University of Southern Denmark

Electrification of the Danish car fleet:
An integrated and dynamic analysis of the material-energy-emission nexus for transportation transition

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BACHELOR THESIS

Authors:	*Supervisors:*
Mathias Sølvbjerg Andersen	Gang Liu
Christopher Håkansson Larsen	Kasper Rasmussen

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Mathias Sølvbjerg Andersen - 92412169

Christopher Håkansson Larsen - 92412779

Abstract

This study aims to make a dynamic analysis of the CO_2 emissions associated with electrification of the Danish car fleet from 2020-2050 when considering the whole material-energy-emission nexus. Within the vehicle system, the future stock of EVs and ICEVs are predicted, and the replacement of EVs are incorporated to asses the inflow of EVs every year. In the energy system, different scenarios for expansion of electricity production capacity are created to supply the EVs electricity demand, and the material system then includes the necessary material for building the needed capacity and the future car fleet. This way, the emissions from production of EV batteries, mining, and refining of materials, and electricity production are all accounted for. The study finds that although electrification of the car fleet initially will result in higher emissions, the annual emissions will after 4-12 years be lower. Long term, the annual emissions are even found to be between a quarter, and half of what a car fleet entirely of ICEVs would emit. The most significant contributors to the total emissions are proved to be the batteries for EVs and electricity production; however these emissions can be reduced significantly. The study also shows the minor influence emissions regarding material extraction have on total emissions. Electrification of the Danish car fleet will also have negative implications such as premature retirement of ICEVs, but considering the substantial reduction in yearly emissions, it is deemed necessary to ensure a sustainable future.

List of Abbreviations

CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DEA	Danish Energy Agency
EOL	End of life
EV	Electric vehicle
GHG	Greenhouse gasses
ICEV	Internal combustion engine vehicle
Kg	Kilogram
LCA	Life cycle assessment
kWh	Kilowatt hour
MWh	Megawatt hour
TTW	Tank-to-wheel
TJ	Terajoule
SDG	Sustainable development goals
SUV	Sport Utility Vehicle
PV	Photovoltaic system
WTT	Well-to-tank

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1. Introduction

In January 2016, the United Nations Development Programme's (UNDP) sustainable development goals (SDG) came into effect. The SDG consists of 17 different goals that, according to the UNDP are a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity [56]. Considering the transport sector it is a part of the solution to three of the SDG, being affordable and clean energy, responsible consumption and production, and climate action. Emissions from the transport sector alone are responsible for 22% of all emissions in Denmark [2]. Although improvements in efficiency over the years have taken place, the burning of fossil fuels is not part of the solution to any of the SDG. Therefore a paradigm shift is needed within the transportation sector in the transition to a more sustainable system. Electric vehicles (EVs) are expected to play a critical role in the future transportation system, as there are no direct emissions from EVs, but there are other factors causing high emissions, such as battery manufacturing.

To accommodate this critical paradigm shift and work towards achieving the SDG, Denmark has constructed national goals. Among many, this includes political goals for the future within the transport sector and future emissions, and some of these goals will be incorporated into this study as projections for the future. There are two goals essential to the dynamic and integrated analysis in this study. Firstly a statement from the Danish prime minister, Lars Løkke Rasmussen, specifying a goal of Denmark having one million EVs in the transportation sector by 2030 [6]. Secondly, a political goal of Denmark being independent of fossil fuels, including the transportation sector, in 2050 [11]. This independence of fossil fuels would result in a very different transport system with EVs making up the majority of this future system. Therefore, it could be of interest to further study the effect of implementing EVs.

Previous studies about EVs have focused on the environmental impact of EVs by performing life cycle assessments (LCA). Two studies [34, 44] focuses on the greenhouse gasses (GHG) from the manufacturing of the vehicles and the production of electricity. They find that the majority of emissions are generated in the production phase of the EVs and that batteries have the greatest impact. A more extensive study regarding the GHG emissions from batteries has been conducted, showing that around 50% of the emissions coming from batteries is due to the manufacturing phase. This suggests that recycling of batteries could reduce their carbon footprint, but since vehicles require a certain quality of batteries, they are no longer considered good enough when less than 80% of the initial capacity remains [50].

Other studies [8, 33] have analysed the life cycle GHG when using larger batteries and increasing the lifetime of the EVs, as well as the effects of different electricity mixes in the use phase of EVs. The size of the battery is found to have a significant impact on the life cycle GHG, ranging from 38 gCO_2/km in a 41 kWh battery to 91 gCO_2/km in a 100 kWh battery, compared to 120 gCO_2/km and

217 gCO_2/km in similar internal combustion engine vehicles (ICEVs). Furthermore, the electricity mix is found to have the most significant impact on the total emissions from the EVs, especially the electricity mix used to manufacture batteries. Regarding the electricity for charging, the electricity produced in Europe is becoming greener rapidly [20]. It is not quite the same story for the countries manufacturing EVs and batteries, where a country like China is only slowly decreasing their CO_2 emissions per produced kWh [61]. So in order to reduce the carbon footprint of EVs, the development in the electricity mix is a crucial factor.

Reviewing other research similar to this study, it all points towards battery manufacturing as the primary contributor to emissions associated with EVs, but also the electricity mix is a vital area where improvements are possible. However, these previous studies only focus on comparing a single EV model to an ICEV model, and some aspects, such as the material system, are not considered at all. Therefore, this project aims to not only analyse the emissions from batteries and energy production, but assess the whole material-energy-emission nexus, regarding the vehicle system, the energy system, and the material system. Materials include the materials necessary to expand the electricity production capacity as more EVs enter the vehicle system and to do this, a dynamic analysis of the emissions is carried out. Additionally, an integrated analysis of the future EV stock in Denmark, as well as the total car stock, will be made and applied to the dynamic analysis.

Ultimately, this project aims to assess the emissions associated with the electrification of the Danish car fleet. Previous studies have not yet considered the aspect of expanding the energy system, but in this study, the emissions caused by the expansion are incorporated. This will result in a dynamic analysis comparing emissions caused by a car fleet consisting of EVs to the emissions from the same car fleet only consisting of ICEVs. The emissions from EVs will include emissions from battery manufacturing, and emissions from electricity production like other studies have done. Furthermore, the emissions from the material system will be included. A car fleet of EVs will increase the electricity demand significantly, and thereby an expansion of the production capacity is necessary. This expansion will require materials and the emission from mining, refining, and processing of the materials can then be led directly back to the EVs, as the extra production capacity would otherwise be unnecessary.

2. Methodology

2.1 Model overview

Before going into depth with the methodology behind this study, an overview of the whole model can help to understand the various analyses and calculations better. To illustrate the model and clarify the systems in this study, a model overview is presented in figure 2.1. This figure also serves as an example of the material-energy-emission nexus, which this thesis revolves around.

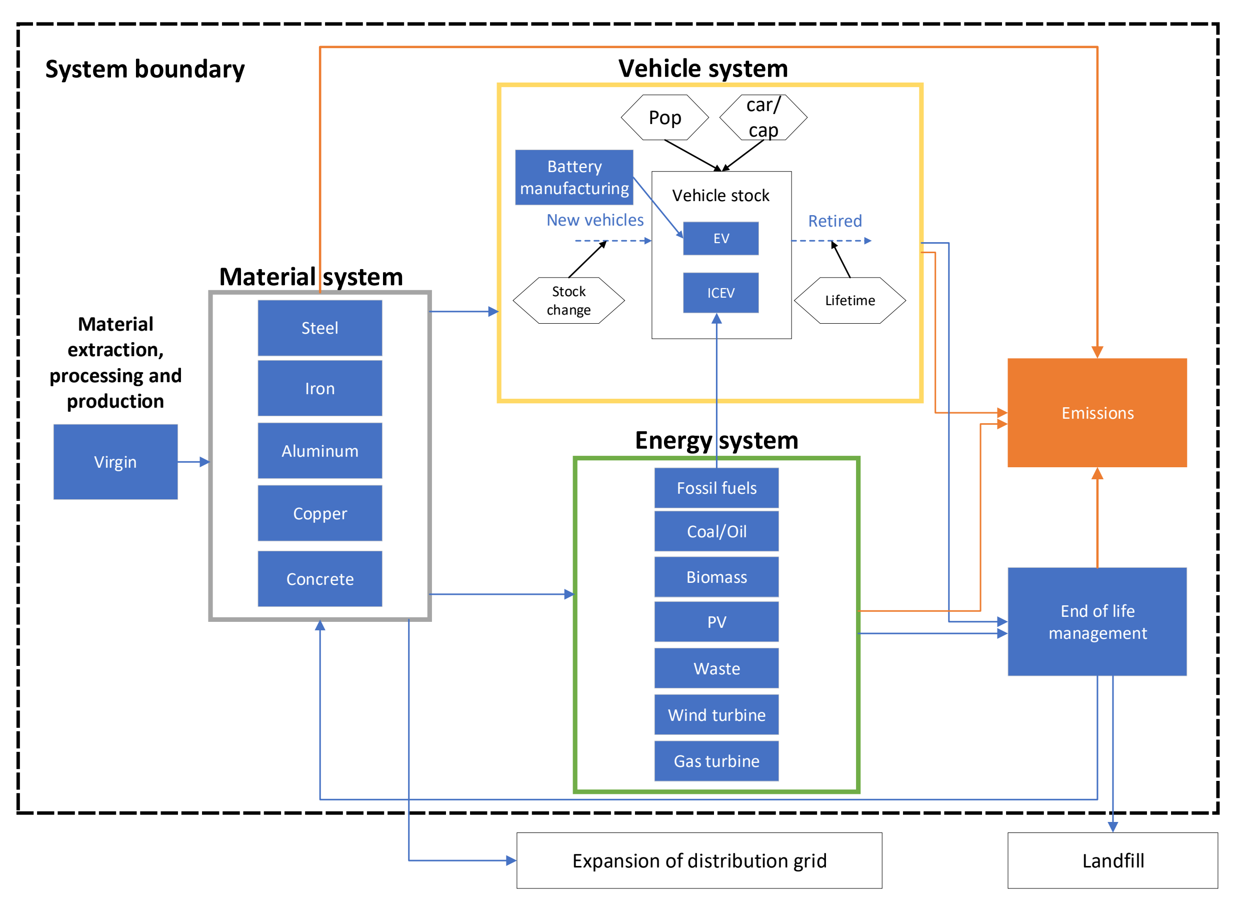


Figure 2.1: Model overview for this study, with hexagons representing drivers, blue arrows material flow and orange arrows emissions analysed.

In the figure, a system boundary is defined, describing where the focus of this study lies and what is excluded. Moreover, the material, vehicle, and energy systems are defined to easier analyse the impact of the individual systems. The hexagons represent drivers which the inputs are dependent on, the orange arrows represent emissions, and the blue arrows represent a flow of material.

The model is built around five different bulk materials, found to constitute the majority of the total weight of the technologies analysed. These materials are steel, iron, aluminum, copper and concrete and both the use of virgin and recycled material is analysed. Other materials are not included as the emissions from these are deemed to have a minor effect on the total emissions from materials. When using virgin materials, the emissions from extraction, processing, and production of the materials are taken into account. When using recycled material, the emission is naturally lower, since no extraction of the material happens. The materials are then used in the vehicle system and energy system.

In the vehicle system, different drivers have been located that play a vital role in development. For the vehicle stock, the population, and cars per 1000 capita are drivers that can be directly translated to how the car fleet develops over time. The car fleet in this model is assumed to consist of only ICEVs and EVs. Therefore the ICEV stock is based on total stock and EV stock. This makes the change in stock the driver for new vehicles. The driver for retired vehicles is the lifetime of vehicles. Evaluating the emissions from the vehicle system, they are solely from battery manufacturing to EVs and fossil fuels, coming from the energy system, for ICEVs. In the energy system, the only emissions in the use phase are coming from coal, oil, waste and gas, as the remaining technologies are based on renewable energy.

At the end of life (EOL) management, an analysis is carried out to assess the benefits of recycling material. The emissions saved are dependent on the recycling rate of each material and the emission factors when using recycled material. Landfill and the impact this has on the ecosystem are not accounted for, as it is outside the scope of this analysis.

An overall increase in energy production and demand from EVs could also lead to an expansion of the distribution grid, although this is outside the system boundaries for this study. The reason for this is discussed in section 2.4 i.e., it is shown that the charging of EVs can be done without the need for expansion when considering only household consumption.

In the following sections of the methodology, a detailed description of the elements within the model is given. The dynamic model will be applied over 30 years ranging from 2020 until 2050.

2.2 Scenario descriptions

Predicting the future can be a challenging task, so in order to analyse a variety of possibilities, different scenarios are constructed. The scenarios in this study cover future electricity production as well as the EV implementation in Denmark. They are constructed based on variables such as consumer patterns from countries with an already established EV industry and already existing scenarios for the Danish energy production in the future.

