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TRANSFORMING TRANSMISSION SYSTEM DEVELOPMENT FROM REACTIVE TO PROACTIVE THROUGH ELECTRIC VEHICLE FLEXIBILITY

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A B S T R A C T

The reduction of carbon emissions in the transportation sector will be aided by the electrification of transportation in RES-based energy systems. However, the inactive addition of electric vehicles is expected to hinder sustainability efforts owing to the rise in power consumption and the significant peak impacts of charging. The three main charging methods for Electric Vehicles (EVs) in Europe are: Smart Charging (SC), Power Charging (PC), and Vehicle-To-Grid (V2G) that give varying degrees of flexibility are examined in this research. This flexibility is compared to the flexibility provided by interconnections. We depict immediate action and future planning in the power organization using the Balmorel optimization tool, and we advance the state of the art by creating new approaches to stand for battery deterioration & at-home charging. Our results show that, up to the year 2050, any rise in charging flexibility reduces system costs, modifies the energy mix, affects spot prices, and reduces CO2emissions.We quantify the reciprocal benefits of flexible charging and variable generation, which limits the economics of permanently installed batteries and causes solar energy to take the place of wind energy in passive charging. The framework that includes and lacks connection development highlights the interplay between European countries in terms of the power price framework of electric mobility. The condition of the nations with the cheapest and most decarbonizes power mix is harmed beneath the most bendable situation at the EU level, even if the best result is achieved. This necessitates an adjusted coordinating strategy at the EU level.

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1. INTRODUCTION

Electric Vehicles (EVs) are becoming more popular as a result of recently tightened fuel efficiency and pollution rules. However, due to low battery energy density, EVs' driving range is still too limited when compared to cars with internal combustion engines. The primary barrier to the widespread adoption of EVs is their low driving range (Knezović et al., 2015). Increasing the battery capacity is one of the common methods for extending the driving range, but doing so increases both the price of the vehicle and the size of the battery. Another popular strategy to increase the driving range is to recycle the vehicle's kinetic energy while braking, which is known as "regenerative braking" in certain literature (Venegas et al., 2021).

The transportation industry is being electrified in response to environmental problems. EVs may significantly decrease CO_2emissions from the transportation segment as to reducing other air pollutants like particulate matter &NO_X as well as clatter levels if they are used in conjunction with a low-carbon power generating matrix. These factors have caused several governments and towns to pass pro-EV legislation, such as tighter CO_2 emissions regulations and low emission zones, which force automakers to increase the fuel economy of combustion engines and create new electric models (Gadea et al., 2018). Due to these causes, the EV industry has seen tremendous expansion. In 2020, more than 3.2 million EVs were sold, a 43% increase over 2019. According to the optimistic International Energy Agency (IEA) scenario, this trend is anticipated to continue, with over two hundred million EVs predicted to be on the roads by 2030 (Mousaei et al., 2023). One or more electric motors provide the power for an EV. Depending on the kind of car, mobility is provided by wheels, spinners, or, in the case of track-follower cars, straight motors. Hybrid vehicles include but are not limited to, automobiles, trains, buses, trucks, aviators, ships, motorbikes, scooters, and spacecraft. This might be powered by a generator or a bank of cells. It could also be powered by a collector system that draws energy from the car's exterior. It features a battery that can be recharged and an electric motor that provides traction (Zhao et al., 2021 & Tirunagari and Meegahapola 2022).

Due to improvements in EV expertise, incentives provided by governments, and policy directions to decrease greenhouse gas emissions in the transportation sector, EVs are quickly replacing fossil-fuel-powered cars. Over seven million EVs (including electric cars, buses, vans, and heavy trucks) were introduced to roadways worldwide over the last ten years (2010–2019), representing an average annual growth rate of 30% (Hu et al., 2015). Presently, there are more than 100,000 EVs on the road in nine nations, and more than twenty countries have a market share of over one percent. By 2030, 145 million EVs are anticipated to be on the road (Weiss et al., 2020). To reduce urban air and noise pollution, to reduce CO_2emissions associated with transportation, and to provide a reliable energy supply for citizen mobility, policymakers promote electrifying the road transportation sector. In Europe, electric passenger vehicles are the focus of most interest since they have a rising market due to subsidies and other incentives (Zecchino et al., 2017). The policy's emphasis is warranted given that the majority of road transportation and its effects on the environment and public health involve passenger automobiles. However, there is also a chance of ignoring electric mobility's greater potential to revolutionize all forms of road transportation (Mesarić et al., 2015).

