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Managing BEV Charge to Obtain a Positive Impact on a National Power System

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Abstract: This paper's research question is to evaluate the potential impact of large numbers of battery electric vehicles (BEVs) on the future electric grid, and whether the flexibility of BEV charging can induce enough system benefits to remunerate BEV users for the change in their recharging pattern. The considered scenario refers to the Italian situation and what might occur through the year 2040, where a share of BEV stock of 40% can be foreseen, as well as significant increases in PV and wind generation. Although this study is focused on Italy, its results are applicable, with minor differences, to several EU countries. This paper first shows that the future impact of increasing penetration of BEVs appears to be compatible with the expected growth of generation from renewable energy sources (RES) and the corresponding reduction in fossil fuel-based generation. It also gives an estimate of the CO_2 emission reduction resulting from these changes, considering an unmanaged BEV charge profile and two different managed profiles that shift the car's charging period to hours of the day when they have no negative impact on the grid and maximize the utilization of RES. Finally, it shows an evaluation of the economic benefits of displacing private car charging ranging from 4 to 10 cEUR/kWh, which could be used as tariff incentives to stimulate this displacing in recharging time.

Keywords: BEV fleet; BEV charge management; RES penetration; RES overgeneration; power system; CO_2 emission

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1. Introduction

The electric vehicle stock is forecasted to grow continuously over the next decades, contributing to the decarbonization of energy uses [1,2]. Many authors evaluated the transformation of current road mobility from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs) [3,4] focusing on smart charging to maximize the benefits of increasing numbers of EVs connected to the power grid [5] and minimize impacts in distribution networks [6].

In the EU, the goal of net zero greenhouse gases by 2050 (Net Zero Emission scenario—NZE) requires that by that date nearly all vehicles on the road will be decarbonized, a goal that appears compatible with the stated ban on the sale of fossil fuel-based vehicles by 2035.

The International Energy Agency, in its global EV outlook 2023 [7] (p. 109), states that to be compatible with the NZE, the EV stock by 2030 should be over 15%, and considering the already stated policies (Stated Policies Scenario—STEPS), it is expected to be over 10%.

If the trend slope taken in Figure 3.1 of [7] around 2030 is extrapolated (i.e., without considering expected further increases in the speed of adoption), by 2037, the EV stock should reach 40% of the total. Part of this stock may be fed by biofuels or e-fuels, but the amount of this part will probably remain marginal, as is inferable by the very estimate of the EV stock scenario from the IEA, which by 2030 does not include them. In 2022, e-fuel and biofuel vehicles were very marginal, with fuel cell vehicle (FCEV) sales being around 0.3% of BEVs worldwide.

This paper focuses on the Italian situation, which is significantly lagging behind the average world situation, as depicted by the mentioned IEA report (2022 BEV sales accounting for 4.7% of the total [8] versus around 10% globally [7]) and many other studies [9]. However, since the EU plans to stop fossil fuel vehicle sales by 2035, and Italy is in the EU, the Italian market can be foreseen to catch up, progressively reducing the lag with the global trend. Therefore, in this study on the Italian market, the 40% share is foreseen to be reached in the year 2040.

In the same time span, strong increases in the RES generation are foreseen (wind and PV by factors of around 3–4 in 2030 and 5–6 in 2040; details in Table 1), accompanied by small increases in the stationary load, if we exclude green hydrogen production, which is highly debated and is connected with the evolution of the green transport which, for reasons already discussed, we totally exclude from our study.

The 40% total of battery electric vehicle stock will need recharging. This justifies our research questions:

Will the existing grid, with already stated or foreseen increases in generation power, be able to safely feed these BEVs?

Will the BEV owners be left to choose their own timing for charging or be subjected to incentives to reduce the burden of recharging on the grid or even facilitate grid energy balance?

This paper aims to answer these questions, and similar issues about electric grid resilience have been investigated in a previous review paper [10]. Other authors analyzed the impact of smart charging stations on the distribution sector [11], low-voltage grids [12], and advanced charging behavior archetypes different from current "liquid fuel" mental models [13]. Another important subject of research is the vehicle-to-grid (V2G) concept, considering BEVs connected to the grid as virtual power plants [14], even though this bidirectional use of BEVs has to be carefully evaluated in terms of battery degradation [15]. This paper will propose only a power balance, based on the Italian production/load profile, and not include possible difficulties arising on the transmission and distribution grid, as well as system security, which will be addressed in future research.

2. The Considered Italian Scenario

2.1. Terna Forecasts on PV and Wind Generation by 2030 and 2040

The national energy and climate plans (NECPs) were introduced by the "Regulation on the governance of the energy union and climate action" (EU) 2018/1999, agreed as part of the "Clean energy for all Europeans" package, which was adopted in 2019. By 30 June 2023, Member States were due to submit their draft updated NECPs, in line with Article 14 of the Governance Regulation [16]. Terna and Snam (the Italian TSOs for natural gas) have recently elaborated the official report "Description of Scenarios" [17], an essential content for development plans of transmission and transport networks in the electricity and gas sectors at the national level.

The document contains two scenarios for 2030:

- Scenario in line with fit-for-55 (FF55) objectives and updated (draft) Italian NECPs;
- Late transition that is substantially in line with the previous version of the NECP (2019).

And three scenarios for 2040:

- Late transition, aligned with the 2030 scenario;
- Global Ambition Italia (GA-IT);
- Distributed Energy Italia (DE-IT).

GA-IT and DE-IT are both aligned with the scenarios prepared by the ENTSOs, which project alternative paths to reach a net zero target by 2050.

In this study, the FF55 scenario and the average between GA-IT and DE-IT were selected for 2030 and 2040, respectively. In Table 1, photovoltaic and wind generation are reported, together with the multiplying factors with respect to 2019.

Table 1. Photovoltaic/wind generation in 2019–2030–2040 and k_{PV} and k_W.

	2019	2030	2040
Photovoltaic generation (TWh/y)	24 [17]	101 [17]	148 [17]
Wind generation (TWh/y)	20 [17]	68 [17]	104 [17]
PV multiplying factor with respect to 2019 generation (k_{PV})	1	4.2	6.1
Wind multiplying factor with respect to 2019 generation (k_W)	1	3.4	5.2

2.2. The 2019 Generation/Load Profile

This study moves from a baseline scenario corresponding to the 2019 Italian electricity generation and consumption. This particular year was chosen because it was the last year not yet impacted by the COVID-19 global pandemic and the global energy crisis caused by Ukraine's war. Later years, from 2020 to 2023, have been strongly affected by the unprecedented extreme variability of energy prices.