2.2.1 Energy system scenarios

As EVs are implemented in the vehicle system, the electricity demand increases, which results in the need to build extra production capacity. This capacity can consist of many combinations of production technologies so different scenarios has to be constructed. Therefore, the first scenarios in this study cover the distribution of energy producing technologies for supplying the EVs power demand. Two scenarios are based on the energy scenarios for 2050 made by the Danish energy agency (DEA), and one scenario is made to be the same as the production distribution in Denmark today. The two scenarios chosen from the DEA are the wind- and biomass scenario [11]. In DEA's energy scenarios, the capacity of different energy-producing technologies are listed with the corresponding full load hours. From this, the production fraction can be calculated for each technology, and this production fraction is the basis of the energy production scenarios in this study. Even though the same capacity of some technologies is installed in the scenarios, it does not necessarily mean they have the same production fraction. This is because the DEA's scenarios also include the heating sector in their calculations, so the total electricity production is not the same. For the scenario as of today, the fraction for each production technology is calculated based on the production in Denmark in 2018 [24]. This scenario is not a prediction for the future energy production, but to assess the effect of not making the transition to a renewable energy system.

The distribution of electricity production in each scenario is illustrated in Figure 2.2, and the exact data used, is listed in appendix A.

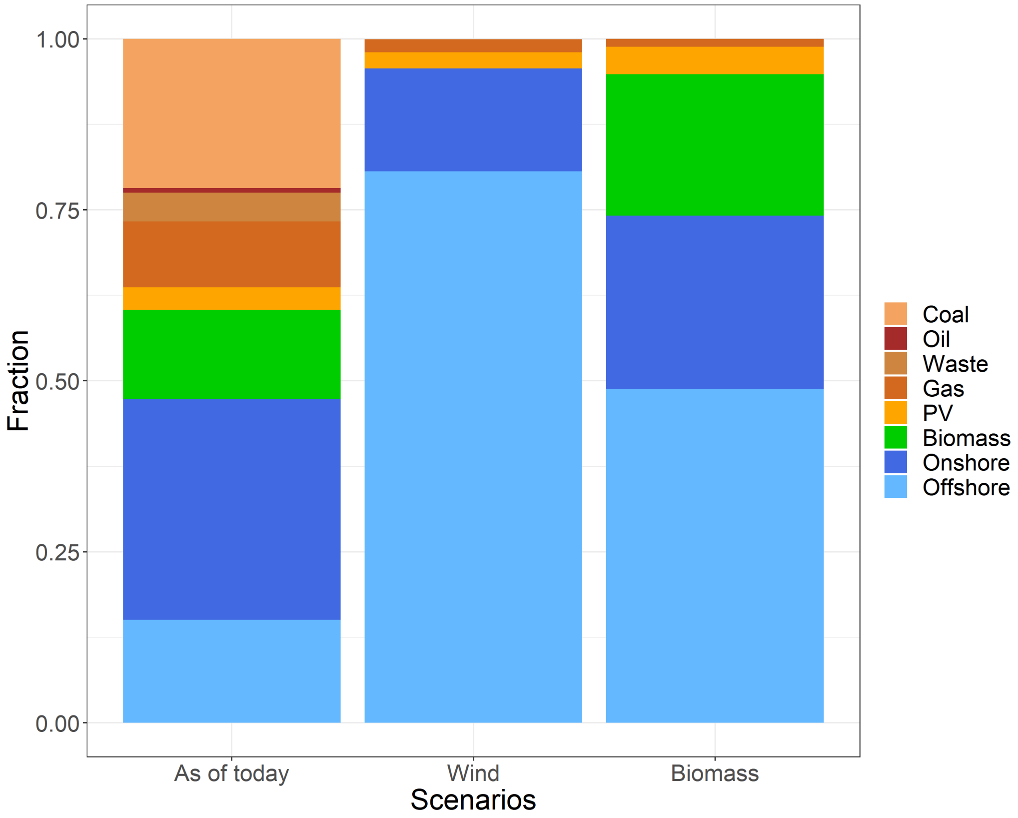


Figure 2.2: Distribution of power producing technologies for scenarios in this study.

The three scenarios have a distinct difference in how the majority of the power is produced. In the wind and biomass scenarios, fossil fuels are no longer a part of the system in order to accommodate the plans for the future Danish energy system, where 100% of the energy consumption should be covered by renewable energy in 2050 [11]. This means the gas used for electricity production is produced by biomass, whereas in the scenarios as of today, fossil gas is used for electricity production. When the electricity is produced partly by fossil fuels, an extra emission is added to the use phase of the EVs, which increases the total emissions in this scenario. The main difference between the wind and biomass scenarios is that the biomass scenarios have a significant production from biomass, where the wind scenario only has a small need for biomass when producing the needed gas. On the contrary, the wind scenario has a much larger production from offshore wind turbines. When installing new wind turbines in the scenarios, only offshore turbines are used. This is due to not only a lack of free space in Denmark, but also because of resistance from the local communities living close to the wind turbines, which is making it difficult to build new onshore wind turbines [39]. As a result of this, the DEA is not expecting the onshore capacity to increase in the future.

2.2.2 Vehicle system scenarios

Regarding the implementation of EVs in this study, two scenarios are assessed. Both will follow the EV implementation computed in section 2.3, but the difference lies in which material consumption is included. In the first scenario, people use their ICEV until it has served its lifetime and then replace it with an EV. In this scenario, they would have to buy a new car regardless, and thus there is no extra material consumption to building the EV except for the battery.

The other scenario is inspired by the current situation in one of the worlds leading EV markets, Norway. Here, 70% of the 60.000 members in the Norwegian Electric Vehicle Association own both an EV and an ICEV due to "range anxiety" [40], meaning that 70% feel like they need an ICEV for the occasional trips that exceed the EV battery range. This results in unnecessary consumption of materials as the ICEV is redundant. Therefore, in the second scenario, 70% of the new implemented EVs will have an additional material flow beside the battery. In this case, people will use their ICEV for vacation travels, which adds a consumption of fossil fuels and thereby extra emissions. However, for the 70% who owns an ICEV, the annual distance driven in the EV decreases by the distance driven in the ICEV. By adding the additional ICEVs to the system, this scenario also increases the size of the car fleet by 70%.

2.2.3 Scenario overview

To sum up the scenarios for this study, an overview is illustrated in figure 2.3. Furthermore, the effect of recycling materials instead of only using virgin materials will be analysed for some selected scenarios.

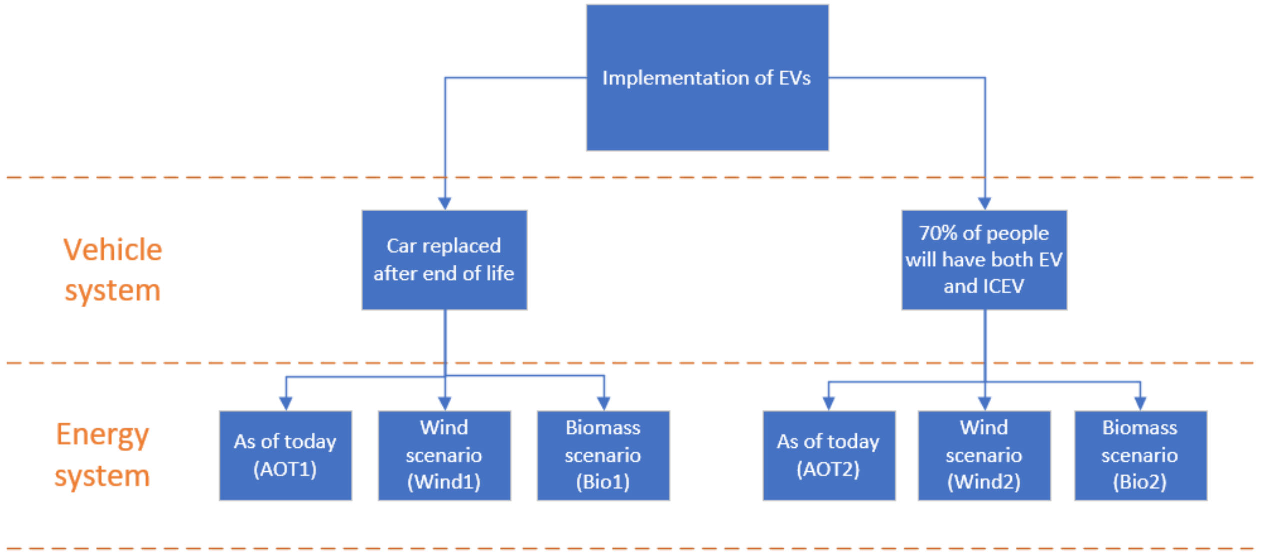


Figure 2.3: Overview of scenarios analysed in the model.

To clarify, in all of the scenarios ending on *1*, EVs make up the entirety of the vehicle system in 2050, following the first scenario explained in section 2.2.2. For the scenarios ending on *2*, 70% of the people who acquire an EV will keep their ICEV as described in the second scenario in section 2.2.2. *AOT*, *Wind* and *Bio* refer to the different energy scenarios described in section 2.2.1. The names of the scenarios in this figure are how the scenarios will be addressed further in this study.

2.3 Development of EV implementation

To predict the future demand for EVs in Denmark is a difficult task as the technology is just starting to emerge in the transportation sector. The implementation curve will likely depend on politics concerning regulations on EVs, and incentives promoting EVs could spark the sales in Denmark. In Norway, the third largest EV market in the world after the USA and China, EVs has become increasingly popular among the citizens due to economic incentives rewarded by the government. These incentives cover, among others, exemption from VAT and road taxes, low import taxes and free parking in the cities [40]. If incentives on a similar scale were introduced in Denmark, the number of EVs could increase rapidly. An integrated analysis of the future car fleet will be carried out and used as the foundation for the dynamic model.

One way to predict the growth of new technology is by applying the simple logistic growth model to create a so-called s-curve. An emerging technology, such as the EVs, tends to follow an s-curve and function parameters can be estimated using a partial data set. It is possible to use the logistic growth model to predict the future EV stock in Denmark. However, the availability of data can be a limiting factor [16] as EVs are just now starting to emerge in the Danish transportation system. The only known data are the current EV stock of ≈10,000 [59]. Besides, the s-curve will be modelled to reach the target EV stock of one million by 2030. The total car stock will also be modelled as an s-curve. 2050 is not included in the calculations so the implementation period will start in 2020 and go 30 years, ending in 2049.

Both s-curves will be modelled for cars per 1000 capita where the total cars per 1000 capita will start at the current level of 445, calculated based on the population in 2019 [18] and the number of vehicles in 2019 [19]. The level of EVs per 1000 capita will start at a level of 10000 EVs divided by the population in 2019. Both s-curves are modelled to reach 550 cars per 1000 capita by 2050, which is an increase of ≈100 compared to the current level. This assumption is made to approach the number of passenger vehicles per 1000 capita in Germany, which in 2016 was 555 [29]. This way, only EVs are present in the car fleet in 2050, and it is thereby independent of fossil fuels.

When the number of cars per 1000 capita is known, the total stock of cars and the EV stock can be calculated for every year by multiplying the level of cars per 1000 capita by the population forecast in the corresponding year until 2050 [18].

The EV implementation is constructed by applying the sigmoidal function, seen in equation 2.1, in MATLAB, where it is multiplied by 550 EVs per 1000 capita, to reach the desired final level. The function is a mapping on the vector x (the years 2020-2049) and depends on the two parameters *a* and *c*. The sigmoidal function in MATLAB is the same as the logistic growth function.

$$f(x,a,c) = \frac{1}{1+e^{-a(x-c)}} \tag{2.1}$$

By a trial and error method, the parameters are adjusted to satisfy the demand of having 1 million EVs by 2030 with an s-curve of appropriate growth. In cars per 1000 capita, 1 million EVs corresponds to a level of ≈164 EVs per capita, calculated by dividing 1 million by the forecasted population in 2029 [18]. In figure 2.4, the effect of changing *a* and *c* can be seen.

