MODELLING AND ANALYSIS OF SUSTAINABLE ENERGY SYSTEMS USING OPERATIONS RESEARCH

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Final Project

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Workload

Jie Xu (s181238) responsible for Mathematical description and Julia code for the optimization models. Sensitivity analysis with Julia. Help with the GAMS code. Plot the figures.

Elena Mongelli (s181214) responsible for co-writing the GAMS code. Conducted research for several input data for the model. Writing of several parts of the final report and final proof reading. Also responsible for the presentation of the interim results.

Martynas Ribaconka (s180029) responsible for research on input values for the analysis, writing parts of the report, and interpreting the model results in results section.

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Abstract

Renewable energies are already taking up an integral part of most of European energy systems. Focusing on Denmark, roughly 44 % of the produced electricity is generated by wind power and overall more than 55 % comes from renewable energies[1].

This paper describes the approach to model the Danish energy system, using the programming language GAMS as the modelling tool. In order to reach the sustainability goals and being independent from fossil fuels by 2050 Denmark, needs an energy system which relies on 100% of renewable energies[1]. The aim of the GAMS model is to find the optimum technology mix from renewable energies and classical energy carriers, taking into account investment and variable costs as well as costs for emission certificates.

After introducing investment cost, fuel and emission prices to the model electric vehicles are implemented in the energy system. The aim of this extension is to model a more flexible demand and how electric vehicles can be used as flexible storage option to deal with fluctuating energy generation from renewable energies.

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1 Introduction

This assignment is describing the approach to model the Danish electricity system and its generators deployment under different possible future scenarios, including changing market and technology conditions. The Danish grid region DK 1 has been used in this paper as a representative area for the energy generation, considering variable and fixed costs as well as already existing wind capacity and, as a consequence, production rates. The aim is to model an energy system with an optimal energy mix between renewable energies and classical energy carriers.

Using GAMS, as a mathematical programming software, two models were developed. To define the base energy generation, conditioned by variable and fixed costs, a base model was established taking into account natural gas and biomass as a fossil energy source combined with on- and off-shore wind as renewable energy sources.

The modeled energy system has been extended to implement electric vehicles using the batteries of the electric vehicles as a flexible energy storage. This was done in respect to the electricity demand of the electric vehicles to ensure operational readiness for the fleet based on estimated driving patterns.

To proof both models upon their robustness towards changes of input parameters a sensitivity analysis was carried out with the results being discussed in the end of this paper. The system robustness was checked with changing variable and fixed costs of different generation technologies investigated.

2 Methodology and data base

The part of the Danish energy system was modelled by developing a optimization model. For the initial model, the energy generation natural gas, biomass and wind power were included.
In order to optimize the initial system, only the area of DK1 of the Danish electric grid was considered, ignoring any transmission capacity between DK1 and DK2. As the area is considered isolated, no import nor export to bordering regions are possible.
Advancing the system model further, an electrical vehicle (EV) fleet was implemented to be used as a flexible energy storage. The fleet was modelled so that it is not a stationary battery, but rather every vehicle is a functional car on its own, subject to specific driving patterns for each and every one.

Data for the initial analysis

The following text describes the data set used for the analysis, as well as the sources and type of input data. Base units used are MWh, MW, monetary units - DKK and Eur, with the conversion ratio being 7,45 to 1.

The data and constants described here are used in base cases of both models - basic and with EV battery storage, with some of the parameters listed, varied in value for further investigation and sensitivity analysis of the study.

Electricity demand and time resolution

The model considers first one representing week of the year using an hourly resolution which leads to 168 time slots in the GAMS code. In an additional analysis the time frame was extended to one year to rule out seasonal changes.
The electricity energy demand in the region DK1 was retrieved from the Danish grid operator *Energinet* [2].

Wind profile data

In order to define the production of wind power, historic wind data were used. The wind profile data in the region DK1 were retrieved from Energinet [2]. To consider the whole production of wind energy, data from onshore and offshore production were added up.

Variable costs

Marginal variable costs for the technologies of wind power, natural gas and biomass were found for the model to define the electricity generation. Wind marginal costs were set to 0, as it does not cost more to produce additional amount of energy. Natural gas marginal costs were found to be 0.4 DKK/MWh [3]. This number was taken as an average of monthly marginal costs values for the year 2018. This assumption was made, as marginal costs are varying for every time period, and although projections could be made, it was found that in the two years span, natural gas marginal costs should plateau at 0.5

DKK/MWh value [4]. The marginal costs for biomass were set to 0.433 DKK/MWh [5].

Fixed costs

Following fixed costs for generation technologies investigated were used in the analysis. For conventional technologies of natural gas and bio mass, fixed costs per unit power deployed at the time step were 0.59 Eur/W and 3.4 Eur/W respectively. Fixed costs for wind were expressed as a monetary value of all the wind turbines installed in Denmark. For instance, according to DEA [1], there are installed 5000 MW of wind turbines and the fixed costs are, according to this document by DEA [6], 1.23 MEur/MW. So, the installed wind turbines can be valued as 6150 MEur, which when annualized considering a lifetime of 35 years, they are worth of 155 MEur/year.

Installed capacities

It is assumed that at the moment of investigation there is 5000MW of Wind turbine capacity installed on the DKK1 electrical grid [6]. It is assumed that the grid is stable and there are enough of conventional generation technologies present and functional, in order to absorb increased demand in case of lacking wind energy generation.

Limitations of the conventional generation technologies

Based on the research done for the conventional gas turbine and biomass combined heat and power technologies some physical limitation constraints are considered. The ramping up or down speed of 100% for gas turbine[7] and 60% of biomass CHP[8] of the generation unit capacity. The minimum running capacity was also implemented, being 23% for gas turbines and 50% for biomass CHP, to satisfy the limitation on minimum working capacity of the respective generation unit.

Emission price

The European emission system works after the "cap and trade" principle after which emission licences is traded on an exchange market [9]. Due to the market based fluctuations in the emission prices an average value of 25 per emitted tone of CO_2 was set and used for the model.

Information on electric vehicles and batteries

Some certain assumptions were made in order to generalize the parameters of vehicles present in the fleet used which got implemented in the second model.
It was assumed that all the vehicles, interacting with the electric grid, are using Li-ion batteries for the energy storage, as it is the most widely utilised technology, and most suitable for electric vehicle application, having best energy density per kilogram capacity [10]. As vehicles are having different battery capacity, it was assumed that each vehicle has a battery capacity of 70kWh, which corresponds to the

average battery capacity of different models of most popular electric vehicle on the market available - Tesla [11].
State of discharge for all the batteries was limited to 96% rate DOD (depth of discharge) to realistically preserve the longevity of the batteries [12].
With every charge and discharge cycle there are inefficiencies present in a process of energy level change. These inefficiencies influences the total amount of energy that can be put and extracted from the electric vehicle fleet and were set to a static value of 97% charging efficiency, while discharging was set to 86% as it is more rapid than the charging, having reduced efficiency [12]. The typical charge/discharge speeds for Li-ion batteries were set to be 0.5C[1] ratio for charging, and 2C for discharging, and used in the analysis [12]. As the size of the fleet used in the analysis was 6039 electric vehicles, charge rates were calculated to be 0.035MW, while discharge - 0.14MW.
Every electric vehicle in a fleet was assumed to be a functional car, following specific driving pattern, described by the kilometers, driven at specific hours, with change in pattern from weekdays to weekends. The total range of one vehicle with a full charge was assumed to be 420km [11], with 0.16kWh of energy used per 1km.

Pricing of EV storage

It is assumed that total battery capacity is an integral part of the grid, and does not get monetised for the usage of it, meaning that charging and discharging at will and availability is not priced.

[1]C-rate describing the rate at which a battery is discharged relative to its maximum capacity

3 Model description

In the following section the optimization model for production investment and economic dispatch is described. The explanation follows the mathematical expression, starting with the the sets, followed by the description of the variables, constants and equations.

