Aalto University
School of Science
Degree programme in Engineering Physics and Mathematics

The effects of CO_2 taxes in renewable energy production share using a capacity expansion model

Bachelor's Thesis
31st August 2020

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Abstract of bachelor's thesis

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Title of thesis The effects of CO2 taxes in renewable energy production share using a capacity expansion model	
Degree programme Engineering physics and mathematics	
Major Mathematics and systems analysis	**Code of major** SCI3029.A
Supervisor Fabricio Oliveira	
Thesis advisor(s) Lucas Condeixa	
Date 31.8.2020	**Number of pages** 8+51 **Language** English

Abstract

The aim of the study is to investigate and discuss the impacts of taxes laid on fossils-based energy production emitting for example carbon dioxide. The future of energy production currently faces an undergoing change towards greener ways of producing electricity. Greener energy generally originates from renewable sources, which are generally less predictable than traditional methods. This causes challenges in adopting such technologies into use. Meanwhile, the demand for electricity is believed to be rising which causes even more challenges for meeting the demand.

This study uses a generation capacity expansion model to simulate the complex situation. A rise of carbon taxes is modelled in four ways, following techniques based on another study. The model consists of eight technologies and six countries which are all based on reality by their parameters.

The results of the analysis show how increasing the carbon tax level also increases the share of renewable technologies used in the energy production. However, the results show a very slight decrease in fossils, which is most likely caused by the data used in the model. The model simulates a situation, where investing in new technologies is not economically worthwhile since the existing capacity is enough to meet the desired demand.

However, the main finding of the study is the phenomenon of passing fossils production to cheaper countries. This is seen in the model when the carbon tax level in, for example Finland, rises a lot compared to the level in Estonia. The production of emitting technologies is then not decommissioned in such low-cost countries. This is also discussed by a Finnish study and should therefore be taken into account when decarbonizing countries with fossils-dependent neighbors.

All in all, the study highlights the importance of good planning and detailed modelling. To make the future less fossils dependent, a lot has to be done, but getting there requires good and well analyzed decisions.

Keywords Operations research, decision analysis, optimization, mathematical modelling, energy systems, the dynamics of emission taxation

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Tekniikan kandidaatintyön tiivistelmä

Tekijä Tuukka Mattlar			
Työn nimi The effects of CO2 taxes in renewable energy production share using a capacity expansion model			
Koulutusohjelma TFM			
Pääaine Matematiikka ja systeemitieteet		**Pääaineen koodi** SCI3029.A	
Vastuuopettaja Fabricio Oliveira			
Työn ohjaaja(t) Lucas Condeixa			
Päivämäärä 31.8.2020	**Sivumäärä** 8+51	**Kieli** Englanti	

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Tekniikan kandidaatintyön tiivistelmä

Tiivistelmä

Työn tavoite on tarkastella hiiliverotuksen vaikutuksia energiantuotannon kustannuksiin sekä jakautumiseen eri tuotantotapojen välille. Maailman energiantuotannon tulevaisuutta muovaa nyt ja tulevaisuudessa kasvava tarve puhtaammalle energialle, sillä energiantuotanto on yksi suurimmista ilmastonmuutosta sekä ympäristön saastumista aiheuttavista tekijöistä. Pelkkä uusiutuvien energiantiotantomuotojen kapasiteetin lisääminen ei kuitenkaan ratkaise ongelmia, sillä niiden epävarmalla ja epäjatkuvalla tuotannolla ei vielä nykyään pystytä suoraan vastaamaan jatkuvaan kysyntään. Jotta tilanteesta saadaan parempi käsitys, voidaan energiantuotantoa mallintaa esimerkiksi tuotannonlaajennusmallilla. Tuotannonlaajennusmalli on yleiskäsite tuotannon kapasiteetin optimaalisen laajentamisen mallintamiselle. Tällaista mallinnusta voidaan hyödyntää päätöksenteossa, jotta päätöksen seurauksista saadaan realistisempi yleiskuva.

Tässä työssä käytettävä tuotannonlaajennusmalli sisältää kuusi olemassa olevaa valtiota, joiden energiantuotannon kapasiteettia, kysyntää sekä joiden välistä kauppaa mallinnetaan käyttäen kahdeksaa erilaista energiantuotantomenetelmää. Valtiot on valikoitu siten, että ne edustavat eurooppalaista kokonaisuutta mahdollisimman hyvin eli mukana on sekä vahvasti hiilituotantoon nojaavia että uusiutuviin energiantuotantomenetelmiin siirtyneitä valtioita. Tuotantoteknologioiden ominaisuudet sekä kysyntä on mallinnettu perustuen näiden valtioiden oikeaan historiadataan vuodelta 2018.

Hiiliverojen vaikutuksia analysoidaan neljällä erilaisella tavalla, joilla hiiliverotusta voitaisiin käytännössä muokata. Tähän kuuluu nykyisten arvojen yhteinäinen kasvattaminen sekä lisäämällä että kertomalla niitä kasvavalla arvolla. Lisäksi simuloidaan tilanteita, joissa hiiliverotus valtioiden välillä olisi yhtenäinen ja hiiliverotuksella olisi minimiarvo.

Analyysin tulokset osoittavat, että hiiliveron kasvattaminen nostaa uusiutuvien tuotantomenetelmien käyttöä. Mallin osoittamat energiantuotannon muutokset olivat hyvin pieniä, mikä johtuu mitä luultavimmin liian suuresta lähtökapasiteetista, jota mallissa käytettiin. Mallin käyttämää kapasiteettidataa on säädetty maiden tiedostettujen alasajosuunnitelmien mukaiseksi, mutta mallin kapasiteetti riittää kuitenkin tarvittavaan tuotantoon, eikä lisäinvestointeja tehdä juuri ollenkaan. Jos malli ei pohjautuisi vallitsevaan tilanteeseen, vaan esimerkiksi täysin puhtaalle pohjalle, olisivat muutokset energiantuotannossa mitä luultavimmin suurempia.

Erityisen huomioitavaa on kuitenkin se, että tapauksissa, joissa hiiliverot ovat hyvin eri tasoilla valtioiden välillä, siirtyy hiilipohjainen tuotanto kalliin hiiliveron maista matalan hiiliveron maihin. Tällöin hiilivalmisteita sähköä vain siirretään takaisin korkean hiiliveron maihin, joissa kokonaistuotanto on saattanut laskea verotuksen vaikutuksesta. Vastaavasta ilmiöstä on tehty jo aiemmin tutkimusta ja se osoittaa energiantuotannon mallinnuksen tärkeyden kestävän päätöksenteon tukena.

Avainsanat Operaatiotutkimus, päätöksenteon tukeminen, optimointi, energiajärjestelmät, hiiliverotuksen dynamiikka.

Preface

The work aiming at this thesis started in year 2019 when I worked at the Systems analysis laboratory. During the summer I got to learn a lot about such phenomena and modeling.

I want to thank Lucas Condeixa and Fabricio Oliveira for guiding me through this thesis. I also want to thank Taru Bister for all support in everything related to studies and organizing my Master's studies plans at TU Munich.

For support, I want to thank Jussi Hakosalo and Katri Niemi, friends of mine who both helped me concentrate and dig deeper in the work.

31st August 2020, Espoo, Finland

Tuukka Mattlar

Contents

Symbols and abbreviations

Main abbreviations

PV - Solar power

GCEM - Generation capacity expansion model

RES - Renewable energy source

RESS - Renewable energy source share

CT - Carbon tax

Scenarios in the modeling

UM - Uniform value multiply, ie. having uniform and increasing CT level for all countries

DM - Data value multiply, ie. multiplying the current values by an uniformly increasing constant

MM - Mixed multiply with a minimum CT level

UA - Uniform adding of an increasing constant

1 Introduction

As climate change awareness has risen, the deployment and development of low-emitting renewable energy sources (RES) has become more vital. Electricity demand needs to be constantly met by the supply side, which has earlier been fairly simple due to the nature of energy resources and simplicity of grids. In Finland, nuclear, coal and combined heat and power (CHP) plants used to fulfill the base load whereas gas, coal plants and RES fulfilled demand peaks. [1]

However, the nature of most RES is uncontrollable and uncertain which results in major issues in adopting RES for fulfilling the base and peak load demand. For example, the demand of energy on a winter morning in Finland peaks and without sunlight, wind nor sufficient run of rivers, meeting the demand requires either large energy storage, import of electricity or new ideas on making such systems work [1] .

Including RES in energy production is a complex system that needs to be modelled and acknowledged in order to make sustainable decisions for RES deployment and cutting emissions. Unfortunately, the actions of directly increasing either RES share (RESS) via quotas or carbon taxes (CT) levels without a thorough analysis can result in even more emissions or at least deporting the coal production to countries with lower CT levels and possibly less efficient plants in terms of emissions and production [5]. Therefore detailed scenario modelling is required for making better and more sustainable decisions.

In 2009, the European Union (EU) announced the objective of reducing the national members emissions on the level of 80-95% by 2050 when compared to the emissions level in 1990. This policy aims at keeping the global warming below 2 °C. In 2015 the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement was declared by 196 nations. Its ultimate goal is to limit global warming to 1.5 °C.[4]. To meet these emission caps nationally, nation-wide emission-control policies are being launched, especially throughout Europe. Such national policies usually involve CT or subsidies for RES.

There are four main types of models used in supporting such decisions. On a high level, these models can concentrate on optimizing the entire or a major part of the energy system for providing potential scenarios. The models can also aim at simulating the entire energy system for providing forecasts or rather qualitative methods for building scenarios. [2]

In this study we concentrate on modeling a multi-nation energy system but keep the main focus on the results in Finland, Estonia and Sweden. We use the model to investigate the effects of CO2 emissions taxes in the whole system. The model, which is a generation capacity expansion model, has a relatively realistic view to current situation since the non-renewable production is cut by 30% and the planned decommission of nuclear in Sweden and Germany are taken into account.

2 Literature Review

2.1 The background and history of energy modeling

In their study, Energy systems modeling for twenty-first century energy challenges, Pfenninfer et al [2] discuss various energy systems models and the challenges these models meet. They argue that the foundations of today's energy policies date back to the oil crisis in the 70s. The oil crisis laid the demand for long-term strategic planning of energy production since energy resources were no longer seen self-evident. The fear of running out of resources then laid the demand for representing energy production in a quantitative way. This representation involved modeling energy systems with the methods of linear programming which had already been used for similar purposes during the second world war. [2]

After an energy awakening caused by the oil crisis in the 70's, plenty of agencies and international councils were launched. Two of these are the Applied Systems Analysis Program (IIASA) and Energy Technology Systems Analysis Program (ETSAP) whose energy models are still relevant in today's planning. [2]

2.2 The models today and in the future

Energy models, in general, were initially designed to investigate the reliability of electricity production and its costs. Later they have been extended to help finding answers to questions regarding adopting new technologies in production. Since the whole field of energy systems analysis, including, for example, transportation and heating, is rather challenging to describe with simple quantitative methods. The models, generally, concentrate on dealing with electricity production related fields. Now and in the future, the system will get even more challenging. The way of separating transportation and electricity production will not remain the same since deployment of electric cars and likely more electricity-dependent transportation in general will also result in less direct transportation emissions but increasing electricity demand. [2]

In terms of climate change, the electricity generation plays a critical role in green house emissions and local air pollutants. Since climate change fundamentally impacts energy generation and vice versa, the policies currently developed try to control the fossil fuels consumption either via limitations or added costs in electricity production. [2]

According to Pfenninfer et al [2], the modern day energy systems modeling faces challenges with the questions related to:

1. Fluctuating and unpredictable energy production methods
2. Flexible demand by new technologies
3. Rising and geographically extending demand for electricity
4. The paradigm of distribution of renewable resource potential requiring higher spatial detail.

Generally, the existing studies and models suggest a wide range of opposite scenarios. Some claim that highly RES-based systems may be feasible both in meeting the demand, as in stability, and providing sufficiently low costs. Some, on the other hand, claim that such results may end up being economically unfeasible. According to Pfenninfer et al [2] these models generally lack in spatial and temporal resolution that result in insufficient reliability and insufficient features for making analysis on the argued feasibility of economic enough supply provided by RES. For our analysis this means that the results should likely be considered only referential, not as a detailed future scenario one could fully rely on in great detail. [2]

2.3 Different types of energy models

Pfenningfer et al define an energy system as "the process chain from the extraction of primary energy to the use of final energy to supply services and goods". Mark Jaccard, a sustainable energy professor at REM British Columbia, defines it similarly as "Combined processes of acquiring and using energy in a given society or economy" in his book Sustainable Fossil Fuels. [2]

Following the definitions, the models may involve technical, environmental and social elements. Most models concentrate on technical and environmental aspects. The results can then be used to analyze the more qualitative party, which generally is the environment and sociological impacts.[2]

The scope and focus of the studies varies as well. Some concentrate on modeling more local systems such as energy production and large industry factories or urban environments whereas some concentrate on more specific topics such as energy market modeling or the integration of RES in existing models.[2]

For more wide scope the studies can, according to Pfenninger et al [2], be grouped in four groups that seek answers to four paradigms. The way they group the studies is as following:

1. Energy systems optimization models that aim at providing scenarios for future evolution
2. Energy systems simulation models that aim at providing forecasts for possible future evolution
3. Power systems and electricity market models that have similar aims to the previous but with more specific goals
4. Qualitative and mixed-methods scenarios that have a less mathematical approach to modeling the systems

The different types of models are used in different situations but for better results all studies should also be considered following quantitative analysis on the results obtained.

2.4 Limiting the emissions

Energy generation today is highly dependent on fossil fuels. Moreover, the increasing demand for electricity, especially in developing countries, and the recent decreases of nuclear after the Fukushima accident in 2011 have lead to even increased deploying of combustion based generation [7, 11]. This topic became, again, a remarkable discussion in the beginning of 2020 when the Fortum owned Uniper launched its new coal-based plant in Datteln, Germany. Fortum argues that new more effective combustion plants are required today in order to ensure a safe and steady transfer process to RES-based production. They also claim to be on the way towards emission-free energy production [24, 25]. According to Greenpeace, these claims are not eligible since the German economy and technology commission has already declared that transferring to RES does not endanger the reliable availability of energy [26]. The topic has a wide range of arguments to both directions but generally, the question is about if the current technologies allow higher renewable energy sources production share (RESS) deployment or it's dependent on political aspects involving non-renewable producers. This question discusses the technological feasibility together with the tense politics involved.

For the economic feasibility, the discussion is about making RES more attractive for investors and users. The low rate of return, generally meaning the profit of investing, in RES investments is currently not attractive to investors which has challenged the financing of RES development and deployment. Changing coal, which is a relatively cheap and stable resource, to more uncertain and financially less attractive RES without considering the effects of emissions does likely not result in a cost effective system. After considering the emissions and their both direct and indirect costs in the future, the system becomes a complex problem. [6] [7] [8] [10] [11]

In terms of actual emissions caused by energy production, the main concern today is the carbon dioxide (CO2) emissions but combustion powered generation also produces for example sulfur dioxide (SO_2) and nitric oxide (NO_x). Thus, most policies aim at limiting CO2 emissions by either direct or indirect methods. Consequently, this is quite directly linked to replacing combustion based production with RES or other non-polluting resource. [7] [8] [10]

Policies limiting and taxing the combustion generation have been set to efficiently limit carbon emissions. The most widely used ones today are the Cap-and-trade (C&T) and Carbon Tax (CT). Subsidies and tax allowances have also been introduced to make RES more attractive to investors [9] [7] [10]. Therefore CT seems like an interesting and important policy to concentrate more on.