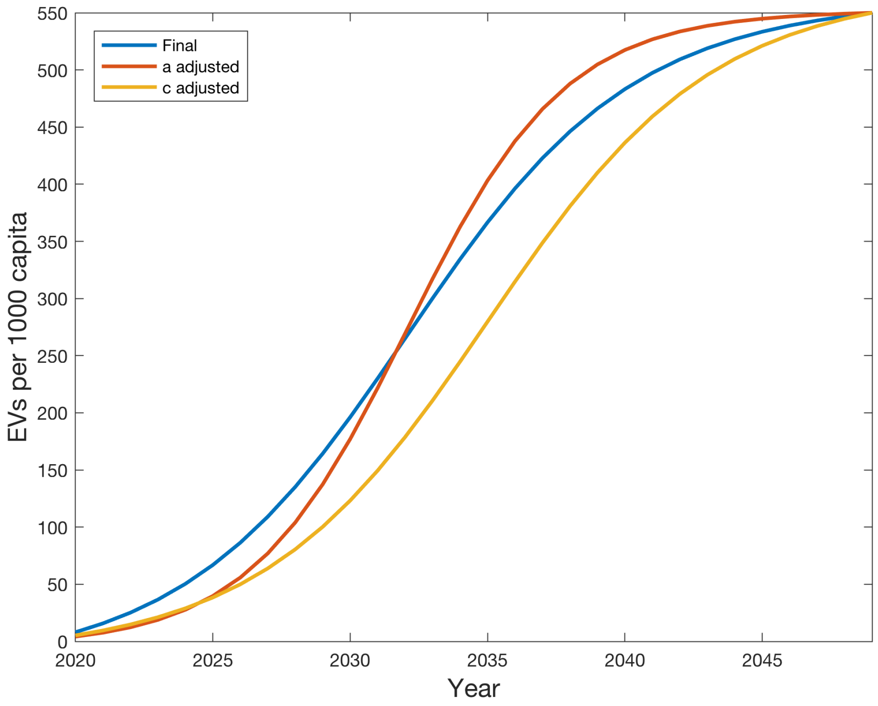


Figure 2.4: The effect of changing parameters in the sigmoidal function.

By changing the parameter, a, the aggressiveness of the growth rate changes, and by changing c, the curve is shifted along the x-axis. Furthermore, the curve is forced to start at a stock of 10000 EVs ($\approx$ 1.7 EVs per 1000 capita) and end at 550 EVs per 1000 capita, and this is the reason the yellow curve is not only shifted but still starts and ends in the same places.

To force the curve to start at a specific point, it is first forced to start in zero. This is achieved by subtracting the starting point from all points. The desired starting point is afterwards added to all points. This, however, results in the ending point being shifted downward, and this has to be adjusted. This is done by dividing the difference between the last point and the desired ending point evenly out on all other points except the starting point. This is a linear approach that alters the s-curve to fit the required ending point, so it does not entirely follow the logistic growth function anymore. However, it is adequate for this study, as it is a prediction based on minimal data. The parameters a and c before mentioned are changed after this adjustment has been made, and the MATLAB script can be seen in appendix B.

The s-curve of the total cars per 1000 capita is made by using the same method but letting it start at a level of 445 cars per capita.

When multiplying both these s-curves by the population forecast until 2050, the total stock in the system is found as seen in figure 2.5. Moreover, the ICEV stock is derivable as the difference between total stock and EV stock under the assumption that only EVs and ICEVs are present in the system.

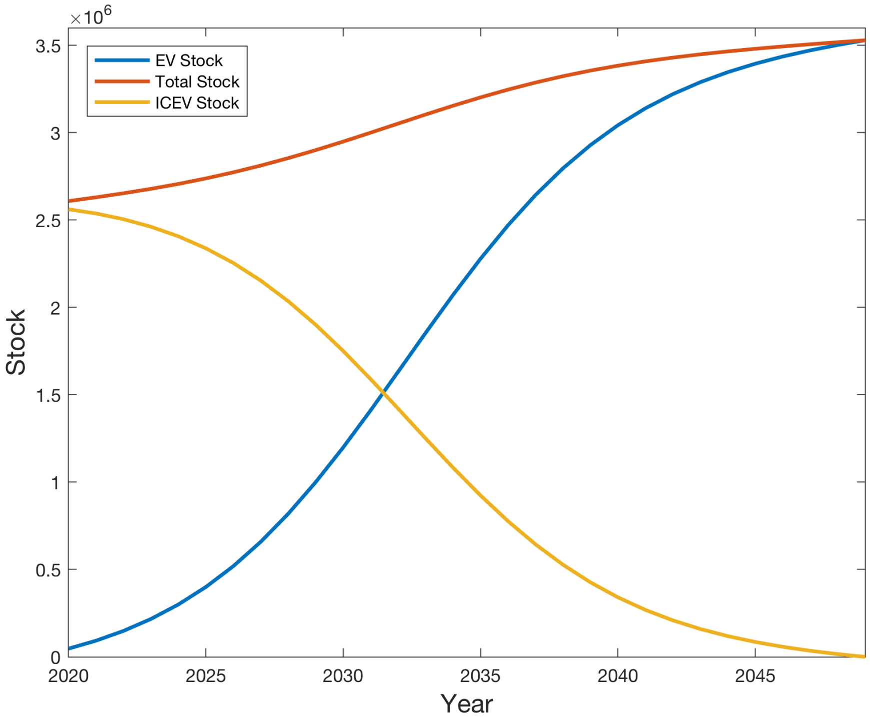


Figure 2.5: EV stock, ICEV stock and total car stock from 2020-2050.

The next step in this study is to assess the replacement of EVs. Like all types of vehicles, EVs have to be replaced at some point, and to this replacement, there are emissions associated. These emissions are from the production of batteries.

The EVs retired every year is calculated based on the age of the EVs in the calculated year, and the mean lifetime of 14.8 years [17] for an average Danish car today. From the average lifetime, a normal distribution is made with an assumed standard deviation of one-third of the mean. The normal distribution can be seen in figure 2.6, showing the probability of a car retiring at a certain age.

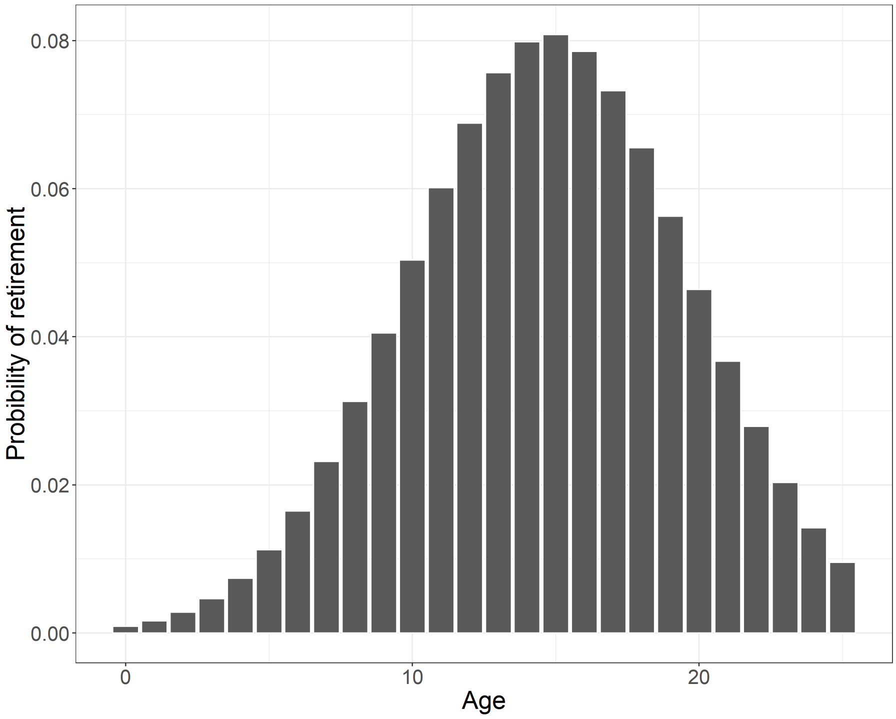


Figure 2.6: Normal distribution of vehicles lifetime in Denmark.

The initial number of implemented EVs is multiplied by the value of the normal distribution for all ages of EVs in the system as in equation 2.2, to calculate the amount of EVs retired in a year.

$$EV_R = \sum_{i=0}^{25} EV_i \cdot ND_i \tag{2.2}$$

This calculation is carried out for all years until 2050 where EV_R is the EVs retired in the calculated year, EV_i is the EVs of the age i, initially implemented and ND_i is the fraction of retired cars at the age i. The EVs retired in one year then have to be replaced the following year to maintain the stock and this is added before the calculation for the next year can be done. Furthermore, the increase in the EV stock also has to be implemented every year.

The number of replaced EVs is then included in the total number of EV inflow every year, as seen in figure 2.7 along with the increase of the EV stock every year.

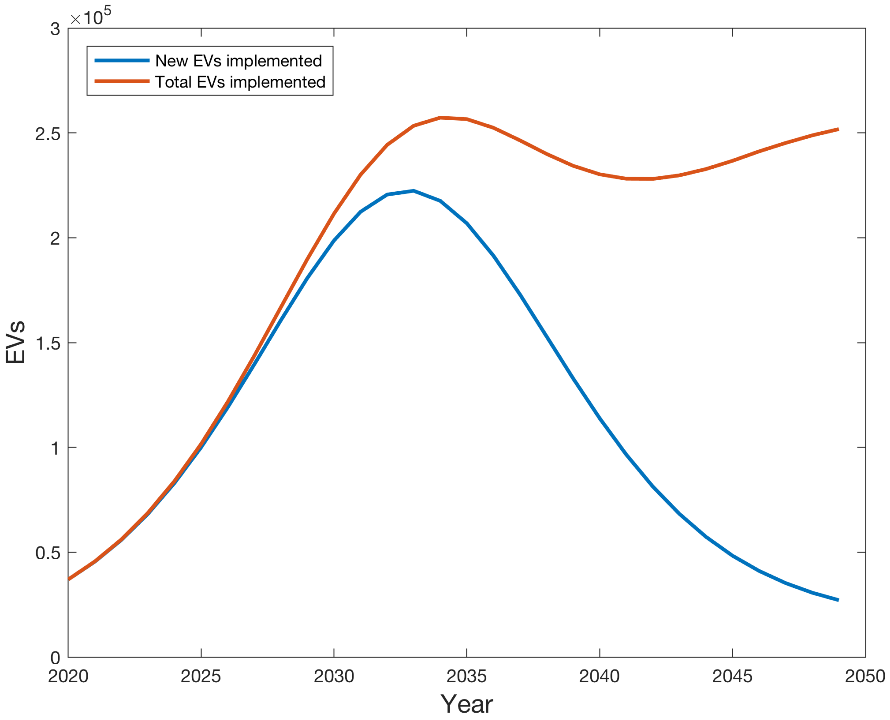


Figure 2.7: Annual EV implementation with and without retired EVs considered.

It is evident that when considering the retired EVs as well, the yearly input to the system increases significantly. For material and emission calculations in section 2.6, both curves are necessary e.g., regarding batteries the total EVs implemented are used, but for material consumption for EVs when people keep their ICEV, only new EVs implemented are used.

2.4 Potential grid expansion

If EVs replace all ICEVs in Denmark, it does not only set demands for additional electricity production, but it could very well put too much strain on the electrical infrastructure, which could result in a needed expansion of the transmission and distribution grids. In this study, only the distribution grid is analysed since EVs would likely have a larger impact on this than the transmission grid.

An analysis of whether or not it is possible to charge the EVs without raising the peak demand is made, to assess if an expansion of the distribution grid is necessary. This analysis is made only based on household consumption, as this does not include consumption from the industry. This better depicts the distribution grid close to the customer. If people come home from work around 16:00, plugs in the EV for charging, and it starts charging right away the peak consumption will increase considerably as the Hyundai Kona Electric used in this study can charge with 7.2kW as seen in appendix E. This is not a problem if a smaller fraction of the cars is EVs, but if the whole car fleet consists of EVs and starts charging around 16:00 the grid will need expansion. An analysis of the required expansion of grid capacity would be quite extensive and is therefore not included in the study.

However, an expansion can potentially be avoided if the consumption from charging were to be evened out during the night, where the consumption usually is low. Doing this, the peak consumption might not increase, and this would indicate that there is sufficient capacity in the distribution grid already. This is achieved through the realization of a smart grid for which, the Danish transmission operator, Energinet, is reviewing the possibilities of [26]. A smart grid can, in a more intelligent way decide when to charge the EV to benefit not only the individual person but also the collective power grid the most. For this analysis, the daily average electricity consumption for a household is assumed to be 12.2 kWh/day [5]. Based on this consumption, a household consumption profile is generated in the software Homer Pro. Then the charging is distributed over 16 hours (16:00-08:00) so the consumption over that period is evened out to be the same. This means the consumption during the 16 hours will consist of the consumption for EV charging added to the original consumption. If the peak consumption is then increased, there is a need for grid expansion. The only criteria when doing this is that the EVs must all be fully charged at 08:00 when people need to use them.

When the daily EV consumption of around 5 kWh calculated in section 2.6.4 is allocated to even out consumption between 16:00 and 08:00 for one household, it alters the daily consumption profile as seen in figure 2.8.