3.1 Production Investment and Economic Dispatch without BEVs

3.1.1 Summary of sets

Symbol	Definition	Value
T	Time Units	1 hour resolution, 1 week length
$tech$	Controllable generation technologies	Gas Turbine, Biomass Power Generation

The set *time* is used to implement the time steps. The resolution for the model is in hourly steps.
The set *tech* is representing the traditional technologies natural gas and biomass, which are implemented in the model.

3.1.2 Summary of decision variables

Symbol	Definition	Unit	Set
cap_{tech}	Capacity of different generation technologies	MW	$tech$
$prod_{tech,t}$	Average power output during time interval	MW	$tech, T$
z	Percent of new wind turbine compared with installed	MW	
x_t	Wind curtailment	MWh over year	

The decision variables are: the capacity for the different energy technologies, the production, which is defined as the average output during one time interval, as well as the the scaling up of the wind generation, in percentage to the already existing capacity, were implemented.

3.1.3 Summary of constants

Symbol	Definition	Unit	Set
w_t	Historical wind power output of installed turbines	MW	T
d_t	Historical electricity demand	MW	T
a	Length of the time interval	hour	
c_{tech}^{fix}	Fixed cost per capacity of conventional generation technologies	DKK / MW	$tech$
$c^{fix,wind}$	Fixed cost per percent capacity of wind turbines	DKK / %	
c_{tech}^{var}	Production cost per unit output of different generation technologies	DKK / MW	$tech$
s_{tech}^{max}	Max percent of controllable increment power output	$\%$	$tech$
β_{tech}^{min}	Minimum percent of load percent of full load	$\%$	$tech$

As an input data for the model the historic data from the wind production were imported. The same was done with historic demand data from the region of DK1. To import data CSV files were generated and included in the model. This has been done to have the model defining on which technology should be invested. Additionally, information on the fixed and variable costs for every technology were researched and implemented in the code. On top of that the fuel costs for natural gas and biomass were implemented.

In the following table 3.1 the fixed and variable costs for each technologies which were used for the model are shown.

Technology	Fixed Costs [DKK / MW]	Variable Costs [DKK / MW]
Biomass	2541	0,433
Natural gas	441	0,4

Table 3.1: Fixed and variable costs for base model

Wind fixed costs have been described in the methodology section.

3.1.4 Base model

$$\min \quad \sum_t c_i^{fix} cap_{tech} + c^{fix,wind} z + a \sum_t tech \sum_t c_{tech}^{var} prod_{tech,t} \quad \text{(DKK)} \tag{3.1}$$

$$\text{s.t.} \quad cap_{tech} \beta_{tech}^{min} \leq prod_{tech,t}/a \leq cap_{tech} \quad \text{tech} \in Tech, t \in T \quad \text{(MW)} \tag{3.2}$$

$$\sum_t prod_t^{tech} \geq d_t - w_t \quad \text{(MWh)} \tag{3.3}$$

$$- s_{tech}^{max} cap_{tech} \leq prod_{tech,t+1} - prod_{tech,t} \leq s_{tech}^{max} y_{tech} \quad \text{tech} \in Tech, t \in T \quad \text{(MWh)} \tag{3.4}$$

1. The main goal of this assignment is to model a energy system in respect to total energy system costs and the integration of renewable energies. Thus, the main objective function 3.1 aims to minimize the total system costs by summing up the investment cost for each technology as well as capacity, the modelled production and variable costs.

2. The first constraint 3.2 makes sure that the average power production in one time unit is not exceeding the installed capacity.

3. The second constraint 3.3 is subtracting the wind power generation from the electricity demand. As wind power is a non-dispacable energy source and cant be used to cover the base load, the fluctuations in the generation are directly implemented in the model.

4. Constraint 3.4 is the constraint on the ramping speeds of different generations. Usually, the power of biomass power generations cannot be increased too much during one time interval, while the gas turbine can respond fast enough to any demand fluctuations.

After we get the result about power generation, equation 3.5 can be used to calculate the wind curtailment x_t [13]. It indicates how much generated wind power is wasted because of the lack of storage devices.

$$x_t = \sum_t prod_t^{tech} + w_t - d_t \quad \text{(MW)} \tag{3.5}$$

3.2 Production Investment and Economic Dispatch with BEVs

In a next step the base model was extended with the introduction of bettery electric vehicles (BEVs). In addition to the existing sets from the base model a set G was introduced to represent the groups of electric vehicles (EV).

3.2.1 Summary of sets

Symbol	Definition	Example
T	Time units	1 hour resolution, 1 week length
$tech$	Controllable generation technologies	Gas Turbine, Biomass Power Generation
G	Groups of electric vehicles	$EV1,..,EV20$

3.2.2 Summary of decision variables

Symbol	Definition	Unit	Set
cap_{tech}	Capacity of different generation technologies	MW	$Tech$
$prod_{tech,t}$	Average power output during time interval	MW	$Tech, T$
z	Percent of new wind turbine compared with installed	MW	
$u^{-}_{g,t}$	Discharge speed of every EV in group g at t	MW	T, G
$u^{+}_{g,t}$	Charging speed of every EV in group g at t	MW	T, G
$l_{g,t}$	State of every EV in group g at t	MWh	T, G
x_t	Wind curtailment	MWh over year	

To simulate the EV in the model three new variables were added to the base model. *U+* is to represent the charging speed of the EV group *g*. *U-* in regards is the discharging speed. To simulate the charging state of the EV group the variable *l* was introduced.

3.2.3 Summary of constants

Symbol	Definition	Unit	Set
w_t	Historical wind power output of installed turbines	MW	T
d_t	Historical electricity demand	MW	T
$d^{EV}_{g,t}$	Historical driving demand	MW	T, G
a	Length of the time interval	hour	–
b_g	Number of EVs in group g	–	G
c^{fix}_{tech}	Fixed cost per capacity of conventional generation technologies	DKK / MW	$Tech$
$c^{fix,wind}$	Fixed cost per percent capacity of wind turbines	DKK / %	
c^{var}_{tech}	Production cost per unit output of different generation technologies	DKK / MW	$Tech$
s^{max}_{tech}	Max percent of controllable increment power output	$\%$	$Tech$
β^{min}_{tech}	Minimum percent of load percent of full load	$\%$	$Tech$
$u^{-,\max}_{g}$	Max discharging speed of EVs in group g	MW	G
$u^{+,\max}_{g}$	Max charging speed of EVs in group g	MW	G
η^{-}_{g}	Discharging efficiency of EVs in group g	$\%$	G
η^{+}_{g}	Charging efficiency of EVs in group g	$\%$	G

In addition to the base model a number of constants had been added to simulate the behaviour of the EV. The constant ß was added to have the necessary threshold for the discharging level for the EV as in reality batteries have a certain value to maintain the life time.
Furthermore, constants were set to define the maximum charging and discharging speeds as well as efficiencies for both procedures.

The following table 3.2 shows the values for the fixed and variable costs implemented in the extended model.

Technology	Fixed Costs [DKK / MW]	Variable Costs [DKK / MW]
Biomass	800	0,2
Natural gas	441	0,4

Table 3.2: Fixed and variable costs for EV extension model

Furthermore, the values for the additional constants related to the EV are are displayed in the following table 3.3.