2.5 Carbon tax and Cap-and-trade

CT is widely adopted in Europe and partially in the USA, Canada, China and Oceania. Other than that, it's generally quire rarely adopted in today's world. However, it is under consideration for example in all Canada, China and Brazil. The implementations vary highly from cap-and-trade like systems to national CT [15]

Cap-and-Trade relies on rather setting quotas and trading systems than putting a cost on the emissions directly. The basic idea is to have certain caps that the country or industry in a country cannot exceed. In case of exceeding the set caps, trade can be made to transfer emission capacity from low-emitting country or industry. A remarkable example of such is the EU emissions trading system (EU ETS), which has been evolving since 2005 in steps. [13]

Generally CTs are seen as a way of setting price for carbon emissions. The idea is to generally lay taxation on more emitting countries or companies in order to support low emitting instances and drive other instances in a low-emitting direction [16]. The same idea is found in cap-and-trade with the exception that, in this policy, trading the emission caps allows for financial benefits for less emitting countries whereas the emitting countries get to pay the environmental harm on others caused by them.

In their study comparing Cap-and-trade and CT, He et al [7] model and analyse the difference of such limiters. They introduce four different emission taxation methods: uniform tax, nodal uniform tax, nonuniform tax and nonuniform tax with subsidies. The study dates back to 2011 so not everything regarding to policies is compatible to today's political environment but the main findings are interesting. They found out that there is no clearly best solution but the most effective way of limiting emissions was a uniform tax, which is same for all countries. However, the economic welfare of this model was predicted low, whereas Cap-and-Trade and nonuniform taxes and subsidies both resulted in high economic welfare and medium emission limitation. [7]

Quiroga et al [9] discuss expansion models under both global and local CT from the Chilean point of view. They point that too high CT can, via the decrease of economic growth, cause situations where investing in RES is not anymore possible. Their model's results show that increase of coal taxes results in greater share of RES and natural gas but local pollutant tax increases also result in decreasing solar investments. [9]

Farsaei et al [5] discuss the impact of Finnish national carbon cap climate policy on the total emissions nearby. The case states a couple new limitations of taxes and policies aiming at total decarbonizing. In Finland's case, removing CHP, which itself is an effective way of producing both electricity and heat, results in a lack of district heat production which would then have to be replaced by less-efficient generation technologies. Also, the surrounding coal-dependent countries, like Estonia, would in this case result emitting more while Finland's capacity to export stable energy decreases when switching to 100% RES [5].

All in all, the lesson inferred from the papers revised is that the system is complex. In some cases, CT is considered the best way of cutting down carbon emissions, on the other hand, according to Tom Tietenberg [12], a well-designed cap-and-trade system has more advantages [15].

3 The Scope of the study

3.1 The selected aim

Energy generation emission reduction is a complex field highly relevant for making future RES deployment plans both financially and environmentally feasible. This study will concentrate on the economy of CTs. The main focus of this study, is to analyze the effect of altering the level of CTs and the production and investment decisions caused by this. Building and implementing a mathematical model, provides good base for attaching qualitative aspects to obtain real-world foresight of different cases. However, as stated by Pfenninger et al [2], the models should be spatially large and up-to-date enough to provide at least some reliable results.

To obtain better understanding, the model is ran with a 30% decrease in combustion production capacity in each country. The aim here is to simulate a future in which deactivating such production has taken place. The nuclear capacity of Sweden and Germany is also decreased since these countries are planning to decommission and are actively deactivating nuclear production [1].

Following the methods stated by Pfenninger et al [2], the focus of this study is on energy systems optimization. This means that the model primarily aims at providing predictive scenarios based on an optimization model. The purpose of such results, in general, is to provide quantitative analysis that aims at giving ground for qualitative analysis and planning.

To make the model realistic, real data is assessed. We select 6 countries with different energy portfolios and geographic locations thus giving a good overview of the possible diversity found across Europe. The data is gathered from ENTSO-E [27] and Renewables ninja [28], which both offer a data portal of energy and RES related topics.

The reason for not including the whole Europe is the computational feasibility that could end up being a major problem in running the model. By using only 6 countries, the results end up being more approximate but this is tried to be minimized by the diversity of the countries.

The model is to be ran over the span of the year 2018 in a hourly resolution. Different seasons result in different demand profiles and RES availability since, for example, solar and wind power are highly dependent on external weather conditions.

Even though we include 6 countries in the model, for the sake of the discussion, we only concentrate on the results of Finland, Estonia and Sweden. The remaining countries, however, are still important for the dynamics of the system.

3.2 Generation and transmission modeling

The selected technologies in the model are the following.

1. Nuclear energy
2. Coal, general
3. Biomass and other combustion fuels
4. Biogas and gas
5. Wind power
6. Solar PV
7. Hydro power, run of river
8. Hydro power, reservoir
9. Battery storage

The technologies involved in the study have more weight on RES which results in modeling for example hydro power in the two main ways while for example combining combustion fuels in just a few main categories. The approximation is based on the features and carbon emission rates of these resources.

Also, the wind power modeling is simplified compared to the reality. In this model, the onshore and offshore production are approximated as just one type of wind power even though these types are separated in the data used.

Storage is also involved, since it has been used in the similar models and it can provide the required balancing between peaking demand and production. It is also to be deployed in many countries with the pioneering capacity already existing. [1]

The model does not cover the possible environmental consequences caused by hydro reservoirs of limited flow, which in real world can cause methane emissions or other kind of environmental damage [18]. Only the additional capacity of hydro power is limited, for example in Finland, since the availability also takes the political aspects into account.

Together with the already defined technologies, the model also involves transmission between the selected countries. Transmission is included to simulate the real-life dynamics of energy production and demand. Transmission doesn't take the real-world pricing system and bidding into account but it is rather a simplified model that makes it possible to transmit energy with a constant price. Transmission losses are not taken into account in this model. [21]

3.3 The selected countries

The selected countries are all from Europe since there are portals offering data of all European countries with an easy access. Also, the European policies would be relatively likely set and adjusted together in real world as well. On top of that, Europe represents a wide mix of different energy production profiles and the countries are still located relatively close to each other for more realistic transmission possibilities.

In more detail, the Nordics are among the first in the world to have a well built own electricity market. This has led to the situation where the Nordics represent already a very low-carbon energy production. An interesting aspect is that the Baltic countries nearby, represent the total opposite where Estonia has the largest dependency on fossil fuels in the whole EU. [2] [5]

Most European countries and their energy profile is represented in the graph 1 below.

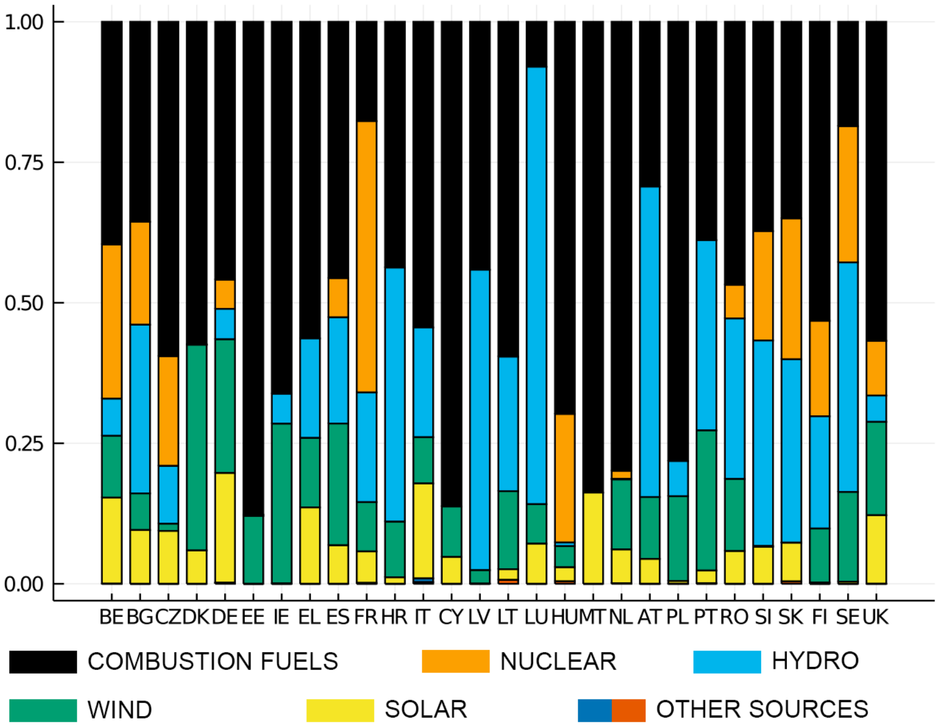

Figure 1: Electricity generation shares in European countries

To select interesting countries, we consider their existing share of RES and potential availability of renewable energy sources. Also, the current plans of decommissioning production capacity and their geographical location for transmission and natural resources are taken into account.

Thus, we decided to include Finland, Sweden, Estonia, Germany, Spain and Poland in this study. These countries represent a good overview of the whole Europe. With these countries, we simulate the situation in Finland, Sweden and Estonia which we will be concentrating on.

Finland has partially limited resources of RES where the RES mostly relies on hydro power [19]. Hydro power in general, is a political issue which is caused by its environmental and economical damage to for example small fishing businesses. The political settings around hydro power in Finland are causing the expansion of hydro unlike in Finland [20]. Wind and especially solar power are even more seasonal than in other countries due to the geographical location and dark winter in the North. The country, however, is willing to thrive towards carbon-free production.

Estonia, as said before, has the greatest dependency on fossil fuels of the whole EU. Most of the electricity in Estonia comes from one large oil shale plan. Estonia has the possibility for larger RES deployment but the current CT level is very low that likely makes deploying RES economically unfeasible at the moment.

Sweden has great availability of hydro power but also relatively good wind power possibilities. Sweden has aimed to depreciate nuclear production while still decreasing the share of fossil fuels production. This is taken into account in the modeling. [1]

Germany lately decided to start decommissioning its nuclear capacity. This resulted in growing fossil fuels production but the country is aiming to increase their already great share of wind power. Germany also has plenty of solar capacity and potential for even more production on this. The decommission of nuclear is taken into account in the modeling. The CT in Germany is currently being taken into use with a relatively low value but it is to be increased twice during 2021-2025. [14]

Spain is geographically privileged in terms of solar potential. Other than that it also has a good access to wind and hydro power. The main reason for including Spain in the model is the large size and existing energy production profile which differs from the energy production profiles of the other countries selected.

4 Methodology

4.1 Notation in the model

Basic Indices and Sets

Table 1: Basic sets and indices of the model.

Index or Set name	Type	Description
T	Set	Set of Production technologies
S	Set	Set of storage
H	Set	Set of hours
R	Set	Set of regions
T^{co2}	Set	Subset of Technologies emitting carbon emissions
T^{nh}	Set	Subset of Technologies without storage hydro
t	Index	Technology $\in T$
h	Index	Time index $\in H$
r	Index	Region index $\in R$
x	Index	Transport index $\in R$

Parameters

Table 2: Parameters of the model introduced.

Parameter	Type	Unit	Description
b_s^{+max}	Set	MW	Maximum charge during one hour
b_s^{-max}	Set	MW	Maximum discharge during one hour
b^{eff}	Double		Battery loss of charge in an hour
$c_{t,r}^{iniT}$	Set	MW	Initial capacity of $t \in T$ in $r \in R$
$c_{s,r}^{iniS}$	Set	MW	Initial capacity of $s \in S$ in $r \in R$
C^{invX}	Set	€/ km	Investment cost of a transmission line
C_t^{var}	Set	€/ MW	Variable cost of $t \in T$
C_t^{fix}	Set	€/ MW	Fixed cost of $t \in T$
C_t^{invT}	Set	€/ MW	Investment cost of $t \in T$
C_s^{invS}	Set	€/ MW	Investment cost of $s \in S$
C^x	Set	€/ MW	Variable cost of transfer
$c_{h,t,r}^{fac}$	Set		Generation factor
h_r^{minRes}	Set		Minimum hydro reservoir level in $r \in R$
h_r^{maxRes}	Set		Maximum hydro reservoir level in $r \in R$
$h_r^{maxOverall}$	Set		Maximum Overall hydro reservoir level in $r \in R$
h_r^{minEF}	Set		minimum hydro reservoir outflow in $r \in R$
x_{r_1,r_2}^{ini}	Double	MW	Initial transfer capacity between r_1 and r_2
x_{r_1,r_2}^{maxCap}	Double	MW	Maximum feasible trans capacity between r_1 and r_2
ξ_t	List	kg/MWh	Production CO2-emission factor for $t \in T^{co2}$
τ_r	Double	€/ton	Carbon tax in $r \in R$
η_t	Double		efficiency of $t \in T$
L^t	Double	years	estimated life time of $t \in T$
L_{r_1,r_2}^t	Double	km	Distance between r_1 and r_2
L^s	Double	years	estimated life time of $s \in S$
f	Double	€/ MW	Cost of ramping in nuclear

Decision variables

Table 3: Variables of the model introduced.

Parameter	Type	Unit	Description
$b^{+}_{s,h,r} \geq 0$	Double	MW	Charge
$b^{-}_{s,h,r} \geq 0$	Double	MW	Discharge
$c^{addT}_{t,r} \geq 0$	Set	MW	Additional capacity of $t \in T$ in $r \in R$
$c^{addS}_{s,r} \geq 0$	Set	MW	Additional capacity of $s \in S$ in $r \in R$
$p_{t,h,r} \geq 0$	Set	MW	Production of $t \in T$ in $r \in R$ at $h \in H$
$s^{level}_{s,h,r} \geq 0$	Double	MW	Storage level at $h \in H$
$h^{resLevel}_{h,r} \geq 0$	Double	MW	Hydro reservoir level in $r \in R$ at $h \in H$
$h^{inFlow}_{h,r} \geq 0$	Double	MW	Hydro reservoir inflow in $r \in R$ at $h \in H$
$h^{outFlow}_{h,r} \geq 0$	Double	MW	Hydro reservoir outflow in $r \in R$ at $h \in H$
$h^{outBypass}_{h,r} \geq 0$	Double	MW	Hydro reservoir outflow bypass in $r \in R$ at $h \in H$
$x_{h,r_1,r_2} \geq 0$	Double	MW	Transfer between r_1 and r_2 at $h \in H$
$x^{add}_{r_1,r_2} \geq 0$	Double	MW	Transfer between r_1 and r_2

4.2 The objective function

The objective function is fairly similar to the one used in REX [1]. It minimizes all direct costs caused by energy production. This does not involve any social costs or costs caused by any environmental damage. The objective function is therefore formed of the sum of fixed and varying costs of production (1), investment costs of production (2), storage (3) and transmission (5) as well as cost of CO2 emissions (4). It also includes costs of transmission (6). Transmission costs are partly artificial since they are mainly set to prevent irrelevant transmission back and forth between two countries at the same time. Therefore the level set for transmission is actually insignificant compared to other costs.

