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Solar Energy Based Charging for Electric Vehicles at Fuel Stations

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***Abstract* – The electricity used for charging electric vehicles (EV) must be produced from renewable energy sources to make EV carbon neutral. Solar PV panels installed at fuel stations can provide a noticeable fraction of charging electricity for EV also in countries located in the Northern region. The study aims to assess the potential dynamics of that fraction given a certain growth rate of the number of EV. System dynamics modelling is used as the method and Latvia is chosen as the case. The model contains parts for the calculation of the number of EV, dynamics of charging units and PV panels at fuel stations as well as in other places, the share of PV-produced power, and the resulting reduction of CO_2 emissions. Economic factors, i.e. subsidies for EV purchase, investments, and costs of charging are considered in the model. Assessment is based on sensitivity analysis. Results show that the subsidies for the purchase of EV and the price of new EV play a decisive role in the growth rate of EV and the resulting reduction of CO_2 emissions from light-duty vehicles.**

***Keywords* – Electric vehicles, renewable energy, solar energy, sustainable transport, system dynamics modelling**

Nomenclature	
EV	Electric vehicle
FV	Fossil vehicle
PV	Photovoltaic
CLD	Causal loop diagram
GHG	Greenhouse gases
O&M	Operation and maintenance

1. INTRODUCTION

The transport sector remains one of the most carbon-intensive sectors of energy sectors, and therefore reduction of direct and indirect emissions of the transport remains one of the core tasks of decarbonization policies. Electric vehicles (EV) have convincingly become one of the most rapidly growing solutions to decarbonize mobility; however, both reduction of the remaining ecological footprint of EV, as well as the improvement of economic performance remains an important task to facilitate even faster growth of electric transport sector. Unlike fossil transport (FV), for EV the costs related to installation and usage of

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infrastructure are a crucial part of the final usage costs. Therefore, many earlier studies have strongly focused on tasks related to the economic and technical optimization of EV charging infrastructure and integration of EV and solar electricity. Research carried out in Portugal on the integration of park-and-ride infrastructure with solar panel production and EV charging services confirmed that in 2017 the projected period for return of the initial investment reached approximately 14 years, thus confirming the feasibility of such a business model [1] Such confirming results can be also applied to the scenario when solar energy and EV charging service is used in synergy with fuel stations, providing additional income from retail operations. Studies also underline significant advantages from the synergy of EV charging and solar energy from the point of view of grid load fluctuations [2]. They identify that with the help of an appropriate pricing policy for charging services, there is a great potential to reduce the need for grid usage and power storage equipment, thus also benefiting the overall carbon emission impact of EV [3], [4]. However, several studies indicate that with the current overall penetration of EV in the transport system and the remaining price differences between the purchase price of FV and EV, the public charging services require public subsidies for their development at more rapid pace [1], [5], [7]. The overall situation in the energy market and trends in the global car industry may also change the economic perspectives of EV charging services significantly – in relation to growing prices for both fossil fuels and power. The proportional economic burden related with EV infrastructure loses may decrease, while solar produced power may gain significant advantages [6], [8]. As an increasingly larger number of policymakers adopt measures to facilitate the usage of EV, it becomes more important to use the available policy tools to reach the largest reduction of carbon emissions and at the same time secures the largest availability of mobility services to society.

This study applies system dynamics model to evaluate the impact of public EV charging in synergy with solar energy on the growth of EV usage and a resulting reduction in carbon emissions. Comparison with other EV transport support measures and factors, such as direct subsidies for acquisition of EV, or promotion of solar power systems is made. Sensitivity analysis allows to measure impact of different strategies, their comparison and allows to identify combined effect of simultaneously applied measures.

2. METHODS

The mathematical modelling of solar energy and EV charging synergy has been studied by many researchers; however, in most cases the modelling was carried out with the focus on economic perspective [8]. or grid operation perspective [5]. However, while evaluating the environmental aspects of the synergy effects, researchers point out that application of similar business model can produce significantly different result in different geographic regions, e.g., in European countries the impact of such synergy can be higher than in many other regions [3], [9]. Therefore, it can be argued that in order to obtain the best results, a comparison of different tools for the facilitation of EV must be carried out for a specific country or region, by using specific parameters which characterize the differences of usage of transport in the country, differences in the efficiency of solar installations, etc. This study uses economic parameters and technical assumptions which characterize countries or regions like Latvia; however, the system dynamics model with the required adaptation can be used for the analysis of other countries or regions.