Data of both national load and generation were extracted from reports of the Italian Transmission System Operator (TSO) Terna [18] with an hourly time scale, which was adopted in this study. In 2019, the Italian electricity generation mix was split, as shown in Table 2.

Table 2. Electricity load and generation, Italy 2019.

	Annual Electricity (TWh)	Annual Share (%)
Italian Total Load (2019)	319.6	-
Biomass	16.9	5.3%
Geothermal	5.7	1.8%
Hydroelectric	47.1	14.7%
Photovoltaic	24.1	7.6%
Wind	20.0	6.3%
RES, total	113.8	35.6%
Residual generation	205.8	64.4%

2.3. The Italian Vehicle Landscape

2019 road transport in Italy can be summarized with data reported in Table 3. Fleet consistency, fuel consumption, and annual mileage are derived from institutional reports [19]; Table 3.22 [20]. CO_2 tailpipe emissions are calculated from annual fuel consumption using the conversion factor of gasoline (73.3 $MgCO_2/TJ$ [19]; Table 3.21). A remarkable number of Italian vehicles are currently fuelled with diesel (73.6 $MgCO_2/TJ$ [19]; Table 3.21), and only a few with LPG (65.6 $MgCO_2/TJ$ [19]; Table 3.21) and natural gas (57.6 $MgCO_2/TJ$ [19]; Table 3.21), so the use of the gasoline conversion factor for the whole fleet seems like a reasonable assumption. Other GHG and pollutant emissions are not accounted for, while buses and two-wheeler fleet segments were not considered in this study. Annual mileage per vehicle and specific fuel consumption are simply derived from other data.

Given this landscape, we apply the percentage of vehicle stock that can be inferred from [7], as detailed in the introduction. By rounding the numbers, in this study, we assume a PC stock that is equal to:

- Forty million in 2019;
- Four million in 2030 (Stated Policies Scenario);
- Ten million in 2030 (Net Zero Emission IEA scenario).

We decided not to consider the Net Zero emission for 2030, since Italy is not on track for this.

Table 3. Italy road transport fleet consumption, mileage, and emissions, in 2019.

Vehicle Type	Vehicles (10^6) [20]	Annual Fuel Consumption (TWh) [19]	Annual CO_2 Direct Emission (Tg)	Annual Mileage (10^9 km) [19]	Annual Mileage per Vehicle (10^3 km)	Specific Fuel Consumption (Wh/km)	Specific CO_2 Emission (g/km)
Passenger Cars (PCs)	39.5	264.6	69.8	410.9	10.4	644	170
Light Commercial Vehicles (LCVs)	3.6	38.4	10.2	41.7	11.6	920	244
Heavy Duty Trucks (HDTs)	0.3	59.0	15.6	23.5	84.5	2512	666
Buses	0.1	11.7	3.1	4.2	42.0	2781	737
Two-Wheelers	6.9	10.5	2.8	28.0	4.1	377	99

2.4. Hypothetical Future Energy Cost

Estimating future energy prices is always a very challenging task, especially from a long-term perspective. Moreover, the recent price shocks experienced by the European energy system have increased the volatility of electricity markets and the uncertainties associated with many energy investments.

Just to set a realistic reference, the present long-term futures of electricity stand at around 120 EUR/MWh, including only the value of the commodity. This price will be used in Section 5 to properly monetize the overgeneration reduction achieved with the correct management of BEV charging profiles.

The all-inclusive electricity price at a charging station is currently much higher, even up to six times. This is due not only to the unavoidable fees related to the electricity transport and the use of the system, as for any kind of passive customer, but also the case of charging stations due to the huge price markup currently applied by the owners of the infrastructure to obtain a quick return on their investment. In the current development phase of the charging infrastructure, this effect is physiological, considering the novelty of the technology, the significant failure rate of the components, the recurrent vandalism, and the maintenance logistics that are not yet optimized. However, we believe that this markup is likely to fade in the long term, especially for AC charging stations.

Based on the above considerations, for the long-term electricity price at charging stations, we assume a value of 200 EUR/MWh, which is only 10 EUR/MWh higher than the sum of the commodity price, the Italian tariffs for electricity transport and use of the system, and the taxes.

3. Methodology

In the previous sections, we discussed the data taken as a reference:

- The Italian 2019 load diagram;
- The Italian situation and forecasted RES generation for 2030 and 2040;
- The load diagram, except for BEV charge needs, is kept unchanged in shape and entity.

From this data, an evaluation of future scenarios in 2030 and 2040 is made using the methodology detailed.

The contribution of fossil thermal power plants and imports from abroad are aggregated and named “residual generation” because even though they are dominant today, this study is focused on future scenarios, characterized by increasing quotes of RES and a decrease in fossil fuel generation, which are, therefore, expected to become more and more limited in share.

BEV charging profiles used in this study are reconstructed with a publicly accessible tool prepared by the International Energy Agency (IEA) under the Global E-Mobility Programme funded by the Global Environment Facility [21]. The "EV Charging and Grid Integration Tool" serves as a companion to the policy maker manual and delivers quantitative estimates through an interactive interface, allowing modifications of many settings by the user. The output of the tool is a weekly profile of charging power with a 5 min resolution, which was exported and converted to a 1 h resolution for homogeneity with national load and the generation of available data. For this study, the IEA tool was used with its original presets, tuning only the annual average mileage with data taken from Table 3 to create three BEV fleet segments (10^4 BEV-PC, 10^4 BEV-LCV, 10^3 BEV-HDT) and unmanaged charging strategies, obtaining three weekly charging profiles, as shown in Figure 1.