The variable and fixed costs are linear approximations based on €/MWh or €/MW, respectively. The units in this case do not make a difference since the time resolution is hourly. The objective function is thus represented below:

$$\min\Bigg(\sum_{h=1}^{H}\sum_{t=1}^{T}\sum_{r=1}^{R}\Bigg(\frac{C_t^{var}\cdot p_{t,h,r}}{\eta_t} + \frac{C_t^{fix}\cdot (c_{t,r}^{iniT} + c_{t,r}^{addT})}{\eta_t}\Bigg) \tag{1}$$

$$+\sum_{t=1}^{T}\sum_{r=1}^{R}\frac{C_t^{invT}\cdot c_{t,r}^{addT}}{L^t} \tag{2}$$

$$+\sum_{s=1}^{S}\sum_{r=1}^{R}\frac{C_s^{invS}\cdot c_{s,r}^{addS}}{L^s} \tag{3}$$

$$+\sum_{h=1}^{H}\sum_{t=1}^{T^c}\sum_{r=1}^{R}\frac{p_{h,t,r}\cdot \tau_r \cdot \xi_t}{\eta_t} \tag{4}$$

$$+\sum_{r_1=1}^{R}\sum_{r_2=1}^{R} x_{r_1,r_2}^{add}\cdot C^{invX}\cdot L_{r_1,r_2}^{t} \tag{5}$$

$$+\sum_{h=1}^{H}\sum_{r_1=1}^{R}\sum_{r_2=1}^{R} C^{x}\cdot x_{h,r_1,r_2}\Bigg) \tag{6}$$

4.3 Conditions and data

4.3.1 Production

The production of all technologies $p_{h,t,r}$, apart from hydro reservoir, can be limited by the product of the capacity factor $c_{h,t,r}^{fac}$ and the sum of initial and additional capacity $c_{t,r}^{iniT} + c_{t,r}^{addT}$. For most production methods, the capacity factor is equal to 1 but for solar PV and wind power, the value varies over time and region accordingly to the natural resources availability.

$$p_{h,t,r} \leq c_{h,t,r}^{fac}\cdot (c_{t,r}^{iniT} + c_{t,r}^{addT}), \forall : h \in H, t \in T^{nh}, r \in R \tag{7}$$

Run of river (RoR) Hydro is modeled similarly here by using a factor to tell the RoR availability compared to maximum capacity. Hydro reservoir is modelled with more specific limitations introduced in 4.3.5.

Additional capacity is limited by the possible maximum availability of each resource. In real world, the limit can be caused by policies or lack of resources.

$$c_{t,r}^{addT} \leq c_{t,r}^{maxT}, \forall : t \in T^{nh}, r \in R \tag{8}$$

4.3.2 Demand

The existing demand has to be met at each time step. The equation also drives the functionality of storage and electricity transmission between the regions.

$$\begin{aligned}\textstyle\sum_{t=1}^{T}(p_{h,t,r}) + \sum_{s=1}^{S}(b^{-}_{s,h,r} - b^{+}_{s,h,r}) + \sum_{r_{from}=1}^{R}(x_{h,r,r_{from}}) \\ + \textstyle\sum_{r_{to}=1}^{R}(x_{h,r_{to},r}) = D_{h,r}, \forall : h \in H, s \in S\end{aligned} \tag{9}$$

4.3.3 Storage

Storage is limited by several factors. The main idea is to model a battery but the model also limits the inflow and outflow of it. The battery technology has a slight loss marked as the b^{eff} which approximately describes the real-world situation of losing charge.

$$s^{level}_{s,h,r} - s^{level}_{h,h-1,r} = b^{+}_{s,h-1,r} - b^{-}_{s,h-1,r} \cdot b^{eff}, \qquad \forall s \in S, h \in H \setminus 1, r \in R \tag{10}$$

$$s^{level}_{s,h,r} \leq c^{iniS}_{s,r} + c^{addS}_{s,r}, \qquad \forall s \in S, h \in H, r \in R \tag{11}$$

$$b^{+}_{s,h,r} \leq b^{+max}_{s}, \qquad \forall s \in S, h \in H, r \in R \tag{12}$$

$$b^{-}_{s,h,r} \leq b^{-max}_{s}, \qquad \forall s \in S, h \in H, r \in R \tag{13}$$

$$c^{addS}_{s,r} \leq c^{maxC}_{s,r}, \qquad \forall s \in S, r \in R \tag{14}$$

4.3.4 Transmission

Transmission capacity simply enlarges the possibility of transferring electricity between countries. The usage of transmission is defined in the demand condition (9).

$$x^{add}_{r,r} = 0, \qquad \forall r \in R \tag{15}$$

$$x_{h,r_1,r_2} \leq x^{ini}_{r_1,r_2} + x^{add}_{r_1,r_2} \leq x^{maxCap}_{r_1,r_2}, \qquad \forall s \in S, h \in H, r_1, r_2 \in R \tag{16}$$

4.3.5 Hydro power

Hydro power is modelled in a two separate ways since there are generally two types of hydro available, one which is a reservoir and other is with just pure dependency on the RoR. The reservoir hydro power is modeled with a limited capacity of the reservoir and including a bypassing flow to prevent the possible overflow of reservoir. In addition, there can be limitations of the lowest possible outflow or reservoir level [1]. RoR is modelled as the other energy sources. The model doesn't involve the possibility of adjusting the river flows for better control of production even though the run of rivers is controlled on a certain level in real life. [17]

$$
\begin{aligned}
h_r^{minRes} &\leq h_{h,r}^{resLevel}, && \forall h \in H, r \in R && (17)\\
h_r^{maxRes} &\geq h_{h,r}^{resLevel}, && \forall h \in H, r \in R && (18)\\
h_{h+1,r}^{resLevel} &= h_{h,r}^{resLevel} + h_{h,r}^{inFlow} - h_{h,r}^{outFlow}, && \forall h \in H \setminus 1, r \in R && (19)\\
h_{h,r}^{outBypass} + p_{h,8,r} &= h_{h,r}^{outFlow}, && \forall h \in H, r \in R && (20)\\
h_{h,r}^{outFlow} &\geq h_r^{minEF}, && \forall h \in H, r \in R && (21)\\
p_{h,8,r} &\leq h_r^{resCap} + c_{8,r}^{addT}, && \forall h \in H, r \in R && (22)\\
c_{8,r}^{addT} &\leq h_r^{maxOverall}, && \forall r \in R && (23)
\end{aligned}
$$

4.4 Using the model for the CT analysis

The model was implemented in Julia in order to allow for high-performance compiling. The optimization engine used is Gurobi.

The run consists of four different cases of altering the CT level. The cases are running coherent tax for all countries and altering the value uniformly as well as using the existing tax as a base for altering values in three ways. The main cases approximately follow the methodology used in the study of He et al [7].

In the first case of coherent tax, a tax value ranging from zero to a relevantly high value is used. The tax will be uniform throughout the countries, thus it is likely that the results will affect the countries production distribution in a greater scope. This will be called uniform multiplied (UM).

```
for i in 1:30
    taxLevel = i*6
```

```
    TAX = [1, 1, 1, 1, 1, 1].*taxLevel
end
```

In the second to fourth cases, the existing taxes used in real life are altered following three different methods. The current values are multiplied by an uniformly increasing value, a combination of multiplying and adding and an uniform value is added to the existing values for the countries.

In the second case of multiplying the existing values, we could easily come across a situation where the CT of a country with already high CT skyrockets. On the other hand the effects in low CT countries can turn out to be minimal. This will later be called data multiplication (DM).

```
for i in 1:30
    taxLevel = i*0.17 - 0.17
    TAX = [62, 2, 112, 1, 15, 0.07].*taxLevel
end
```

In the third case of dynamically changing the CT we replace the lowest CT with a base level and then multiply the CT values with an uniform variable. The idea here is to set a minimum value for the carbon tax. The main limitation of this case will be the lack of analysis for the minimum CT which could also remarkable affect the results. This will later be called mixed multiplication (MM).

```
for i in 1:30
    taxLevel = i*0.17 - 0.17
    TAX = [62, 10, 112, 10, 15, 10].*taxLevel
end
```

In the fourth case of adding an uniform constant to the values we might have greater results in the currently low CT countries. This will later be called uniform adding (UA).

```
for i in 1:30
    taxLevel = i*3 - 3
    TAX = [62, 2, 112, 1, 15, 0.07].+taxLevel
end
```

4.5 Run time of the model

The complexity might make the model timely infeasible thus the model was first ran in testing purposes using the UM way of altering CT levels. The computer used had an Intel i7-8665U 2.11 GHz processor and 16 GB RAM. By testing the model this way we can determine an efficient way to test using it for the real analysis.

For each amount of hours included, the model is ran twice and the plot is drawn based on the average of these two run times. The graph 2 shows that the run times of the model are very stable until we reach around 4000 hours which is approximately 5.5 months or mid-May. After this, the run times have sharp peaks, especially at around 6000 hours or 8 months, thus the run times turn in less predictable. This might also be due to the changing availability of resources caused by autumn, where all RES lose on availability.

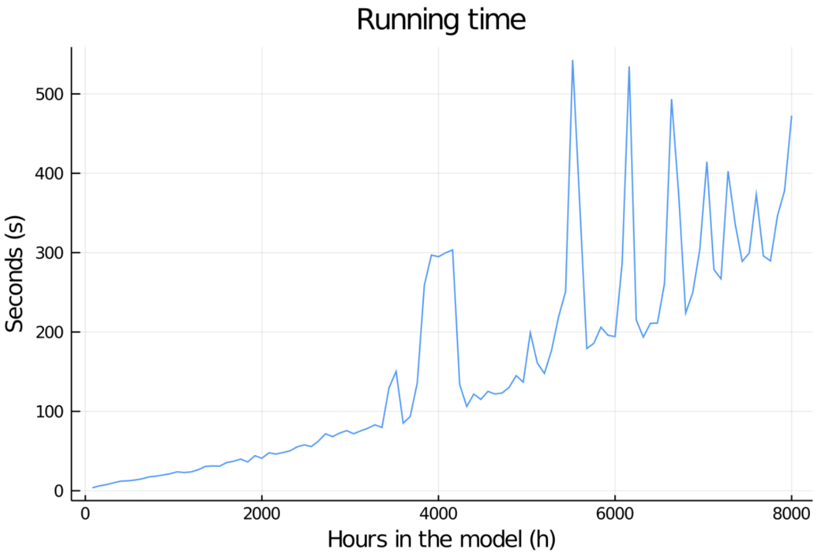

Figure 2: Run times of individual iterations of the model represented with certain amount of hours included.

Following the run time analysis the model can be ran at the time span of 8759 hours, which represents a full year. The run time, according to this analysis, should be around 400 seconds, thus looping the model over 30 iterations in four cases should result in around 12 hours of total computing. However, it is not yet known if the level of CT or the way of increasing CT affects the run time, or another unpredictable factor affects the run of the simulation.

5 Results

5.1 Results in general

Running the model in the actual settings takes around 16 hours to accomplish. Each of the four cases in this case, are run 30 times.

The following abbreviations are used to make this section easier to read:

1. **UM** - Uniform value multiply
2. **DM** - Data value multiply
3. **MM** - Mixed multiply
4. **UA** - Uniform adding of an increasing constant

In the figure 3 the global RESS is shown with respect to the increasing total value of CT.

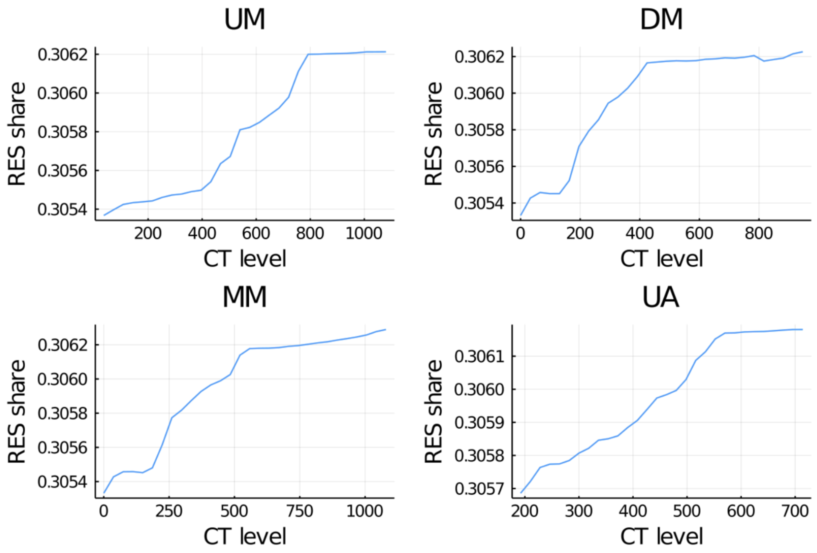

Figure 3: Total RESS of the system against total CT.

The figure 3 shows that the increasing CT level seems to be increasing the RESS as well. The increases in RESS, however, are very moderate since we are talking about a global RESS rise of less than a percent.

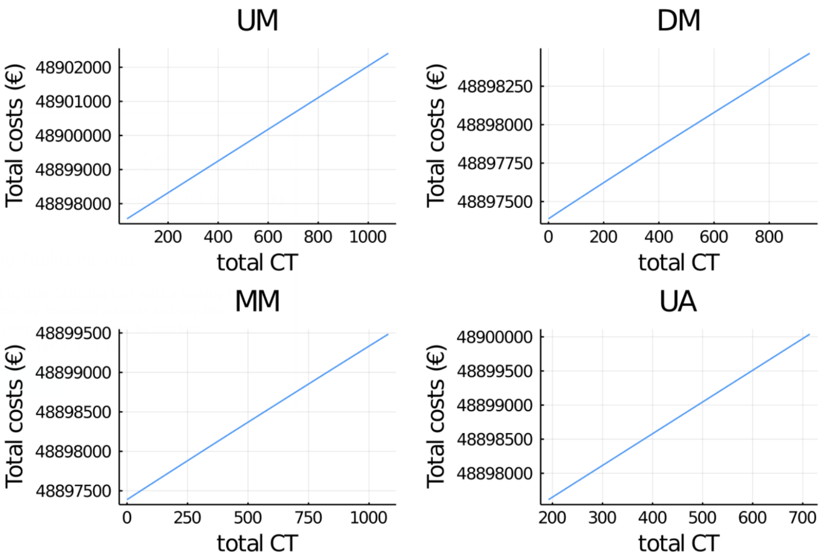

Figure 4: Total costs of all energy production related in comparison to total CT.

The figure 4 represents the total costs of all energy production related including investments, production expenses and the carbon taxes due. One can detect that the proportion of CT costs in the system is relatively low. The plots seem to be similar but a closer look reveals how the UM and UA cases have higher costs for for example total CT of 600€. The differences, however, are not relatively significant in the magnitude of the values.

In the figures 5 and 6 we can see an interesting phenomenon where the RESS in Finland solely increases but meanwhile the RESS of Estonia decreases. However, the decrease in Estonian RESS is very slight whereas in Finland the RESS significantly increases, especially in the cases of data based multiplication DM and MM.

