Future Smart Charging Profiles in Danish Homes

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Abstract

Passing the Climate Action Plan, Denmark seeks to reach decarbonization targets by 2035, incentivizing EVs to Danish consumers. This transition requires widely available charging infrastructure and a flexible renewable energy-sourced grid to meet future transportation energy demand. Denmark's government is targeting fossil fuel independence by 2050[1]. This transition requires widely available charging infrastructure and a flexible renewable energy-sourced grid to meet future transportation energy demand. Similar to California, measures include banning the sale of new gasoline, hybrid, and diesel light-duty vehicles. Consequently, the anticipated demand for Electric Vehicles (EVs) will heighten rapidly in the coming decade. Partnering with the Danish Technological University (DTU), creating charging profiles to characterize when and where Danes are charging EVs allows governmental and private entities to pinpoint potential regions for grid improvements and expansion. This report aims to project the future demand for electricity in Denmark due to its ambitious goals to decarbonize its transportation sector. This report explores smart charging scenarios to decrease peak load, carbon emissions, and consumer costs. Analyzing available charging data from a climate similar to Denmark, the United Kingdom, three categories of charging profiles are present: Slow Charging (<7kW), Rapid Charging (7<value<22), and Fast Charging (>22kW). Additionally, two scenarios were created: Scenario 1, reducing idle time, and Scenario 2, reducing grid intensity. Projecting to 2035, smart charging was shown to be beneficial. On an hourly basis, shifting 24% of charging instances results in a 14% reduction in greenhouse gas (GHG) emissions and 8% of saved costs to consumers. Further research could be done utilizing Danish charging data if available. Recommendations include shifting consumer charging times outside of 7:00 am - 10:00 am and 5:00 pm to 9:00 pm to reduce grid use during peak demand hours.

Key Words

Electric Vehicles (EVs), Plug-In Hybrid Electric Vehicles (PHEV), Plug-In Duration, and Smart Charging.

1. Introduction

1.1. Denmark's Climate Goals

In 2013, children in Denmark ages 10-15 were asked whether they would mostly bike or drive for local commutes when they grew up. Despite Denmark's legacy as a cycling epicenter, the study found that 80% of the children were interested in driving for local commutes and owning their vehicle[2]. Concurrently, the same children overwhelmingly recognized the importance of protecting the environment and pushing Denmark toward a greener future[3]. A decade later, in 2023, the polled children are now 20-25. Despite the time that has passed, the question remains the same: Are Danes seeking environmental policies alongside increasing car ownership?

In 2020, the Danish Parliament passed the Climate Act, recognizing the nation's need to decarbonize the state, combating the impacts of climate change, and promoting human health and welfare. To improve air quality by reducing greenhouse gas emissions (GHGs) from the transportation sector, the Climate Act bans the sale of gasoline and diesel light-duty vehicles (LDVs) by 2030 and plug-in hybrid vehicles (PHEVs) by 2035. Thus, the Danish government is expanding its infrastructure and political incentives for the ownership of electric vehicles (EVs). In 2023, monetary incentives were introduced through legislation, such as tax benefits, financial reimbursements, and funding new charging stations[4]. Before the passing of the Climate Act, EV ownership in Denmark was particularly low compared to other European Union (EU) member states, representing less than 2% of newly registered passenger vehicles. By 2022, two years after the law passed through parliament, the amount of newly registered passenger vehicles increased rapidly to 18.5% EVs and 15.2% PHEVs[5].