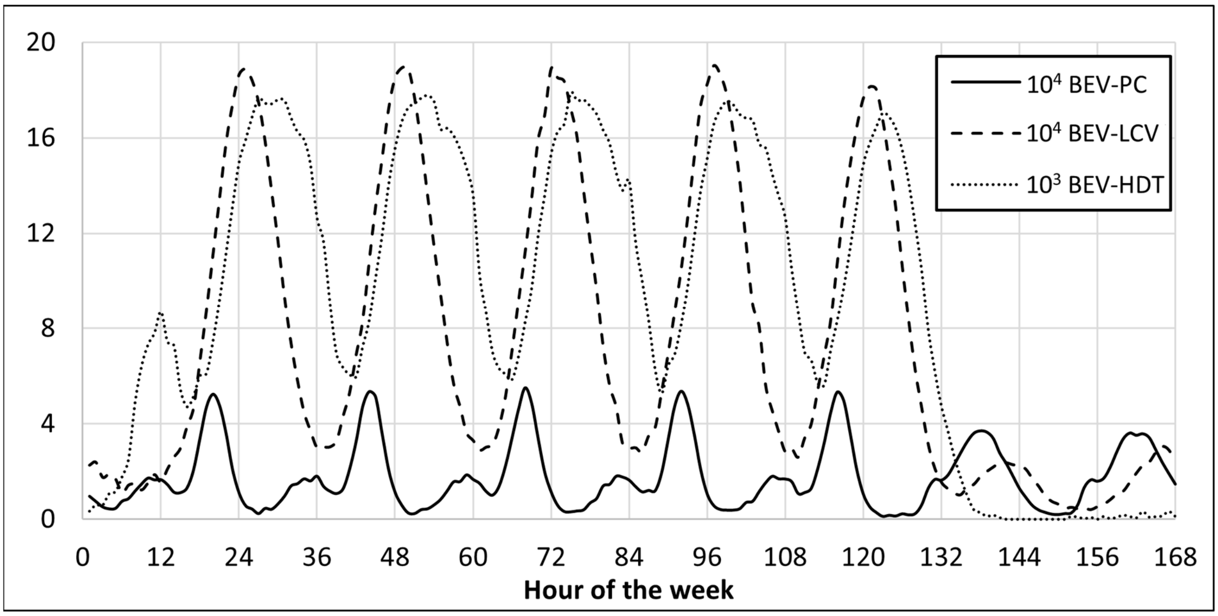

Figure 1. Weekly unmanaged BEV charging profiles, B_{PC}, B_{LCV}, B_{HDT}, using the IEA tool [21] (MW).

These weekly profiles are repeated throughout the whole year, obtaining three annual load profiles (B_{PC}, B_{LCV}, B_{HDT}), which are upscaled with corresponding multipliers (k_{PC}, k_{LCV}, k_{HDT}) to reach the desired size of the BEV fleet. The result is an annual profile of BEV-associated load, L_b:

$$L_b = k_{PC}B_{PC} + k_{LCV}B_{LCV} + k_{HDT}B_{HDT} \quad (1)$$

Three different levels of BEV penetration were considered in this study, as shown in Table 4, with corresponding annual consumption. The additional annual electricity load associated with BEV penetration of 10–40% ranges from 10 to 42 TWh, corresponding to 3% and 13% of the 2019 Italian total load.

Looking at the vehicular data [22,23], the WLTC consumption of modern cars is around 150 Wh/km. However, this is expected to reduce; a combined study by JRC-Eucar-Concawe, dated 2020, considers, for the average car in 2030, a WLTP consumption of 130 Wh/km [24]. However, it must be noted that WLTP refers to mild weather conditions, with air conditioning being off. It is a common experience that loss of efficiency during the winter is large. According to a study [25], an average loss of 30% occurs during winter. Considering that air conditioning is not always activated, we assumed a 15% average loss due to air conditioning for our study. So, the resulting a specific consumption of passenger cars considered in this study is 150 Wh/km.

Table 4. BEV fleet composition and annual consumption, case studies.

	Penetration—Year BEV Type	10%—2030 (STEPS)	40%—2040 (NZE)
Number of vehicles (10^6)	PC	3.95	15.80
	LCV	0.36	1.44
	HDT	0.027	0.108
Annual consumption (TWh)	PC	6.27	25.09
	LCV	2.75	11.00
	HDT	1.52	6.08
	Total	10.54	42.16

A simple mathematical model (illustrated with a scheme in Figure 2) was created to calculate, hour by hour, the balance between generation (residual generation G_r and RES generation G_{res}) and electricity load (stationary load L_s, BEV load L_b and RES overgeneration G_o):

$$G_r + G_{res} = L_s + L_b + G_o \quad (2)$$

with:

$$G_{res} = G_{Hy} + G_{PV} + G_W + G_{BM} + G_{GT} \quad (3)$$

where G_{Hy} represent hydroelectric generation, G_{PV} is photovoltaic, G_W is wind, G_{BM} is biomass, and G_{GT} is geothermal.

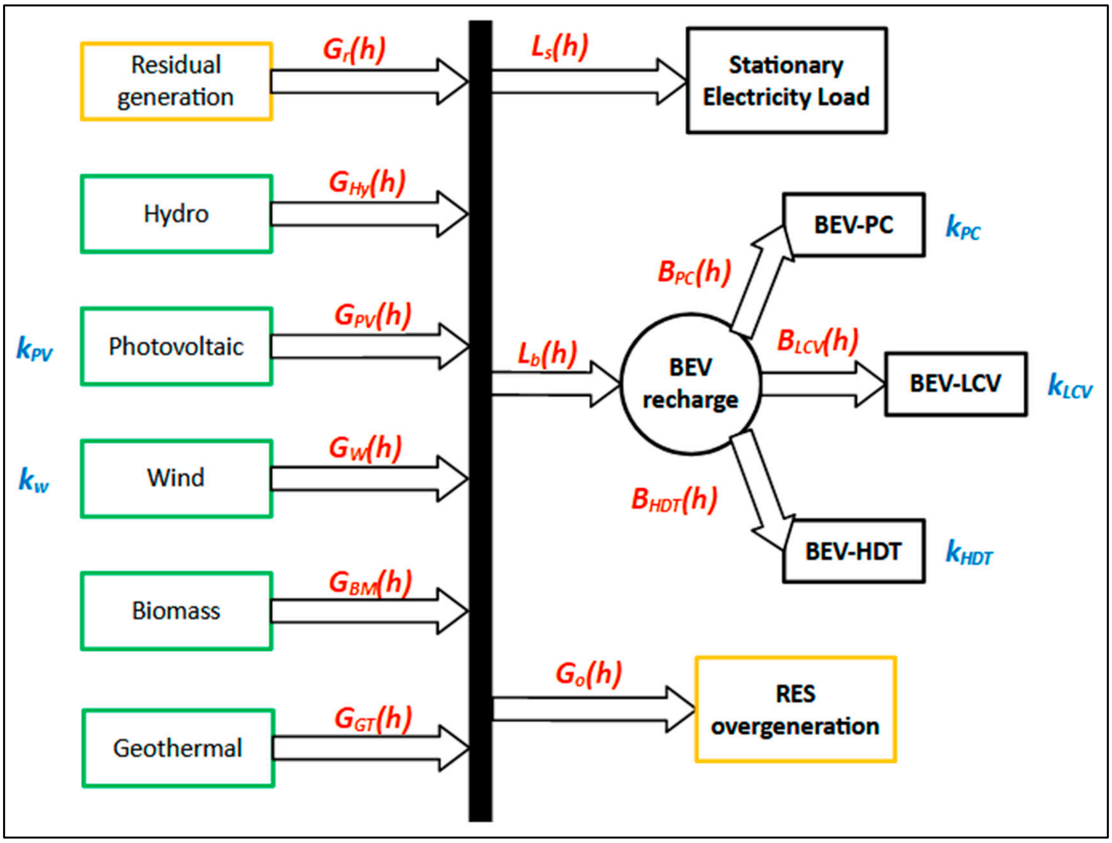

Figure 2. Conceptual model representation, energy flow, and balance.