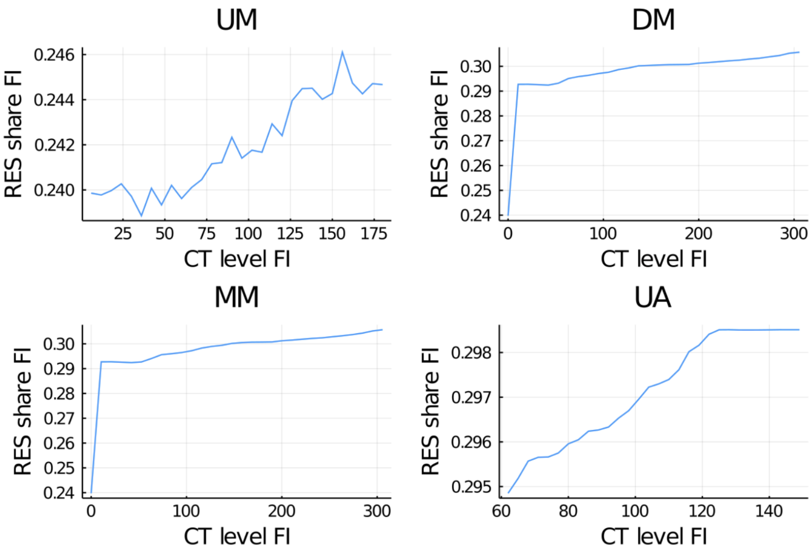

Figure 5: RESS level of Finland against the Finnish CT.

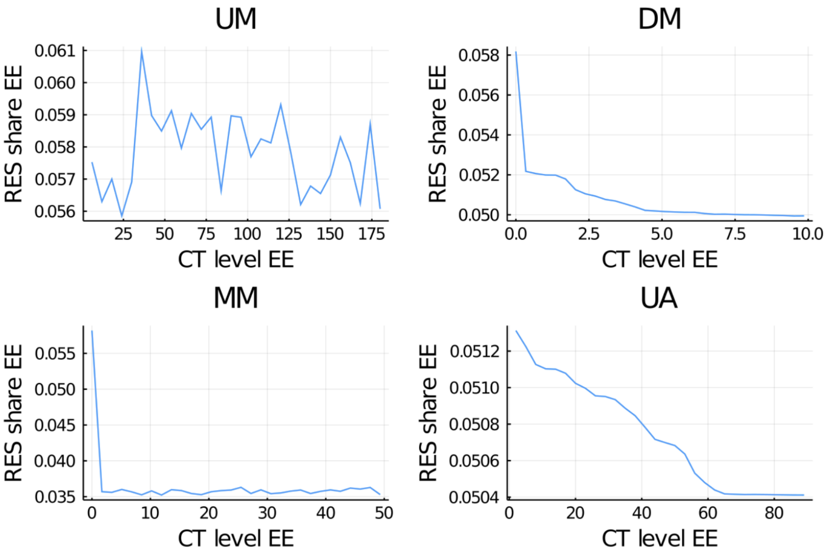

Figure 6: RESS level of Estonia against the Estonian CT.

The figures of Estonian and Finnish production repentant the whole picture which can be seen in more detail in the appendix A. Generally saying, the RESS of Finland, Sweden and Spain, the countries that already maintain higher RESS and CT levels, increases while the RESS of the other countries, Germany, Poland and Estonia, decreases.

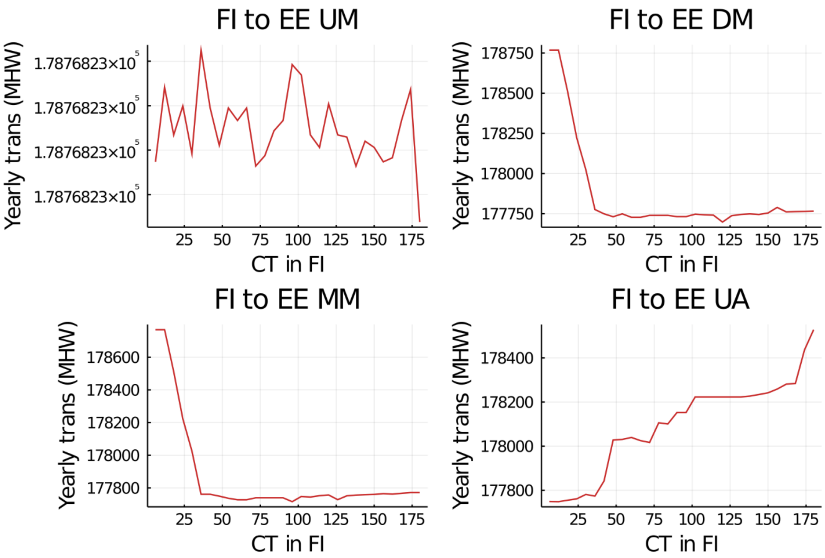

Figure 7: Transmission between Finland and Estonia, where positive values indicate the direction from Finland to Estonia.

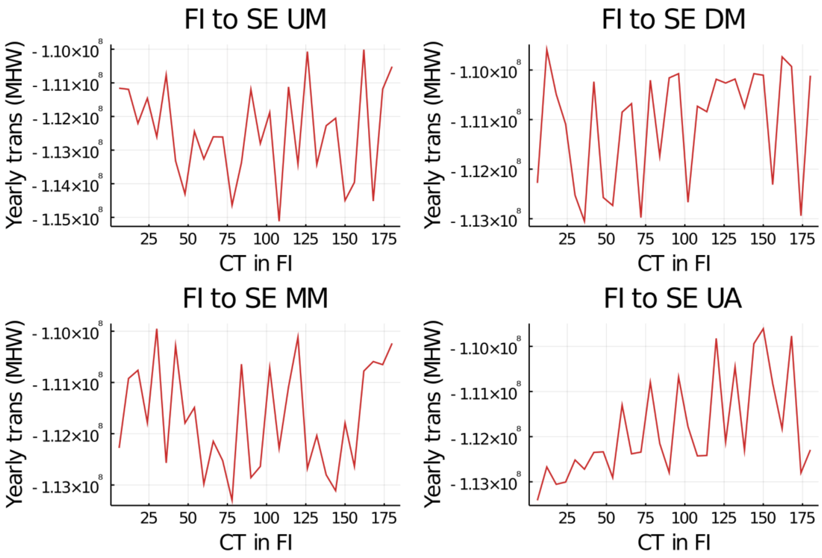

Figure 8: Transmission between Finland and Sweden where negative sign indicates direction to Finland.

Figures 7 and 8 indicate the electricity transmission of Finland following each case. The transfer between Sweden and Finland is relatively constant at all times in a way that electricity is imported to Finland. For Estonia, the transfer comes from Finland and heavily depends on taxation model and tax level.

We now take a closer look at the results in each case separately. In the cases we concentrate on the overall investments and more detailed results of Estonia and Finland, since these represent different portfolios of existing capacity and are geographically close to each others. More results can be found in the appendices A and B.

5.2 Uniform multiplication with uniform values

According to the figure 9, new investments are made on gas and hydro reservoir. The levels of invest do not vary remarkably while the tax levels rise.

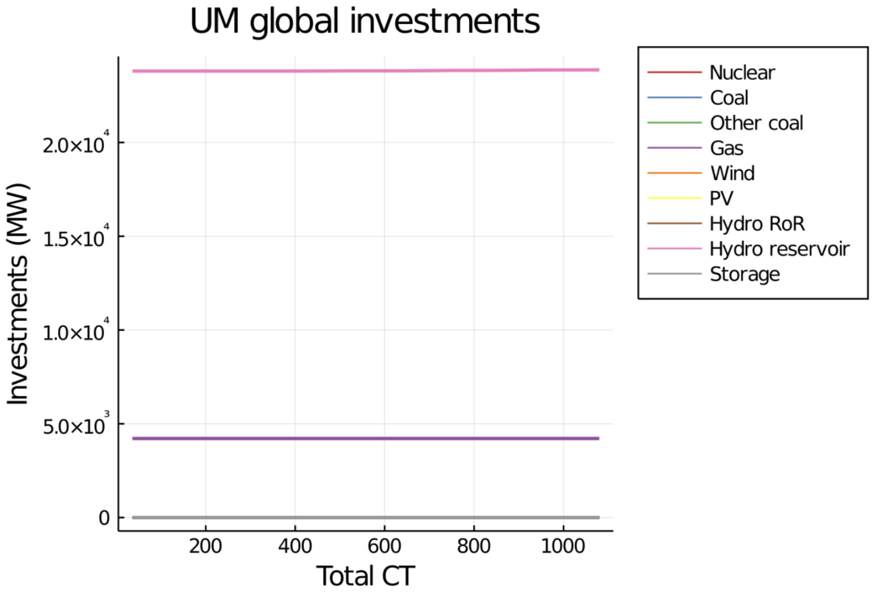

Figure 9: Global investments in MW.

To describe the situation in more detail, the figures 10 and 11 show the change in overall production versus the increase of CT. As seen, the share of coal production slowly decreases in Finland but in Estonia, no significant changes are done. This is probably due to the good existing capacity so no expansion is considered cheap enough to replace the increasing CT levels. The other countries have relatively similar results.

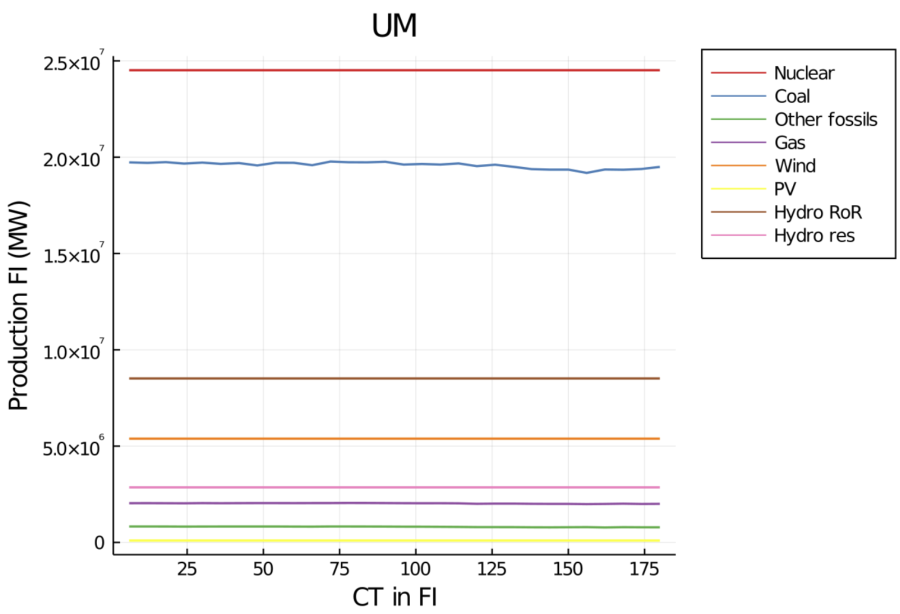

Figure 10: The Finnish production over the increasing CT.

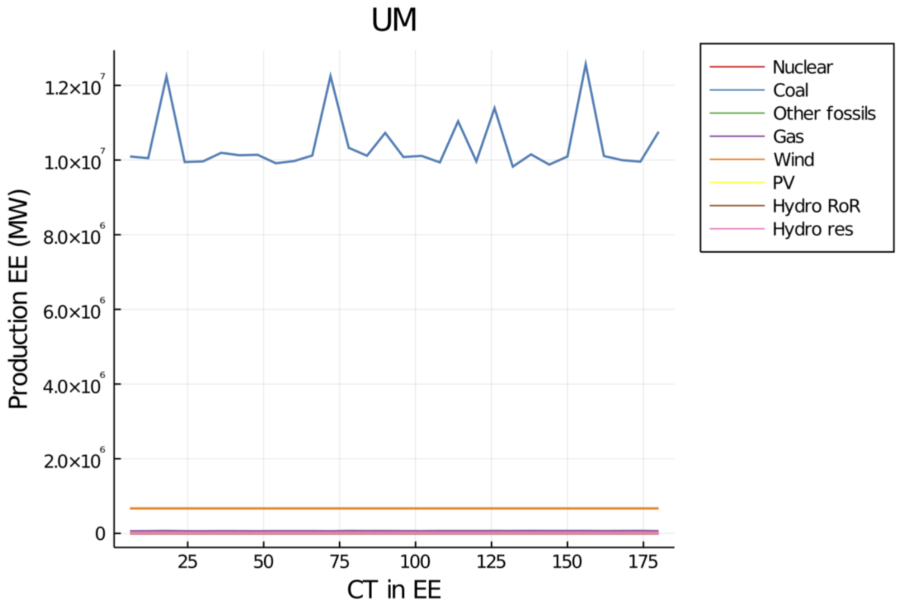

Figure 11: The Estonian production over the increasing CT.

5.3 Data based multiplication

In the case of data based multiplication (DM) CT, an interesting aspect of large investments in storage is done as seen in the figure 12. Based on the figure 3 the data based multiplication reached the highest RESS for cheapest total CT.

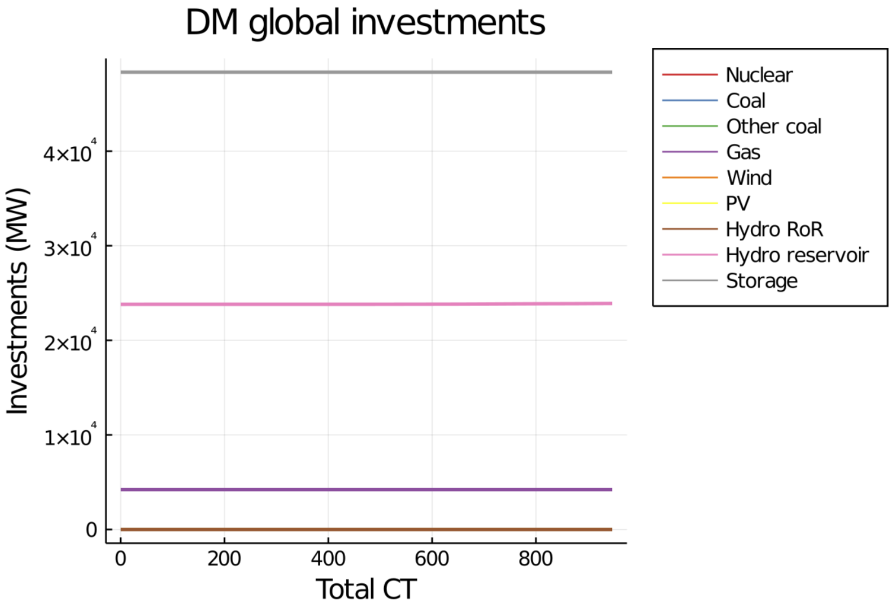

Figure 12: Global investments in different technologies when setting the CT with the DM technique

To see what is really happening, we again take a look at the situations in Finland and Estonia in more detail. The production changes are described in the plots 13 and 14 . The rest of the data can be seen in the appendix A but to sum it up, the production of combustion, especially Coal, was highly decreased in Finland and Sweden but increased in Estonia, Poland and Germany. As seen in the figure 3, the total use of combustion production was decreased but it relevantly changed origin from high-CT countries to low-CT countries. This is easy to explain by the way CT works in case DM. Since the last case, UM, consisted of uniformly growing CT, it only showed slight changes in RESS increase, since the countries with already higher CT levels were not affected much. In the case of DM, the countries with already high CT are affected a lot, since their CT level skyrockets, as can be seen in the case Finland 13 when comparing to Estonia 14. Also, the figure 7 showed, how in DM, the electricity exported from Finland to Estonia decreased. This explains the increased production demand.