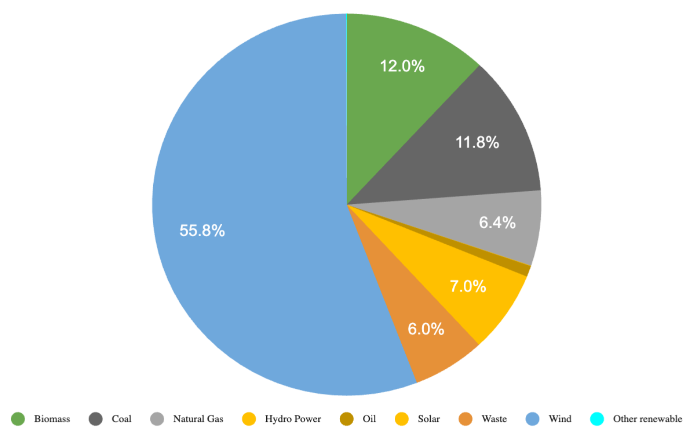
Alongside the Climate Act, as a member of the United Nations (UN), Denmark committed to reaching the UN Sustainable Development Goals (SDGs). Created in 2015, the UN SDGs aim at improving the welfare and protection of natural resources across the world through various pledges, including "affordable and clean energy,"

[1] The Danish Energy Agency, 2015
[2] Sovacool et al. 2019.
[3] Sigurdardottir et al. 2013
[4] Skatteministeriet et al. 2023
[5] Statistics Danmark, 2023.

"sustainable cities and communities," and "climate action." Of 163 participating member states, Denmark ranks No. 2 in progress, behind Finland and before Sweden and Norway. However, Denmark had achieved many goals before pledging, thus, entering as a high-achieving country. Additionally, Denmark has the highest spillover index, meaning their efforts to be sustainable come at a high cost to other developing countries, representing the negative spillover effect. The negative spillover stems from the high amount of goods Denmark imports annually, accounting for plastic waste (7.4 kg/capita), electronic waste (22.4 kg/capita), and lastly, SO2 (10.2 kg/capita), NO2 (kg/capita), and CO2 (4.1 tCO2/capita) emissions embodied in imports[6]. Regarding "affordable and clean energy," however, Denmark is a model nation. According to the 2022 Organization for Economic Cooperation and Development (OECD) Development Report, Denmark had 100% of its population able to access electricity, alongside an increase to 35.8% in the share of renewable energy in the total primary energy supply.

1.2. Renewable Energy in Denmark

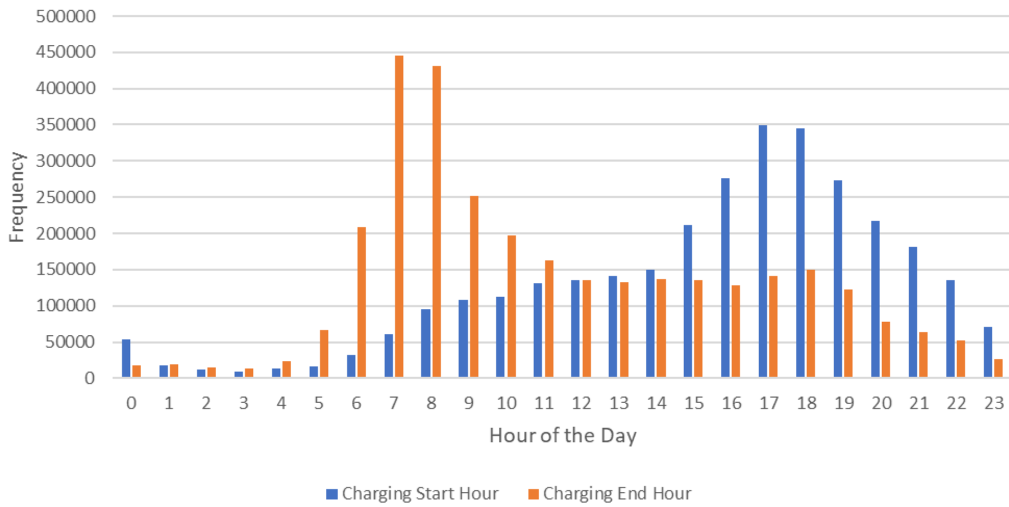
As a small nation of 5.93 million people, the country has high trust and public support for the Danish Parliament, alongside a high approval rate for Danish Queen Margrethe II. Demographically, 96.1% of the population is white, 86% of whom are ethnic Danes. The median income in Denmark is 17,154 USD[7], making the nation the ninth highest in the world behind Sweden. Thus, Denmark is considered a highly homogenous state. Between Germany and Sweden, Denmark lies between the North and Baltic Seas. As a temperate marine climate zone, high winds push along the coast. Thus, capturing wind power offshore allows Denmark to capture more energy through wind turbines than through burning fossil fuels. In 2022, 55% of the grid's electricity mix was wind-generated (off-shore and on-shore), followed by 12% biomass, and 11% coal, illustrated below.