Constant	Value	Unit
Max. charging level	0,028	MWh
Min. charging	0,07	MWh
Charging speed for EV	0,035	MW
Discharging speed for EV	0,14	MW
Charging efficiency	94	%
Discharging efficiency	88,6	%

Table 3.3: Constants for electric vehicles

3.2.4 Model with electric vehicle implementation

$$\min \quad \sum_t c_i^{fix} cap_{tech} + c^{fix,wind} z + a \sum_j \sum_t c_{tech}^{var} prod_{tech,t} \quad \text{(DKK)} \tag{3.6}$$

$$\text{s.t.} \quad cap_{tech} \beta_{tech}^{min} \leq prod_{tech,t}/a \leq y_{tech} \quad \text{for } tech \in Tech, t \in T \quad \text{(MWh)} \tag{3.7}$$

$$\sum_t prod_{tech,t} + \sum_{g \in G} b_g \eta_g^- u_{g,t}^- \geq d_t - w_t * z + \sum_{g \in G} b_g u_{g,t}^+ \quad \text{for } tech \in Tech, t \in T \quad \text{(MWh)} \tag{3.8}$$

$$-s_{tech}^{max} cap_j \leq prod_{tech,t+1} - prod_{tech,t} \leq s_j^{max} y_{tech} \quad \text{for } tech \in Tech, t \in T \quad \text{(MWh)} \tag{3.9}$$

$$l_{g,t+1} = l_{g,t} + a u_{g,t}^+ \eta_g^+ - a u_{g,t}^- - a d_{g,t}^{EV} \quad \text{for } g \in G, t \in T/t_{max} \quad \text{(MWh)} \tag{3.10}$$

$$l_{g,t}^{min} \leq l_{g,t} \leq l_{g,t}^{max} \quad \text{for } g \in G, t \in T \quad \text{(MWh)} \tag{3.11}$$

$$u_{g,t}^+ \eta_g^+ \leq u_g^{+,\max} \quad \text{for } g \in G, t \in T \quad \text{(MW)} \tag{3.12}$$

$$u_{g,t}^- \eta_g^- \leq u_g^{-,\max} \quad \text{for } g \in G, t \in T \quad \text{(MW)} \tag{3.13}$$

$$u_{g,t}^+ d_{g,t}^{EV} = 0 \quad \text{for } g \in G, t \in T \quad \text{(-)} \tag{3.14}$$

$$u_{g,t}^- d_{g,t}^{EV} = 0 \quad \text{for } g \in G, t \in T \quad \text{(-)} \tag{3.15}$$

In addition to the base model the following constraints were added to simulate the EV extension. The constraint 3.10 is determining the charging level of the batteries with respect to the charging level of the previous time step.
With constraint 3.11 it is defined that the level of charging can not exceed the maximum / minimum battery level and must not undercut the lower boundary of the battery.
The equations 3.12 and 3.13 are constraining respectively the maximum and the minimum speed of charging to the upper / lower boundary of the charging speed.
Furthermore, the constraints 3.14 and 3.15 are stating that the EVs can not be charged or discharged while they are in use.

4 Results

4.1 Model without BEVs without Subsides

Firstly, the results for the base model without any subsidies are shown. The referring parameters, constraints and optimisation variable have been described in 3.1.4.

In table 4.1, the average values for the variables of the base model are shown.

objective, [DKK]	cap$_{gas}$, $[MW]$	cap$_{bio}$, $[MW]$	newwind, [%]	wind curtailment, [MWh over year]
5001299	2734.75	0	100	1453852

Table 4.1: Base Model variables without subsidies

While, in figure 4.1, it's shown how these variables are behaving over the first week of November. Wind $_{\text{total}}$ represents the whole wind production, while wind$_{\text{net}}$ is the injected wind production to power grids after the curtailment.

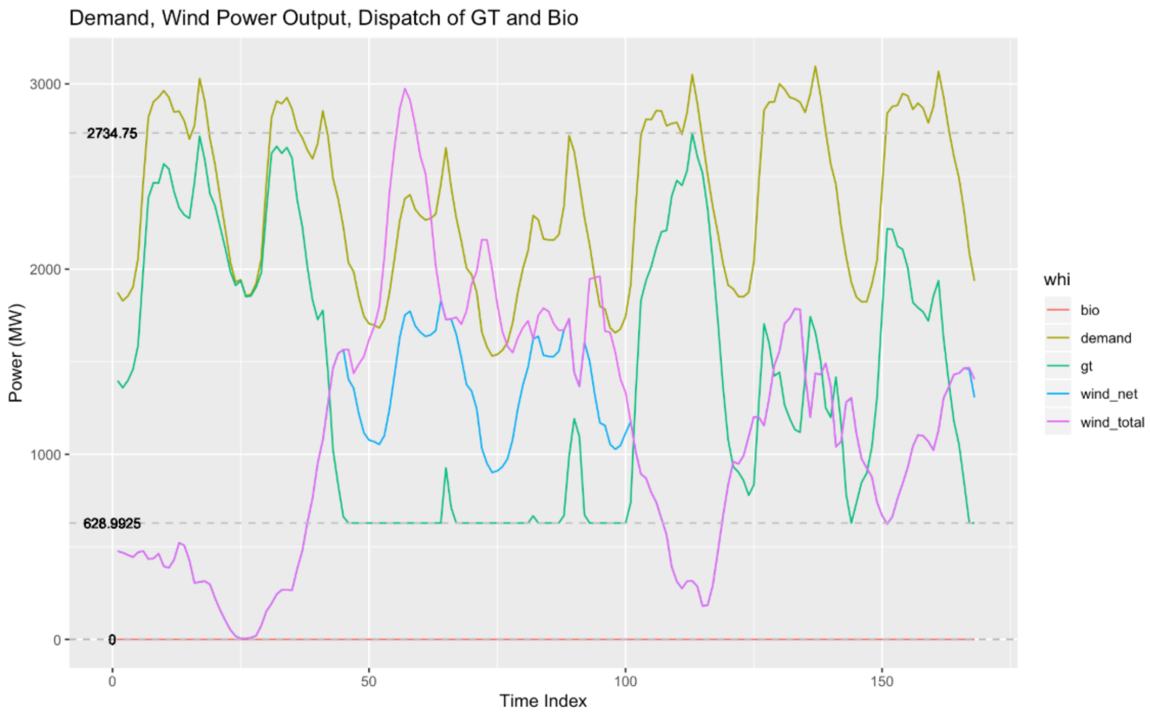

Figure 4.1: Base Model without subsidies

Biomass is not present since it's by far the most expensive technology for both fixed and variable costs. This problem has been addressed with subsidies in the improved version of the model.

So, the whole energy production is left to wind and gas turbines. After the two peaks on the demand, there are the two days for the weekend and it's evident that the wind is heavily curtailed over there. In the worst moment, $wind_{total}$ is reaching 3000 MW but $wind_{\ net}$ is around 1700 MW, so $wind_{\ curtailment}$ peak is 55%.

This happens because gas turbines are forced to be between 2734 MW and 626 MW, due to the ramping up / down constraints. So, during this first analysed week, wind production is both affected by the demand reduction during weekend and by the minimum power produced by gas turbines.

4.2 Model without BEVs with subsides

In figure 4.2 it is shown how the model is behaving with different subsidies which have been introduced in order to reduce the dependency on gas turbines. This choice has been made to push the system to invest more in biomass, which is considered a greener energy than gas, to better represent what the Danish government is planning to do in the next years.