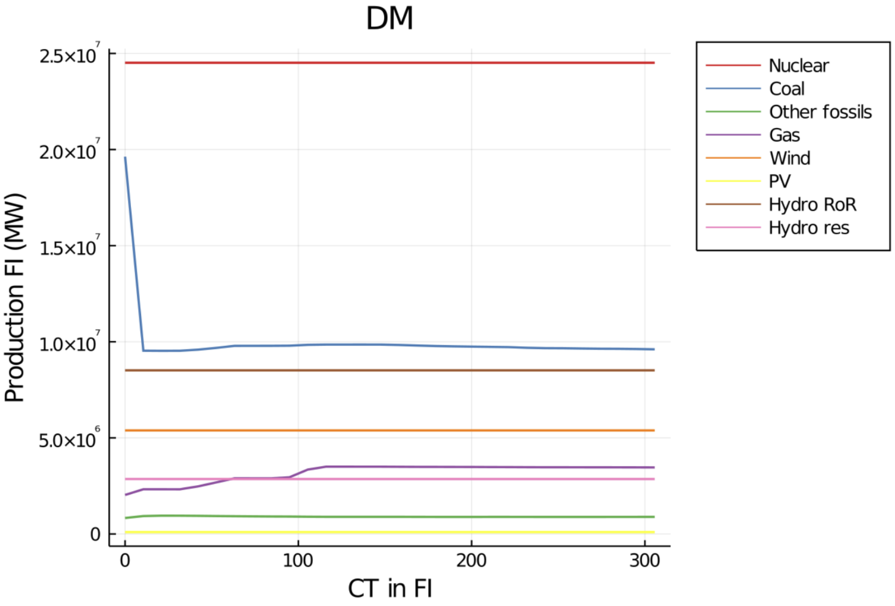

Figure 13: The Finnish production over the increasing CT.

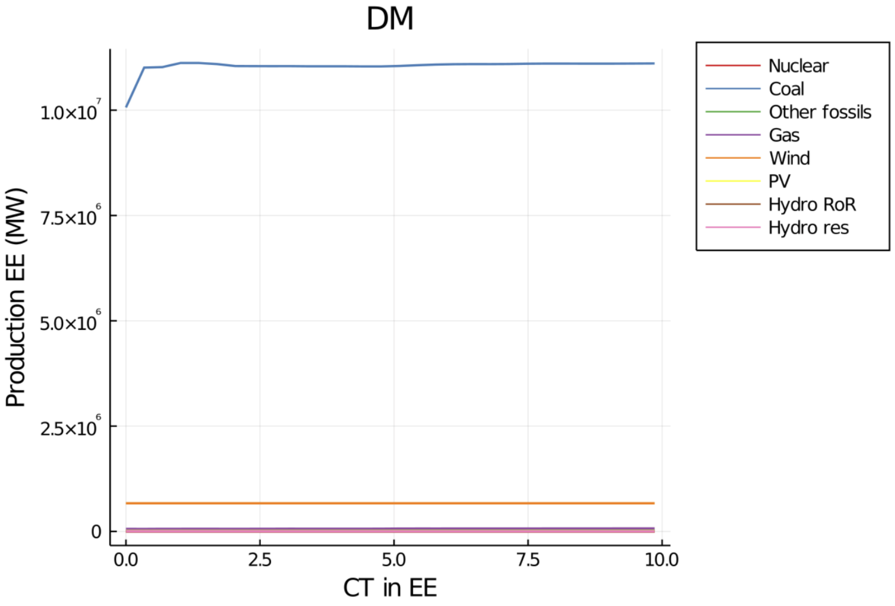

Figure 14: The Estonian production over the increasing CT.

5.4 Mixed multiplication

The same effect as seen in the case of DM is also seen in the minimum level multiplication case in figure 15. This is not surprising since the cases have a very similar base for CT. The effect of combustion production changing its location seen in the case of DM is also noticeable in MM as can be seen in the appendix A

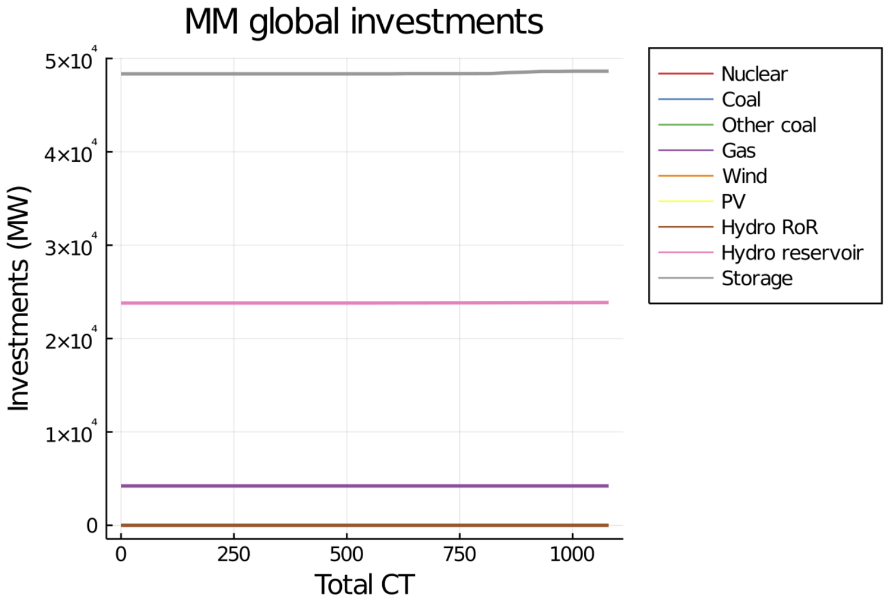

Figure 15: Investments in different technologies when setting the CT with the MM technique.

5.5 Uniform addition

The case of an uniform addition to CT seems to make only very minor changes over the scope of increasing CT. This is probably mainly due to the relatively low change in values set for already high-CT countries.

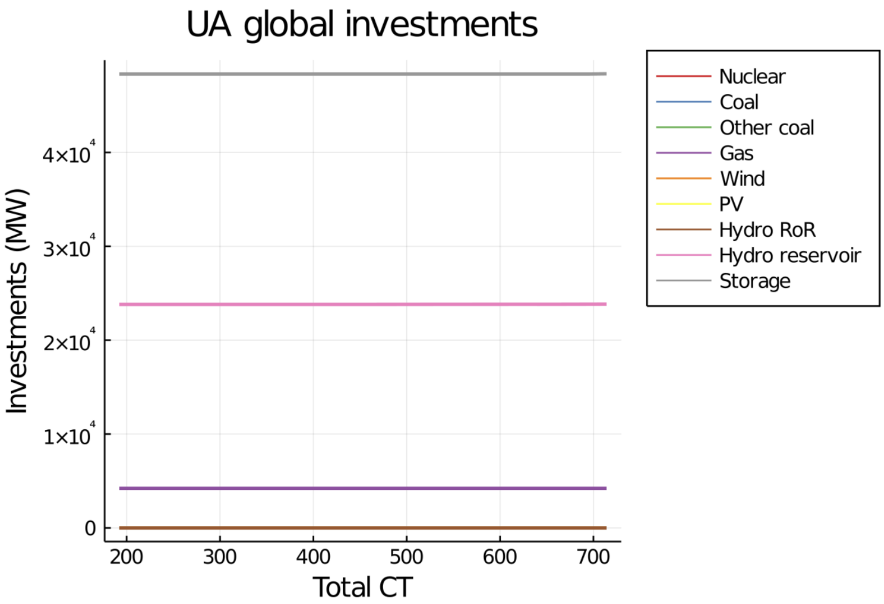

Figure 16: Investments in different technologies when setting the CT with the UA technique.

The figure 16 shows how the increasing CT does not affect the new investments at all. Large investments are placed on storage and hydro reservoir and minor investments are also done on gas. The figure 17 reveals only minor decrease in coal and gas production while the tax level rises

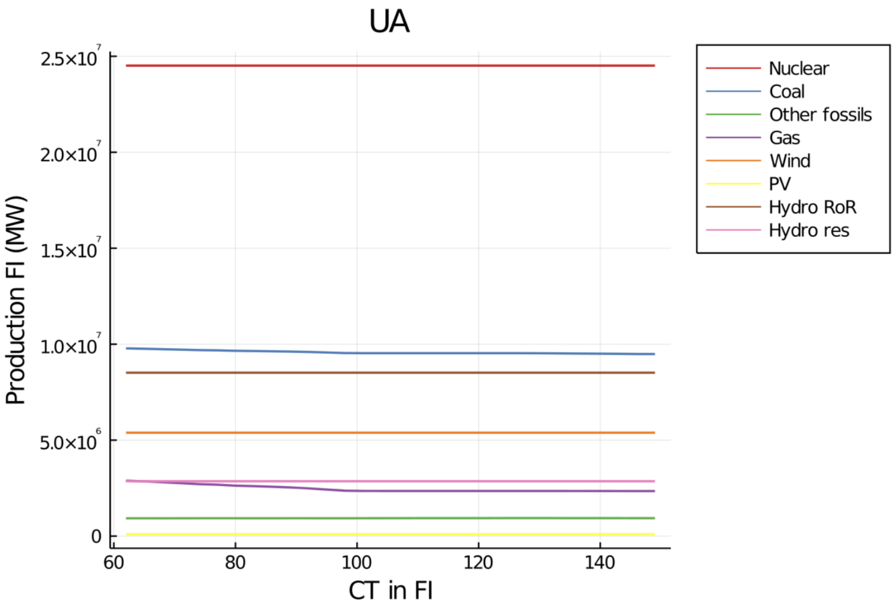

Figure 17: Investments in different technologies when setting the CT with the UA technique.

6 Discussion and conclusions

6.1 The key findings

According to the results obtained, increasing the carbon tax (CT) levels results in higher RESS. Even though the model seems not to take the possibility of decommissioning old production into account enough, the results in general show more significant rise in RESS in the already high-CT countries. However, the difference between high and low-CT countries highlight the real-world fear of switching fossil fuels-based production to cheaper countries, also discussed in the article by Farsaei et al [5].

The differences between the taxation methods result in different change in production. It is surprising that the model does not end up increasing storage capacity at all in the case of an uniform multiplication. Also, it is interesting to see, how little difference the UM taxation makes for each country.

The DM results show remarkable rise of RESS is in Finland. This is very logical, since CT rises on a very high level for Sweden and Finland in this scenario. The same applies to MM, which is surprising since there is a significant difference in Estonia's and Poland's CT level when compared to DM.

The difference between DM and MM is very minor. The RESS increases more with lower total CT in the DM, which is logical, since not as much taxes are paid by low-tax countries while still switching over to less emitting production in high-CT countries.

In the case of UA, there was nearly no difference in the Finnish RESS. The increase in CT is not as remarkable as in other cases, so the dynamics of the system seems to let Finland emit more and make sure that for example Estonia can keep up its production while the CT level increases rapidly.

Overall the increase of RES share in this model was relatively low compared to the real-world aims at cutting emissions to zero by 2050. This was likely due to the high investment costs required for such technologies when there already is enough capacity to produce energy. Also, the existing capacity was not set to be decommissioned more than the already applied -30% in fossil fuels. By doing so, we would have had more of a greenfield model rather than a capacity expansion model, which means a model with non-existing initial capacity. One should bear in mind that the changes in RESS and eventual decommissioning of non-renewable plants is not done over one year. Therefore modeling only one year and getting a remarkable rise in RESS is practically unfeasible in reality.

So, the way the model works in this study represents more the current situation and indicates how without decommissioning the existing capacity and rising current consumption levels, the investments in RES are not economically worthwhile. Again, the vice words by Pfenninger et al [2] claim that the modeling needs to be up-to-date and very high in spatial resolution to give reliable answers to RES related questions. This means that our model is not accurate enough to show reliable results in RES deployment but it may give some hints on the possible settings seen when altering CT levels.

Further analysis discovering how decommissioning of fossil fuel plants affects the economical profitability of RES is required to answer further questions. The model used simply slightly decommissioned the existing capacity. This applies for a more short-term scenario, since all capacity has their life span and thus decommissioning production is not only dependent on cutting down the polluting facilities.

All in all, the key findings therefore are the effect of changing origins of combustion production and the surprisingly low effectiveness of CT in the situation where decommissioning existing capacity is not planned in a great extend.

6.2 Limitations of the model

Expansion

The model was ran on data from 2018. According to many researches, e.g.[4], [2], the energy consumption is likely to only increase in the future. Therefore further analysis on future scenarios should involve more analysis with the increasing demand. On top of this, the scenario in the model is already at least almost functional, since the selected countries did not run out of electricity during 2018. However, we only use 70% of their fossil-fuel-based generation capacity but the capacity is not always fully occupied. What this means for the model is that the actual capacity expansion was understandably not an attractive choice since existing capacity already covered the demand and building new production costs relatively much compared to just paying for the emissions. Also, apart from nuclear and non-renewable production, the models do not take the possibly planned decommission of any renewable technologies into account.

Transmission

Transferring electricity between countries is in real life not as straightforward as in the model. The models only set a constant cost to all transfer therefore missing out on the real world bidding game. In reality, the transfers could therefore work in a different way, but the model gives example scenarios of what would likely be a possible case. [21]

The generation technologies

The results show that the modeling of nuclear production in this model might not describe its nature well enough. In the model used in this study, the ramping of nuclear production was only highly limited but no detailed modeling was done. In the model that does not fix nuclear share, the nuclear capacity was not always fully utilized whereas in the real world this wouldn't be clever in any sense due to the nature of nuclear production. Also, the yearly maintenance breaks of nuclear plants are not taken into account here. [22]

The fossil fuel technologies, in general, are modeled on a very approximate scale. For example, the biomass and other combustion fuels technology combines a variety of small-scale technologies which leads to strong approximation of their features, costs and emissions. In other models, many combustion technologies are modeled the same way but gas, at least in REX [1], is split in Combined Cycle Gas-Turbine (CCGT) and Open Cycle Gas-Turbine (OCGT). The scope of his study simply does not cover the technologies on this depth and therefore the results are most likely more approximate.

The hydro power is modelled following the REX [1] model. However, the parameters required for this, such as minimum hydro reservoir or minimum run of river, are not easily accessible nor, in detail, applicable in such large-scale modeling. By this we mean that using just one minimum value for the whole country does not correspond to the need of individual plants very well.

For storage technologies, the models simplify the processes a lot. Since large scale batteries, artificial hydro reservoirs and other modern and emerging storage technologies are still widely a vision for future, the constraints and parameters of storage modeling are not accurate enough for reliable results.

The time span

Using just a one-year scope for the time span can bring limited results for more general analysis. For example, the year 2018 was historically high in temperatures [23] which could give generally unconventional view to the demand and supply of, for example, solar power. To prevent bias, merging multiple years or just running the model over several years could have been helpful. In the case of merging and averaging several years, the characteristics of especially PV and wind power could have been lost. In the case of running the model over several years we should have had more computational capacity. With the current computational capacity, running the model over several years would have resulted in days of computing.