1.3. Charging Stations & Consumer Behavior

In the European Union, the 2014 Alternative Fuel Infrastructure Directive (AFID) regulates public electric vehicle supply equipment deployment. The policy recommended that EU member states reach 10 electric light-duty vehicles (LDVs) per public charger by 2020. The Alternative Fuelling Infrastructure Regulation [AFIR]) would mandate 1 kW of publicly available charger per BEV and 0.66 kW per PHEV as well as the minimum public charger coverage on highways. In 2021 Denmark will have 35.5 LDVs per charger and .5 kW of charging per EV[8]. In 2023, Denmark had 5,581 charging stands with 11,702 charging sockets. The most common chargers available are Type II, CHAdeMO, and CCS, whereas the least common are CEE 5, Schuko, ComboUS, and Type I[9].

[6]Sustainable Development Report, 2023.
[7]World Bank, 2023.
[8]EUR-Lex, 2021.
[9]Duckwise, *Copenhagen Electric*, 2023.



In Denmark, less than 2% of EVs drive more than 200km daily, with most driving 10 km daily. Meanwhile, each EV has a different charging time[10]. Currently, most EV owners start charging once they arrive home in the afternoon or early evening right after work, while the time they arrive might also vary between individuals and days. Meanwhile, more charging events and higher electricity consumption occur on workdays compared to non-workdays. More than 98% of the EV are available for charging at nighttime because the owners are not commuting during nighttime. In other words, shifting the charging events to nighttime helps to investigate smart EV charging schemes. Delaying charging events will benefit the energy system since the electricity supply is 'greener' at night as wind primarily contributes to the grid.

In the future, load shifting of EV charging by 15-30% might help to manage Denmark's grid by relieving the electricity consumption intensity of the grid in periods when other sectors, such as residential and industry, have a high demand for electricity[11]. Though the total electricity consumption might remain the same, the load profiles indicate that time shifting will bring long-term changes to reducing GHG emissions. On the individual level, suggesting people begin charging before going to sleep and perform charging at night will facilitate the load-shifting process[12].

2. Objective

Denmark seeks to ban the sale of gasoline and diesel light-duty passenger vehicles by 2035. By incentivizing EV ownership by Danish consumers, greenhouse gas emissions from internal combustion engines such as NOx and SOx can be reduced, improving regional air quality. Expanding Danish EV car ownership contributes to the future electricity demand from the grid. By analyzing the charging behavior of people who drive EVs, the optimized time to charge EVs can be determined based on the lowest costs to consumers and the lowest greenhouse gas emissions released.

3. Methods

3.1. Summarize EV users' charging behavior

3.1.1. Compiling Peer-Reviewed Literature

Utilizing ScienceDirect, Scopus, and the UC Davis EV Research Center, literature surrounding the EV market, consumer behavior and charging habits, and the future of decarbonization through incentivizing EV policy and grid capacity was compiled and reviewed from the past decade. Specifically, literature from similar geographies and political climates to Denmark, including research focused on Denmark, was incorporated into the project's framework, analysis, and final recommendations.

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[10] Andersen et al. 2013.
[11] Spencer et al. 2021.
[12] Friis et al. 2016.