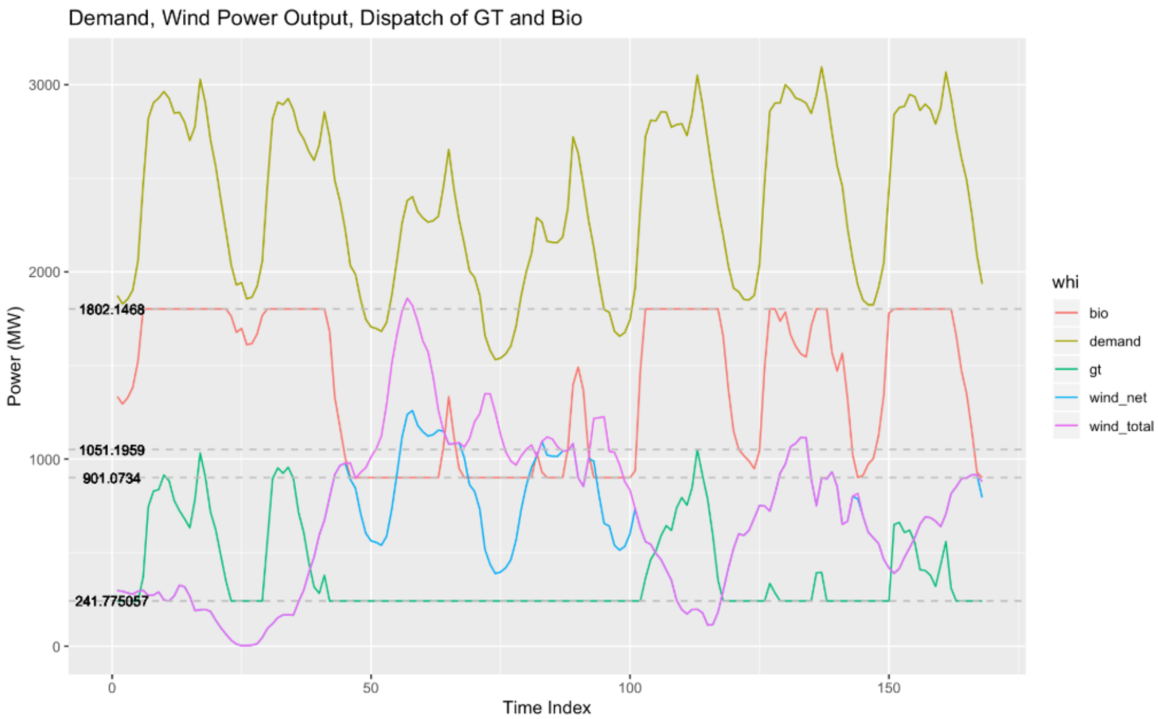

Figure 4.2: Base Model with subsidies

-	c_{bio}^{fix}	c_{bio}^{var}	c_{wind}^{fix}	c_{gt}^{var}
Unit	DKK/MW	DKK/MW	DKK/%	DKK/MW
Old	2541	0.433	10^6	0.4
New	800	0.2	$2.6*10^6$	0.5
Percentage	-30%	-46%	-26%	+25%

Table 4.2: The Constants with and without Subsides

objective, [DKK]	$\text{cap}_{gas}, [MW]$	$\text{cap}_{bio}, [MW]$	newwind, [%]	wind curtailment, [MWh over year]
8649843	1051.19	1802.14	62.49	4716997
+57%	-34%	inf	-38%	+300%

Table 4.3: Base Model variables with subsidies

Biomass costs have been reduced of 30%, so now the system finds economically viable to invest in this technology as well. This technology is constrained by s^{max} for bio, as stated into 3.1.3 and into 3.4. This is affecting the maximum and the minimum power output by biomass, which are respectively 1802 MW and 901 MW. In Denmark there is a high dependency on biomass and this can also be seen by this model where biomass is at least producing 901 MW.

In the analysed week, this is happening when $\text{wind}_{\text{total}}$ can potentially produce more than 1800 MW alone but the wind $_{\text{net}}$ is reduced to 1100 MW, so the curtailment is heavily present. This curtailment is much higher than the one present in base model without any subsidies, due to the new biomass presence which is constrained to a minimum of 901 MW while gas turbines are constrained at a minimum of 241 MW. In model without subsides, gas turbines were constrained to be at minimum 626 MW, see figure 4.1.

Gas turbines ramping up / down constraints are less stringent than biomass, this is evident looking at the slope when the gas technology is called by the system.

CO_2 costs haven't been touched because they are determined by the EU trading system [9]. As a consequence, the Danish government doesn't have a direct influence on that has it can be with the described policies.
Electricity prices are going to be constant at 0,2 DKK/MWh for the advanced model because they are decided by the biomass marginal costs. This means that the biomass producers are never going to make a profit out of their power plants. While, on the base model, electric prices are at 0,4 DKK/MWh and they are decided by the gas turbines.

4.3 Model with BEVs with Subsidies

Model results for a case with an electric vehicle fleet connected to the grid extension, as described in the model description section are presented in table 4.4.

objective	cap$_{gas}$	cap$_{bio}$	newwind	wind curtailment
DKK	MW	MW	%	MWh over year
8548432	708.74	1949.68	62.48	4634433

Table 4.4: Expanded model variables with subsidies

Time series plot of the power capacity utilised of different generators and electric vehicles acting as a battery. together with a demand profile are presented in figure 4.3.

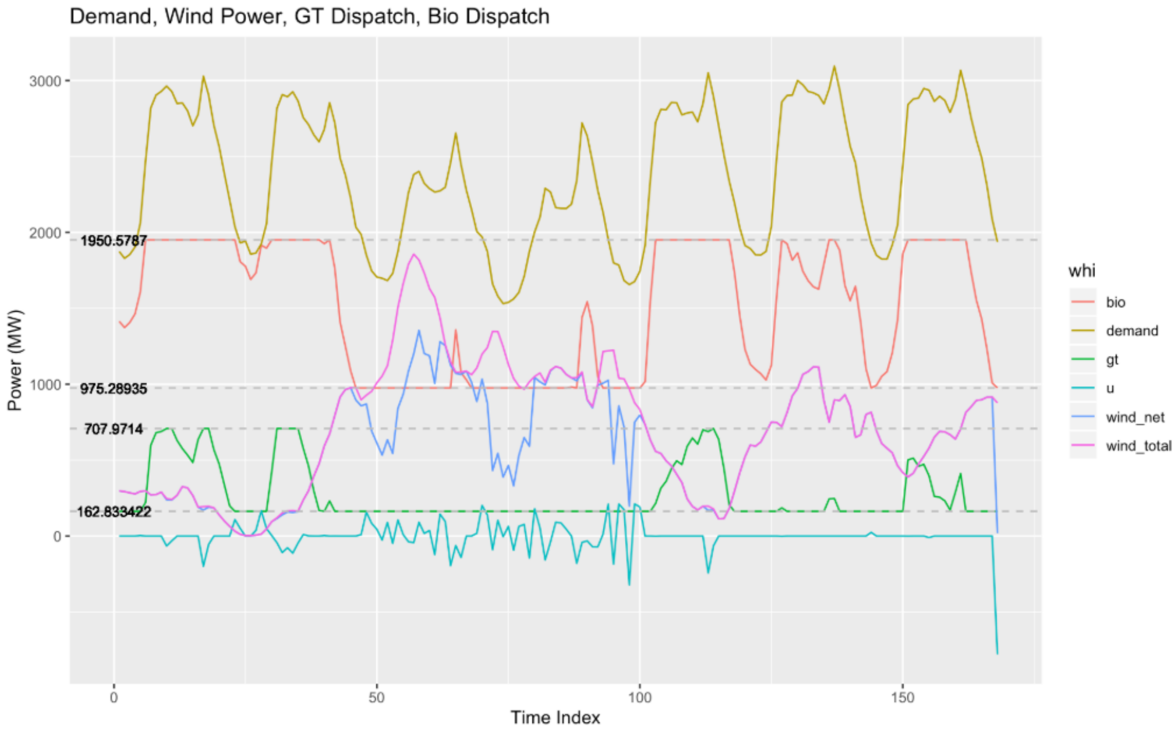

Figure 4.3: Model with Electric vehicles

As seen in the figure above the load of EVs acting as a battery have both positive and negative instantaneous power values. Positive values corresponds to the time slots when the EV battery array is feeding energy to the grid, where negative means that electric vehicles connected to the grid at that instance are charging.

Comparing the EV case with the base case with subsidies, we see that introduction of such type of battery storage, lowers the utilisation of the gas turbines, while energy generation from biomass increases. Introduction of the battery in the system, changes the dynamic of the system, allowing it to run more economically feasible generators.

Analysing EV charging-discharging and wind curtailment interdependency further, as can be seen in figure 4.3, it could be observed, that electric vehicle battery storage is being utilised with the abundance of wind in the instances where there is a curtailment happening, meaning the two systems are coupled and have potential to absorb the surplus wind energy, but as argued above, the fleet of EVs should be greatly expanded to allow the appearance of such positive effect.