Photovoltaic and wind generation profiles ($G_{PV} + G_W$) are upscaled with corresponding multipliers (k_{PV}, k_W in Table 2) to simulate an increase in installed capacity:

$$G_{PV} = k_{PV} G_{PV,ref} \tag{4}$$

$$G_W = k_W G_{W,ref} \tag{5}$$

where the reference values, as already stated, are the values measured in Italy for 2019. According to both the original and updated (2023 draft) versions of the Italian NECP [16], ambitious targets of RES penetration in the electricity sector will be achieved mainly through these two sources of additional capacity. Other RES addition potential in Italy is limited.

Since the sum of RES generation G_{res} and the stationary L_s are fixed, hour by hour, a balance is reached with the following simple rules:

- when $G_r > 0$, then $G_o = 0$ ($G_r > 0$ when needed to make up for the lack of energy when $G_{res} < L_s + L_b$).
- when $G_{res} > L_s + L_b$, then $G_o > 0$ and $G_r = 0$.

The methodology here adopted relies on the following main assumptions:

1. RES generation can be dispatched and consumed without transmission and regulation constraints. Assessments regarding system stability (e.g., rotating inertia reserve) and electricity transportation are completely neglected;
2. Import/export, load modifications induced by the electrification of other sectors (e.g., building HVAC, industry), and electricity storage are not considered. Looking at the Italian TSO forecasts in [17] and subtracting BEV charge and hydrogen electrolysis, future additional demand for electricity will grow very slowly; less than 1% per year;
3. Future installations of photovoltaic and wind power plants will not significantly affect the current generation profile shape. In other words, it is assumed that the geographic locations and performances of future PV panels and wind turbines will be similar to the current ones.

Assumption 1 is justified by the nature of the "generation-load balance" of this paper. This is a typical study that precedes verifications of dynamical stability, e.g., to determine the amount of spinning reserve (while in the future, a different name may be adopted, such as dynamic reserve).

Assumption 2 is made since we want to isolate the impact on the system of only BEV charge, without mixing with other simultaneous changes.

Assumption 3 is reasonable because both PV and onshore wind are expected to be installed in areas comparable to the existing ones (or even in the same locations for wind repowering projects). The only significant change could be caused by largescale offshore wind farms in open water because these sites may have a different wind potential than the existing ones. However, the updated draft of the Italian NECP set the 2030 target to only 2.1 GW of offshore wind capacity with respect to the total wind capacity of 28.1 GW and 79.9 GW for photovoltaic [16,17], so the expected impact at the national level will be very limited.

The following annual indicators can be defined to summarize the main results.

$$P_r = \frac{\sum_{h=1}^{8760} G_{r,h}}{\sum_{h=1}^{8760} L_{s,h} + L_{b,h}} \tag{6}$$

$$P_{res} = 1 - P_r \tag{7}$$

$$I_o = \frac{\sum_{h=1}^{8760} G_{o,h}}{\sum_{h=1}^{8760} G_{res,h}} \tag{8}$$

These quantities indicate residual generation penetration (P_r), RES penetration (P_{res}), and the overgeneration index (I_o).

Estimations regarding CO_2 emitted by residual generation are assessed using the emission factor of Italian natural gas power plants in 2019, which is equal to 368.7 gCO_2eq/kWh_{el} [26].

4. Simulation Results

4.1. Load Analysis

BEV charging profiles (B_{PC}, B_{LCV}, B_{HDT}) are synchronized to the 2019 national load, day by day and hour by hour, and summed together to obtain yearly profiles of the total electricity load $L_s + L_b$. Sorting those 8760 consecutive hourly loads in descending order, so-called "duration curves" can be derived for each case. A duration curve is often used in electric power generation to illustrate the relationship between generating capacity requirements and capacity utilization.

Load duration curves (Figure 3) hide some information regarding the evolution of the load over time but give a clear view of some useful information, such as peak load (top left value) and x-th load percentiles (corresponding to the x-th percentile of hours per year). Table 5 shows some values of different percentile loads. As can be deduced in Figure 3, BEV recharge impacts whole duration curves. When considering the maximum annual peak, it is important to remember that this study is based on the L_s profile of a single year (2019). For this reason, this value should be interpreted with caution, as it could be affected by singularities of that specific year. In contrast, the high percentiles (99th, 95th, 90th) are less susceptible to these singularities.