Electric power trains not only enable the operation of cars with no direct emissions of CO_2or air pollutants, but they also loosen significant design restrictions placed on traditional vehicles, which must fit a large cylinder block, a crankshaft, and a gearbox. Numerous tiny motors may be arranged in a variety of ways and mounted on one or more axles, directly in the wheel hub, or on several axles to provide high torque and power for electric power trains (Mao et al., 2019). EVs and renewable energy sources are getting more and more attention globally due to growing environmental concerns (Patel et al., 2021). The number of EVs worldwide hit 3.1 million in 2017, up fifty-seven % from the previous year, and is predicted to reach 125 million by 2030, according to figures from the International Energy Agency (Wang et al., 2022). China will be the first country to Begin the transition to electric automobiles from conventional fuel vehicles. However, renewable energy sources will only comprise fifty percent of China's overall energy consumption in 2030 (Dong et al., 2021).

The further sections of the article include Section 2, which lists relevant studies, section 3, which describes the methodology, section 4, which lists the conclusion, and Section 5, which summarizes the study.

2. RELATED WORKS

An EV signal hardware-in-the-loop model was proposed and contains a real-time operating driving system and vehicle model. Implementing realistic test cases validates the model. The findings of this work may be helpful in future investigations on electric vehicles (Vo-Duy Ta 2016). Guo et al., 2021 introduced a unique neural-fuzzy-based adaptive sliding mode automated navigation organize an approach to enhance the powerful presentation of vision-based unmanned EVs with time-varying and unknown characteristics.

The findings further show that the proposed control method has outstanding resilience and error convergence characteristics. A novel fuzzy method is utilized for the best anti-skid control design for electric cars, according to Li et al., 2021. When there are uncertainties, the anti-skid control is used to keep the wheel speed constant. The control can stop a vehicle from sliding with the least amount of control effort under unpredictable conditions, according to numerical simulations. A multi-objective optimization problem was presented Battapothula et al., 2019 to find the instantaneous residency and sizing of distributed generations, with constraints on the number of EVs in each zone and the maximum figure of DG possible based on the proposed system's highway and electrical network.

The electrical distribution scheme for the 118-bus evaluates the performance of the suggested method. The specifications of the battery type are significantly impacted by low temperatures. The suggested technique decreases how much experimental calibration there is for the battery model parameters and does not need to store a lot of offline data for battery model parameters. At varied ambient temperatures, the suggested method's maximum error is within 2%. The suggested procedure is also unaffected by the starting condition of the charge value. The results of the studies demonstrate the remarkable accuracy of the lithium-ion battery model at various temperatures Guo et al., 2020. To increase the thermal-hydraulic performance of microchannel condensers and the COP of the air-conditioning system in electric cars, Liu et al., 2021 investigated both sides of the devices. The findings show that by correctly lowering the fin pitch at certain frontal air velocities, the high-temperature exchange performance of the microchannel condensers may be improved.

3. ELECTRIC VEHICLE FLEXIBILITY POTENTIAL

3.1 Offering flexibility via pricing structures

Flexibility provision through chargingschemes refers to the use of pricing strategies to incentivize the flexible use of electricity by consumers. Charging schemes can be designed to encourage consumers to adjust their electricity usage patterns to match the available supply of electricity on the grid. The study investigates the effects of three various EV electricity procedures: SC, PC, and V2G charging. PC is the current cutting-edge charge system, where EVs start when connected in, charging at their full potential and ceasing when completely charged. The scheme lacks flexibility and can increase a strain on the electrical infrastructure during peak times, leading to high prices. SC, on the other hand, is considered a choice that could offer the electrical grid flexibility. There are planned energy acquisitions based on rates for power and damages incurred, allowing for more efficient use of energy and a decrease in system stress at peak times. V2G charging is the most flexible option investigated in the study. With a bidirectional charger, EVs can not only charge from the grid but also discharge their batteries back to the grid, providing balancing services to the energy system. However, V2G charging requires additional charger technology and may result in higher costs due to the additional usage of EV batteries.