4.4 Model using One-Year Data with subsidies

In addition to the analysis with a time frame of one week simulations were run to model the behaviour within a whole year. The seasonal fluctuations can be considered, such as higher demand and higher production from wind energy in winter, compared with lower values during summer months.

The results are lay out in the two tables below, for the model without EVs 4.5 and the one with EVs 4.6.

objective	cap_{gas}	cap_{bio}	newwind	wind curtailment
DKK	MW	MW	%	MWh over year
8121686	2103.12	1078.09	68.44	5042755

Table 4.5: Base Model variables with subsidies for one year

objective	cap_{gas}	cap_{bio}	newwind	wind curtailment
DKK	MW	MW	%	MWh over year
8012378	1733.29	1216.46	67.90	4977200

Table 4.6: Expanded model variables with subsidies for one year

Results of the extended timeframe case compared to the base case, provides different results than results of one week timespan, showing the possible missrepresentation of one week analysis approach on the greater trends of the system.

Looking into the objective function output value, it is seen that for both subsidised market model cases, with and without EV, objective is lower for one year simulation that for the respective model analyses of the the one week. This means, that total price level of system varies from one week to another, however relation, that implementation of EV into the system lowers the price of the system, is still valid.

Another observation comparing the results of different timeframed models, is that with more time, optimal wind capacity expansion is bigger, meaning, that wind is viable option for addition into the generation pool both in short and long timeframes.

Looking into the dispached capacities, for longer time frame, gas turbine gets utilised more than biomass CHP generation, compared to the one week model result, meaning that even with subsidy, gas turbine, due to its flexibility as described in the model constraints, is a very valid generation option in system.

Average wind curtailment, comparing the two timespan cases does not drastically change in value, meaning that the curtailment problem can be reflected using the model with one-year data.

5 Sensitivity analysis

Some performance metrics may be very sensitive to the parameters in the model, so the sensitivity analysis is conducted to explore the sensitivity of objectives, wind curtailments, capacity of gas turbines, capacity of biomass power plants and capacity of newly installed wind turbines to fixed cost of wind turbines, variable cost of gas and biomass and number of BEVs.

5.1 Sensitivity to Fixed Cost of Newly Installed Wind Turbines

Base model

For the first sensitivity analysis the fixed costs of wind were varied by ± 5%, looking from the base case number $2.6[MDKK/\%] \pm 5\%$.

Looking at the results in 5.1 it can be stated that the most sensitive variable is the installed gas capacity, represented by y_{gas}. While the objective function, the system costs, is slightly affected by the changes.

	curtailment	obj	y_bio	y_gas	z
+5%	+2%	0%	+3%	-6%	-2%
-5%	-4%	0%	-1%	+3%	+4%

Table 5.1: Sensitivity analysis - wind fixed costs base case

The following plot shows the changes in a graphically way, with the middle line representing the base case $\pm 0\%$, positive variable change towards the right end and negative variable change towards the left end of the plot.

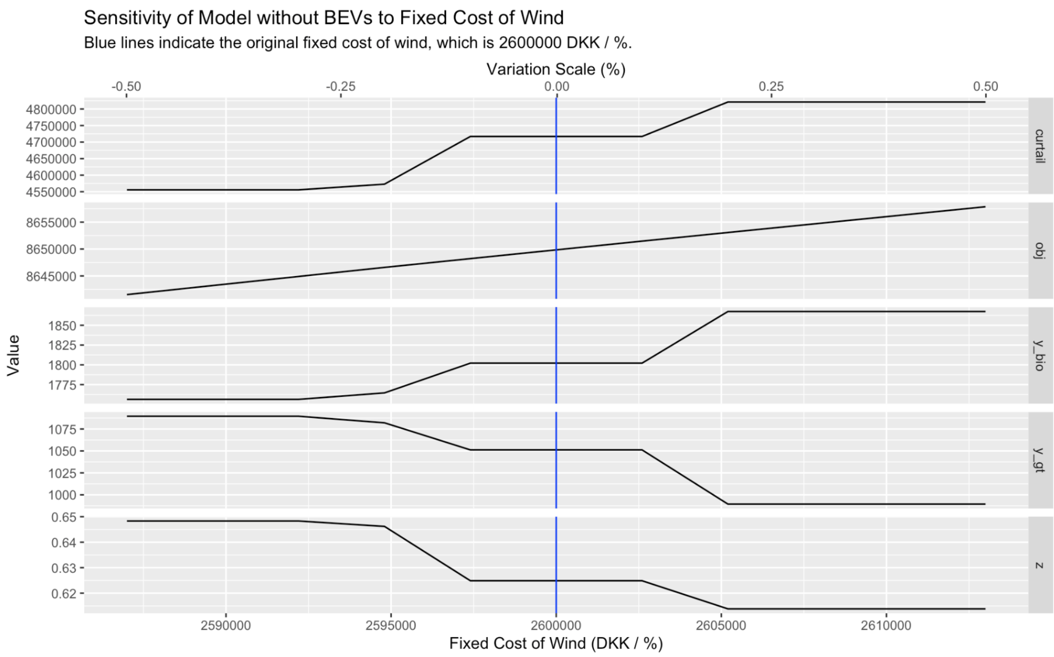

Figure 5.1: Sensitivity analysis of fixed costs for wind turbines

Model with BEVs

After carrying out the first sensitivity analysis the wind fixed costs were analysed on their robustness, this time for the extended model with electric vehicles. The results for the changes with a change of $\pm 5\%$ are shown in the table below 5.2.

	curtailment	obj	y_bio	y_gas	z
+5%	+0%	0%	+1%	-2%	0%
-5%	-1%	0%	-2%	+4%	+1%

Table 5.2: Sensitivity analysis for wind fixed costs in the advanced model

Furthermore, the results of the sensitivity analysis are layed down graphically in the following plot 5.2.

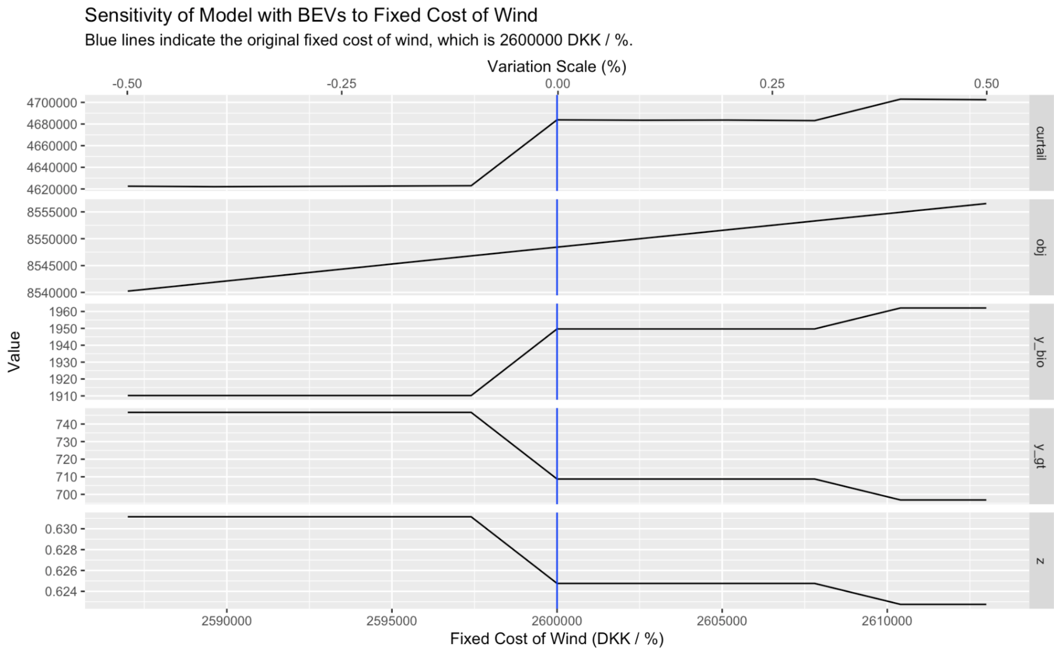

Figure 5.2: Sensitivity analysis of wind fixed costs with electric vehicles

It can be seen that the model after the introduction of BEVs is more robust towards the variation of the wind fixed costs, when the results from both steps are analysed. This improved robustness is probably due to the higher demand and flexibility from energy storage.