Other limitations

The geographical scope of the study was quite limited in terms of production and demand distribution since the countries were seen as just one region. Therefore especially the national-level results should be analyzed in more detail. Approximating countries as just one to a few regions is a widely used way of approximating and making the models feasible for lower computing power. However, this model does not involve modeling the national transmission nor distribution of electricity and, therefore, leads to cheaper operation and simplified functionality when compared to the reality.

Future power systems also bring possibilities to better balance electricity consumption. This means that power could be used in a more dynamical way depending on its availability. This is nonetheless out of the scope of this study.

The costs were modelled in a linear way. This is an easy way of modeling capacity expansion but it might result in adding irrelevantly small amounts of production capacity. This means that the capacity of, for example, nuclear power could be increased by 1 MW which in reality wouldn't be feasible to build at the cost produced linearly. On the other hand, building very large power plants is likely to be more expensive than in the reality.

6.3 Conclusions

The conclusions of the study and the literature review have a clear outcome. Not widely enough planned climate policy might end up causing even more damage at least in short term. This does make sense in the wider scope too, since changing something highly complex has many opportunities of going wrong.

The way of multiplying current carbon taxes has good results in increasing RESS in high-CT countries, but meanwhile the other countries ended up producing more coal-based electricity. None of the systems really had any remarkable results, but the gentle dynamics were very different and in real life, could give insight to how different increases in CT might end up looking like.

Planning and implementing sustainable and effective energy production is the key to keep the global warming under the desired level. Such goals can be challenging to achieve, but without limitations to today's energy production, these goals are by far, unfeasible. Moreover, the local pollutants damaging human health directly are similarly cut down by reducing the use of fossil fuel or at least changing the way those work.

6.4 Next steps

The next possible steps include referring to expanding the model in terms of time span, decreasing the initial capacity and analysing the effects caused by that or possibly modeling the possibility of deactivating initial capacity better. This would also require larger but still dense enough spatial resolution which would then require either more computational capacity or a more efficient model. Clustering methods to boost the efficiency of the model are discussed by Pineda and Morales in their study of Chronological time-period clustering for optimal capacity expansion planning with storage [3]. The model used in the clustering investigation was partly used in this study as well, but no clustering techniques were utilized.

Also, the use of the European cap-and-trade system, EU ETS, could have be taken into account. Mixing cap-and-trade and carbon taxes increases the complexity of the system again, but gives more realistic insights to the real dynamics of such systems.

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A CT levels

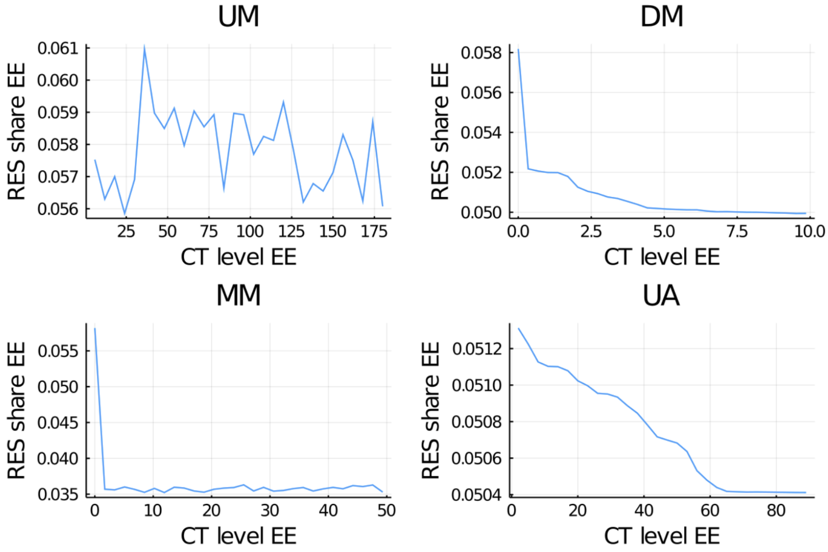
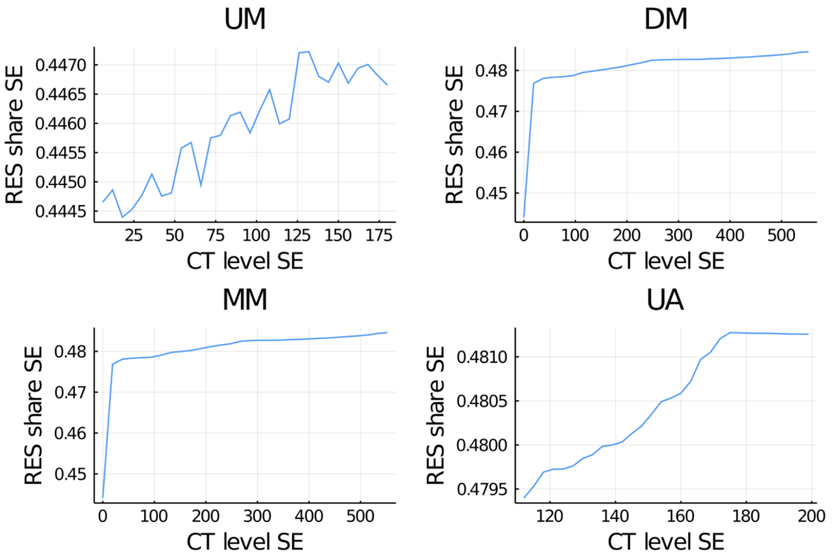


Figure 18: RESS of the system in Estonia.



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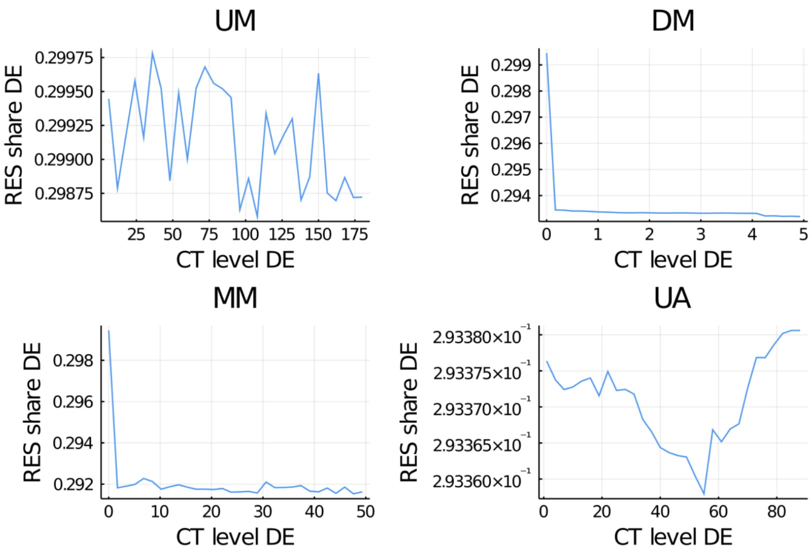


Figure 20: RESS of the system in Germany.

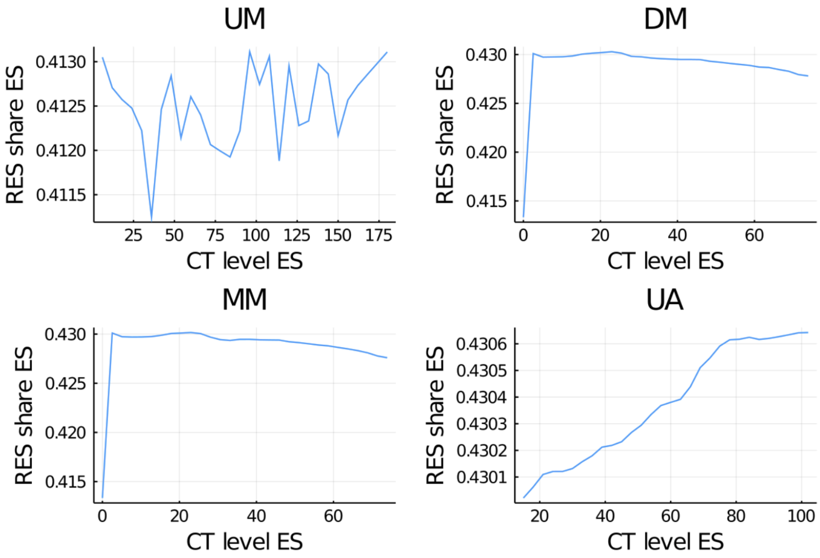


Figure 21: RESS of the system shown in Spain.

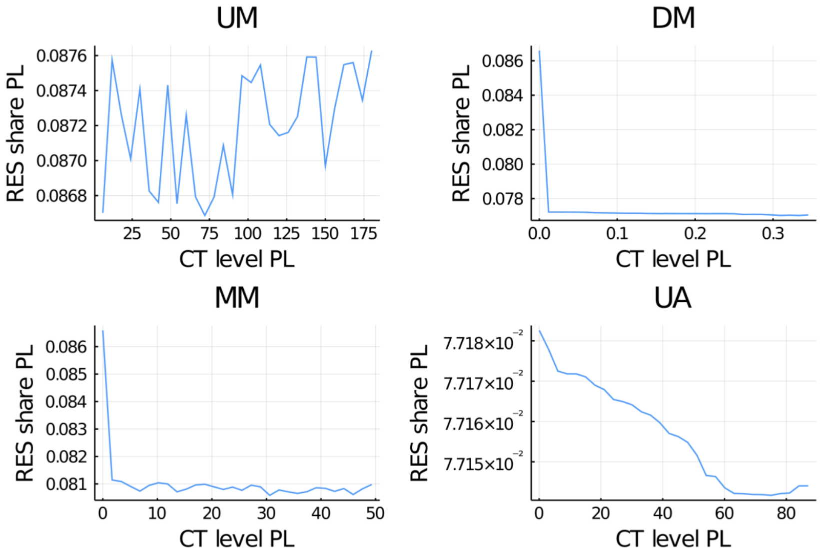


Figure 22: RESS of the system shown in Poland.

B Production

B.1 UM

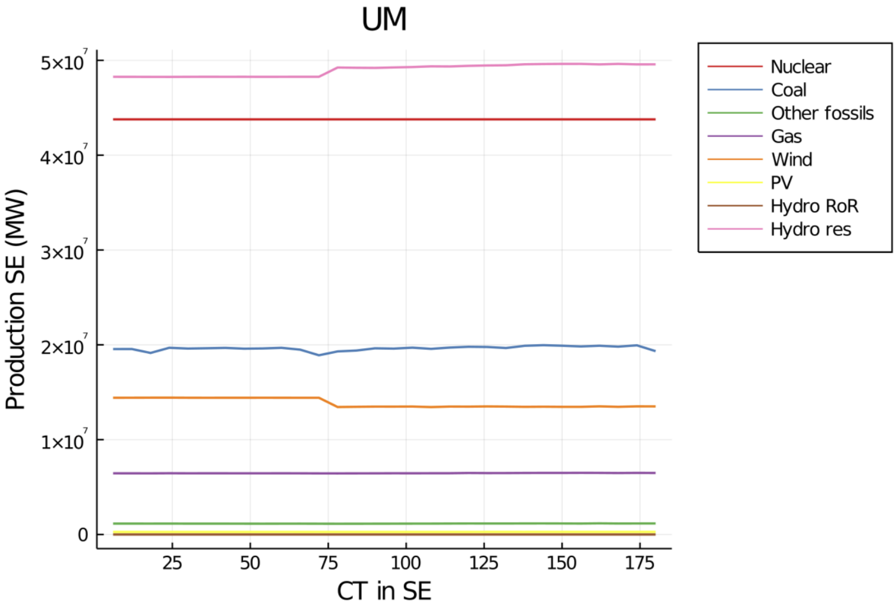
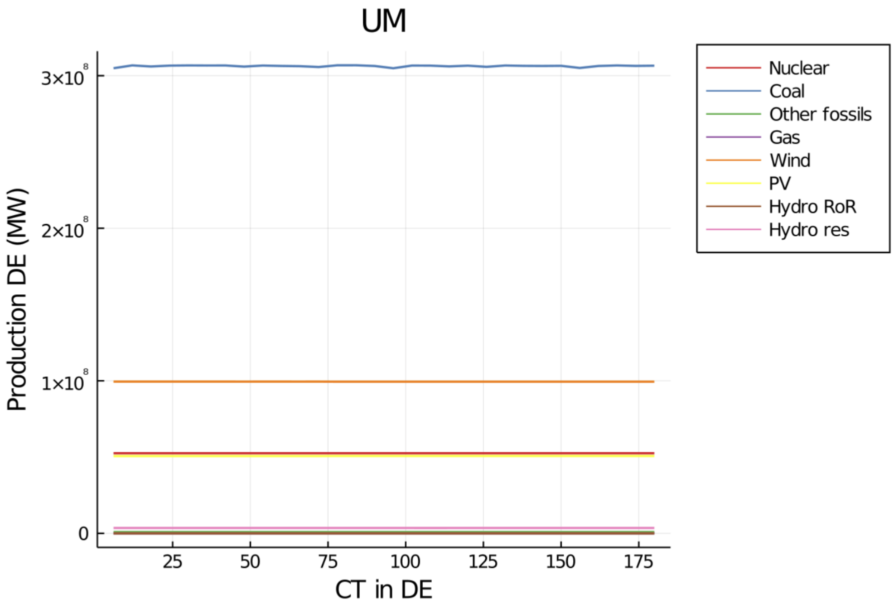


Figure 23: Production compared against the CT levels in Sweden.