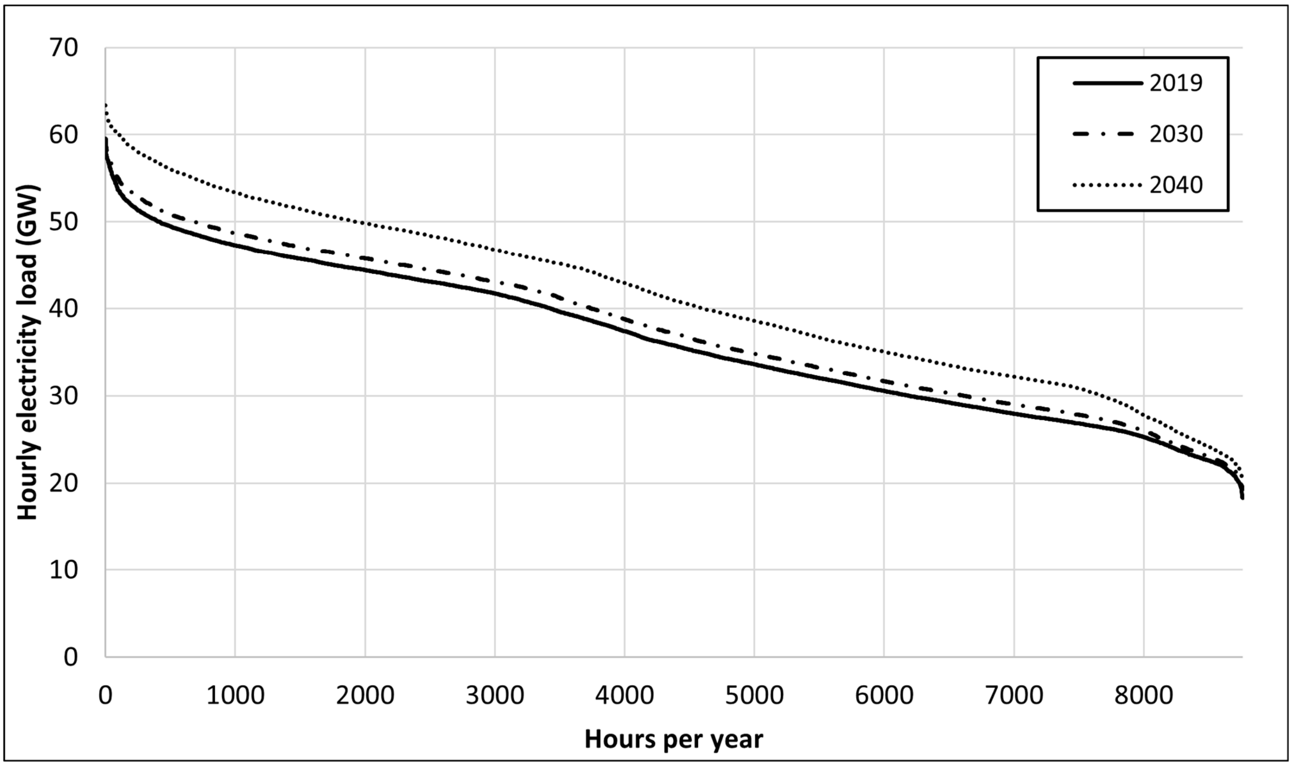

Figure 3. Italian national load duration curves, L_s + L_b, 2019–2030–2040 cases.

Analyzing the hourly profiles of L_s and L_b in detail, it is clear that the unmanaged strategy of BEV recharge causes a remarkable increase in the late afternoon load peak (Figure 4 shows a week in January as an example). In particular, BEV-PC recharge (green line in Figure 4) is the main contributor to that spike. Such high demand in those hours is a challenging issue for the electrical system, which is already facing a loss of RES generation in the same hours due to photovoltaic power decrease with sunlight. To cover that load, the system will use all remaining RES, use importation from other countries, and electrical storage if available, as well as calls to operational "peaker" thermal fossil power plants. It is self-evident that in this case, BEV-PC recharge may represent a problem that has to be managed, especially when BEV penetration in the entire fleet reaches a moderate/high percentage.

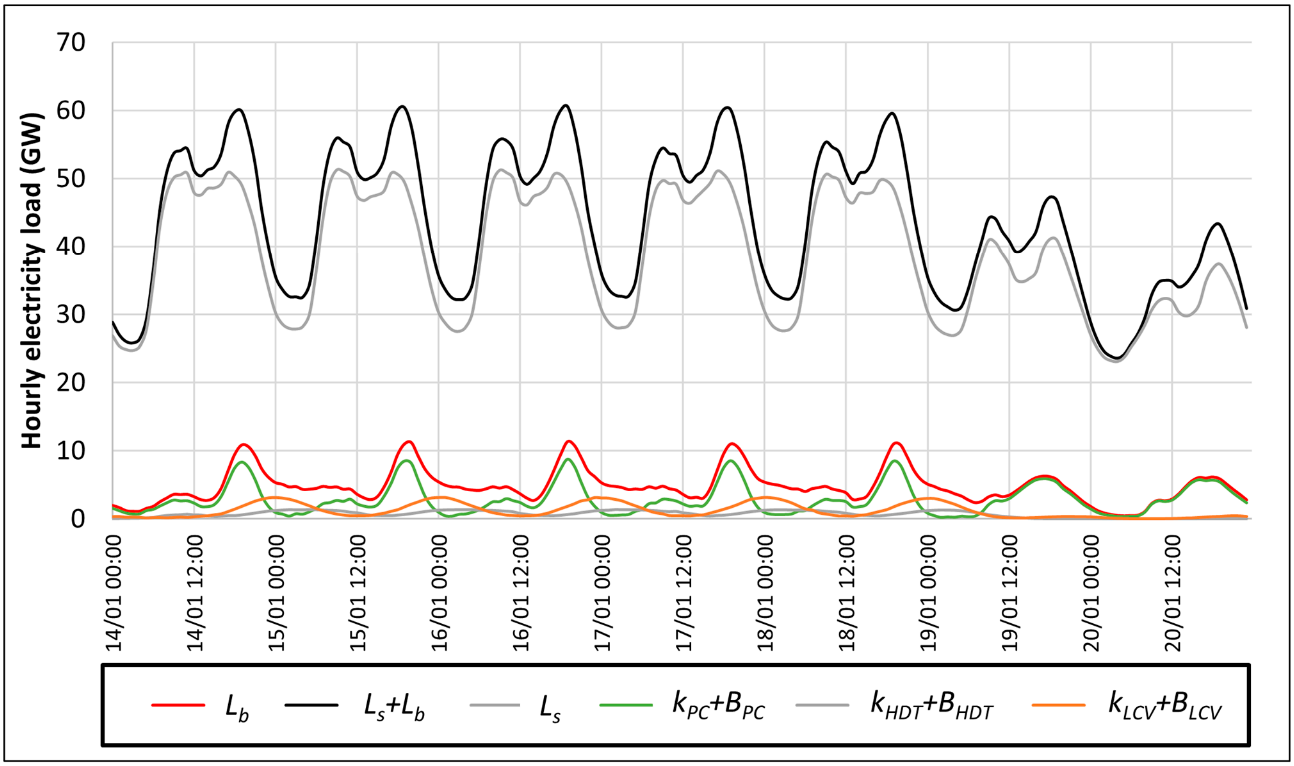

Figure 4. Weekly load profiles in the middle of January, 2040 case.