3.2 Forecasting Consumption and Flexibility

Equities of electric vehicles

The technology's uptake must be examined to predict future requirements for EVs and their chance for flexibility. Tables 1 and 2 provide an overview of the nations concerned with projected vehicle stocks. Multiple sources are used to predict the vehicle stockpiles, with data extrapolated linearly out to 2020. Denmark (DK), Narvey (NO), Sweden (SE), Finland (FI), France (FR), Belgium (BE), Netherlands (NL), United Kingdom (UK), Germany (DE), and Poland (PL) are used to provide country-specific predictions. The shares in question during Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) are presumed in predictions where they are missing. As a consequence, the demand generated by EVs may be predicted.

Table 1. The nordic and baltic regions' ev stock developments are predicated on a thousand automobiles, respectively.

Type	Year	DK	NO	SE	FI	EE	LV	LT
BEV	2020	4.1	10.1	19.1	2.1	0.5	1.6	1.6
PHEV	2020	22.1	20.1	64.1	07.1	1.6	1.6	1.6
BEV	2030	258.9	2157.3	241.6	072.4	32.6	50.8	77.2
PHEV	2030	451.5	536.8	1122.8	472.5	227.4	285.5	171.6
BEV	2040	472.2	0612.7	1183.8	504.2	245.7	111.3	206.6
PHEV	2040	721.2	0001.8	1689.1	766.9	112.5	206.2	453.8
BEV	2050	587.4	1243.9	1503.6	672.5	111.1	131.1	203.6
PHEV	2050	650.1	0148.4	1638.5	742.7	111.2	152.8	231.9

Table 2. Assumptions for the growth of the electric car fleet in central North West europe in terms of thousands of vehicles.

Vehicle	Year	UK	DE	NL	PL	BE	FR
BEV	2020	71.1	101.1	52.1	1.5	49.1	71.8
PHEV	2020	171.1	106.1	101.1	1.5	13.4	173.1
BEV	2030	3372.0	4341.6	2873.6	1701.1	517.2	3415.8
PHEV	2030	3372.0	4341.6	1740.5	1701.1	517.2	3415.8
BEV	2040	7272.0	8473.6	4184.4	3401.1	1033.6	7366.5
PHEV	2040	5454.2	6355.5	2733.5	2551.1	775.4	5525.1
BEV	2050	11701.1	12397.2	5321.6	5101.1	1550.1	11853.0
PHEV	2050	7801.1	8265.2	2394.7	3401.1	1033.6	7902.3

Demand is driven by electric vehicles

Technical vehicle assumptions also statistics about driving from “Denmark's National Transport Survey” are used to determine the demand for driving. Technical and financial information in Table 3 contains data on both vehicles and batteries, to calculate the fundamental energy needs.The table comprises assumptions for vehicle efficiency $\eta^{\mathrm{Bat,ch}}$, battery storage volume $\overline{SOV}^{BEV}$for BEVs, investment expenses V^{Bat}, power volume $\bar{B}^{Ch}$, and expenseV^{Ch}.

Table 3. Data about EVS' and their chargers' yearly technical input.

Year $[-]$	$\eta^{\mathrm{V\,eh}*}$ $[-]$	$\overline{SOV}^{BEV}*$ $\left[\frac{MW□}{1000ve□}\right]$	$\overline{GQV}^{BZAC}*$ $\left[\frac{MW□}{1000ve□}\right]$	$\bar{B}^{C□}*$	V^{Bat**} $\left[\frac{\epsilon}{MW□}\right]$	$V^{C□**}$ $\left[\frac{\epsilon}{MW□}\right]$
2020	0.18	31	11	0.02	176000	221.0
2030	0.17	31	11	0.02	150000	61.1
2040	0.16	41	11	0.016	106000	60.7
2050	0.15	51	11	0.03	71000	58.5