In particular study, mathematical modelling, using the system dynamics approach, i.e. modelling of the systems as structures consisting of stocks and flows, was used as the method of study. The system dynamics model was created in the Stella Architect program [10]. The time horizon for modelling is from 2021 to 2050 with a time step (dt) of ¼ of the year since

the smallest time constant in the model is one year. Data, which could be found in the statistics databases, publications or reports were used, and assumed values were used for the data which could not be found in information sources. The model was used to study the development of light-duty passenger road transport. The structure of the model is shown in the form of a causal loop diagram (CLD, Fig. 1.) which reflects the main elements of the model and their interrelation. CLD allows making a dynamic hypothesis regarding the behaviour of a system, but the hypothesis can be tested only in the quantitative model using stocks and flows.

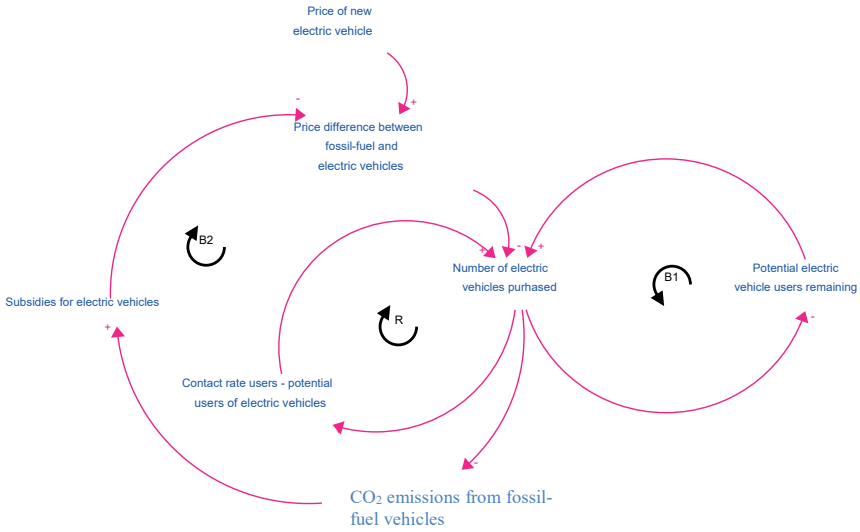


Fig. 1. Causal loop diagram (CLD) of the model. 'Plus sign' means that an increase/decrease in a cause results in an increase/decrease in effect relative to what otherwise would have been if everything else remains the same. 'Minus sign' means that an increase/decrease in the cause results in a decrease/increase in the effect relative to what otherwise would have been if everything else remains the same.

The stock of electric vehicles (EV) is the most important parameter in the model affecting the total CO_2 emissions from light-duty vehicles. This stock is controlled by the inflow of 'Number of electric vehicles purchase' (Fig. 1). As the 'Number of electric vehicles purchased' increases, the contact rate between users and potential users of EV also increases, and due to the 'word-of-mouth' effects even more EV are purchased in the future. This is the reinforcing feedback R (Fig. 1), which gains strength at the initial phase of growth of the EV stock. With the increase of the 'Number of electric vehicles purchased', a stock of 'Potential electric vehicle users remaining' is depleted and the rate of 'Number of electric vehicles purchased' starts to decrease when the balancing feedback B1 becomes stronger than the reinforcing effect R. The 'Number of electric vehicles purchased' is strongly affected by 'Price difference between fossil-fuel[2] and electric vehicles' (Fig. 1). The price difference, in turn, depends on 'Subsidies for electric vehicles' and 'Price of new electric vehicles.' The 'Subsidies for electric vehicles' is an endogenous parameter, since it may be affected by 'CO_2 emissions from fossil-fuel vehicles.' Namely, the amount of the subsidies, i.e. the total budget for subsidies, the subsidies per vehicle, timing, etc., is politically decided. The political decision may be affected by the gap between actual CO_2 emissions in transport and the goal of the CO_2 emissions. The larger the gap, the more willing are politicians to provide subsidies

[2] Alternative definition – internal combustion engine (ICE) vehicles. This definition, probably, is more accurate since ICE vehicles can be run also on biofuels or synthetic fuels.

for the purchase of EV, and vice versa. This is the balancing feedback B2 since an increased 'Number of electric vehicles purchased' leads to reduced 'CO_2 emissions from fossil-fuel vehicles' and reduced 'Subsidies for electric vehicles' (due to reduced political willingness), resulting in a larger price difference than otherwise would be, ceteris paribus. The larger price difference means a reduction in the 'Number of electric vehicles purchased.' Purchases of new EV only are considered in the model. The 'Price difference between fossil-fuel and electric vehicles' is also affected by the 'Price of new electric vehicle', which is an exogenous parameter in the model. The price is not affected by the market in Latvia due to its small size. It is also worth mentioning that the availability of a charging infrastructure does not have an effect on EV purchase decisions, and it is assumed in the model that the charging infrastructure is developed at a sufficient rate along with the growth of EV.