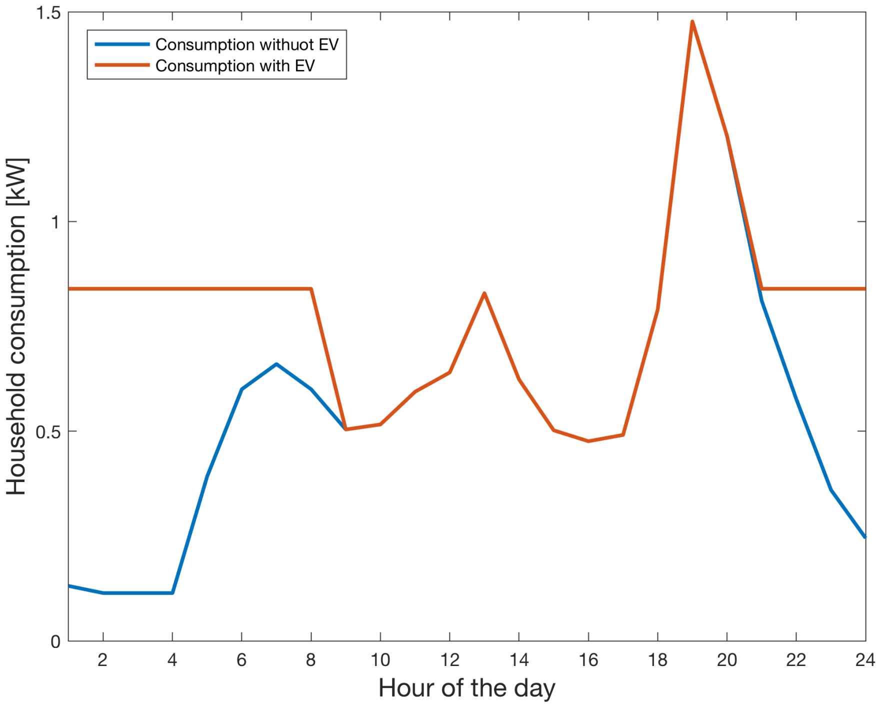


Figure 2.8: Daily consumption for a household before and after an EV is introduced.

The figure shows a significant increase in consumption, but it does not raise the peak consumption, meaning that the distribution grid already has a sufficient capacity if a smart grid solution is introduced. It is also evident that there is still capacity for a further increase in consumption during other times than the peak hour. This analysis is made based on the average daily electricity consumption for EVs, but in reality, it would look different depending on the day as the consumption from the EVs would vary throughout the week.

2.5 Material breakdown and emissions

The expansion of energy-producing capacity and implementation of EVs includes a material consumption and an associated emission from these materials. In this section, the amount of material used for each energy-producing technology and for the production of cars is assessed, and the corresponding emission factors are listed.

2.5.1 Energy production technologies

The bulk materials consumed for the production of the energy producing technologies are listed in table 2.1.

The biomass and waste power plants are assumed to have the same material composition as the coal power plant, as the data for these technologies were unavailable. This assumption is justified since old coal power plants are converted to biomass [46], and the same is also true for the conversion of coal-powered plants to waste [37]. For the gas turbine, only data on the total material and the steel used were available, and it is stated that the majority of the remaining material is concrete. Therefore it is assumed the remaining material, which is not steel, consists of 10% iron, 10% aluminum, and 80% concrete. The technical lifetime of each technology is found from the technology catalogue by the DEA [14] and is included in table 2.1.

Table 2.1: Material breakdown and lifetime for energy producing technologies.

Technology	Offshore [42]	Biomass	PV [32]	Gas turbine [52]	Waste	Coal [51]
Lifetime [years]	27	25	30	25	25	25
Steel [kg/MW]	158610	50721	331452	30968	50721	50721
Iron [kg/MW]	19990	619	0	9817	619	619
Aluminum [kg/MW]	330	419	49774	9817	419	419
Copper [kg/MW]	1520	0	565	0	0	0
Concrete [kg/MW]	0	158758	50419	78533	158758	158758

These materials have a corresponding embodied carbon coefficient, which states how much CO_2 is emitted from mining, refining, processing, transportation, and production of the material. In other words, it represents all of the emissions from the material up until the use phase [9]. These coefficients are listed in table 2.2 for both virgin and recycled materials.

Table 2.2: Embodied carbon coefficients for the analysed materials [9].

Material	Steel	Iron	Aluminum	Copper	Concrete
Emissions virgin [kg CO_2-eq/kg]	2.89	2.03	12.79	3.81	0.11
Emissions recycled [kg CO_2-eq/kg]	0.47	0.47	1.81	0.84	0.11

For iron, not enough data was available, so in this study, the same emission factor as steel is assumed for recycled material. Concrete is according to USGS not recyclable, so the embodied carbon coefficient factors are equal for virgin and recycled [57].

A notable difference in emissions can be seen as a result of the removal of mining and refining of raw materials when using recycled materials. Additionally, it shows that aluminum has by far the largest emission factor, and thus, a small amount of aluminum can still have a significant impact on the total emissions.

2.5.2 Vehicle materials

When comparing EVs and ICEVs, there are obvious differences like fuel and engines. This study will not focus on the different compositions of the cars but more on the difference emission wise.

Therefore, the differences when comparing the two types of cars is the battery and fuel. The EVs have a battery and run on electricity containing zero or little CO_2, depending on the scenario, whereas ICEVs run on either diesel or gasoline, which emit a significant amount of CO_2.

The material consumption for the EV, Hyundai Kona Electric, is based on an extensive study of different types of vehicles, where the percentage by weight of various materials is listed [7]. The distribution of steel, aluminum, iron, and copper is then assumed to be the same in the Hyundai Kona Electric, as found in this study. This distribution and the curb weight of a Kona (1108kg) is then used to approximate the material in one EV. The operational weight given by Hyundai [35] includes the weight of a person and various fluids, so to get the own weight 125kg should be subtracted [31]. The weight is of the ICEV Kona to make sure the heavy battery is not included. Regarding the battery, the emissions from the entire battery pack are used, and not from specific material as the production phase is critical to include. The emission factors are the same as listed in Table 2.2 and materials consumed to produce one EV are listed in table 2.3.

Table 2.3: Hyundai Kona material breakdown.

Material	Weight [kg]
Steel	683.6
Aluminum	76.5
Iron	122.9
Copper	21

These materials do not add up to the total weight of the car because the total weight also includes other materials. These are, however, excluded from this study.

2.6 Emission modelling

2.6.1 Vehicle models

The Danish car fleet consists of cars in a variety of different sizes fueled by different sources. In this study, both a diesel- and a gasoline-fueled ICEV is chosen as well as an EV. In order to make these cars comparable, the size has to be similar, and thus the same model of diesel, gasoline, and electric is used for the study. The chosen model is the Hyundai Kona, where a new electric model was recently released. The Kona is a smaller SUV, and this type of car is picked since the SUV was the most sold car type in Denmark in 2018 [30]. The specifications of the cars used in the study can be seen in table 2.4.

Table 2.4: Vehicle specifications for the Kona models in this study [36, 35].

Hyundai Kona Model	Fuel consumption	TTW [$kgCO_2/km$]	WTT [$kgCO_2$-eq/km]
1.6 CRDI ISG Life Diesel	20.4 km/l	0.129	0.029
1.0 T-GDi 120 kp Life Gasoline	16.1 km/l	0.142	0.038
Electric 39.4 kWh	150 Wh/km	0	-

The well-to-tank (WTT) factor covers all aspects of the production of the fuel, whereas tank-to-wheel(TTW) covers the emissions from the combustion of fuel in the engine. For the ICEVs the WTT emissions are calculated based on data from the UK for kg CO_2 per produced liter diesel and gasoline [15] and the fuel consumption of the cars in table 2.4. In the case of EVs, the emissions from the electricity production depend on the electricity mix, and it is only in the scenario as of today where there is an emission associated with producing electricity.

The emissions E from gasoline cars, G and diesel cars, D, in the year i can then be calculated by equation 2.3 and 2.4, as the sum of WTT and TTW multiplied by the product of the yearly distance traveled (YD) and the ICEV stock in the year. Furthermore, the share of gasoline (GSh) and diesel (DSh) cars are accounted for. This share, as well as yearly distance, is assessed in the following section.

$$E_i = \left(TTW_G + WTT_G\right) \cdot YD \cdot ICEV_i \cdot GSh \tag{2.3}$$

$$E_i = \left(TTW_D + WTT_D\right) \cdot YD \cdot ICEV_i \cdot DSh \tag{2.4}$$

This calculation is used to find the emissions from an ICEV stock corresponding to the EV stock for comparison. Furthermore, in the scenario where people own both an EV and an ICEV, it is assumed that people who own an ICEV drives 2000 km annually.

2.6.2 Danish driving habits

To carry out this study, it is also necessary to know how much the Danes drive, and the share of diesel and gasoline cars in the system if only these types were present. The share is calculated to ≈31% diesel cars and ≈69% gasoline cars, based on the stock in the system in 2017 [59]. For further calculations, it is also essential to know how many kilometers an average car in Denmark drives every year. This is calculated from the car stock and population in Denmark, and a transportation habit survey made in 2013 [55], stating the average distance travelled by car for every Dane and the share of this distance covered by the driver. This yields an annual distance of ≈13,000 km travelled every year per car.

2.6.3 Battery emissions

To assess the emissions from the batteries, it is necessary first to know how much CO_2 one battery for the Kona emits in production. It is estimated that producing a Li-ion battery can emit between 130 and 180 kg CO_2-eq per kWh [50] so using the high estimate as a worst case; one 39.4 kWh battery is the cause of 7056 kg CO_2-eq emission. To calculate the yearly emissions from battery production, the emission from one battery is multiplied by the number of implemented EVs in that year including replaced EVs, see figure 2.7. Furthermore, the battery might have to be replaced before the EV, but in this study, the battery lifetime is assumed to be the same as the EVs. The warranty for the battery is valid for eight years or the first 200,000 km [36]. Divided by the average distance per car per year this yields a lifetime of around 15 years, the same as a car. The warranty of eight years is not necessarily equal to the lifetime, and therefore the distance is used to estimate the lifetime. This is, however, still a conservative approach as the battery should work longer even though the warranty is expired. There is still uncertainty regarding the range of EV batteries as EVs are still a new technology and there are claims that a battery can last for 500,000 km [8].

2.6.4 EV electricity demand

The extra consumption every year due to EVs is found as the product of the yearly distance driven per EV and the electricity consumption in table 2.4, which is multiplied by the addition to the EV stock every (see figure 2.7), resulting in a yearly consumption of ≈1.9 MWh per EV. The retired EVs are not considered as a replaced EV will not increase the electricity consumption further. From this yearly extra consumption, the needed installed capacity every year can be calculated.

2.6.5 Installed capacity

The installed capacity is where the scenarios created in section 2.2.1 differ from one another. To calculate how much of each technology should be installed the production share (PSh), the capacity factor (CF) and the charging period (CP) is used. The charging period is assumed to be from 16:00, where people get home from work to 8:00, where they leave for work again. When calculated on a yearly basis, the charging period in which the electricity has to be produced amounts to 5840 hours/year. The capacity factor is found from the full load hours from the DEA's energy scenarios [11]. To find the installed capacity (IC), equation 2.5 is used, where t represents the technology for which the calculation is carried out and YC is the yearly extra consumption.

$$IC_t = \frac{\frac{PSh_t \cdot YC}{CP}}{CF_t} \tag{2.5}$$

The capacity factor for biomass, coal, gas, and waste is set to one as they can produce whenever necessary. The capacity factor for offshore turbines is ≈0.47, and for PV it is ≈0.1

2.6.6 Material system emissions

When the annual installed capacity of each technology is known, the consumption of materials is found using the data in table 2.1. The materials for EVs every year are found by multiplying the material consumption for one EV in table 2.3 by 70% of the addition to the EV stock, see figure 2.7 for illustration. The replaced EVs are not included as these are not considered to be an additional consumption of material. There is only an additional material consumption in the case where an EV is bought as the second car, and people keep the ICEV as explained in section 2.2.2.

When all materials consumed during a year is known, the emissions associated with theses material are found using emission factors listed in table 2.2. The material emissions are initially calculated as if only virgin material was used. Afterward, the recycling rates in table 2.5 are considered, so the fitting emission factors for the recycled and virgin material are used. The results of the calculation will show the impact that recycling can have on emissions.

Table 2.5: Recycle rate of materials for electricity production and vehicles.