The maximum battery capacity for PHEVs $\overline{SOV}^{BEV}*$ is always 10 kW/h. Additional technical information on battery degradation is included. Smarter charging systems will take into consideration the aging of the cells since EV owners want to use their batteries for as long as feasible. Cyclical deterioration and calendrical aging are also determined to be crucial elements based on the most significant degradation factors. The quantity of the power source's capability that is assessed in a single cycle is regulated by the Depth Of Discharge (DOD), which also has an impact on cyclical degradation. The crucial input into the model is the creation of dependable driving patterns for vehicle fleets. On the one hand, it establishes the private transportation sector's need for power. However, a detailed examination demonstrates that EVs can assist the energy infrastructure and significantly lower the cost of charging.

4. MODELLING STRATEGY USING BALMOREL

Putting a focus on the electrical system, Balmorel an open-source probabilistic energy-system optimization model is used in this work. To expand the range of technologies, fuels, and investment options, there are several add-ons. Additionally, flow-based modeling is used to depict the transmission system. Some of the topics that have been explored in publications investigating energy-system modeling include the potential of sustainable transitional gases from the current electrical system to the district heating system. The initiatives NETP16 and Flex4RES provided the general modeling assumptions and the optimization's calibration. Three separate sets of limitations are included in the EV add-on. Initially, there is a baseline set of PC limitations. The second set of limitations concerns the car's ability to work with a smart charging infrastructure. Since Balmorel merely replicates the next-day market, restrictions for balance or the regularity of the market involvement are implemented. The V2G charging system is subject to the final set of restrictions.

4.1 Explanation of the electric vehicle add-on mathematically

Passive Charging

The intrinsically determined PC charging demand $\Omega_{x,g,d}$ restriction is first presented in equation (1). In this equation $B^{BV}_{x,e,c,g,d}$, stands for the rigid PC load, which depends on the year x, the area b in every nation, the season g, the hour d, and the PHEV and BEV vehicle technologies. In the used optimization model, Δd denotes the size of a time step. Balmorel used hourly figures for the investigation in this study.

$$\Omega_{x,g,d} = \sum_{e}^{E} \sum_{c}^{C} B^{PC}_{x,e,c,g,d} . \Delta d \qquad (1)$$

The cost associated with the cyclical degeneration of $PC_{x,g,d}^{Deg,and\ Cyc}$[∈]is determined using equation (2). It merely takes into consideration the vehicle's charging for sake of simplicity. The battery cells' cycle deterioration is represented by the cycle factor$\gamma^{Deg,Cyc}$. The highest charge that may be used $\overline{SOC}_{x.e.c.g.d}$ of the fleet that is presently on hand is used to calculate the DOD, which is then multiplied by a factor called $\alpha^{Bat,Qg}$to increases the size of the fixed battery for taking into consideration the difference between available and the added capacity. The lifetime factor $\alpha^{Bat,Lft}$ is then applied to the battery replacement cost $V_{x.e.c.g.d}^{Bat,Rept}$[∈], taking into account the assumption that by reaching a 25% capability, the power source's life decreases.

$$\Phi_{x,g,d}^{Deg,Cyc} = \sum_e^E \sum_c^C \gamma^{Deg,Cyc} . \frac{V_{x.e.c.g.d}^{Bat,Rept}}{\alpha^{Bat,Lft}} . \frac{B_{x,e,c,g,d}^{PC} . \Delta d}{\alpha^{Bat,Qg.} \overline{SOC}_{x.e.c.g.d}} \tag{2}$$

The costs related to $PC\Phi_{x,g,d}^{Deg,and\ Cal}$[∈] deterioration brought on by calendar aging are calculated using equation (3). Because the expense is only applied to the battery when it is connected, SOC throughout journeys is unknown. Aging's inevitable component is representedby $\gamma^{Deg,CalV}$, while its flexible component is linked to $\gamma^{Deg,CalL}$ and depends on the charge's status. When a PC is charged, the fleet's state of charge is shown by the value of the parameter $SOC_{x.e.c.g.d}^{PC}$ [MWh].