3.1.2. Data cleaning

This project applies a UK household charge point dataset with around 3.3 million EV charging instances recorded and 25,082 individual charge points included. The dataset includes the start time, end time, duration, and energy supplied by a charging instance. Outliers were filtered out based on charging duration using R Studio. Any charging instance that lasted over 72 hours was removed because they account for less than 1% of the data and are often due to user error when ending a charging session. Also, any charging instances that lasted less than 0.05 hours (3 minutes) were removed because they often had no associated energy supply. After filtering the data, a secondary dataset, including the average start time, end time, duration, and energy supplied by each Charge Point ID (CPID), is also generated in R Studio. After data filtration, about 1.5 million charging instances were kept, equating to over 20,000 CPIDs.

3.1.3. Data analysis

After filtering the data, we analyze the charging behavior based on the primary dataset (all charging instances) and secondary dataset (CPID) based on: (1) Average start time (plug-in) and end time (plug-out) in a day, (2) Charging frequency over days of a week, (3) Charging frequency over months in a year, (4) Average charging duration, (5) Average energy supplied, and (6) Charging rate.

3.2. Future of EVs and electricity in Denmark

3.2.1. EV volume

According to Statistics Denmark, the historical and current EV volume in Denmark has been increasing since 2011. Up to April 2023, the total EV in Denmark is 131,867[13]. The full historical dataset and plot of EV number from 2011 to 2023 is included in the appendix section. To meet Denmark's carbon natural goal, 1 to 1.5 million EVs must be deployed by 2035[14]. For this project, we will use an EV stock of 580,000 for calculation and calculated based on the population (World Bank, 2023), fleet size per capita (Abegaz, 2020), and EV stock share. All three variables concern time and are projected into 2035. The EV stock can be calculated with the following formula:

$$EV\ stock_t = population_t * \ fleet\ size\ per\ capitaa_t * \ EVstock\ share_t$$

3.2.2. Electricity generation and energy source

Dataset of electricity generation and the corresponding energy sources at different times are obtained from ENERGINET. Danish electricity generation is recorded hourly, daily, monthly, and yearly. The energy sources of Danish electricity generation are broken down into biomass, coal, fossil gas, hydropower, oil, solar, waste, wind, and other renewable sources. The yearly, monthly, and hourly dataset from ENERGINET is included in the appendix. We also assume that the grid mix 2035 will stay the same as in 2022. We summarize the trends of Danish electricity generation and the energy sources for time based on (1) the yearly level of 2022 and 2023, (2) the monthly level from May 2022 to May 2023, and (3) the hourly level of the summer solstice (06/21/2022) and the winter solstice (12/21/2022).

3.2.3. Electricity pricing

Data on the current and historical electricity pricing in Denmark is obtained from NordPool, which provides the day-ahead electricity prices hourly, daily, monthly, and yearly. We also calculated the electricity prices on different days of the week by taking the average prices from May 2022 to May 2023. The full dataset will be included in the appendix section. We also assume that this project's pricing will stay constant through 2035.

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[13] Statistics Denmark, 2023.
[14] Anderson et al, 2021.

3.3. Create baseline scenarios and future scenarios of EV charging behavior

3.3.1. Baseline Scenario

To create the baseline scenario, we make the following assumptions: (1) Business as usual, (2) UK and DK charging behavior are similar, (3) Average VKT is constant through 2035, and (4) Average EV efficiency is constant. With the projection model and assumptions, we can obtain the total energy consumption and GHG emission by EV charging, which can be calculated with the following formula:

$$Energy\ consumption_t = EV\ stockk_t * EV\ Efficiency * VKT * Charging\ Profile\ Share_t$$
$$GHG\ Emission = Energy\ Consumption\ (i, t) * Grid\ Mix\ Profile * CO2\ eq\ (i)$$

$Charging\ Profile\ Share_t$ = % of users who start charging monthly, daily, and hourly,
t = year from 2022 to 2035,
i = energy sources of Denmark's electricity production,
$Grid\ Mix\ Profile$ = annual grid mix profile
$CO2\ eq(i)$ = Carbon Dioxide Equivalent of different energy sources (i).