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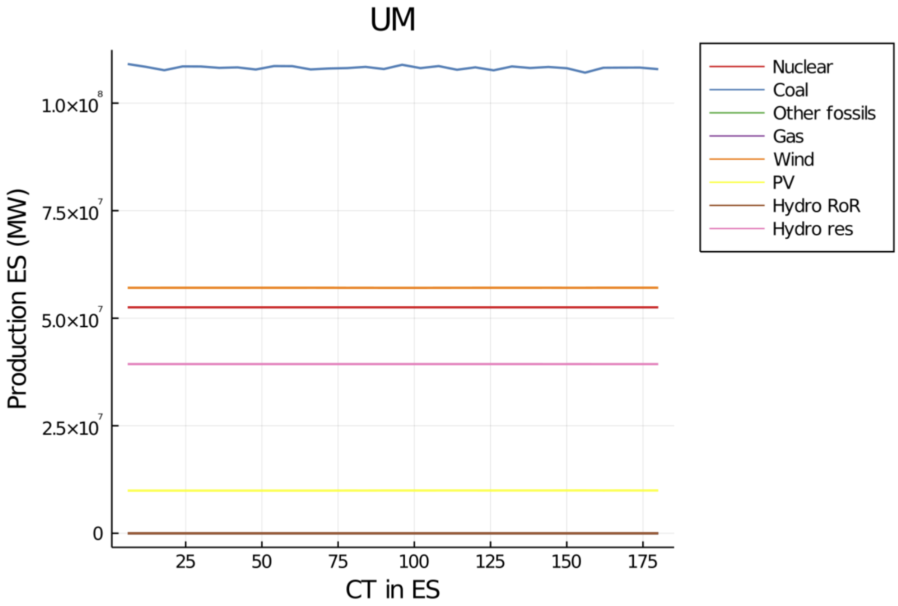

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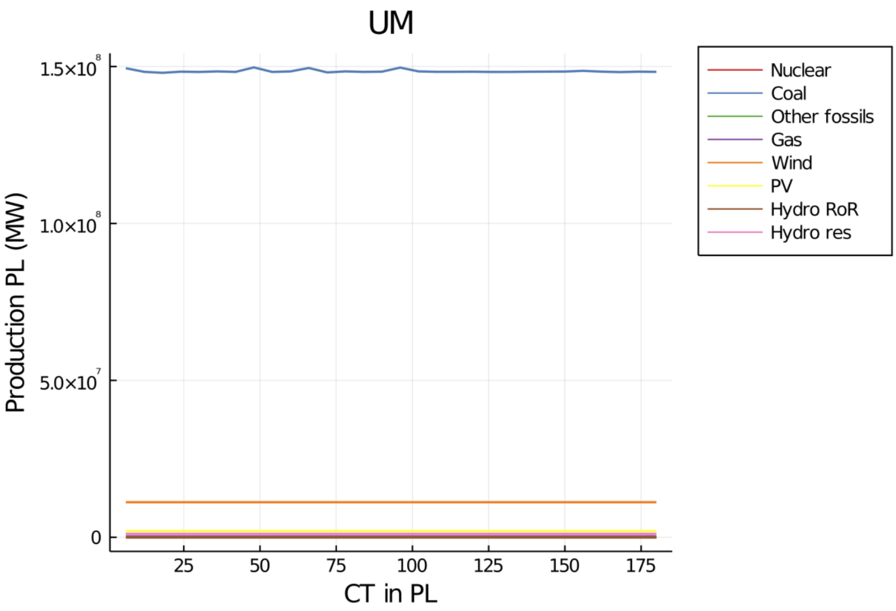
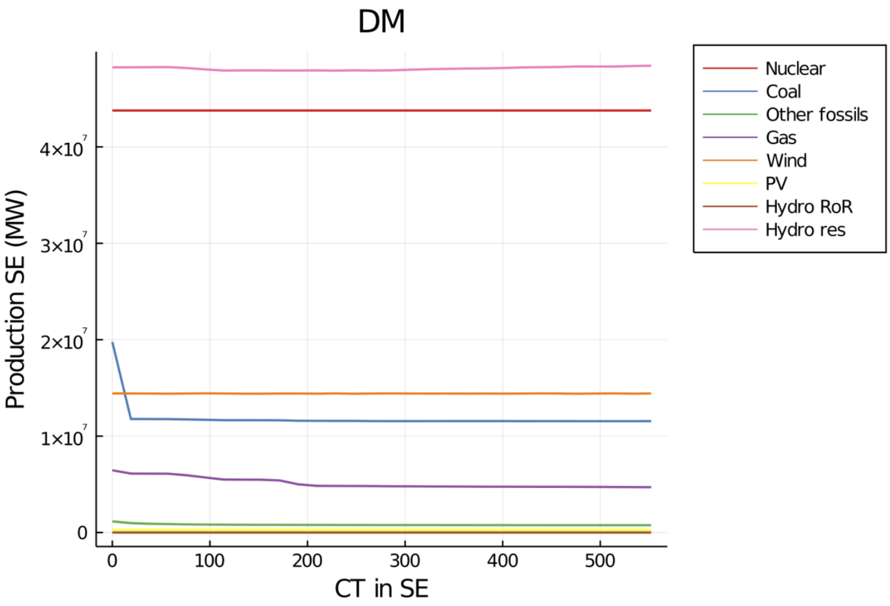


Figure 26: Production compared against the CT levels in Poland.

B.2 DM



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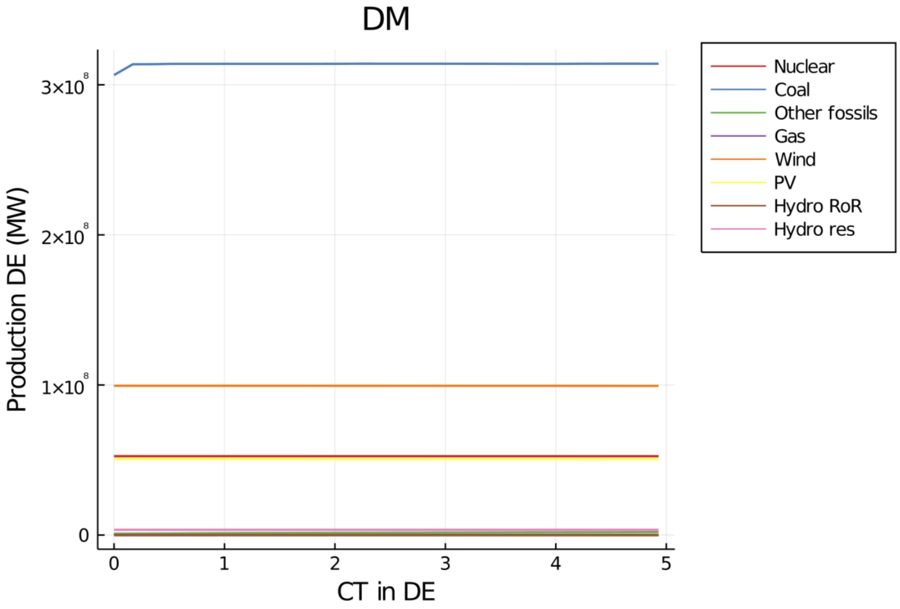

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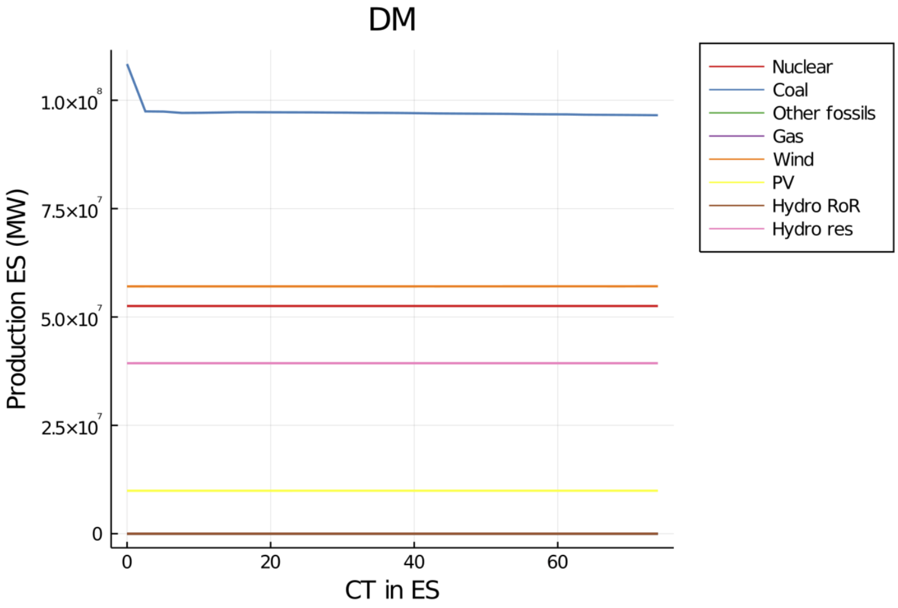

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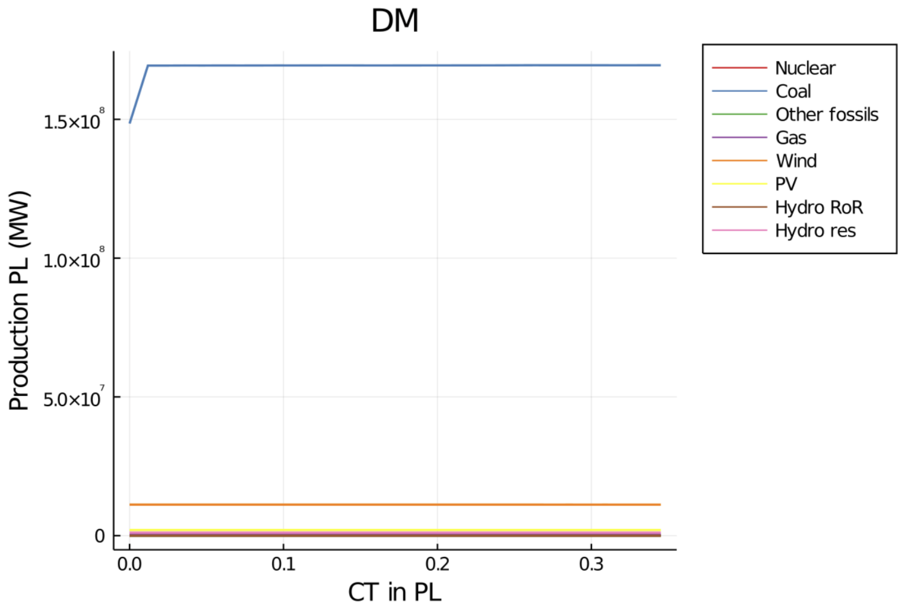


Figure 30: Production compared against the CT levels in Poland.

B.3 MM

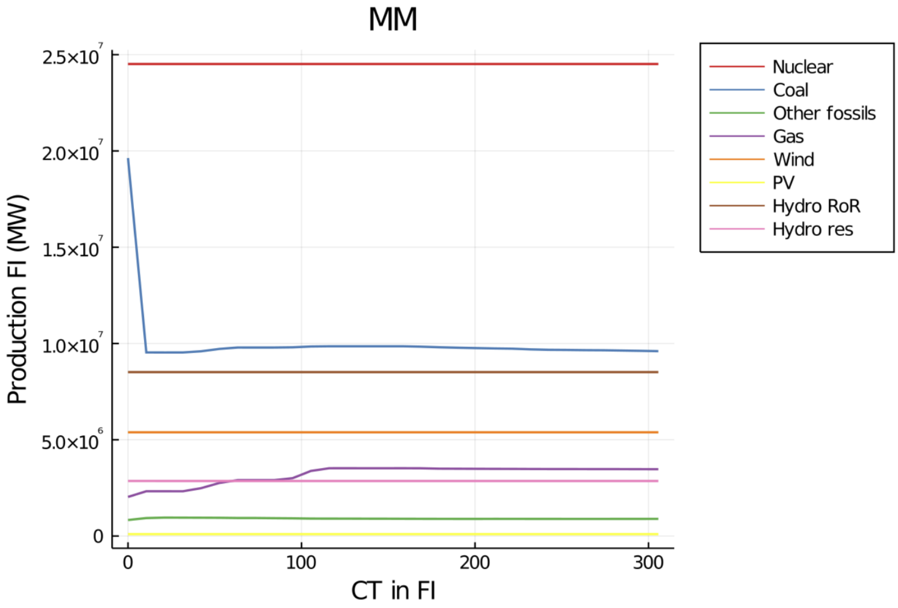


Figure 31: Production compared against the CT levels in Finland.

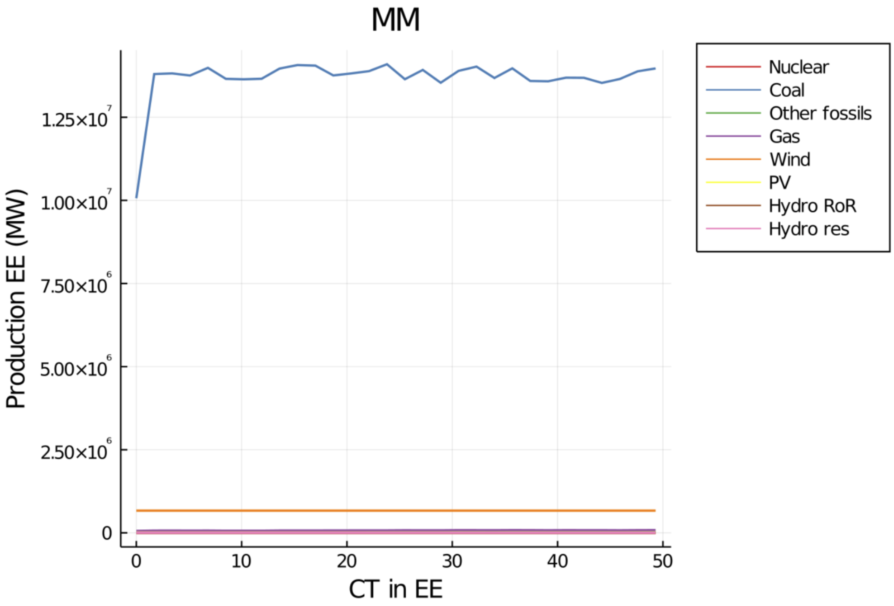
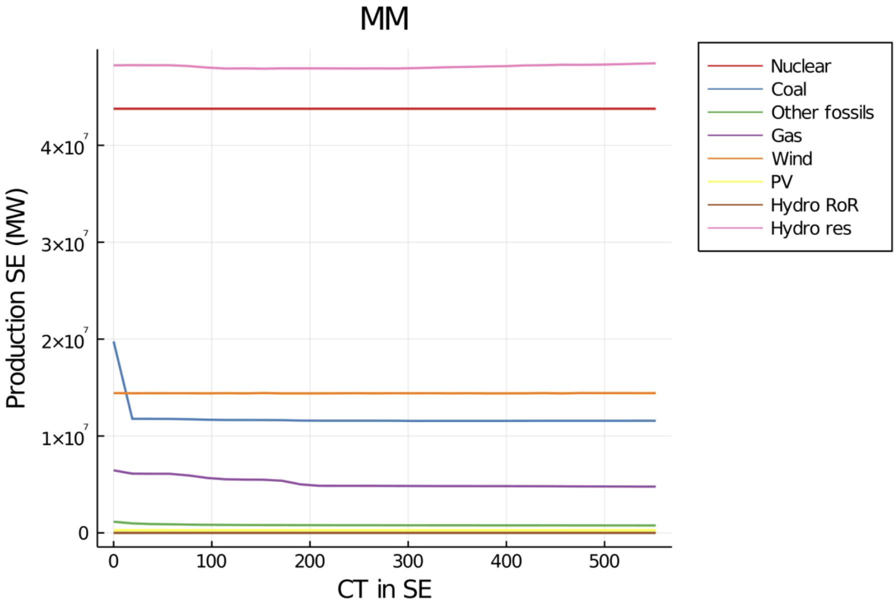


Figure 32: Production compared against the CT levels in Estonia.