$$\Phi_{x,g,d}^{Deg,Cal} = \sum_e^E \sum_c^C \left(\gamma^{Deg,CalV} + \gamma^{Deg,CalL} . \frac{SOC_{x.e.c.g.d}^{PC}}{\alpha^{Bat,Og.} \overline{SOC}_{x.e.c.g.d}}\right) . \frac{V_{x.e.c.g.d}^{Bat,Rept}}{\alpha^{Bat,Lft}} \tag{3}$$

Smart Charging (SC)

SC is the following charging method to be discussed. According to equation (4), the need for SC charging $\Omega_{x,g,d}$must be adjusted. While $CB_{x,e,c,g,d}^{Flex}$ the fluctuating battery load that may be changed, $B_{x,e,c,g,d}^{Inflex}$ is the obstinate filling that takes place when the vehicle arrives from its trip with fewer resources than the required minimum amount for emergency trips.

$$\Omega_{x,g,d} = \sum_e^E \sum_c^C B_{x,e,c,g,d}^{Inflex} . \Delta d + CB_{x,e,c,g,d}^{Flex} . \Delta d \tag{4}$$

For the impacts of the saturation condition, equations (5) and (6) adjust the cycle degradation cost $\Phi_{x,g,d}^{Deg,Cyc}$[∈] and the calendrical aging costb$\Phi_{x,g,d}^{Deg,Cyc}$[∈], respectively. The sum of the flexible and constant charging loads now determines cyclical expenses, and the parameter may also be changed to lower the schedule aging cost$V\,SOC_{x.e.c.g.d}$, which denotes the fleet's state of charge for SC.

$$\Phi_{x,g,d}^{Deg,Cyc} = \sum_e^E \sum_c^C \gamma^{Deg,Cyc} . \frac{V_{x.e.c.g.d}^{Bat,Rept}}{\alpha^{Bat,Lft}} . \frac{B_{x,e,c,g,d}^{Inflex} + CB_{x,e,c,g,d}^{Flex}}{\alpha^{Bat,Qg.} \overline{SOC}_{x.e.c.g.d}} \tag{5}$$

$$\Phi_{x,g,d}^{Deg,Cal} = \sum_e^E \sum_c^C \left(\gamma^{Deg,CalV} + \gamma^{Deg,CalL} . \frac{SOC_{x.e.c.g.d}^{BV}}{\alpha^{Bat,Og.} \overline{SOC}_{x.e.c.g.d}}\right) . \frac{V_{x.e.c.g.d}^{Bat,Rept}}{\alpha^{Bat,Lft}} \tag{6}$$

Implementing more storage and charging restrictions is necessary. Equation (7) depicts the storage's energy status, taking into account both flexible and rigid charging, as well as efficiency losses $\eta^{Ch,Dch}$and energy withdrawals $Dk_{x,e,c,g,d}$ during vehicle journeys. The lower and higher constraints on the state of charge $C\,\overline{SOC}_{x.e.c.g.d}$ and $\overline{SOC}_{x.e.c.g.d}$, which indicate the possible useable capacity range, are time-dependent.

$$CGQV_{x.e.c.g.d} = CGQV_{x.e.c.g.d-1} + GQV_{t,v,d}^{Flex} + \eta^{Ch,Dch}\left(B_{x,e,c,g,d}^{Inflex} + CB_{x,e,c,g,d}^{Flex}\right) . \Delta d - Dk_{x,e,c,g,d} \tag{7}$$

$$\overline{SOC}_{x.e.c.g.d} \leq \overline{SOC}_{x.e.c.g.d} \leq SOC_{x.e.c.g.d} \tag{8}$$

The greatest amount of the charger's electricity output $\bar{B}_{x,c}^{Ch}$, and the quantity of plugged-in vehicles, $Odx_{v,g,d}^{Bat,Avail}$, determine how well the charger works. Equation (9), although stating that $CB_{x,e,c,g,d}^{Flex}$ [MWh] cannot be negative, states that the total should not exceed the current charger capacity for both flexible and inflexible charges that is now available.

$$0 \leq B_{x,e,c,g,d}^{Inflex} + VB_{x,e,c,g,d}^{Flex} \leq \bar{B}_{x,c}^{Ch} . Odx_{v,g,d}^{Bat,Avail} \tag{9}$$

$$0 \leq CB_{x,e,c,g,d}^{Flex} \tag{10}$$

Vehicle-to-Grid (V2G)