3.3.2. Optimization Scenario

To optimize charging behavior, we shift the start time of users' charging instances, which means they can plug in their vehicle, but let the vehicle start charging later. Compared to the baseline scenario, the optimization scenario will have an optimized hourly profile share, which means the percentage of users charging at different hours will be different. Meanwhile, the daily and monthly profiles will remain the same, where the total daily and monthly energy consumed by EV charging will be the same in both the baseline and optimization scenarios. The optimization scenario contains the following principles:

The goal: To reduce the grid intensity, peak load, GHG emission, and consumer costs.
Target instances to shift:
  i. *Instances that start charging between 16:00 and 21:00.*
  ii. Charging less than 5 hours.
Optimization: *Their start times will be shifted 6 hours later (i.e., 16:00 to 22:00, 21:00 to 3:00).*
Create a new probability distribution of charging instance start time.

4. Result & Discussion

4.1. GHG emission

For emissions, Scenario 1 resulted in an estimated GHG emissions reduction of up to 14.2%, cumulatively reducing 153.4 million kg of CO2e. Scenario 2 decreased GHG emission reductions by 1.1%, cumulatively reducing 11.5 million kg of CO2e into the atmosphere. Thus, Scenario 1 grants the environmental benefits to Denmark, with the lowest emissions to consumers.

4.2. Pricing

For pricing, Scenario 1 saved costs to consumers up to 8.3%, cumulatively reducing costs by 175 million USD. Scenario 2 saved up to 4.3%, cumulatively reducing costs by 91 million USD. Thus, Scenario 1 grants the most monetary benefits to Danish consumers.

4.3. Sensitivity analysis

A sensitivity analysis is also performed on total energy consumption. The variables we test include EV stock, VKT, and the efficiency of EV. We applied Monte Carlo Simulation to estimate the upper and lower limit of all variables. The EV stock is assumed to vary by ±12.5%. In contrast, the VKT is assumed to vary by the 2022 level of different EU countries, and EV efficiency is assumed to vary by different popular EVs. Figure 2 below shows the sensitivity analysis result, which indicates that VKT has the highest sensitivity.

5. Recommendations & Conclusions

As the result and discussion section shows, shifting the start time of EV charging instances will significantly impact GHG emission reduction. The study finds smart charging an effective way to curtail GHG emissions while reducing costs to Danish consumers, alongside decreasing charging during peak demand times on the grid. On an hourly basis, shifting 24% of charging instances results in a reduction of 14% in GHG emissions and 8% in costs. With countries similar to Denmark, this study can be applied elsewhere to model potential reductions and costs in emissions, decarbonizing different states.

Encouraging a shift in consumer behavior without government support is challenging. Considering costs to consumers, such as commuting distance alongside work time and time at home, equity in whom to shift presents itself as a hurdle. Regarding equity, self-incurred expenses may be unmanageable for the average Dane. The cost of upgrading existing charging infrastructure to smart chargers is high. Additionally, there could be limited access to private parking spaces to install chargers at home. Geographically, much of the Danish population resides within the "Finger Plan," a high-density sphere within the Copenhagen metropolitan area. Coincidingly, this region houses. Though not all "fingers" of the region are affluent, northeastern Denmark houses more wealth than the rural southwest. With less density in the agricultural regions, the availability of charging stations is sparser than within the larger cities of the north. Thus, spatially, Danes with longer-distance but frequent travel may continue to rely on ICE vehicles with a limited range of EVs. For Danes who seek to lower personal expenses and their carbon footprint, public transportation across Denmark is more efficient and interconnected than the vast majority of the world. The Danske Statsbaner (DSB), or the Danish State Railways, allows Danes to travel affordably and rapidly across the nation. Additionally, the Danish Parliament allocated 1 billion USD to electrify the DSB rail fleet[15]. Electrification of the railway will lower GHG emissions and follow Denmark's environmental goals and decrease maintenance and fuel costs for the railway companies. In turn, this lowers costs to consumers.