5.2 Sensitivity to Prices of Natural Gas

Model without EVs

Fuel costs in base model have been tested with a variation of gas fuel prices of $0.5[DKK] \pm 5\%$. In 5.3, it can be seen that the installed capacities for both gas and bio are really sensible about a small increase in the price. On the other hand, a decrease on this price is not affecting the installed capacity that much. Wind installed capacity is more robust that the other two technologies.

	curtailment	obj	y_bio	y_gas	z
+5%	+4%	0%	+8%	-14%	-3%
-5%	-1%	0%	-3%	+5%	+2%

Table 5.3: Sensitivity analysis for gas prices in base model

Model with EVs

Looking at figure A.3, where the sensitivity analysis is conducted for the advanced model and 5.4. Installed gas capacity is far more sensible to natural gas prices, compared to the base model. This is true also for the new installed wind capacity, called z.

	curtailment	obj	y_bio	y_gas	z
+5%	2%	0%	9%	24%	-6%
-5%	-2%	0%	-3%	-21%	2%

Table 5.4: Sensitivity of Model with BEVs to the Prices of Natural Gas

5.3 Sensitivity to Prices of Biomass

Model without EVs

Another sensitivity analysis was carried out looking at the robustness of the model in respect to the fixed costs of bio fuels. Once again the input value was changed by $0.433[DKK] \pm 5\%$.

	curtailment	obj	y_bio	y_gas	z
+5%	-6%	0%	-8%	+10%	+6%
-5%	+4%	0%	+8%	-5%	-3%

Table 5.5: Sensitivity analysis for bio prices in base model

The results for the sensitivity analysis plots can be find in the appendix A.4 and A.5.

Model with EVs

After conducting the sensitivity analysis on the base model the extended model was checked on robustness for the change of fixed costs. The results are layed out in the following table 5.6.

	curtailment	obj	y_bio	y_gas	z
+5%	-5%	0%	-8%	+11%	+4%
-5%	+5%	0%	+8%	-6%	-2%

Table 5.6: Sensitivity analysis for bio prices in EV model

5.4 Sensitivity of Model with EVs to Number of EVs

Sensitivity analysis for the model was done, checking the number of electric vehicles influence on the decision variables investigated. The results are summarised in the table 5.7. The number of vehicles was varied with a multiplier of 0, 1, 2, 3. The values are shown in the figure 5.3.

	curtailment	obj	y_bio	y_gas	z
+100%	-1%	-1%	-1.2%	-1.2%	+2.4%

Table 5.7: Sensitivity analysis for number of electric vehicles

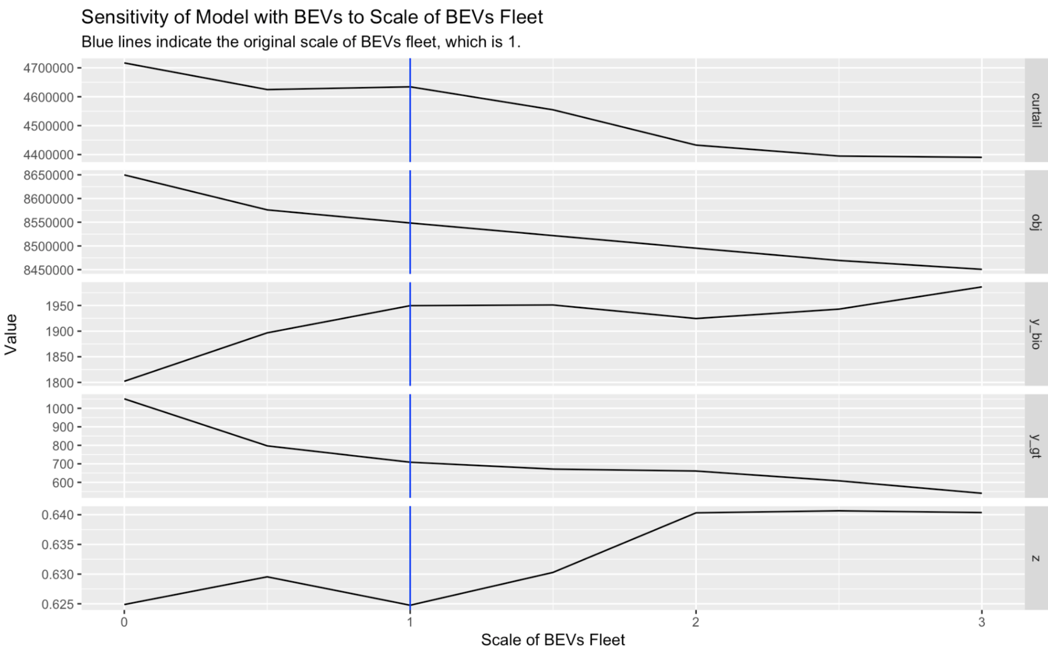

Figure 5.3: Sensitivity of Model with EVs to Number of EVs

As it has been mentioned in the result section for the extended version, electric vehicles have a positive effect on the reduction of wind curtailment. So though the number of wind turbines is increasing, the curtailment is decreasing with more and more BEVs. Because the system is more flexible, the need to ramping up and down the power generation is not that urgent, so more biomass power plant can be added to lower the cost. Additionally, the introduction of BEVs can lower the system costs, because the cost of BEVs is not included in the objective function.

6 Discussion

6.1 Wind curtailment

In a system which is highly dependent on wind and renewable energy generation, wind curtailment weakness can be mitigated after a few years through the expansion of transmission networks and market design and optimization. This option has to be evaluated for this system, because already a value of 10% for wind curtailment is alarming [14].

This problem could have been avoided constraining the curtailment so adding an extra level of refinement. For instance, in [13], the authors are using this equation:

$$\sum_{t=1}^{T} w_c(t) \leq K_c \times \sum_{t=1}^{T} wg(t) \tag{6.1}$$

Where w_c (t)is the wind curtailment at time, k_c is the proportion of the wind power that can be curtailed in one year and wg(t) is the wind power production. In this way, an extra term of flexibility is added in the system because it can include 1-K_c x wg(t) in the considered time length.

It's worth to mention that, in this paper, electricity prices have been taken into account while in this model they haven't been considered and the optimization has been conducted only considering fix and variable costs, see 3.1.3

6.2 Biomass - Base load

Biomass is in reality considered to be a base load energy, as reported by [15]. Base load is typically at 30-40% of the maximum load, so the amount of load assigned to base load plants is going to be tuned to that level. The main characteristics of these plants are cost efficiencies, as well as slow response time. In this model, biomass is able to change of 50% in a short period of time, so this technology is not representative of its real alias.

Also Denmark is changing, before 2023, its coal power plant, which are a base energy plant, into biomass fuel, as reported into [16].

6.3 Time frame

The time frame analysed in the base model contains of one representative week from one year. Representing one week during the early winter in November with a higher wind power generation and increased demand. In order to have reliable and robust results it would be necessary to investigate rather larger time frames as it was done with modelling one year. However, for even more precise results, more years could be investigated, with changing wind profiles.

6.4 Electricity prices

In reality the electricity price is underlying fluctuations, sometimes within the time frame of seconds. This is due to the fact that the electricity price is not only depending on generation and demand but is also determined by the electricity exchange and speculators on the market. These fluctuations are however neglected in this calculations. This is especially decisive looking at the charging cycles of the implemented electric vehicles. In reality electricity will mainly be charged in times with a low market price to be re-released in times of high prices to gain profits. To model this behaviour would exceed the frame of this paper and was thus neglected.