In times of a lot of energy costs, the V2G pricing plan promises to actively sell energy, while the SC scheme just permits load shifting. The demand constraint for $\Omega_{x,g,d}$ as given in equation (11) is positively impacted by this. The variable $CB_{x,e,c,g,d}^{V2G}$ represents the ability to discharge and decreases the cost for EV customers as well.

$$\Omega_{x,g,d} = \sum_e^E \sum_c^C B_{x,e,c,g,d}^{Inflex} . \Delta d + CB_{x,e,c,g,d}^{Flex} . \Delta d - CB_{x,e,c,g,d}^{V2G} . \Delta d \tag{11}$$

Since cyclical deterioration is only enforced to charging and the calendar aging is still dependent on the state of charge, equations (5) and (6)'s degradation limitations may both be utilized. However, constraint 7 about the energy balance has to be adjusted. The vehicle's energy drain from discharging multiplied by the efficiency losses is now in equation (12).

$$CGQV_{x.e.c.g.d} = CGQV_{x.e.c.g.d-1} + GQV_{t,v,d}^{Flex} + \eta^{Ch,Dch}\left(B_{x,e,c,g,d}^{Inflex} + CB_{x,e,c,g,d}^{Flex}\right) . \Delta d \tag{12}$$

$$-\frac{1}{\eta^{Ch,Dch}} . CB_{x,e,c,g,d}^{V2G} . \Delta d - Dk_{x,e,c,g,d} \tag{13}$$

In equation 14, the charger constraint 9 is also updated appropriately. It is assumed that although charging and discharging the same vehicle at the same time is still not conceivable, a whole fleet can do so. The virtual charger's capacity, however, continues to set a restriction on the amount of charging and discharging that may be done about the installed capacity. In equation (15), a non-negative constraint is also imposed on the variables $CB^{V2G}_{x,e,c,g,and\ d}$.

$$0 \leq B^{Inflex}_{x,e,c,g,d} + CB^{Flex}_{x,e,c,g,d} + CB^{V2G}_{x,e,c,g,d} \leq Odx^{Bat,Avail}_{v,g,d} \tag{14}$$

$$0 \leq CB^{V2G}_{x,e,c,g,d} \tag{15}$$

Due to the established limits, energy must flow through the passive charging system at its maximum power after the battery has fully charged. The SC limitations balance the expense of deterioration with the acquisition of energy. However, V2G also permits whenever there are price signals; energy returns to the grid from the design suggest lucrative times. Additionally, V2G enhances the charging process. In Balmorel, the limitations of the billing methods are now presented and put into practice. The EV add-on situations are presented in the next section.

5. TRANSFORMING TRANSMISSION SYSTEM DEVELOPMENT

Transforming transmission system development from reactive to proactive through EV flexibility means leveraging the flexibility provided by EVs to proactively manage the electricity system rather than reactively addressing issues as they arise. Traditionally, transmission system development has been reactive, with the grid being designed to meet peak demand and any unforeseen events or faults. However, this approach is inefficient and costly, as it often leads to overcapacity and underutilization of the grid during non-peak periods. By using EV flexibility, such as smart charging and V2G charging, grid operators can proactively manage the grid and balance supply and demand in real-time. While V2G charging enables electric vehicles to discharge their batteries back to the grid during peak hours when power is more costly, smart charging allows electric vehicles to charge during off-peak periods when electricity is cheaper. Through this approach, grid operators can optimize grid usage and reduce the need for expensive grid infrastructure investments. Additionally, it can help to integrate renewable energy sources more efficiently, as EVs can be used to store excess energy generated by renewable and discharge it back to the grid when needed. Therefore, transforming transmission system development from reactive to proactive through EV flexibility is a promising approach to optimizing grid usage and reducing costs while enabling the transition to a more sustainable energy system.

6. EXPLANATION OF THE CIRCUMSTANCE

The circumstances are intended to demonstrate different EV integration methods into the energy grid. The six simulations are listed in Table 4.

Table 4. Summary of the situations that were looked at and the abbreviations that were utilized.