With government aid, Denmark's decarbonization goals would be more achievable for more people. Based on our findings, we recommend that the Danish Government (1) provide subsidies or tax benefits to consumers who install smart charging stations and use them as recommended, (2) require smart charging stations in national, regional, municipal, and local plans, and (3) and expand public sharing programs, promoting multi-passenger, multi-use EVs. Under an academic lens, researchers are encouraged to analyze the commercial and workplace charging stations, incorporating predictive grid mix, pricing measures, and modeling scenarios for Denmark to 2075.

On the Danish grid, renewable energy sources, EV use, and infrastructure expansion benefit the country and consumers by reducing GHG emissions and the electricity grid's peak load. As nations seek to decarbonize and mitigate the impacts of climate change, Denmark's role as a sustainability-leading state, and its initiative to plan for the future, set a precedent; in the UN, the EU, and across the world.

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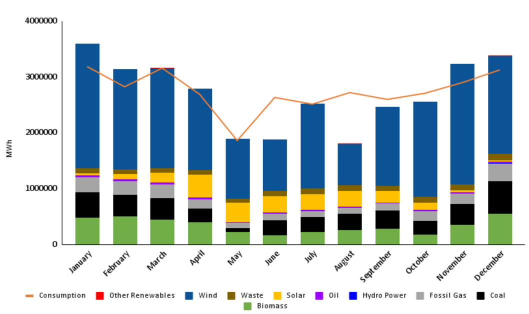
Appendix

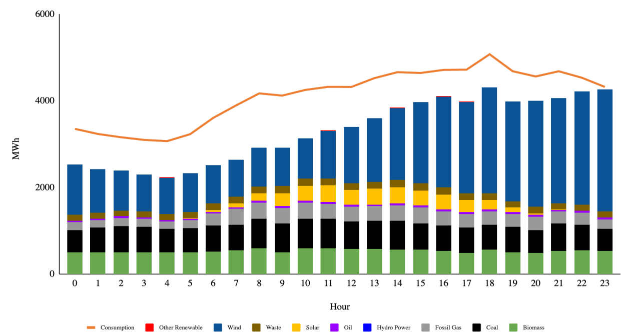
Table 17, Trip lengths and forms of transport in Denmark in 2006, based on numbers from the Transport Survey. "Other" is ferries, aircraft, etc [42].