The model contains sub-models (Fig. 2) of stocks and flows for the calculation of the number of EV, dynamics of installation of charging units and PV panels at fuel stations, the share of power produced by solar PVs, and the resulting reduction of CO_2 emissions. Economic factors, such as subsidies for EV purchase, investments in EV charging infrastructure and solar PVs, and costs of charging are also considered in the model.

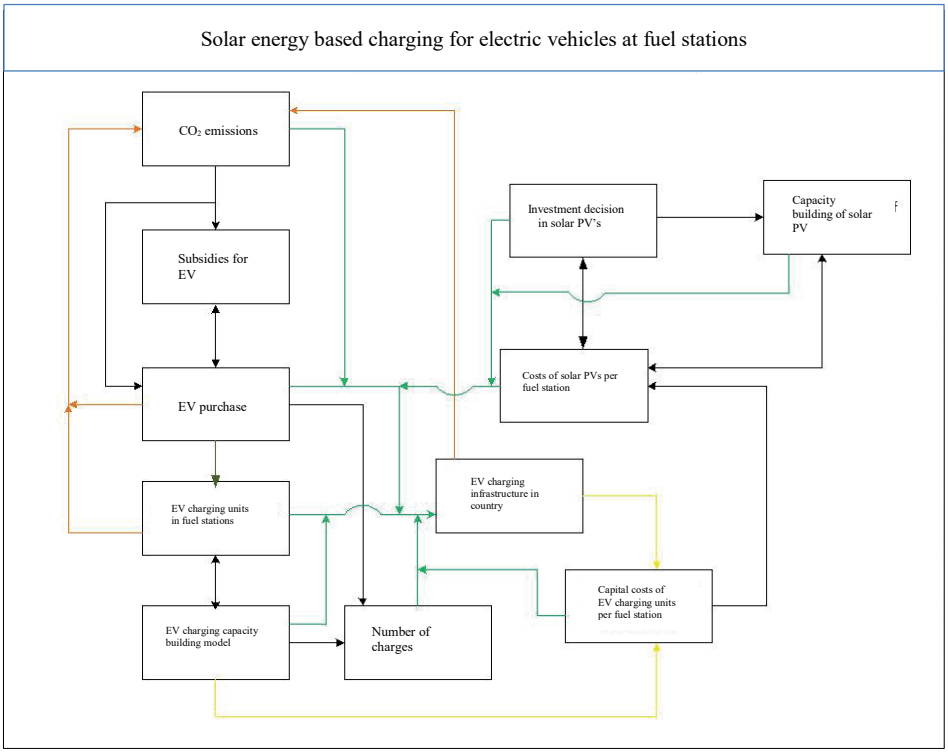


Fig. 2. Sub-models of the main model.

Rate at which EV are purchased depends on subsidies, both the total amount of subsidies represented as a stock and the subsidies per new EV, represented as auxiliary. EV purchase depletes the subsidy fund, and once it is depleted, new amount is injected in the stock with interval of five years (Eq. 1).

$$EV_{\mathrm{sf}}(t) = \int_{to}^{t} \left[Sa_{\mathrm{EV_s}}(t) - Sw_{\mathrm{EV_s}}(t) \right] \mathrm{d}t + EV_{\mathrm{sf}}(t_0), \quad (1)$$

where

$EV_{\mathrm{sf}}(t)$ EV subsidy fund, EUR;
$EV_{\mathrm{sf}}(t_0)$ initial EV subsidy fund, EUR;
Sa_{EVs} subsidies allocated to EV subsidy fund, EUR/year;
Sw_{EVs} subsidies withdrawn from EV subsidy fund, EUR/year.

The inflow to the subsidy fund depends on the gap between the actual and target CO_2 emissions, the price difference between EV and FV (Fig. 1) as well as potential buyers of EV (when the number reaches 1000, allocation of subsidies is terminated). The price is decisive vehicle purchase decision. As the price of new EV decreases, the share of subsidies per new EV will increases, ceteris paribus, and this will increase the motivation to buy a new EV. The number of EV in the country determine the amount of electricity consumed for charging EV, the construction of charging infrastructure at the fuel stations, as well as development of solar PVs.