Scenario	Charging scheme	Transmission investments
$PC_{noTransAx}$	Passive	Off
$SC_{noTransAx}$	Smart	Off
$V2G_{noTransAx}$	V2G	Off
$PC_{TransAx}$	Passive	Off
$SC_{TransAx}$	smart	Off
$V2G_{TransAx}$	V2G	Off

From 2020 through 2050, the model is run four times independently, replacing the preceding simulation period's investment choices each time. In two separate situations, the earlier described PC, SC, and V2G charging strategies are used. The first instance, denoted by the acronym $no_{TransAx}$examines the relationship between EV flexibility and the ENTSO-E TYNDP's ambition to expand the transmission infrastructure until 2030. After 2030, In some cases, grid extension is possible, enabling an examination of the fundamental case and the changes brought about by changing the charge methods. In the next scenario, all EV charging methods are used after 2030 while adapting for more grid growth. The power system in this instance is flexible and optimized for balancing the fluctuating energy supplies across markets. This analysis of the flexibility levels offered by electric batteries, the transmission system, and the interconnectors is denoted by the letter $\_\ TransAx$ for these situations.

6.1 System cost

The total system cost of scenarios without transmission expansion will depend on the specific details of the scenarios, such as the mix of generation resources and the level of demand. However, in general, scenarios without transmission expansion tend to have higher total system costs compared to scenarios with transmission expansion. The overall yearly expenses of the whole energy system are examined to evaluate the advantages of the flexible integration of EVs. The system cost, which includes stationary batteries, constant and variable O&M expenses, and fuel costs, is a comprehensive measure of the cumulative effect of EV flexibility in the SC & V2G scenarios relative to PC. Network investment expenses and the price of producing power or heat are included in this total. When comparing the different situations, it is clear that the system costs are going down while the amount of flexibility provided by EVs is increasing. This is because integrating low-cost renewable energy resources, like wind and solar power, from distant regions may be made possible via transmission expansion, hence lowering the total cost of electricity. Without transmission expansion, it may be necessary to build more expensive generation resources, such as gas-fired power plants, closer to demand centers, which can increase the overall cost of electricity.

6.2 The use of electric cars and the market linkage of stationary batteries will increase flexibility

Electric vehicle storage and load-shifting capabilities have significant effects on competing technologies. As was already indicated, the majority of significant financial savings come from eliminating the requirement for fixed batteries. The cumulative effect on storage space ability expenditures on the model throughout the whole period is summarized in Figure 1.

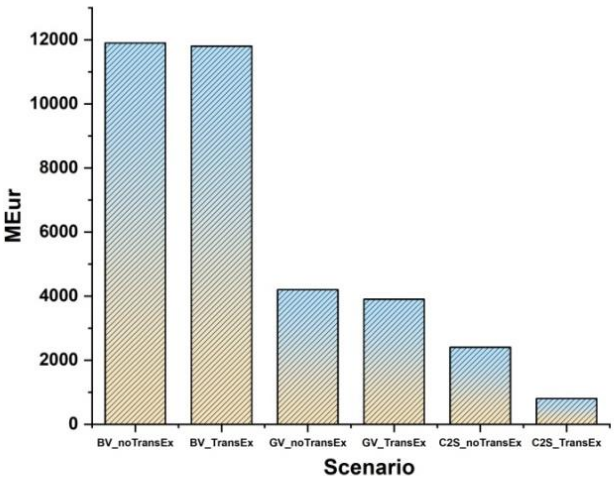

Figure 1. Investments in portable batteries during the full model space, spanning all years

To prevent grid growth, the model in the PC scenario makes significant investments in grid-scale battery technology. While transmission expansion may save costs by 1.3%, the sums invested in battery capacity amounts to 11,874 M ∈in$PC_{noTransAx}$. When smart-charging technologies are used, the need for stationary batteries is constantly reduced, with investments falling by around 62% and 67% without and with expenditures in transmission, respectively. When comparing the two scenarios, transmission grid expansion and no expansion, the V2G offering is paired with an EV development, and stationary battery investments are decreased by 80% to 93%.