	Concrete	Copper	Iron	Steel	Aluminum
Recycle rate - electricity production [47]	0 [58]	0.95	0.98	0.98	0.98
Recycle rate - vehicles [28]	-	0.9	0.9	0.9	0.9

2.6.7 Energy system emissions

The last emission considered in this study is only relevant to the AOT1 and AOT2 scenarios. In this case, the electricity demand for EVs will be partly produced by burning fossil fuels and this emission has to be included. The power production emissions (PPE) can be calculated in the year, i for the technology t, as in equation 2.6. Here, Con represents the consumption, PSh is the production share from section 2.2.1, Eff is the efficiency and EmF is the emission factor for the used fuel. The consumption increases as more EVs enter the system, and thus, the emissions increase every year.

$$PPE_i = \frac{Con_i \cdot Psh_t}{Eff_t} \cdot EmF_t \tag{2.6}$$

This is calculated for power produced from coal, oil, fossil gas, and waste. The efficiency and emission factors used can be seen in table 2.6.

Table 2.6: Efficiency for power producing technologies and emission factors EmF for the fuel.

Technology	Efficiency [%] [14]	Emissions [kg CO_2-eq/GJ fuel] [12]
Coal fired plant	46	94.5
Oil in coal fired plant	41	79.2
Gas turbine	42	57.1
Waste powered plant	23	37

3. Results and Discussion

3.1 Annual emissions

Following the methodology and the dynamic model developed, the emissions every year from 2020 to 2049 is visualized for the different scenarios in figure 3.1. The biomass scenarios have been excluded as they are very similar to the wind scenarios, and the wind scenarios are slightly better (see appendix D).

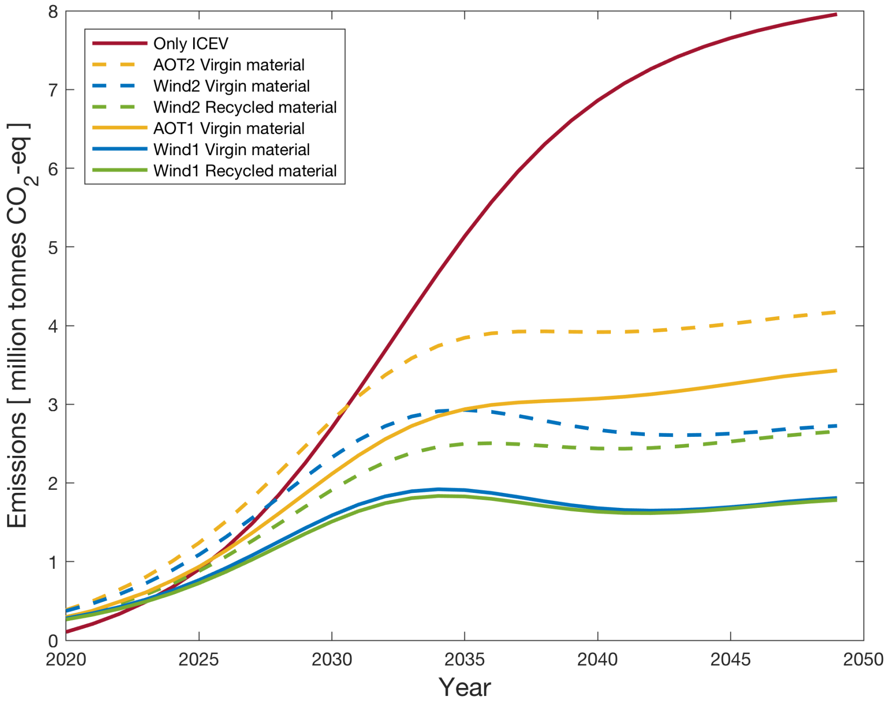


Figure 3.1: Annual emissions from EVs over 30 years compared to emissions from the same number of ICEVs.

The dotted lines represent the scenarios where 70% of the EV owners also have an ICEV, whereas the solid lines represent the scenarios with only EVs. *Only ICEV* illustrates the emissions from ICEVs, where the number of ICEVs corresponds to the number of EVs in the other scenarios. It is evident that the emissions from a system consisting entirely of ICEVs, in the end, will have a significantly higher emission of CO_2 associated with it. However, it also appears that during the first years, EVs have higher emissions, which can be explained by the high initial emissions when implementing an EV due to the production of the battery. Although when looking over a longer period, EVs are better as there are no direct emissions in the use phase. Looking at the intersection between the emissions from the ICEVs and the other scenarios, it takes between 4 and 12 years for the EVs to emit less CO_2 during a year, depending on the scenario.

If comparing the wind scenarios with virgin material to their counterparts where the recycled material is used, the impact of recycling can be understood. It is evident that recycling results in slightly lower emissions, but the impact is more significant when an extra car is included. Recycling only focuses on the bulk materials in the system, but other elements such as batteries are also recyclable, which is addressed later on.

Another point deductible from figure 3.1 is how much the production of electricity can contribute to the yearly emissions. The *AOT1* and *AOT2* scenarios have a much larger yearly emission than the wind scenarios, and the *AOT1* scenario emits more than the *Wind2* scenario. This proves how important the renewable production of electricity is and the meaning of converting from a fossil-fueled energy system to a system relying on renewable sources. In section 2.2.1 the fraction of electricity produced by fossil fuels was found to be around 40%, so a different electricity mix could emit a higher amount of CO_2. The impact of a worse electricity mix is evaluated in section 3.8. However, to continue the electricity production as of today is not a realistic scenario. It shows what the case would be if nothing were changed but in future coal will not be a part of the electricity production portfolio. By 2030 there will be no more electricity production from coal, and companies have already started preparing to shut down their coal-fired plants, e.g., Ørsted has decided not to use coal on their plants in Denmark from 2023 [38].

3.2 Accumulated emissions

As this study aims to asses the material-energy-emission nexus with a focus on the emissions, further analyses will be made to present the energy, vehicle and material systems individually and the cause of emissions in these systems. In figure 3.2, the origin of the emissions in the system is shown as the accumulated emissions over the whole calculation period (2020-2049). The material system includes materials for expanding the production capacity and the materials for an ICEV besides the EV. Within the energy system, the emissions from energy production are included. The vehicle system covers the emissions from gasoline and diesel burned by ICEVs and the emissions associated with batteries for the EVs.

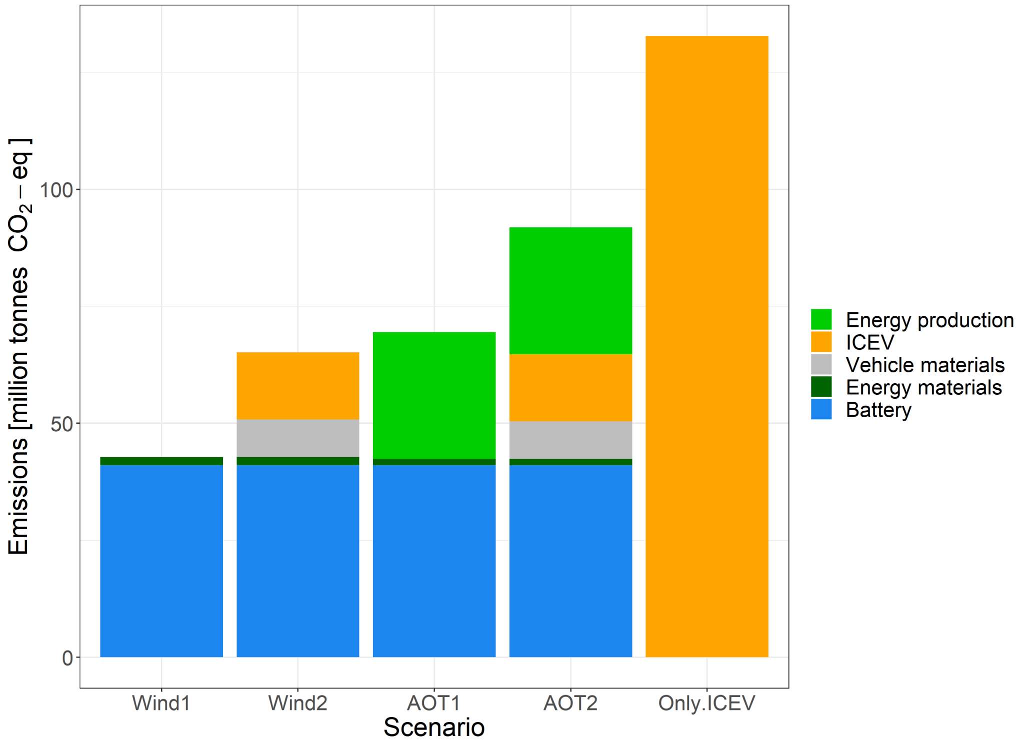


Figure 3.2: Origin of emissions in the scenarios shown as the accumulated emissions over 30 years.

Regarding the material system, it constitutes a small part of the emissions relative to the other systems, whereas the majority of the emissions take place in the vehicle system. Energy production only emits CO_2 in the as of today scenarios where fossil fuels are used for production, but it contributes to a significant part of the emissions in these scenarios and is the explanation for the difference in the as of today and the wind scenarios. The electricity mix used in the as of today scenarios in this study contains 238 g CO_2 per kWh. Using only renewable energy and not having an ICEV is logically the scenario with the lowest emission but with the battery being the cause of almost the entire emission, it is clear how much the batteries in EVs contribute to the emissions. This emission associated with EV batteries clarifies why ICEVs emit less CO_2 than EVs during the first years in figure 3.1. This entire emission is factored in when an EV is implemented where the emission from an ICEV is generated steadily over the years. Furthermore, the low emissions from materials help to understand why recycling does not seem to have a significant impact on the yearly emissions in figure 3.1.

3.3 Impact of recycling

When looking at the material system isolated recycling decreases the emissions significantly and to analyze to what extent, the emissions from virgin materials are compared to the emissions when the recycling rates, in combination with emission factors for recycled material, are applied. This comparison is shown in figure 3.3 as the total emissions in the material system over the 30 years for the *Wind2* scenario.

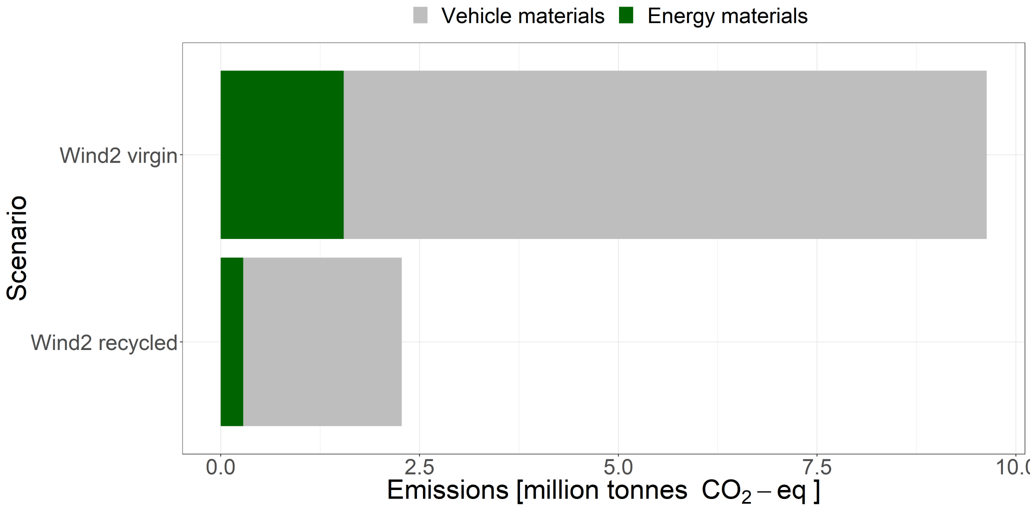
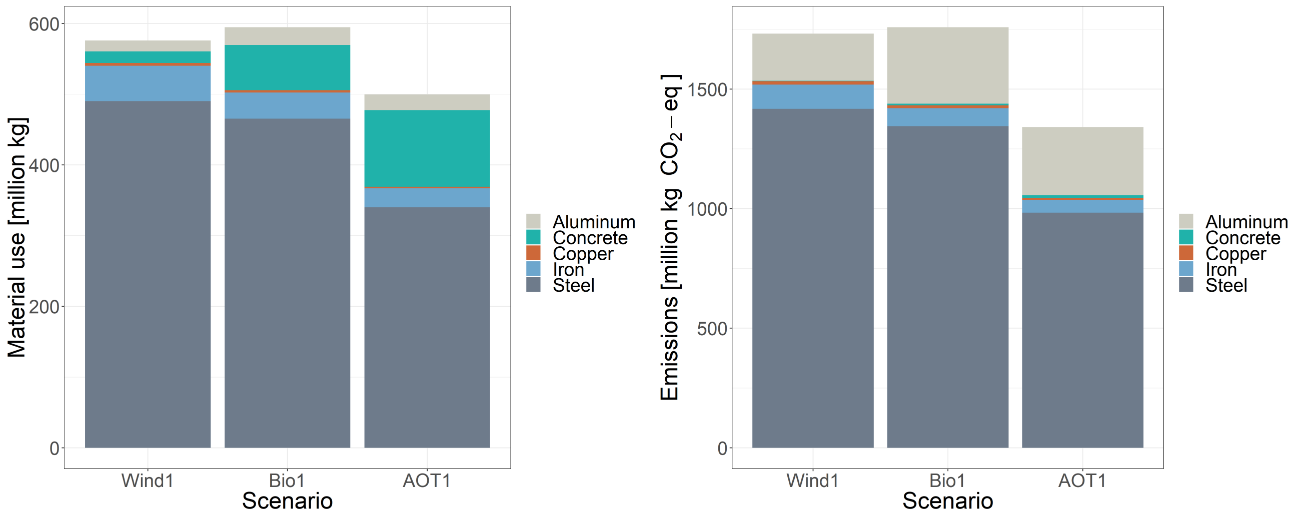


Figure 3.3: Effect of using recycled materials as opposed to virgin.