6.5 EV battery predictability

Using the battery of electric vehicles as energy storage comes with a few disadvantages which needs to be addressed. Firstly, one single EV is not able to hold a noteworthy amount of energy, only combined with a great number of EV this kind of storage can be seen as a serious option. Secondly, the problem with using EV as a storage is the predictability. As EV can just be used as storage when connected to the grid, meaning not driving, the available capacity is changing, this counts especially for rush hours when a lot EV are in use.

6.6 Diversification effects on generation capacities and wind utilisation

With the results analysis of models done, it was noted that for a system to be flexible, it must have a diversification of the energy generation technologies available. Under model investigated, addition of biomass subsidy, introduces it to the generation dispatch, however the inherent minimum running capacity value of the technology, reduces the flexibility of the system to utilise cheaper alternative energy generation, such as wind in the investigated case, as without biomass generator, wind can not cover the demand alone. This sows the importance of generation technology diversification not only in different price levels, but in technological capabilities as well, in order for the grid to be reactive in effective way under many different and changing scenarios.

6.7 Additional constraints on EV case

In the models investigated it was assumed that system does not incur any prices of using the battery storage of electric vehicles connected to the grid. It could be argued, that this argument is flawed, as the EVs are privately owned assets, which with every charge-discharge cycle looses the energy storage capacity of their batteries. This decrease in storage potential degrades the value and longevity of the asset, therefore it is only reasonable, that private owner would not let the electrical grid operators use the storage for free. This potential price for storing the electrical energy would change the price dynamic of the system, as it might not be economically feasible to store energy surpluses at some timesteps.

Additionally, it also could be argued, that the electric vehicles implementation in the model, should have additional constraints, describing the user expectations for the minimum energy available at all times in a more diversified way. Meaning that the current set minimum battery capacity value might not be representing the true case, and battery total storage value is reduced. These constraints are not present in model, therefore the model is lacking in this regard.

7 Conclusion

The models developed were used to attempt emulation the Danish electrical energy system. This objective has been reached implementing three different technologies in the base model: wind turbines, gas turbines and biomass power plants. Constraints were ensuring that the demand was met at every time step as well as the ramping up and down times for the power plants and wind curtailment.

Then, a fleet of electric vehicles with their own driving patterns during a week has been introduced. The following indicators from the model output have been analyzed:

1. Overall system costs
2. Newly installed capacity of gas turbines and biomass power plants
3. Newly installed capacity of wind turbines
4. Production of gas turbines and biomass power plants
5. Wind curtailment

The base model has been improved with possible subsidies to incentives the usage of biomass, but this negatively affected the system cost and the wind curtailment.

The advanced model is building up on the base model equations, variables and constrains. Additionally, the demand constraint has been changed adding the charging and discharging status for the electrical batteries and the constraints not being able to drive while the vehicle is using a power station. Furthermore, maximum and minimum levels for the battery status, efficiency as well as charging speed were implemented.

Finally, a sensitivity analysis has been performed to prove the different factors on their robustness for the system.

The more BEVs there are, the more flexible the system is. We find that the wind curtailment can be reduced with the introduction of BEVs, so more and more wind turbines can be built to lower the operation cost. Besides, more less flexible biomass power plants can be invested instead of expensive gas turbines.

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A Appendix

A.1 Model results with EV without subsidies

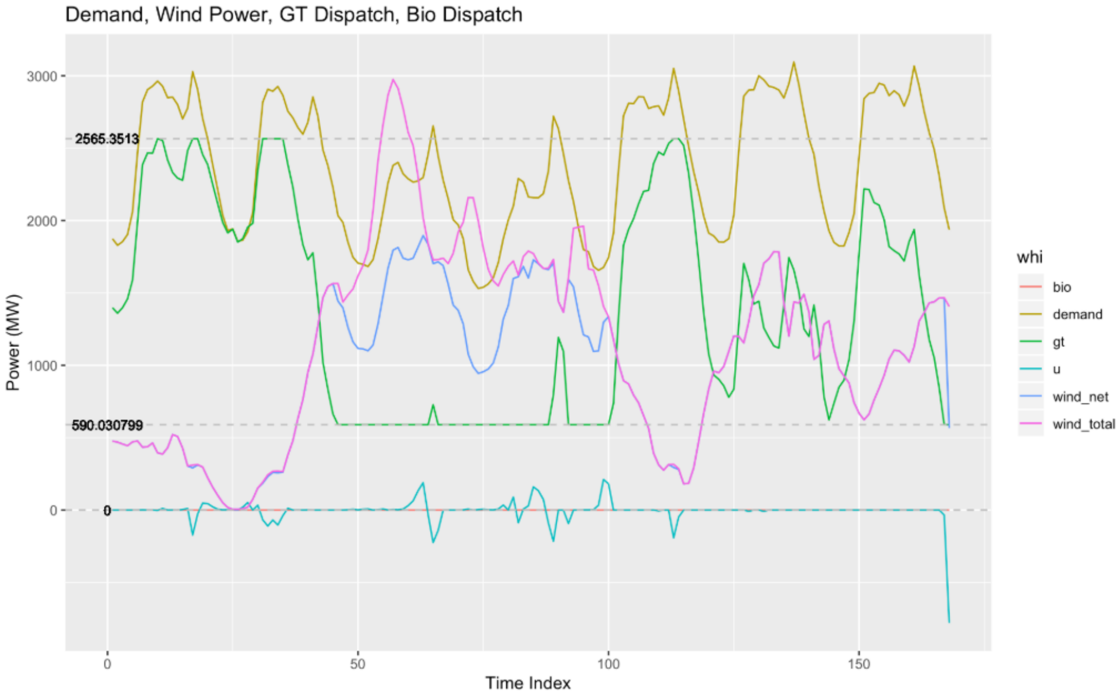

Figure A.1: Model with Electric vehicles without subsidies

Opt Variable	cap_{gas}	cap_{bio}	newwind%	average wind curtailment
4931940	2565.35	0	1	22166437

Table A.1: Model variables without subsidies

A.2 Graphs of sensitivity analysis

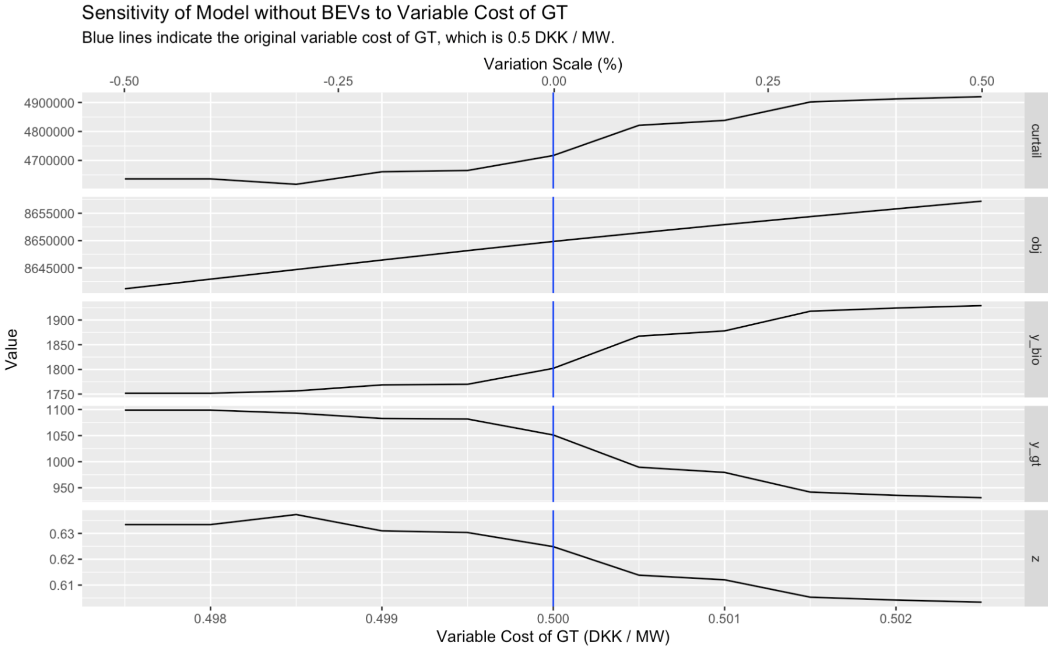

Figure A.2: Sensitivity analysis - variable costs gas turbine, base model

Plot A.2 shows the sensitivity analysis for the variable costs of natural gas in the base model and figure A.2 shows the related trends.