Potential EV buyers are divided into two categories, those who can afford to buy a new EV without subsidies and those who need subsidies (see Table 1). As the potential EV users purchase EV, they become EV users, and are moved out of the stock of 'Potential EV users who made purchase decision' at a rate of EV purchase, i.e. 'EV user increase rate' (Eq. 2).

$$P_{\mathrm{EV_u}}(t) = \int_{to}^{t} \left[D_{\mathrm{EV}}(t) + P_{\mathrm{s}}(t) - EV_{\mathrm{IR}} \right] \mathrm{d}t + P_{\mathrm{EV_u}}(t_0), \quad (2)$$

where

$P_{\mathrm{EVu}}(t)$ potential EV users who made purchase decision, people;
$P_{\mathrm{EVu}}(t_0)$ initial potential EV users who made purchase decision, people;
D_{EV} decision to purchase EV, people/years (rate of purchase by the population that does not need subsidies);
EV_{IR} EV user increase rate, people/years;
P_{s} purchase decision due to subsidies, people/years (rate of purchase by the population that needs subsidies).

Rates of decision to purchase EV are influenced by 'word-of-mouth' effect (Fig. 1), which is a decisive driving force in the group of population that does not need subsidies for EV purchase. A separate module (Fig. 2) is used to determine rate at which EV charging units need to be installed in the fuel stations. The already existing fuel stations and charging infrastructure is considered. Since the maximum number of EV charging units per fuel stations is assumed to be six, the development of the charging units outside the fuel stations was also considered. 169 EV charging units have been built in Latvia by 2021, of which 16 are located at the fuel stations and 11 are publicly available free charging units in other places. Since the charging infrastructure of EV in Latvia is mostly based on EV charging units that are located outside the fuel stations, the model is considers installation of the EV charging units in the fuel stations and also in other places. Electricity consumption for EV charging in the fuel stations depends on the number and duration of EV charging at those stations. This is estimated by considering that on average, 52 charges per EV per year will take place at the fuel stations. The rest will take place at home or other charging places (office, shops, etc.). A congestion coefficient of 0.8 is also considered, meaning that 20 % of EV may find the charging units busy and leave the fuel station to look for alternative charging place. Electricity required to charge EV is calculated considering electricity consumption per km

based and average distance travelled per EV per year (see Table 1).

Solar PVs, most likely, will be installed on the roof area of the fuel stations and Table 2 shows the data used for calculation of maximum capacity of the solar PVs that can be installed in the fuel stations. Investment decision for installation of the PV system (Fig. 2) is made only if NPV for that investment is equal or larger than zero. It means, that the price of grid electricity has to be sufficiently large to generate the required cash flow of energy cost savings. It NPV is less than zero, the required subsidies are calculated to make the investment economically feasible. Decrease of initial specific investment of solar PVs due to the learning curve is also considered in the model. Installation of solar PVs, similarly to installation of EV charging units, is modelled as capacity building model consisting of several stocks and flows. These stocks and flows portray that the capacity is initially ordered and moved into stock of capacity under construction (Eq. 3). Average construction time determines the rate at which that capacity is moved to the stock of capacity in operation, i.e. 'commissioning rate.' Average lifetime of that capacity determines the discard rate of the capacity.

$$PV_{\mathrm{uc}}(t) = \int_{t0}^{t} \left[Or_{\mathrm{PVFS}}(t) - Cr_{\mathrm{PVFS}}(t) \right] \mathrm{d}t + PV_{\mathrm{uc}}(t_0) \,, \tag{3}$$

where

$PV_{\mathrm{uc}}(t)$ number of solar PV's under construction in fuel stations, units/stations;

$PV_{\mathrm{uc}}(t_0)$ initial number of solar PV's under construction in fuel stations, units/stations;

Or_{PVFS} order rate of solar PV's in fuel stations, units/stations/years;

Cr_{PVFS} commissioning rate of solar PV's in fuel stations, units/stations/years.

For calculation of electricity by solar PVs it is considered that duration of installed capacity utilization is 850 hours per year, but this value can vary greatly from country to country depending on the geographical location. Since there could be mismatch between solar PV production and EV charging, it is assumed that 0.2 of the solar PV production is used for other purposes than the charging of EV. Since the amount of solar power will not be able to cover all the required demand of EVs, part of the electricity is purchased from grid.

The main output of the model is the reduction of CO_2 emissions that is reached by replacing fossil fuel vehicles with EV vehicles. The total size of the vehicle fleet is assumed to remain constant, and no dynamics in the FV vehicle fleet related to fuel mix, age and resulting per km CO_2 emissions were considere. No changes in power production mix regarding the grid electricity were considered either. Therefore, CO_2 emission factors for FV and grid electricity were assumed to be constant (see Table 1).

