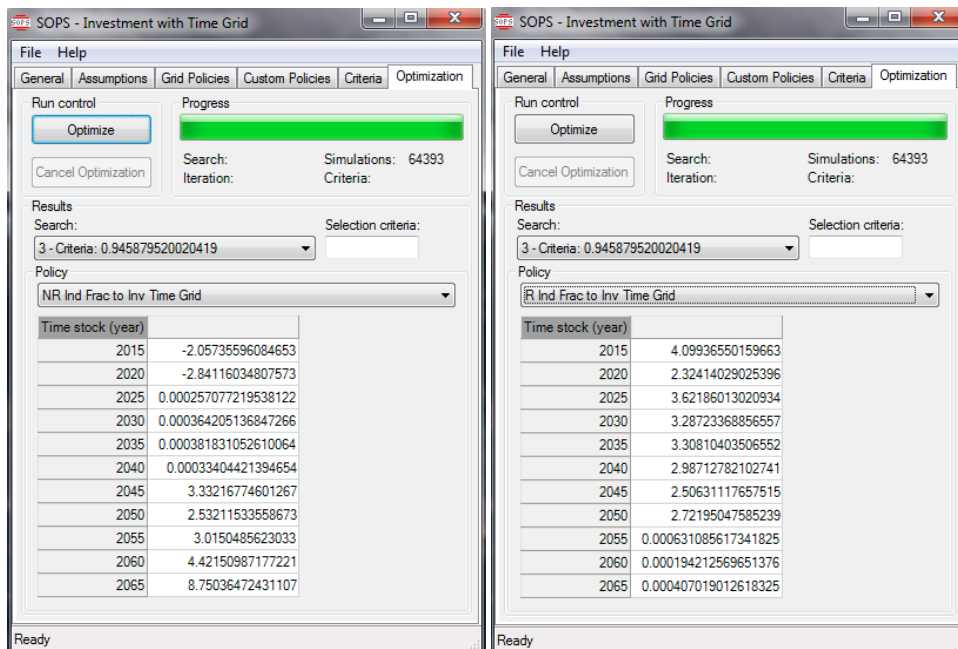


Figure 68: Optimal Time Grid Policy SOPS results

8.3.4 OPTIMAL GRID POLICY

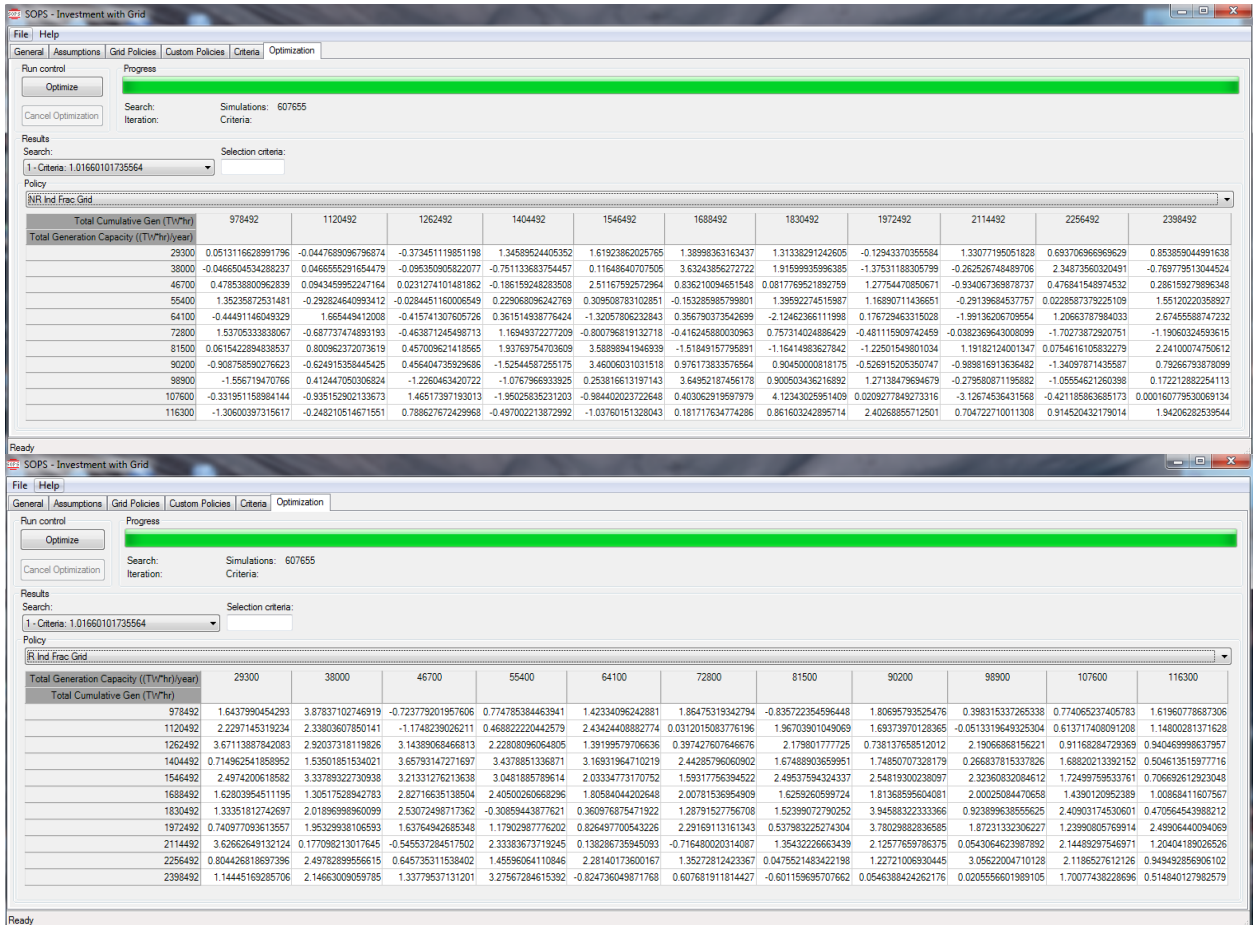


Figure 69: Optimal Grid Policy SOPS results