To help with the management of the electrical system, two opposite approaches can ideally be adopted:

- Shift BEV-PC recharges to the night hours to reduce the afternoon peak and compensate for the huge overnight downtime. To simulate this strategy, *a* +7 h shifted BEV charging profile was defined: $L_{b+7}(h)$:

$$L_{b+7}(h) = k_{PC}B_{PC}(h+7) + k_{LCV}B_{LCV}(h) + k_{HDT}B_{HDT}(h) \tag{9}$$

- Shift BEV-PC recharges to the central hours of the day when photovoltaic plants will produce large amounts of electricity and when overgeneration is also statistically likely to occur. In this case, the BEV-PC recharge is anticipated for 7 h: $L_{b-7}(h)$:

$$L_{b-7}(h) = k_{PC}B_{PC}(h-7) + k_{LCV}B_{LCV}(h) + k_{HDT}B_{HDT}(h) \tag{10}$$

It is rather obvious that shifting all personal car recharge times is unreasonable. The idea of this paper is to imagine a scenario in which incentives are given to users to shift their charge, and only a fraction of them will adhere to this policy. However, just to understand the effects of those shifts, for the sake of simplicity, in this analysis, the whole stock of personal cars is imagined to be shifted. On the other hand, LCVs and HDTs are imagined to be much more rigid to shift since nearly all of these vehicles are work tools and are more frequently linked to rigid working hours. This is an approximation as well because some LCV and HDT users would probably be adequate if they received enough incentives to use a shifted charging profile pattern.

The choice of a systematic translation of 7 h is rather arbitrary. The rationale behind the choice of this 7 h time is that it allows transferring of the evening peak into the night (where the stationary load is much lower) or around noon, when PV generation, especially during summers, is much larger. Moving the load to night hours is a common strategy use by current electric systems dominated by thermal power plants (confirmed by lower electricity prices during the night), but the future of highly PV-penetrated systems will require an opposite strategy. This is another deep change that the electrical system has to face in the next few years.

In Figure 5, the effect of these shifts is shown for the same week in January.

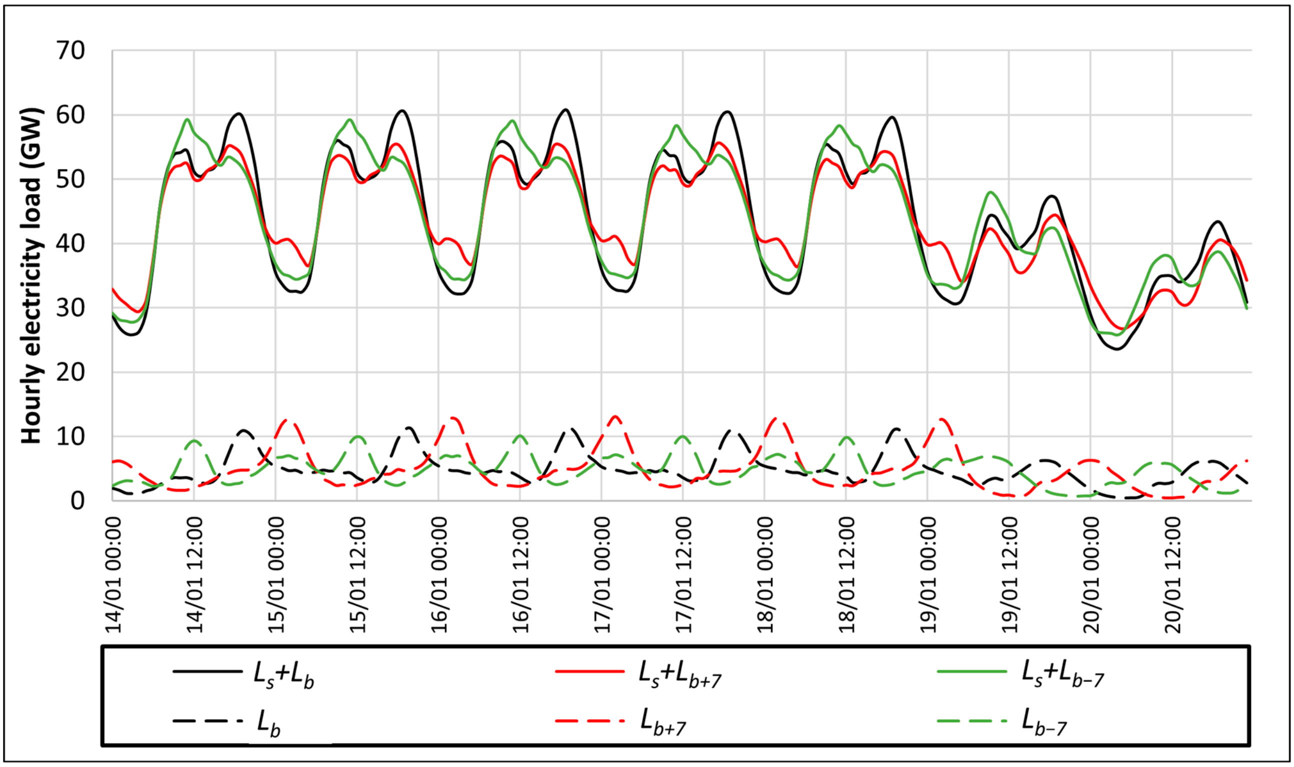

Figure 5. Weekly load profiles in the middle January, the 40% BEV 40% case with BEV-PC shifts.

Looking at the corresponding duration curves in Figure 6, the effect of a 7 h time shift is even more evident. A delay (+7 h) in the BEV-PC charge to the night hours led to a remarkable reduction in the highest 3000 h of the year and to a sort of "flattening" of the curve. The effect of an opposite shift to the central hours of the day (−7 h) is less perceptible in terms of the duration of the curve, which is similar to the baseline, apart from the maximum peak, which occurs in a few days of the summer during central day hours, and it is emphasized by this shift.

Table 5 shows some numerical values taken from these curves. Percentiles might be useful to gain sensitivity since the pure peak variation may be a consequence of the year (2019) chosen for comparisons.

Table 5. Electricity national load at the different percentile of the duration curve and the curve's integral.