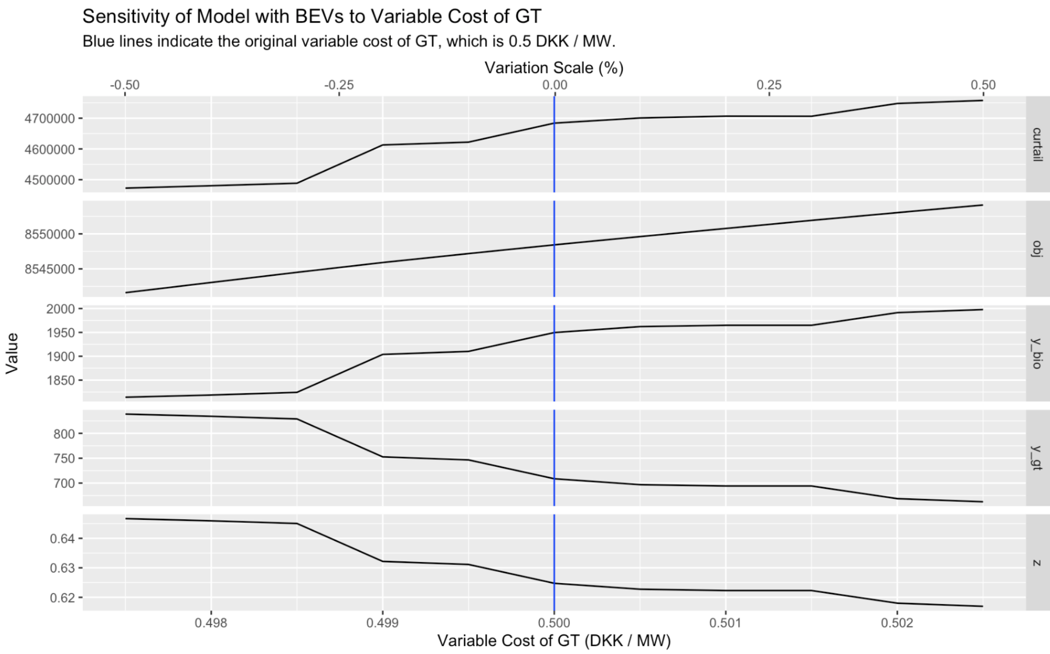

Figure A.3: Sensitivity analysis - variable costs gas turbine, EV extension

Plot A.3 shows the sensitivity analysis for the variable costs of natural gas in the extension model.

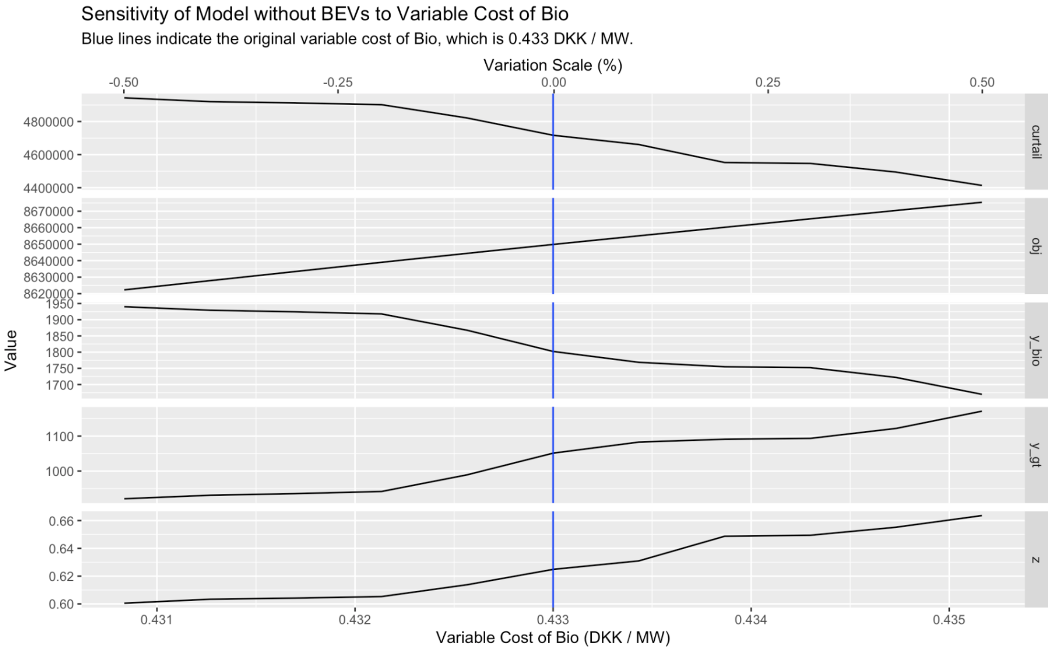

Figure A.4: Sensitivity analysis - variable cost biomass, base model

Plot A.4 shows the sensitivity analysis for the variable costs of bio mas in the base model.

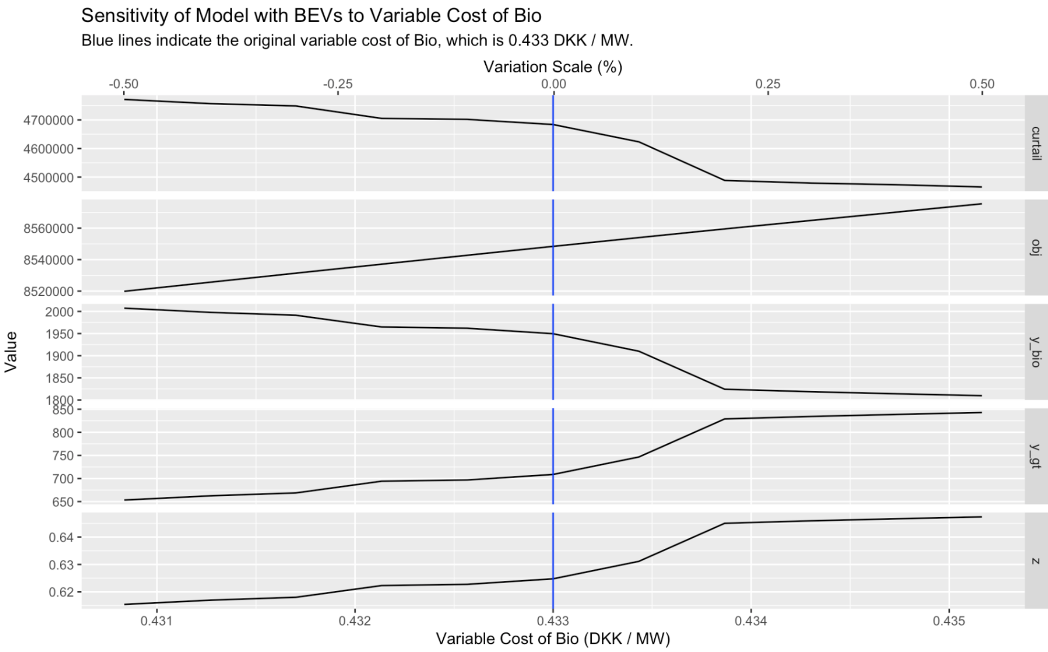

Figure A.5: Sensitivity analysis - variable cost biomass, EV model

Plot A.5 shows the sensitivity analysis for the variable costs of bio mas in the extension model.