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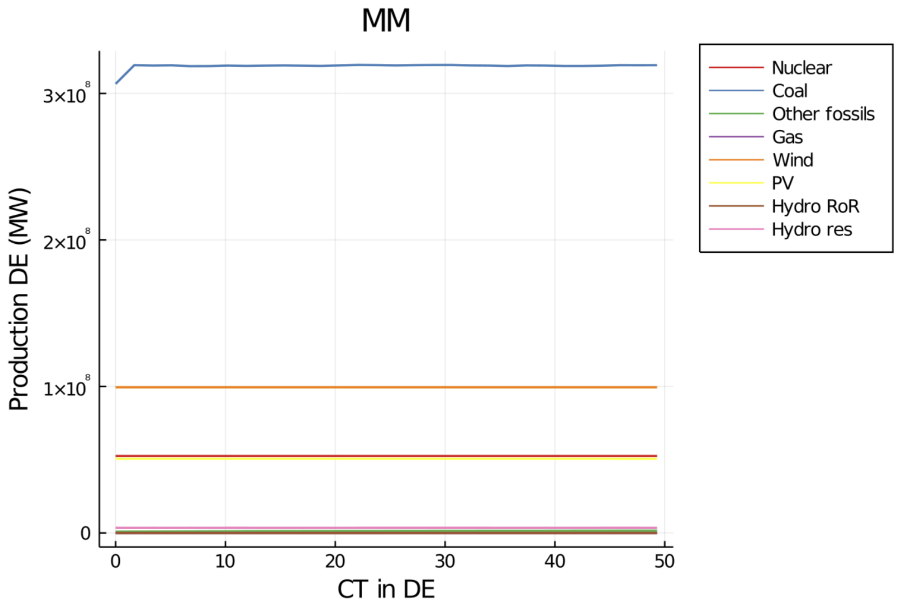

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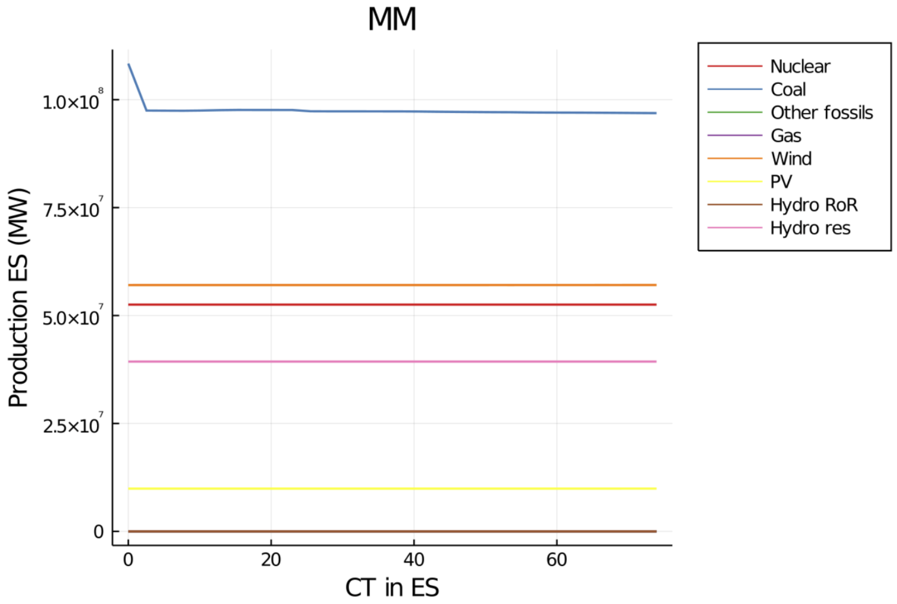

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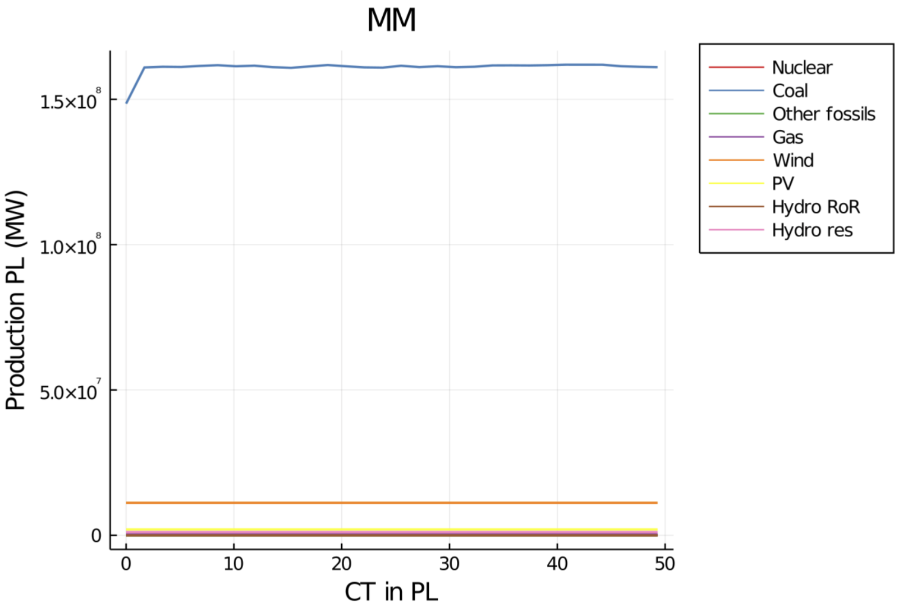


Figure 36: Production compared against the CT levels in Poland.

B.4 UA

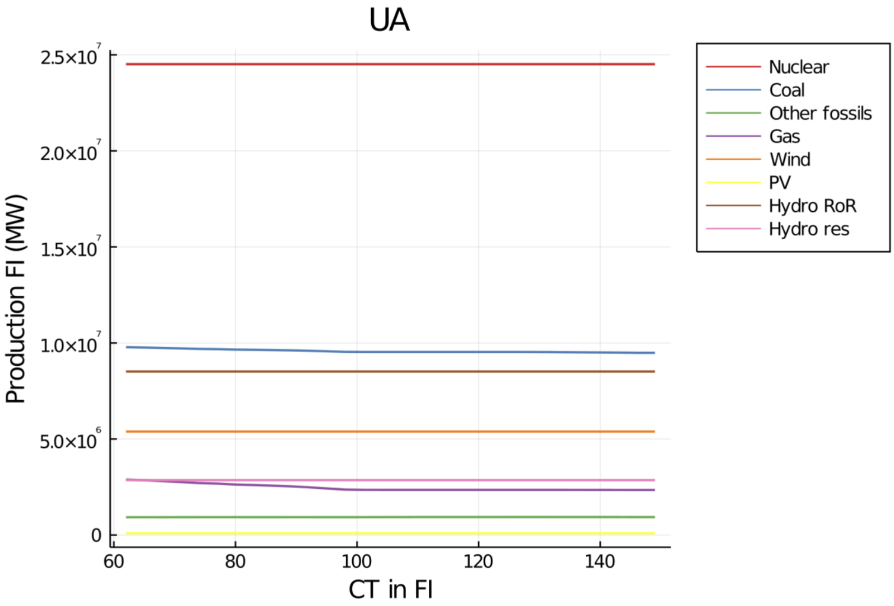


Figure 37: Production compared against the CT levels in Finland.

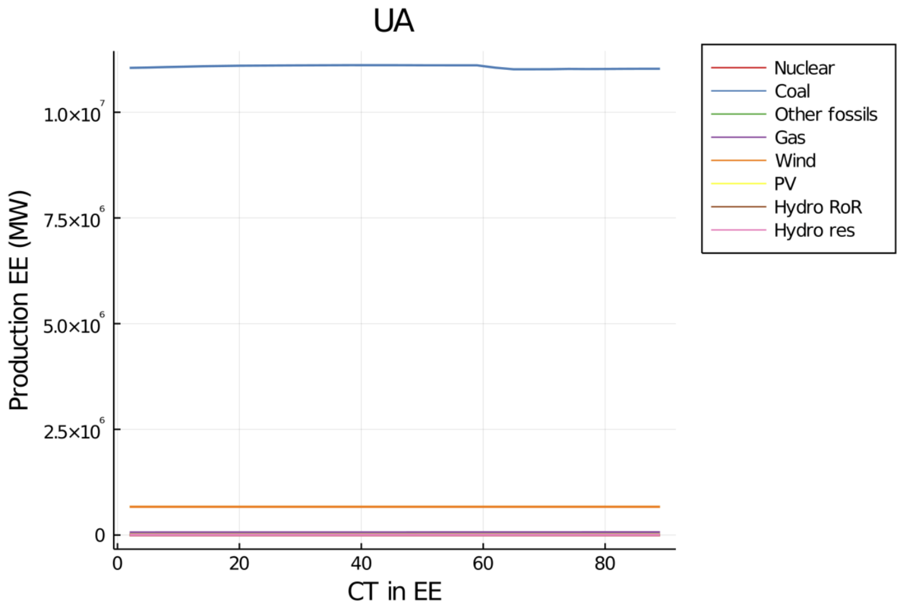
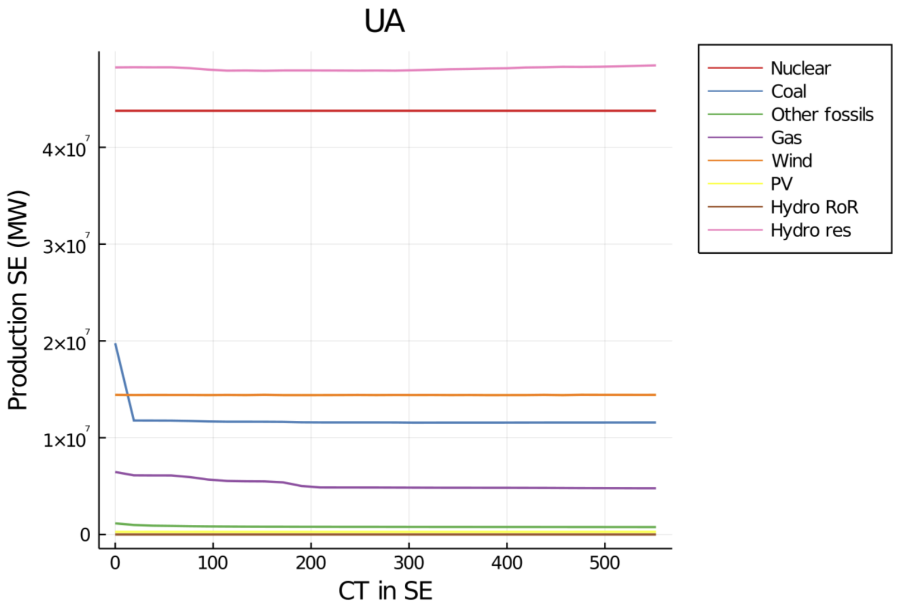


Figure 38: Production compared against the CT levels in Estonia.



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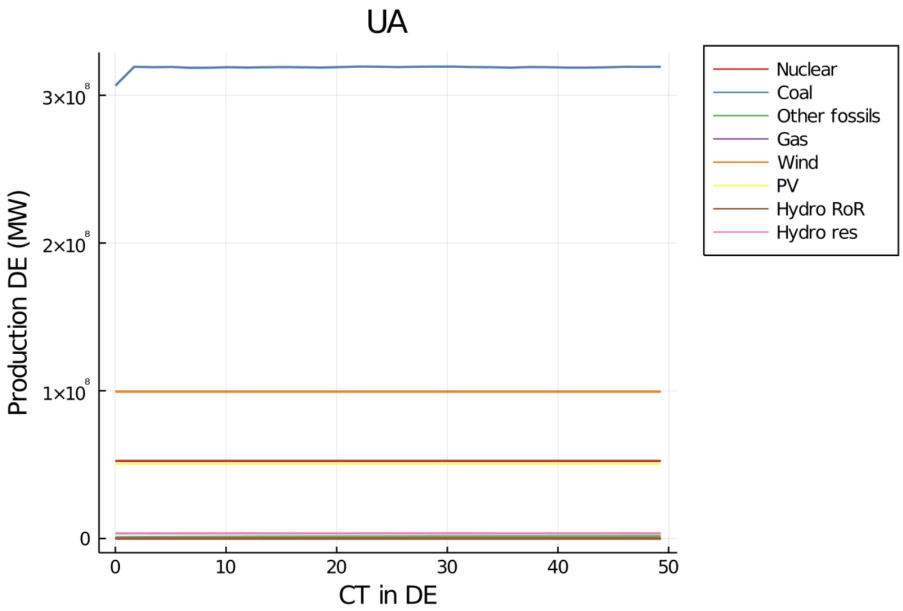

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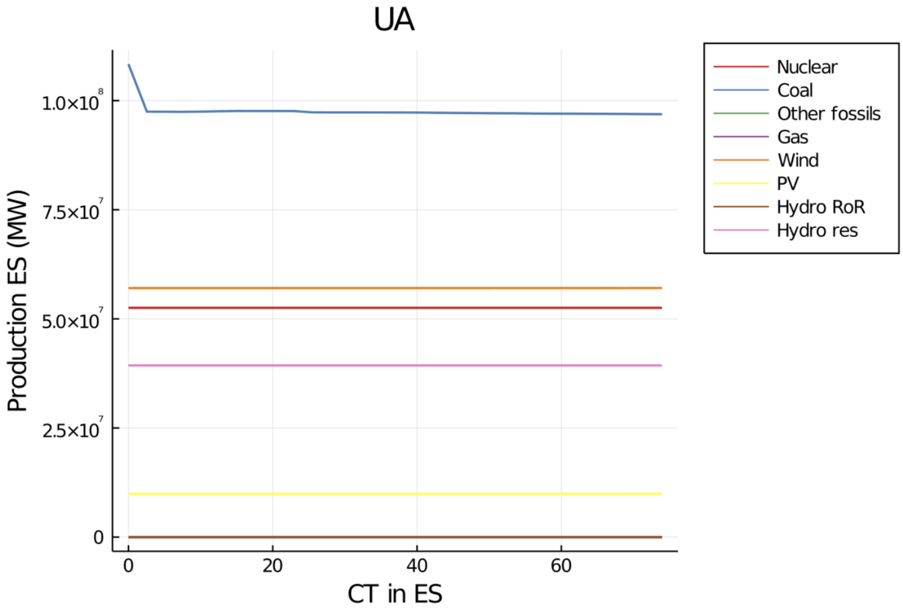

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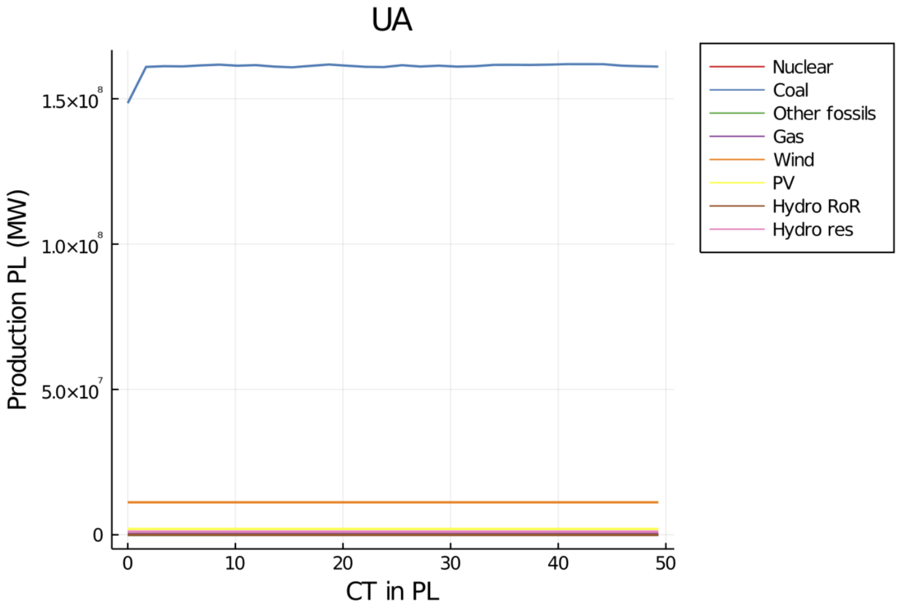

Figure 42: Production compared against the CT levels in Poland.