TABLE 1. VALUES USED IN THE MODEL FOR THE BASE SCENARIO

Name	Value	Measurements	References
Indicated budget for EV subsidies	10	Mill. EUR	[11]
Indicated subsidies per new EV	4500	EUR/vehicle	[11]
Initial average price of new EV & fossil vehicles	33 000/18 000	EUR/vehicle	[12]
Initial number of EV	2106	vehicles	[13]
Initial fraction of EV users with subsidies	0.8	unitless	assumption
Decrease fraction of average price of new EV	0.02	Unitless, per year	assumption
Decrease fraction of specific investment in solar PV	0.025	Unitless	assumption
Probability of convincing subsidy population	0.4	People/contacts	assumption

Contact rate with subsidy pop	6	Contacts/people/year	assumption
Probability of convincing no-subsidy population	0.5	People/contacts	assumption
Contact rate with no-subsidy pop	12	Contacts/people/year	assumption
Max number of charging units per fuel station (FS)	6	Units/station	assumption
Aggregated goal of EV per charging unit	10	Vehicles/units	[14]
Number of fuel stations	436	stations	*
Initial number of public charging units in operation	11	units	*
Initial number of charging units in FS	16	units	*
Average lifetime of charging units	20	years	assumption
Average lifetime of EV	10	years	assumption
Initial specific investment in solar PV	945	EUR/kW_p	[15]
Average lifetime of PV system	25	years	[15]
Discount rate	0.05	unitless	assumption
Power density of solar PV	0.155	kW/m^2	[16]
PV size	0.166	m^2/units	assumption
Fuel station roof size	200	m^2/stations	assumption
Electricity consumption of EV per km	0.2	kWh/km	assumption
Electric capacity of charging unit	50	kW/units	assumption
Capacity fee for grid connection per kW	10	EUR/kW/year	assumption
Grid electricity price	143	EUR/MWh	[17]
Per unit O&M costs of PV	0.012	EUR/kWh	assumption
CO_2 emission factor for grid electricity	101	t/kWh	[18]
Average vehicle travel distance	13 000	km/year/vehicle	[19]
Total number of vehicles	749 909	vehicles	[20]
CO_2 emissions per fuel vehicle per km	168	g/km	[21]

* Various sources – the values were obtained by summarizing information from various sources about the fuel stations and the location of the charging units.

3. RESULTS AND DISCUSSION

The ultimate goal for the introduction of EV and the development of solar PV – based charging infrastructure at fuel stations is the reduction of greenhouse gas (GHG) emissions. CO_2 emissions, as being the major part of GHG emissions, is considered as one of the main model outputs. Gradual substitution of fossil fuel – based vehicles (FV) with EV and installation of solar PVs should result in the reduction of CO_2 emissions. The results (Fig. 3) show that the reduction of the emissions from FV take place and at the end of the modeling period only CO_2 emissions associated by grid electricity remain.

However, the reduction of the CO_2 emissions is negligible until the year 2040, when the change happens very fast. This is because of the large price difference between EV and FV even with the subsidies, that start in 2022. If the difference between subsidized EV and FV exceeds 5000 EUR, EV are purchased only by the population that do not need subsidies, and the fraction of this population is assumed to be 20 % (see Table 1). When the price difference reaches 5000 EUR, also the population that needs subsidies for the purchase of EV engages (Fig. 3), i.e. the purchase decision becomes larger than zero. The S-shaped graph of the purchase decision shows a fraction of the population that needs subsidies making an EV purchase decision as the price difference declines. The shape of the graph is assumed.

However, even if a large part of that population is ready to purchase EV, a relatively small amount of EV can be subsidized due to the limited total budget of EV subsidies. A considerable increase of the number of EV starts (Fig. 5) only at the point (around the year 2040) when the price difference reaches 4500 EUR/vehicle, and no subsidies are needed from that point on (Fig. 3). As the number of EVs increases, so does the electricity consumption from the power grid and the CO_2 emissions from the grid start to increase (Fig. 4). However, this amount of emissions is considerably smaller than the amount originating from FV.