Percentile	2019 (GW)	2030 (GW)	2040 (GW)	2040 PC + 7 h (GW)	2040 PC − 7 h (GW)
1 (peak load)	58.8	59.6	63.4	62.3	67.8
0.99	54.0	55.2	60.2	57.2	61.1
0.95	49.8	51.3	56.5	53.3	56.1
Total energy (TWh)	319.6	330.1	361.7	361.7	361.7

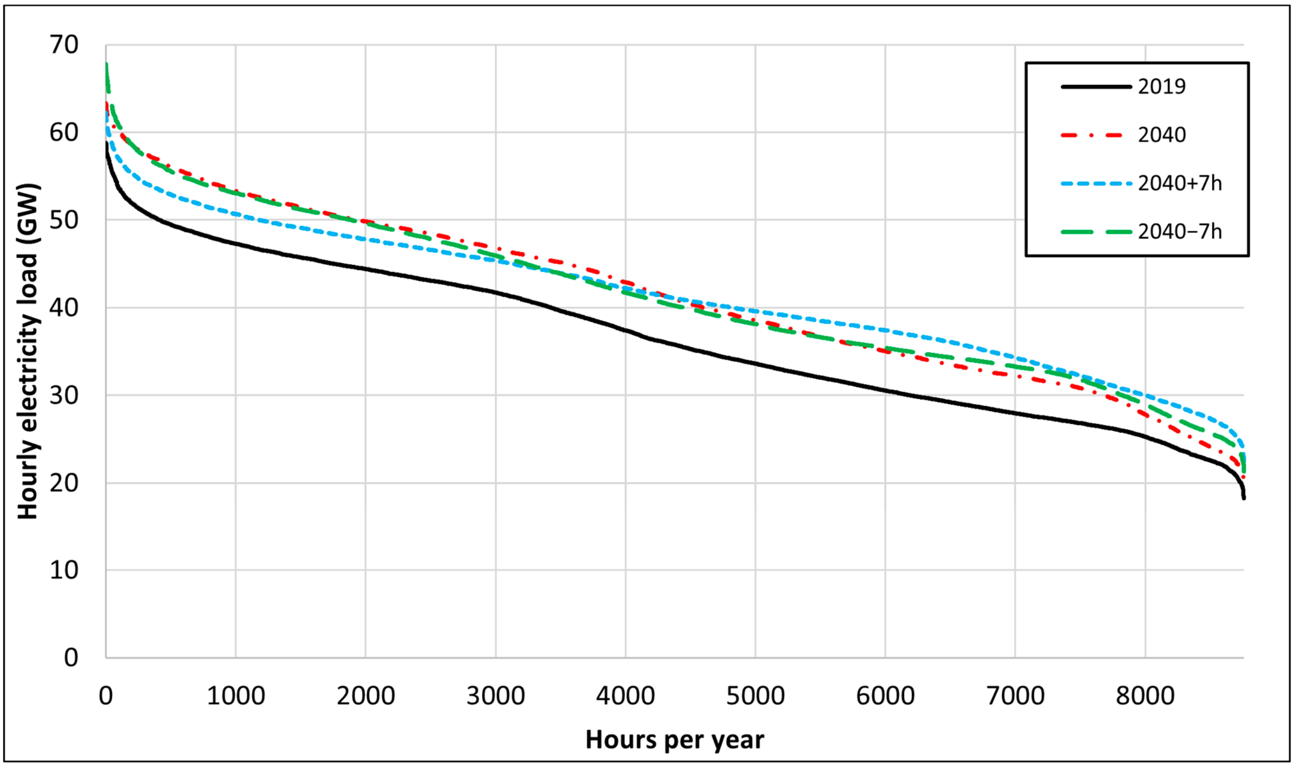

Figure 6. National load duration curves, $L_s + L_b$, 2019, 2040, 2040 cases with PC + 7 h and PC − 7 h in 2040.

4.2. Electricity Generation Analysis

The duration curve analysis is used to investigate residual generation (when positive) and overgeneration (negative values). In Figure 7, all cases are plotted showing the deep change with respect to 2019. RES penetration almost doubles, and the residual generation halves. The residual generation peak in 2030 remains similar to 2019 (ca. 40 GW) and increases in 2040 (47.4 GW).

Overgeneration from RES appears in 2030 and 2040 for almost 2000 h/y and 3000 h/y, respectively, with an overgeneration index I_o of about 0.1 and 0.2.

Table 6 shows other results of all simulated cases, such as the highest and lowest percentiles of the duration curves and the electricity annual emission factor. The shifting strategy PC − 7 h confirms the best results in terms of RES exploitability pushing up RES penetration by a non-negligible 2% on an annual basis (P_{RES}), with a consequent reduction in the electricity emission factor from 107 to 100 gCO_2/kWh_{el}.

Table 6. Main results of all cases.

	2019	2030	2040	2040 PC +7 h	2040 PC − 7 h
Total load (TWh/y)	319.6	330.1	361.7	361.7	361.7
P_r	0.644	0.346	0.291	0.302	0.272
P_{RES}	0.356	0.654	0.709	0.698	0.728
I_o	0	0.096	0.201	0.212	0.180
Overgeneration (h/y)	0	1938	2974	2920	2880
Overgeneration (TWh/y)	0	23.1	64.4	68.2	57.66
Residual generation (h/y)	8760	6822	5786	5840	5880
Residual generation (TWh/y)	205.8	114.2	105.4	109.1	98.6

Table 6. *Cont.*

	2019	2030	2040	2040 PC +7 h	2040 PC − 7 h
Annual electricity emission intensity (gCO_2/kWh_{el})	237	128	107	111	100
Residual generation peak (GW)	40.2	40.1	47.4	41.5	40.3
0.99 percentile (GW)	36.6	34.5	40.3	35.9	34.0
0.95 percentile (GW)	33.4	29.6	33.6	32.0	29.6
0.05 percentile (GW)	13.2	−18.2	−39.3	−41.2	−35.8
0.01 percentile (GW)	10.2	−28.2	−52.1	−54.3	−49.2
Overgeneration peak (GW)	0	−39.9	−66.6	−69.2	−64.1