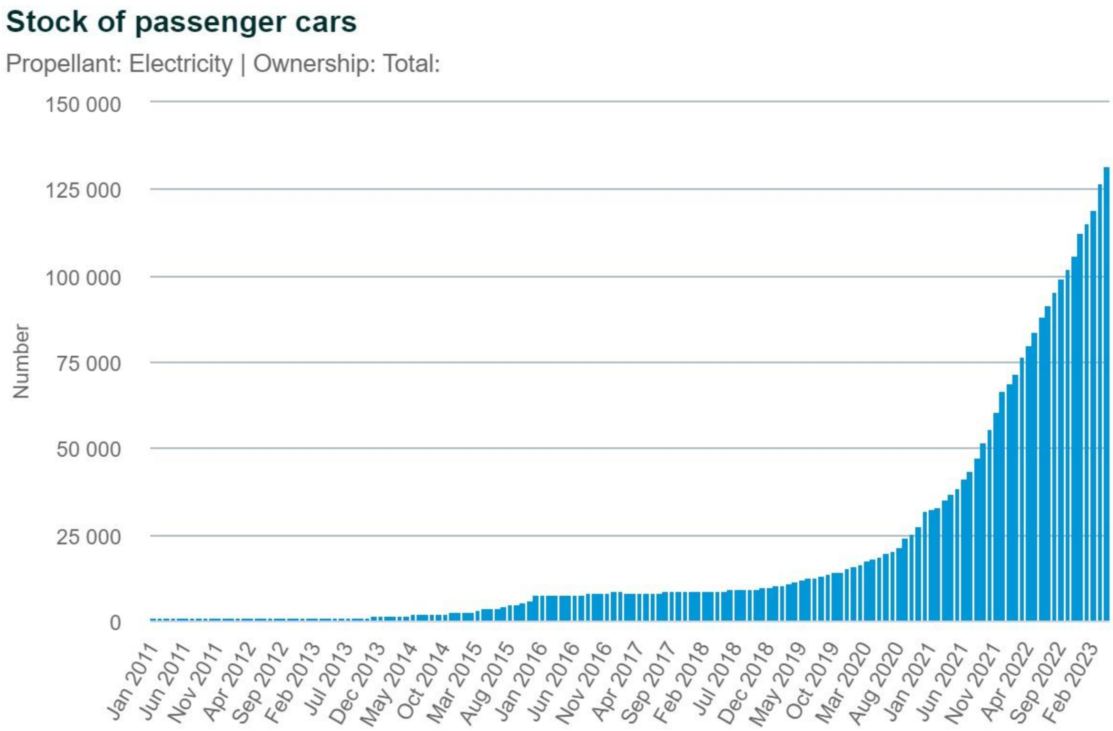
Trip length (mill, km)	Other	Walk	Bi-cycle	EU moped/ motorcycle	Driver in vehicle	Van/ Lorry	Passeng er in vehicle	Bus	Commuter train, undergrd,	Train	Sum
1-2 km	4	612	528	18	618	18	93	34	4		1,929
3-4 km	7	233	519	33	1,466	78	288	87	17		2,728
5-6 km	20	110	404	39	1,250	73	340	145	32	5	2,418
7-10 km	38	32	378	91	3,076	170	780	295	71	14	4,945
11-15 km	59	12	210	87	3,472	166	969	303	151	47	5,476
16-20 km	60	3	82	66	2,981	272	891	178	177	131	4,841
21-30 km	50	5	68	69	4,767	367	1,304	208	380	170	7,388
31-40 km	47	6	31	35	3,479	252	802	147	309	305	5,413
41-50 km	18		64	20	2,652	332	839	16	84	291	4,316
51-100 km	193		42	33	6,838	968	2,138	100	63	1,040	11,415
101-200 km	293				6,099	740	2,105	119		1,423	10,779
201-300 km	649			49	1,072	416	556	102		883	3,727
301 km -	503				991	775	288	210		906	3,673
Sum	1,941	1,013	2,326	540	38,761	4,627	11,393	1,944	1,288	5,215	69,048
% under 50 km	16	92	98	85	61	37	55	73	74	20	57

Month	Profile Share	Day	Profile Share	Hour	Start Profile Share	End Profile Share
Jan	0.08	Sun	0.13	0	0.017	0.005
Feb	0.08	Mon	0.14	1	0.006	0.006
Mar	0.09	Tue	0.15	2	0.004	0.005
Aprl	0.05	Wed	0.15	3	0.003	0.004
May	0.06	Thu	0.15	4	0.004	0.007
Jun	0.06	Fri	0.15	5	0.005	0.021
Jul	0.09	Sat	0.13	6	0.010	0.066

Hour	Start Profile Share	End Profile Share	S1 End Profile Share	S2 Start Profile Share
0	0.017	0.005	0.067	0.044
1	0.006	0.006	0.137	0.020
2	0.004	0.005	0.127	0.011
3	0.003	0.004	0.069	0.007
4	0.004	0.007	0.007	0.004
5	0.005	0.021	0.021	0.005
6	0.010	0.066	0.005	0.010
7	0.019	0.142	0.01	0.019
8	0.030	0.137	0.014	0.030