The figure shows a major difference in emissions when using recycled material, with a difference of approximately 7.5 million tonnes CO_2. This corresponds to the emission coming from the entire car fleet in 2050 if it were made up exclusively of ICEVs, see figure 3.1. As material constitutes such a small part of total emissions, the effect of recycling is also minor, when looking at the total system. This is due to the fact that only recycling in the material system is considered, but in reality, other elements can be recycled as well. Recycling of batteries is in this study not included since they cannot be recycled and made into new EV batteries and therefore the EVs always require new batteries. However, the batteries can serve other purposes. When an EV is replaced the battery cannot be used for a new EV because the capacity at this point has decreased, but it still works and can, therefore, be utilised in the energy system as storage [50]. This storage capacity could then help to minimize the installed capacity necessary to supply the demand. So it can be concluded that although the total impact from materials at first glance is small, there is a potential to reduce the emissions significantly.

3.4 Material distribution

When looking at the total system emissions, the emissions from materials for the energy production capacity has proven to have a minor impact on the overall system. Regardless it is still interesting to analyse and see how the scenarios differentiate from one another.



(a) Material use within the energy sector in the three scenarios with only an EV.

(b) Emissions from the materials used.

Figure 3.4: Material use and emissions listed for the scenarios with only EVs in the vehicle system.

The material use and emissions for the installed capacity are shown in figure 3.4 for the three scenarios where only EVs are in the vehicle system. The figures show that the total material used in the *Wind1* and *Bio1* scenarios are very similar, while the *AOT1* scenario is significantly smaller. If the scenarios are compared, the distribution of materials used is quite similar, and steel is in all scenarios by far the most used material. In the *Bio1* and *AOT1* scenario, concrete is the second most used material, since this is commonly used in biomass and coal-fired plants, but as the figure also shows there are almost no emissions related to the use of concrete. For aluminum, the opposite is true, where the use is fairly small, but aluminum is the second largest contributor to the total emissions, as a result of the very high emission factor. The emissions from aluminum is also what makes the *Bio1* scenario surpass *Wind1* because more PV is installed in *Bio1* than *Wind1* and more aluminum is used for PV than for wind turbines.

3.5 Implications on the energy system

To further assess the implications of electrification of the Danish car fleet, looking at the energy system isolated can contribute. In figure 3.5, the total capacity built in each scenario is shown, ranging from 2799 MW in the wind scenario to 2245 MW in the scenario as of today. The difference in capacity in the scenarios, is a result of the intermittency of renewable energy sources, meaning that a greater amount of capacity has to be built to cover the same demand due to the capacity factor of renewable production units.

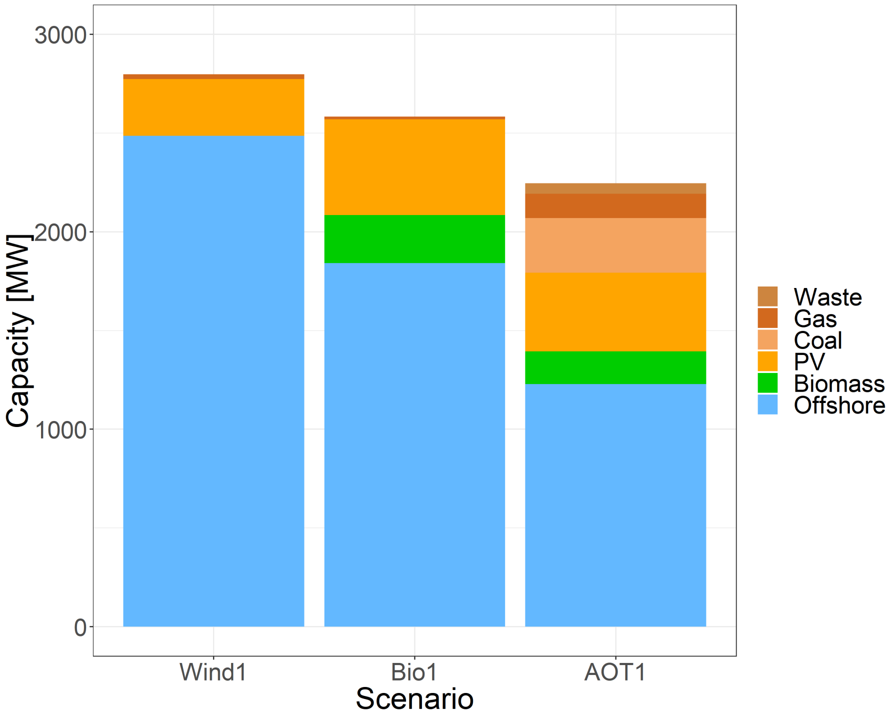


Figure 3.5: Capacity installed in the three energy scenarios.

To put this into perspective, in 2017 Denmark had an installed capacity of 14,368 MW [13], meaning that if the wind scenario became a reality, the installed capacity would increase by 19% from 2017 to 2050 due to EVs.

This extra capacity is built with the sole purpose of covering the EV demand, but this demand has to be covered during the 16 hour charging period, so that still leaves an 8 hour period where the capacity does not need to support the EV demand and therefore can produce to cover demand elsewhere. These remaining 8 hours amounts to an annual production of 12,600 TJ. In 2017 Denmark produced 111,741 TJ [13], so 8 hours of production is therefore equivalent to 11% of the total produced energy. This shows that the capacity needed is not unobtainable, and the greatest concern is how Denmark takes advantage of all the potential excess electricity introduced.

It should be noted that in reality, capacity is not built solely to cover the demand of one sector, the vehicle system in this case, and more as a response to the overall increase in demand. In today's energy system, there is already a buffer that can handle an increase in consumption, but it is complex to quantify [25], and might come from fossil fuels. Therefore the capacity calculated in this study reflects what is needed overall in the system to cover the demand from EVs, but in reality, the installed capacity could be smaller due to this buffer. On the other hand, this study has been made under the assumption that smart grid is implemented to even out the EV consumption. If this is not the case for the future, the charging period shortens significantly, and this would result in a greater need for extra production capacity. The need for future capacity also depends on several other factors, such as a change in consumer habits or even new data centers in Denmark. All these aspects have to be evaluated collectively when planning the production capacity in the energy system.

Recently, another study has concluded similarly to the findings of installed capacity in this study.

On May 29th. 2019 an article regarding the implementation of EVs in Denmark, was published by DR. This article concludes that a transition towards only EVs in Denmark will require an increased capacity of around 2800 MW [4] which is very similar to the result for installed capacity obtained in this project.

3.6 Retirement of vehicles

As in the energy system, additional implications on the vehicle system can also be analysed, and an essential aspect is to consider the retirement of the ICEVs in the system. Considering this aspect, a conclusion that can be drawn from this study is that if the Danish car fleet is to consist of EVs entirely in 2050, the ICEVs have to be scrapped at a faster rate than today, meaning their lifetime decreases. In section 2.3 the stock of ICEVs for each year was determined, and with the current stock and age of the cars [59], it is calculated how many ICEVs retire every year like it was calculated for EVs in section 2.3. For ICEVs the yearly input is not known but can be estimated as the difference between the ICEV stock, see figure 2.5, and the number of ICEVs in the system that year. The number of ICEVs in the system for a year is found as the stock of ICEVs the previous year subtracted the retired ICEVs that year. The demand for new ICEVs in the system is modelled in figure 3.6.

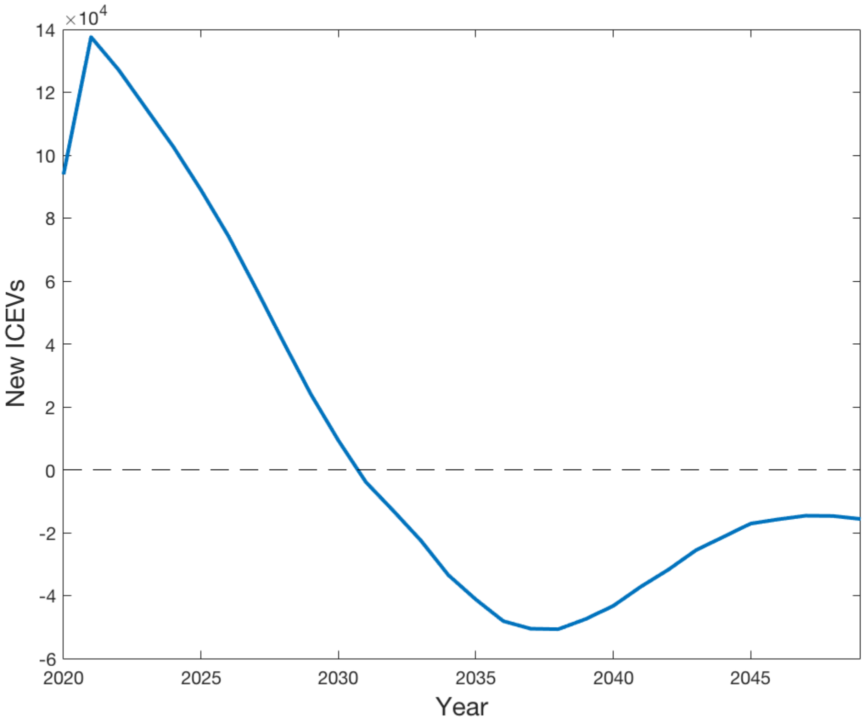


Figure 3.6: New ICEVs implemented every year.

The fluctuation in the first year can be explained by the stock level in the beginning. The total stock curve was made to start at 445 cars per capita, which was the level in 2018. The calculations are started in 2020, and when using the level from 2018, this causes a slight deviation in the beginning.

Apparent from the figure, is that from 2031 a negative number of ICEVs has to be implemented every year. This means ICEVs that have not served their whole lifetime has to be retired in order to follow the predicted stock in this study. Electrification of the Danish car fleet has proven to reduce the emissions, but from an economic perspective, it might have negative implications of scrapping ICEVs earlier than necessary as it will add an unnecessary cost to the Danish car fleet. However, there might be solutions to this problem, and some political goals from parties in Denmark could contribute to this. The current government has stated that by 2030 there should be no more sales of new cars running entirely on fossil fuels [43]. This is certainly a suggestion that would benefit the EV implementation, but as there is already a negative inflow of ICEVs in 2031, this would not change the fact that ICEVs would have to be scrapped earlier, according to this study. However, another suggestion from a party is that there should be sold no more diesel and gasoline cars from 2025 [53]. If this were to be realised, the ICEV stock would not have an inflow from 2025, and this would result in fewer ICEVs being scrapped earlier. It is a very ambitious goal; nevertheless, other countries have made similar goals e.g., Norway has decided all new cars from 2025 should be zero emission cars[41]. Another way to realise this is to introduce a monetary incentive that rewards people if they decide to scrap their vehicles early for EVs. This has already been introduced in countries like Norway and Germany and has encouraged many people to scrap their vehicles before due time [1, 49].

This regulation combined with a potential ban of sales of new gasoline and diesel cars could help bring down the ICEV stock at a fast rate and boost the number of EVs, to achieve the electrification of the transportation sector faster.