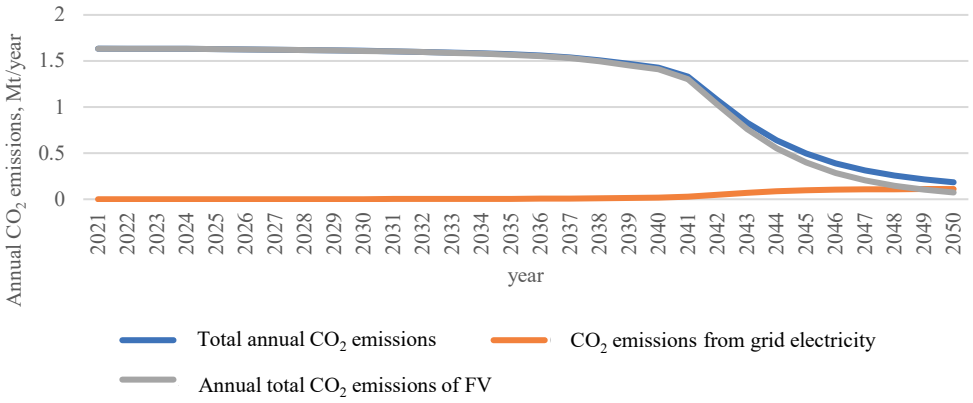


Fig. 3. Annual CO_2 emissions: the total, from fossil fuel – based vehicles and from grid electricity.

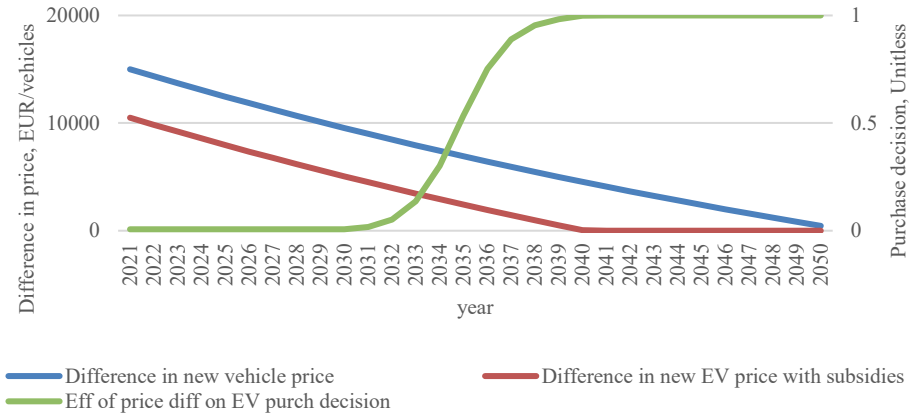


Fig. 4. Price difference effect on EV purchase decision.

The price difference between EV and fuel vehicle decreases due to the development of EV production technologies, i.e. learning effect. This is modelled as assumed annual fraction of price decrease (see Table 1 and Fig. 5). If the rate of price decrease is larger, the time it takes for the price of new EV differ from the price of FV by no more than 4500 EUR reduces. This results in earlier ‘exploding’ of EV purchases (Fig. 5).

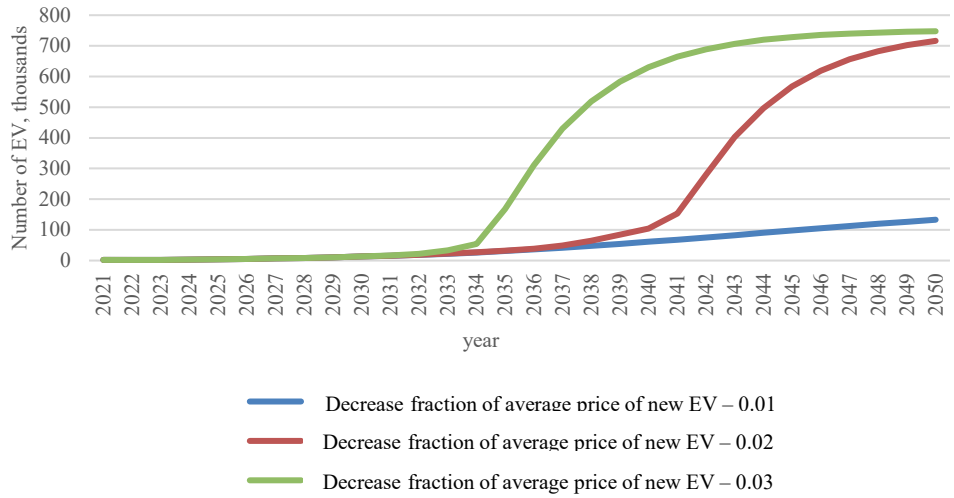


Fig. 5. Electric vehicle growth dynamics depending on the rate of average prices decrease rate of new EV. Average price decrease for the base scenario is 0.02.