Stock of passenger cars
Propellant: Electricity | Ownership: Total:
Number
150 000
125 000
100 000
75 000
50 000
25 000
0
Jan 2011
Jun 2011
Nov 2011
Apr 2012
Sep 2012
Feb 2013
Jul 2013
Dec 2013
May 2014
Oct 2014
Mar 2015
Aug 2015
Jan 2016
Jun 2016
Nov 2016
Apr 2017
Sep 2017
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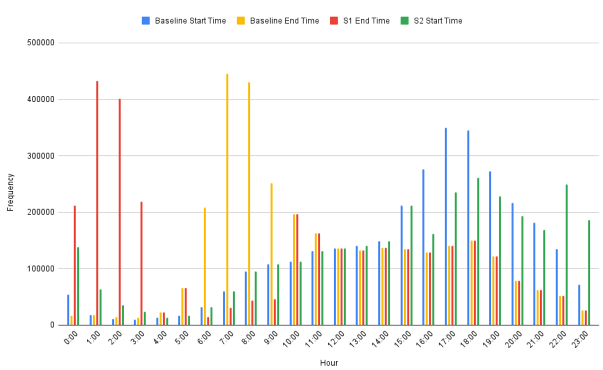
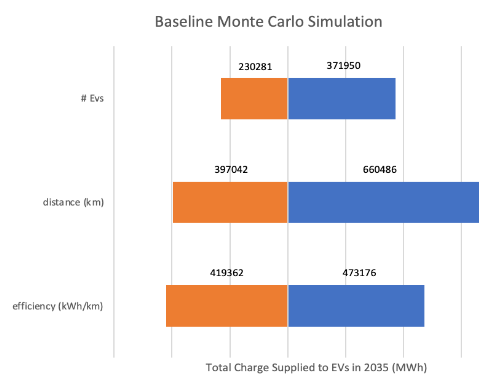
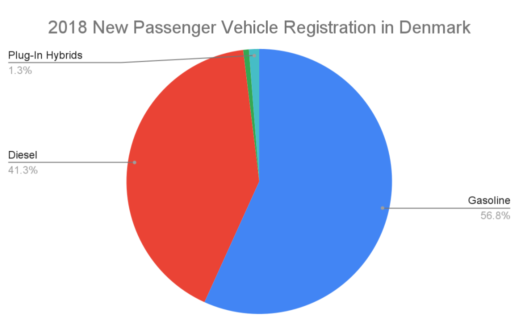
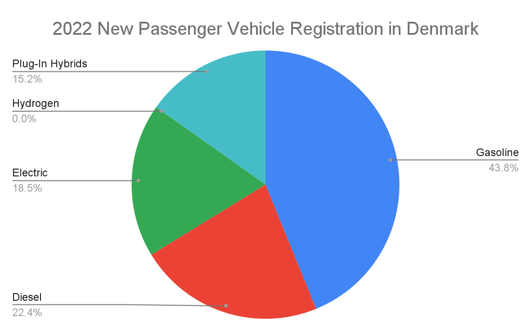
Apr 2022
Sep 2022
Feb 2023


Baseline Start Time
Baseline End Time
S1 End Time
S2 Start Time
Frequency
Hour


Baseline Monte Carlo Simulation
Evs
230281
371950
distance (km)
397042
660486
efficiency (kWh/km)
419362
473176
Total Charge Supplied to EVs in 2035 (MWh)


2018 New Passenger Vehicle Registration in Denmark
Plug-In Hybrids
1.3%
Diesel
41.3%
Gasoline
56.8%


2022 New Passenger Vehicle Registration in Denmark
Plug-In Hybrids
15.2%
Hydrogen
0.0%
Electric
18.5%
Diesel
22.4%
Gasoline
43.8%