3.7 Grid expansion assessment

In section 2.4 it was found that grid expansion could be avoided if smart grid was implemented to even out the EV consumption during the night. It was also stated that a more extensive analysis was necessary to better asses this need for grid expansion, as many elements needed consideration. Dansk Energi published such a study on May 24th 2019 assessing the actual need for expansion if 1 million EVs are implemented by 2030. In this study, the need for grid expansion is assessed in two cases, referred to as the expensive case and the smart case. This is the same analysis as this study has conducted with and without smart grid, but Dansk Energi takes more than just the consumption from one household into consideration. They found that a significant expansion is necessary if the consumption is not distributed throughout the day (no smart grid), and only a minor expansion is necessary otherwise (with smartgrid). This points towards the same conclusion made in this project, that the implementation of smart grid is vital to decrease the need for expansion. However, Dansk Energi finds, that already with one million EVs in the system, an expansion cannot be avoided so if the entire car fleet is to consist of EVs, further expansion is inevitable. This will result in material use, and this extra consumption of materials would increase the emissions coming from the material system.

3.8 Sensitivity analysis

The main result of the analysis showed that during the first years, the ICEVs emitted less CO_2 than the EVs, but ultimately the EVs were the cause of less yearly emissions regardless of the scenario. Parameters like electricity mix and battery production were found to impact the total emissions significantly, so an analysis of how a change in these parameters would affect the result is conducted. The effect of changing the battery size and in one case, also changing the electricity mix is shown in figure 3.7. The *Wind1*, *Wind2* and *Only ICEV* lines are kept as reference points from the initial results, and the battery size is then increased to 64 kWh, which is the greatest capacity available in the Hyundai Kona series [36], and 100 kWh which is the greatest capacity available on the market [60]. Additionally, a scenario is set up, showing the effect of only producing electricity with coal combined with a 100 kWh battery. This shows the result of increasing the battery size has a major impact on the emissions, and how much EVs can potentially emit in a worst-case scenario.

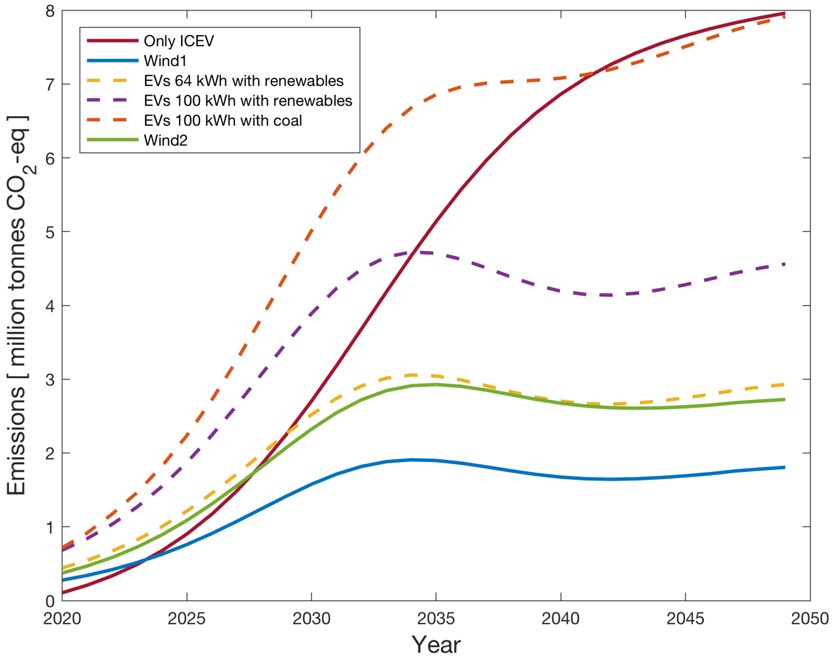


Figure 3.7: Sensitivity analysis on the battery size and electricity mix shown with dotted lines plotted with the original findings.

If comparing *Wind2* and 64 kWh EVs the carbon footprints show that if one were to choose between an EV with 39 kWh battery and an ICEV for longer trips or just an EV with 64 kWh battery, the solution with the smaller battery and an ICEV has a slightly smaller carbon footprint. These calculations are all based on the high estimate of emissions from batteries meaning there is a large potential in decreasing emissions during the battery manufacturing phase. This could be done by moving production to countries with a better electricity mix [50] which would make the scenario with a larger battery more feasible than the *Wind2* scenario. If increasing the battery capacity to 100 kWh, the carbon footprint is a lot higher and in this case, the battery emissions should be reduced substantially for a 100 kWh battery to be a better solution than keeping an ICEV for longer trips.

For the scenario with a battery of 100 kWh and an electricity mix based entirely on coal, a worst case scenario can be seen. A very high capacity of the batteries combined with a production exclusively from coal means that there is basically no difference between the yearly emissions in 2050 from this worst case and only ICEVs. In fact, through 30 years, the accumulated emissions from the scenario with power produced by coal are higher than the emissions from ICEVs through the same period. This, of course, is not a realistic scenario for Denmark, because of the high renewable production already present in the energy system, but other countries such as Poland still base their electricity production on coal [22]. Of course, an electricity mix like this in 2050 is not a possibility, since the EU has made long term goals to prevent countries from continuing down a path like this [10]. Additionally, the battery capacity of 100kWh, with a rated range of over 600 km, according to Tesla [54], is also a lot more range than what the average person needs. According to a survey done by DTU [55] less than 5% of the trips the Danish people travel by vehicle exceeds 300 km. Therefore the Hyundai Kona with a 64 kWh or even a 39 kWh battery is sufficient, with a rated range of 449 and 289 km respectively [36], for the majority of the trips. The few people who do need a bigger battery can then elect to get it, but others can be satisfied with a smaller car and battery than the Kona 39 kWh.

The results from the sensitivity analysis can also explain why there is still skepticism towards the electrification of the car fleet. The results can display the point that a writer wants to make by adjusting the parameters and the period for which the calculation is made. There are people claiming that EVs are no more sustainable than ICEVs, and one such example is an article [48] criticizing, among other things, the production of EV batteries. This article has two main points being that EVs do not have a lower emission of CO_2 than ICEVs, and neither are EVs better for the environment. The point about the environment is based on the consequences of extracting lithium from the underground. This process affects the level of the groundwater, and with a decrease in the level of the groundwater, the livelihood for the biology in the area disappears. There is no denying that there are negative consequences of mining materials for the EVs, but saying that EVs are therefore less sustainable is not a fair point as there are just as many or even more negative consequences by extracting oil for fuel, which is a known problem to a variety of biological life [27]. Considering the point of EVs having just as large emissions as ICEVs it is very relevant to this study as the article also takes the battery production and power production into account, which are the two main contributors to the EV emissions. The article states that a Tesla has to drive around 500,000 km before it is better than a diesel car of the same category. Looking closely at the numbers behind, however, reveals just how misleading this result is. The result is from an article brought in a Danish journal, Ingeniøren, [21], but here it is stated that the calculations are based on emission coefficients from Germany in 2013, which is an energy system undergoing a major transition. The German electricity mix in 2013 is found to contain around 500 grams of CO_2 per kWh [3], which is more than twice as much as the electricity mix used in this study. This helps to explain how the result was obtained and why it is not a fair conclusion to draw that EVs do not emit less CO_2 than ICEVs. By changing parameters in the dynamic model in this study, a similar conclusion can be made, assuming the power production is coal based and the entire car fleet consists of EVs with the largest batteries on the market as seen in figure 3.7. However, this scenario is very far fetched and unrealistic. The results from this study all show that EVs do, in fact, emit considerably less CO_2 than ICEVs and the emissions from the car fleet in 2050 can be reduced by up to 75%.

4. Suggestions for further studies

Due to time constraints it has for this project been necessary to focus on a few selected aspects, but for many elements, further analyses can be conducted. These analyses cover the stability of the energy system, the variety of the car fleet, and the production of batteries.

Within the vehicle system in this study, only one EV, gasoline car and diesel car model were included. The study could be extended by including different cars of different sizes, reflecting the current vehicle system. This would give a more accurate estimate for future emissions.

Also, regarding the batteries, the study could be extended. In this study, an estimate of CO_2 per kWh battery capacity was used consisting of emissions from mining, refining, and production of battery grade materials and manufacturing of the batteries. The manufacturing stage contributes to 45-60% of the total emissions, where most of these emissions can be lead back to power production with a fossil share of 50-70% [50]. In this study, the manufacturing stage emits 110 kg CO_2 per kWh out of the total 180 kg CO_2 per kWh and if assuming 100 kg can be lead back to the electricity production, the effect of eliminating this emission can be seen in figure 4.1.

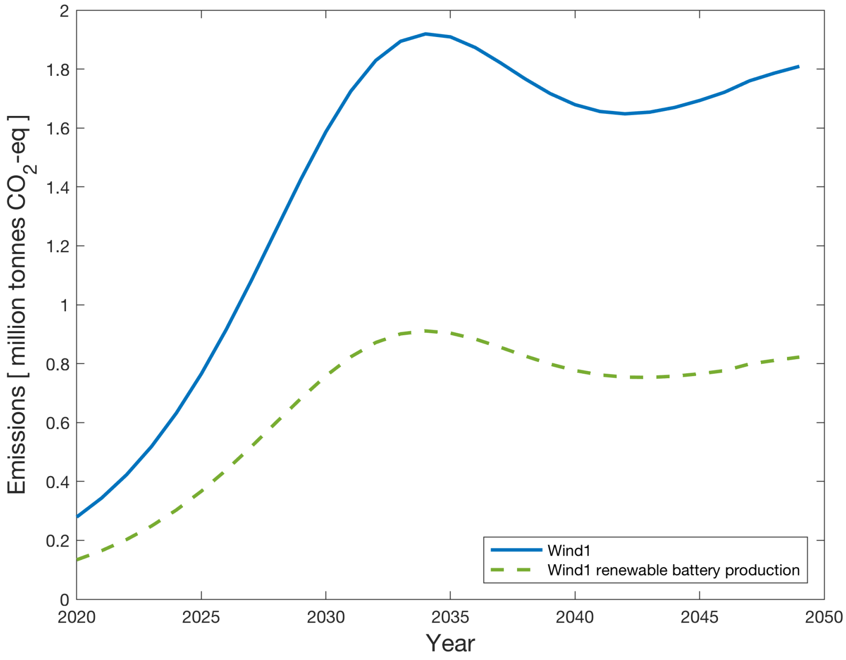


Figure 4.1: The effect of manufacturing batteries using 100% renewable energy.

This represents the effect manufacturing of batteries using renewable energy could have, and it is very likely emissions associated with mining, refining, and production of battery grade material could also be decreased. A study within this area could be conducted, where the total battery emissions are analyzed depending on the country where the batteries are manufactured and the material extracted. This would show the true potential for how much emissions from the car fleet could be reduced.

Another aspect that has not been included in this study is the economic cost of electrification of the Danish car fleet. This analysis could cover the cost of materials, both regarding power production and vehicles as well as the potential cost of scrapping ICEVs early to meet political goals. This could also include the development of the infrastructure of charging stations, that especially in Denmark is lacking. Research in Denmark suggests that 250 charging stations have to be built every day to deliver enough energy for 1 million EVs in Denmark by 2030 [23, 45]. This would enable one to calculate the total cost to electrify the car fleet in Denmark fully, both from the consumer standpoint but also the government if subsidies or other incentives should be introduced.

5. Conclusion

This study has mapped the material-energy-emission nexus associated with the electrification of the Danish car fleet, and a dynamic analysis of the emissions has been conducted. The results from this analysis point towards the emissions associated to an entire car fleet consisting of EVs, being between a quarter and half of what the same number of ICEVs would emit in 2050, depending on the scenario. In 2050, the annual emissions from ICEVs reach around 8 million tonnes of CO_2, where the best scenario will emit less than 2 million tonnes. However, because of the high emissions from battery production, the EVs are initially not a better solution, but after 4-12 years, all scenarios with EVs have less annual emissions than the scenario with only ICEVs.

By further analysis of the material, vehicle and energy systems, it is found that the material system constitutes a very small part of the total emissions in all scenarios, which also explains the overall insignificance of recycling. This also proves that the expansion of production capacity does not have any significant influence on the electrification of the car fleet regarding emissions.

The results also reveal that the production of electricity influences the total emissions greatly. If the electricity is produced as of today instead of a scenario with 100% renewable energy, the emissions from the energy system are the second largest contributor to the total emissions. The most significant contributor to emissions is found to be the batteries for the EVs due to the emissions from manufacturing. However, there is a potential to reduce these emissions greatly. An aspect, which proved to affect the results a lot, was the future prediction of how EVs are implemented. If people keep an ICEV besides their EV for occasional longer trips, an increase in emissions is apparent. This increase is in the sensitivity analysis found to be similar to the increase when choosing an EV with a larger battery. In this case, the emissions from the larger battery could be reduced, which would deem a larger battery a more viable solution for people who need an extended range.

In the study, other implications than emissions have also been analysed. It is found that if the car fleet is to consist entirely of EVs in 2050, the ICEVs in the vehicle system will have to be scrapped at a faster rate than currently, which would require some incentives from the government.