Solar PV panels in fuel stations are installed relatively fast and reach the maximum capacity in the fifth year (Fig. 6) since the electricity production costs are competitive with the grid electricity from the beginning of the simulation period. The amount of electricity produced at fuel stations by solar PVs placed on the roofs of fuel stations is circa 2 % of the total electricity required for EV charging. As the amount of electricity produced from PV panels installed at fuel stations is relatively low, the possibility of installing PV panels at other charging points located outside the fuel stations is being considered in order to obtain larger share of renewable energy. The results show that PV panels located outside the fuel stations can provide about 14 % of the total amount of electricity required for EV charging.

That small impact is because of the fact that the main driver for a purchase decision is the price difference between EV and FV, and most of EV purchase takes place after the difference between subsidized EV price and FV price shrinks to zero due to the development of EV (Fig. 4). Therefore, the subsidies per EV play an important role in the purchase decision, and if those subsidies per EV are doubled then a considerable increase in the number of EV starts much earlier and by the year 2050 the whole stock of FV is replaced by EV. Doubling of the total budget for subsidies increase the rate but not much. Faster rate of FV substitution by EV means lower cumulative CO_2 emissions during the simulation period, although the total annual CO_2 emissions might be the same at the end of the simulation period. Sensitivity analysis of cumulative total CO_2 emissions depending on subsidies per new EV (Fig. 7) shows that increase of the subsidies from 1000 to 10 000 EUR/vehicle decreases the total cumulative CO_2 emissions by more than 50 %, ceteris paribus.

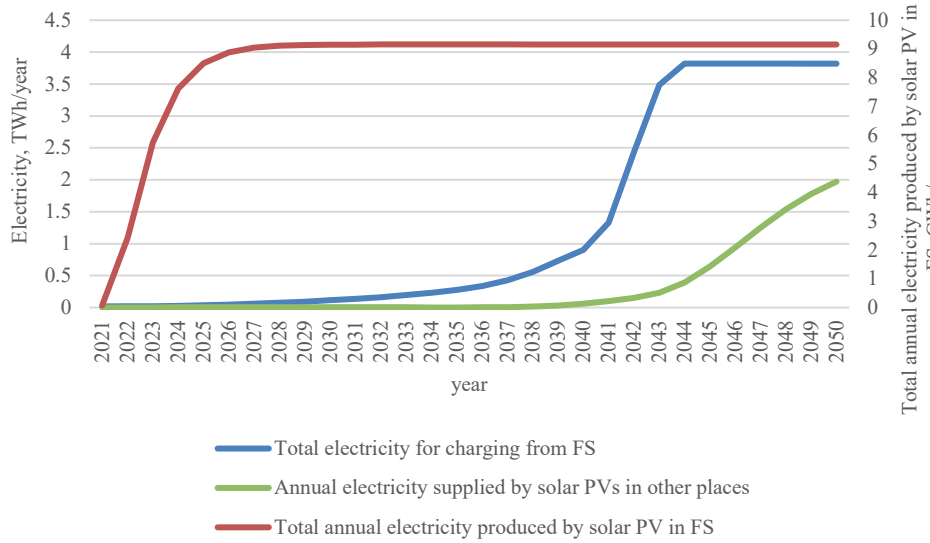


Fig. 6. Amount of the total annual electricity supplied for charging of EV from fuel stations (FS), the total annual electricity produced by solar PVs in FS (right-hand axis) and the total annual electricity produced by solar PVs in other places where the charging units are installed (left-hand axis).

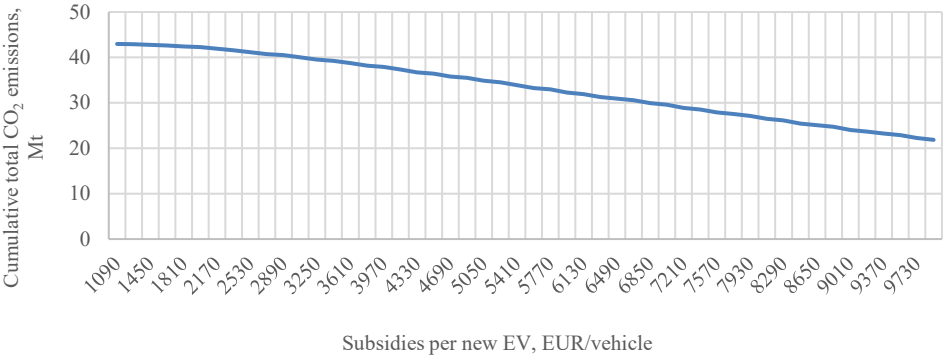


Fig. 7. Cumulative total CO_2 emissions depending on the subsidies per new EV.