6.3 Consumption of electricity throughout the years

In the combination of power and heat, the various pricing methods also provide flexibility that may replace other technologies. Figure 2 depicts the development of power production in the $PC_{noTransAx}$base case.

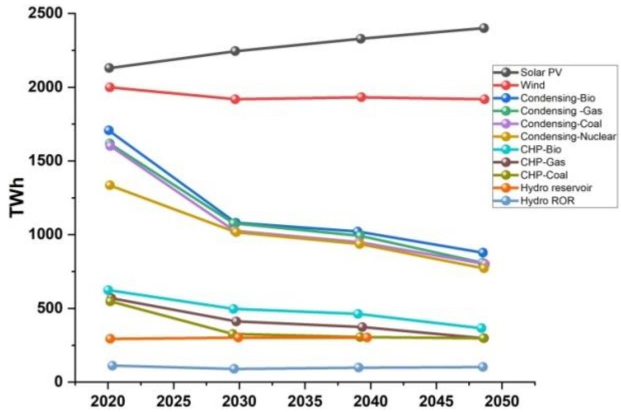

Figure 2. Percentage of electricity produced in $BV_{noTransAx}$across time

Depending on the EV charging situation, the decade from 2020 to 2030 sees the most change in generating technology. As early as 2030, both windmills and solar energy systems start to dominate the method, producing 61% of the system's power. Contrarily, the use of coal in CHP and condensation units is being phased out quickly, whereas that of natural gas will continue to be used until 2040, accounting for 3% of the energy supply. Due to developments in France and Finland, the percentage of nuclear energy stays mostly steady and significant until 2050 after declining in the 2020s as a result of the retirement of outdated power facilities. In 2050, wind, solar, and nuclear energy will together account for 1019 TW h, 473 TW h, and 430 TW h, or 66% of the world's electrical supply. CHP and condensing power plants that burn biofuels provide a little (6.2% in 2050) contribution to energy generation. According to the model, the heating industry uses biofuels more often. However, as the transportation industry continues to change, biofuel costs will soar even higher, lowering their competitiveness and commercial potential in the heat sector.

6.4 Loss of CO_2emissions due to flexibility

The reduction of CO_2 emissions from flexibility provision refers to the use of flexible energy resources to help reduce greenhouse gas emissions. Flexible energy resources include energy storage systems, demand response programs, and distributed energy resources such as solar and wind power. By using these resources, electricity grids can balance supply and demand, which reduces the need for fossil fuel-based power plants to operate, thus reducing CO_2 emissions. For example, if a solar power plant produces excess electricity during the day, it can store the excess energy in a battery and use it later when the sun is not shining. This reduces the need for fossil fuel-based power plants to generate electricity during peak demand periods. Demand response programs are another way to reduce CO_2 emissions from flexibility provision. In these programs, customers can voluntarily reduce their energy consumption during peak demand periods, reducing the need for fossil fuel-based power plants to generate electricity.

7. CONCLUSION

The transformation of transmission system development from reactive to proactive through EV flexibility is a crucial step toward achieving a sustainable energy system. The increasing adoption of EVs and renewable energy sources has resulted in unpredictable and intermittent electricity demand and supply, which puts a strain on the transmission system. However, with the integration of EVs into the grid, their batteries can act as energy storage units, providing flexibility to the system. This research examined the impacts of EV charging plans and transmission extensions on long-term energy-system planning by focusing on investment decisions in power production and lines for transmission, electricity price, heat and electricity production, and CO2emissions. PC, SC, and V2G are all included in the scenarios, both with and without the possibility of transmission system extension. This flexibility allows the transmission system operators to better manage and balance the electricity demand and supply in real-time, reducing the need for reactive measures such as load shedding and blackouts. Additionally, EVs can participate in demand response programs, where they can charge or discharge their batteries to help balance the grid during times of peak demand. Moreover, the use of EVs and their batteries can also support the integration of more renewable energy sources into the grid, as they can store excess renewable energy for later use when the demand is high. Therefore, the transformation of transmission system development from reactive to proactive through EV flexibility is a win-win situation for both the electricity system and EV owners. It enables a more stable and reliable grid while providing EV owners with the opportunity to benefit financially from their participation in demand response programs.

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