In the future, clean energy is essential, and climate action has to be taken as two of the SDG describe, but there is not just one solution towards achieving these goals. This study has found that the electrification of the Danish car fleet would contribute to these goals and further emission reductions are possible. The greatest potential for further reduction lies within battery manufacturing, but as several contributions towards achieving the goals are necessary, this should not be the only focus. Regarding the expansion of the electricity production capacity, emissions can also be reduced, and the importance of renewable energy production cannot be ignored as a crucial element when reducing emissions to take climate action.

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A. Distribution of energy technologies

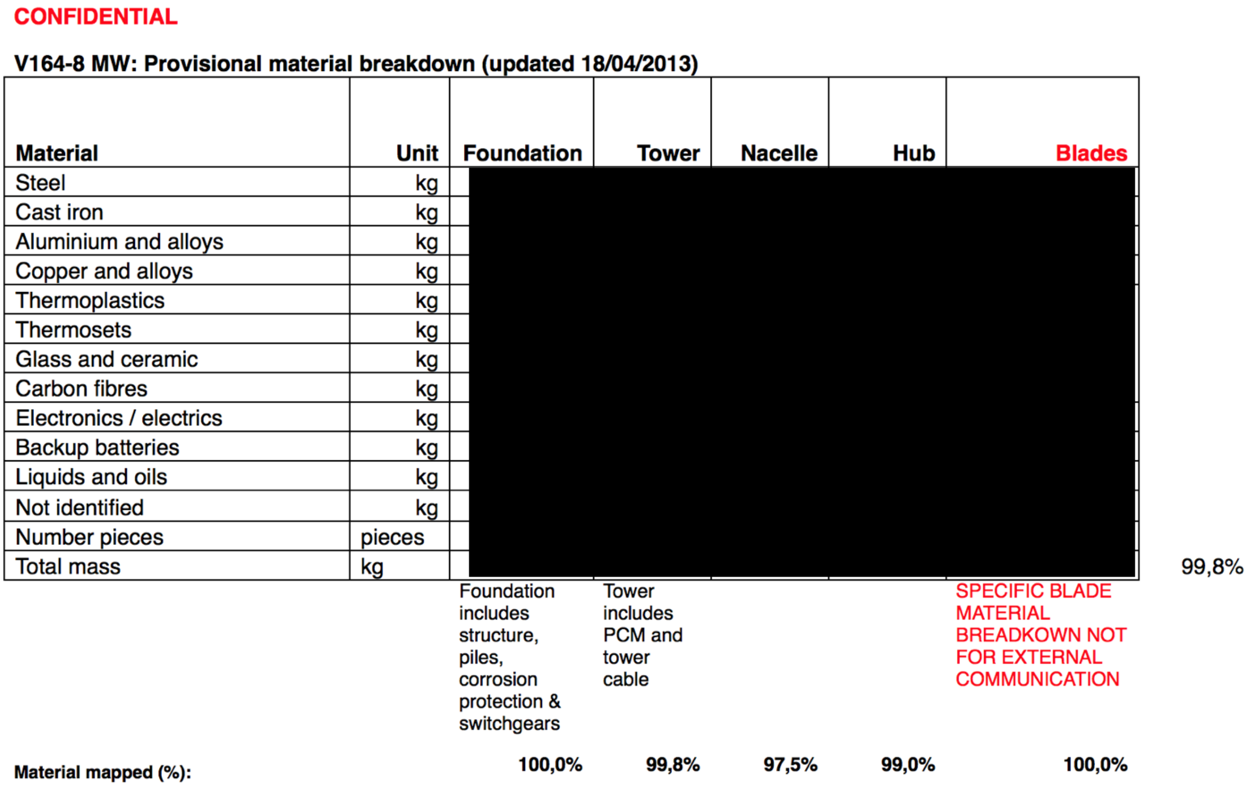
Table A.1: Exact fractions for the different scenarios used in the distribution of technologies in figure 2.2.

Technology	Onshore	Offshore	Biomass	PV	Gasturbine	Waste	Oil	Coal
As of today	0.323	0.15	0.1304	0.0327	0.096	0.042	0.007	0.218
Wind	0.151	0.806	0	0.024	0.019	0	0	0
Bio	0.337	0.451	0.182	0.036	0	0	0	0

B. EV implementation - MATLAB script

```
%%EV stock per 1000 capita
x = 0:1:31;
% The period for which the s-curve is made (2019-2049)
y2 = 550*sigmf(x,[0.25, 13.083164]);
% The sigmoidal function multiplied by desired final level
% with a and c values found by trial and error
y2=y2-y2(1)+10000/(5814303/1000);
% Defining the starting point of EV’s per 1000 capita

EV=y2(2:31);
k2=EV(30);

for i=1:30
    EV(i)=EV(i)+((550-k2)/30*(i));
end
% Distributing the difference between last point
% and the desired last point evenly throughout the years

X=2020:1:2049;
% Defining the x-axis

plot(X,EV)
hold on
xlabel(’Year’)
ylabel(’EVs per 1000 capita’)
ylim([0 550])
xlim([2020 2049])
% Plot specifications
```

C. Material breakdown V164



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V164-8 MW: Provisional material breakdown (updated 18/04/2013)

Material	**Unit**	**Foundation**	**Tower**	**Nacelle**	**Hub**	**Blades**	
Steel	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Cast iron	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Aluminium and alloys	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Copper and alloys	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Thermoplastics	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Thermosets	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Glass and ceramic	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Carbon fibres	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Electronics / electrics	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Backup batteries	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Liquids and oils	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Not identified	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Number pieces	pieces	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Total mass	kg	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	99,8%
		Foundation includes structure, piles, corrosion protection & switchgears	Tower includes PCM and tower cable			SPECIFIC BLADE MATERIAL BREADKOWN NOT FOR EXTERNAL COMMUNICATION	
Material mapped (%):		**100,0%**	**99,8%**	**97,5%**	**99,0%**	**100,0%**	

Figure C.1: Material breakdown for the offshore wind turbine V164. The turbine is later tuned to 10 MW without significant extra consumption of material. The total materials can be seen in table 2.1 but the material in each component is hidden due to confidentiality.

D. Comparison of Bio1 and Wind1

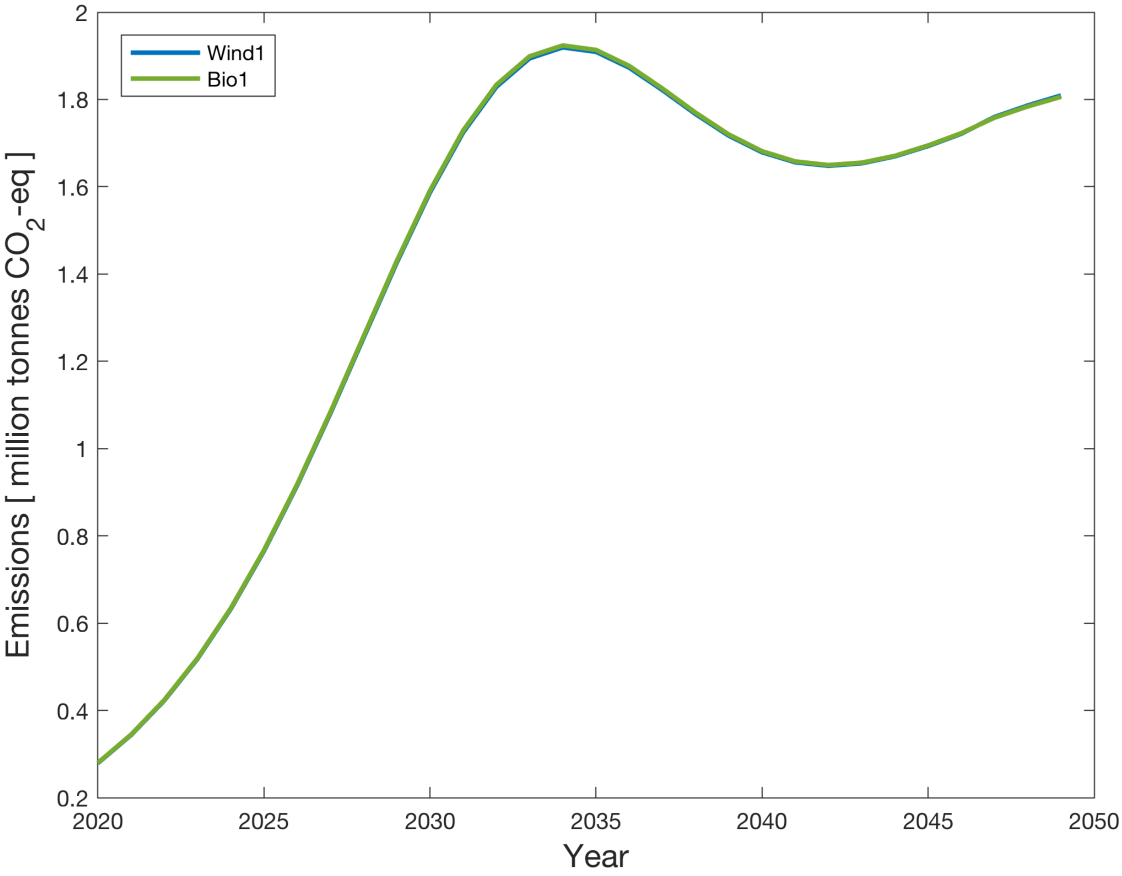

Figure D.1: The biomass scenario with only EVs compared to the wind scenario shows almost no difference. Accumulated the biomass scenario emits 3.7% more, when building the needed capacity for power production, than the wind scenario.

E. Household consumption without smart grid

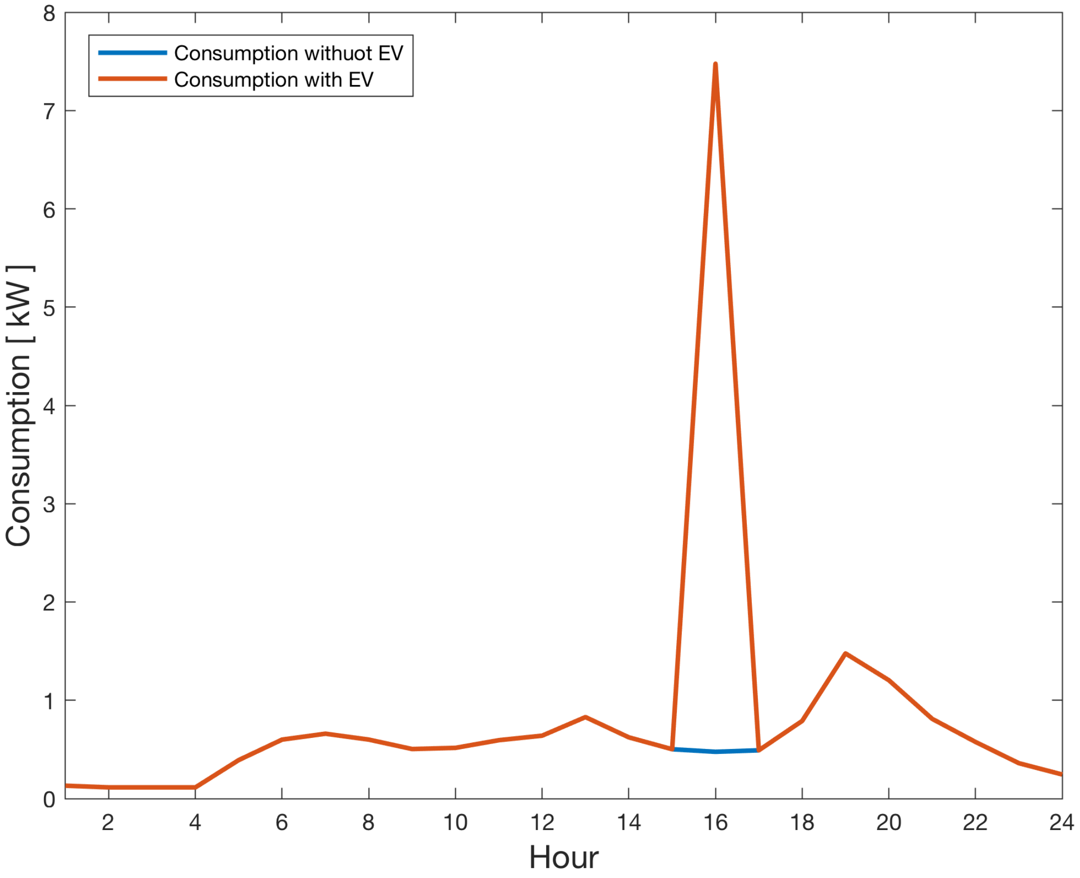

Figure E.1: Household consumption without smart grid.