To find out the impact of subsidies on cumulative total CO_2 emissions, a sensitivity analysis was performed, in which the total indicated subsidy budget is changed from 5 to 50 MEUR with the subsidies per EV remaining at 4500 EUR. The difference in the cumulative total emissions over 30 years is circa one Mt of CO_2 (Fig. 8) or approximately 3 %. It means that the amount of subsidies granted has a greater impact on the cumulative total CO_2 emissions than on dynamics of EV, i.e. the number of EV at the end of the simulation period.

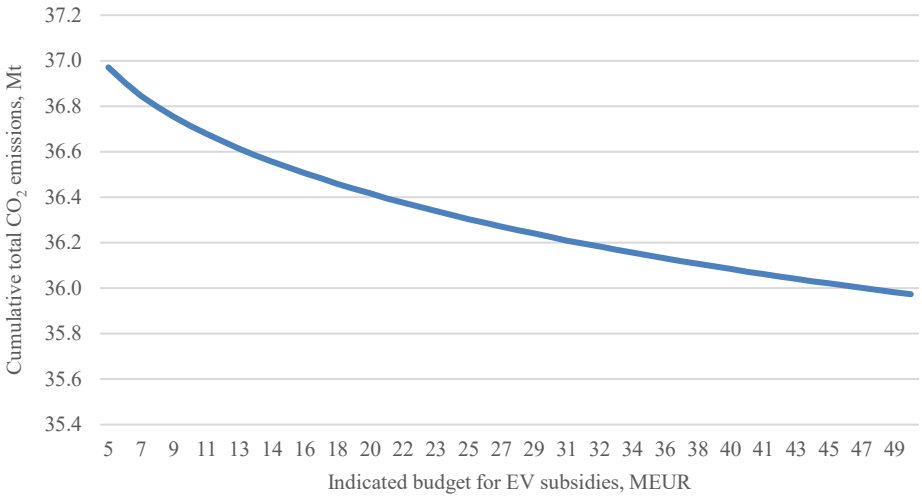


Fig. 8. Cumulative total CO_2 emissions depending on the indicated budget for EV subsidies.

4. CONCLUSIONS

The goal of the study was to evaluate the amount of electricity, which can be produced by solar PV panels installed in fuel stations and provided for EV charging. System dynamics model was used for the study and Latvia was chosen as the case. The results show that installation of solar PV panels in the fuel stations can provide circa 2 % of the total electrical energy needed for EV charging in Latvia. Contrary to the expected, the share of solar PV-produced power at the fuel stations is relatively small comparing to 14 % of the electrical energy provided for charging of EV by solar PVs installed at other charging units outside the fuel stations, i.e. in public charging places. Thus, the installation of solar PVs in other, public EV charging facilities and an increase in the share of renewable energy in the electricity production mix is required for a substantial share of renewable energy sources in the power supplied for EV [22]. The rate of replacement of FV fleet with EV is the most decisive factor in the reduction of CO_2 emissions in transport. The largest impact on the rate of growing of EV is the difference between the prices of new EV and FV. Two main mechanisms lead to the reduction of the price difference between EV and FV – a decrease of the price of EV and the direct subsidies for the acquisition of EV. If the EV average price annual decrease rate, which is due to the technology learning effect, is changed from 2 % to 3 %, a considerable increase in the number of EV starts circa 10 years earlier (Fig. 5). Thus, the direct subsidies for EV purchase could be the most effective policy tool for support of transport decarbonization and electrification. These subsidies are most effective in the initial phase of the EV diffusion process. As the prices of new EV will shrink due to technological development, the number of EV, and thus, annual CO_2 emissions at the end of the simulation period will not be strongly influenced by the total subsidy budget for EV. However, the cumulative CO_2 emissions are strongly affected by the subsidies per EV (Fig. 7), since the early transition from FV to EV lead to a reduction of the cumulative emissions for the whole period. The effect of subsidies the cumulative CO_2 emissions is not linear (Fig. 7, Fig. 8) and increase of the amount of the subsidies is very important at the lower end. Consequently, for energy policy design, the main conclusion is that the policy tools have to be targeted at

stimulating a fast transition from EV to FV as early as possible and reduction of the price difference between those vehicles in the near term, to reach the transition. The production source of power used for EV charging is of secondary importance in relation to the cumulative CO_2 emissions in the transport sector.

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