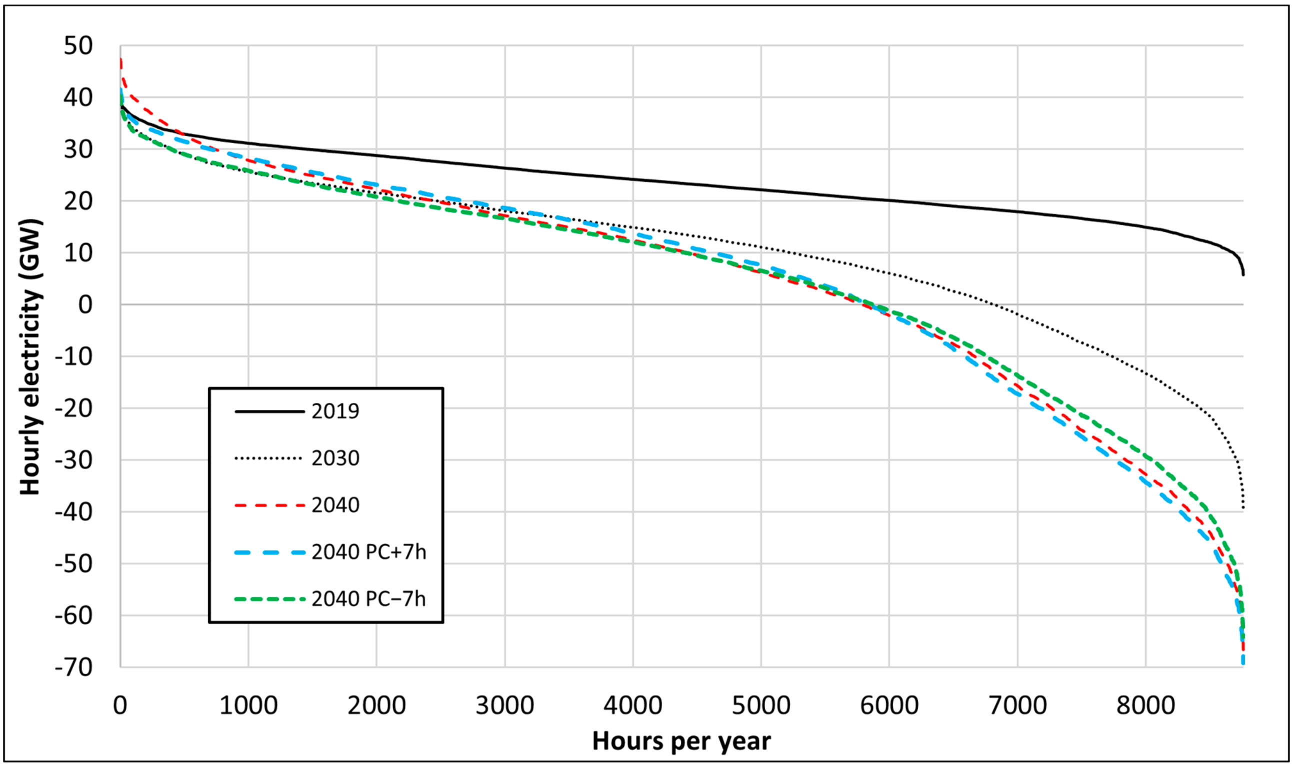

Figure 7. Residual generation and overgeneration duration curves, all cases.

4.3. GHG Emissions Evaluation

A balance of GHG emissions for all cases was assessed, considering CO_2 emissions from residual generation, and emissions from the substitution of current ICE vehicles with BEVs were avoided.

Just for comparison and a sort of indirect validation, the case with k_{PV} = 1, k_W = 1, and BEV 0% (corresponding to 2019 load and generation) totaled 75.9 Tg of CO_2 with the adopted methodology of CO_2 calculation, while other authors, with more complex methodologies [26], made an estimation of 81.1 Tg of CO_2. The underestimation with the methodology proposed is mainly caused by coal power plants (with much higher emission factors) still in operation in 2019, which are only partially compensated by imports of nuclear electricity from abroad. The assumption made in this study of a future residual power generation only from natural gas plants is in accordance with the national target of coal phase-out in this decade.

The increase in CO_2 emissions with BEV penetration is due to the larger quantity of electricity to be produced to supply this additional large load. To evaluate the impact in terms of general CO_2 emissions, it is necessary to also consider the elimination of tailpipe emissions to the conversion of some vehicles from ICE-based into BEVs.

This was performed, and the results are shown in Figure 8, where the annual emission from residual generation is plotted for increasing BEV penetration and for ±7 h BEV-PC recharge shifts. According to a previous evaluation, a penalty must be paid in terms of CO_2 emissions from residual generation when BEVs penetrate the fleet of a system that is not fully dominated by RES electricity generation (see P_{RES} values in Table 6).

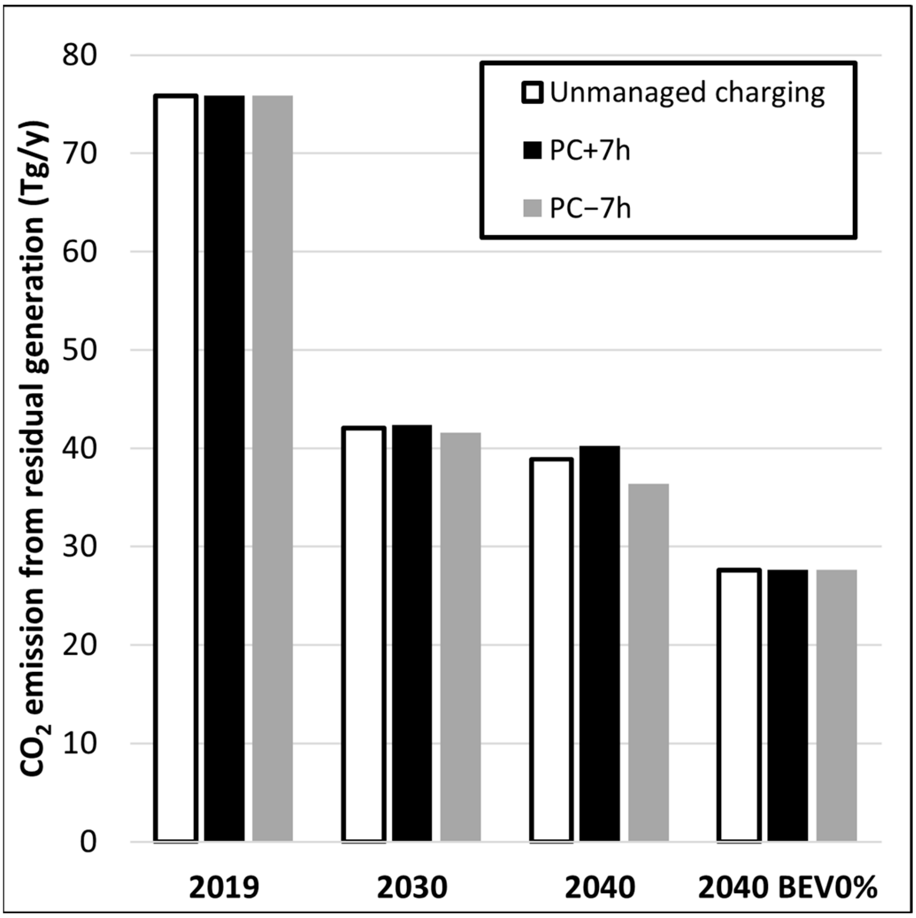

Figure 8. Annual emission of CO_2 from residual generation.

However, if the total CO_2 emitted and avoided by electricity, and the transport sector is taken into account, the positive balance is clear and undeniable. In Figure 9, CO_2 emission variations with respect to the 2019 case are reported. The CO_2 benefit comes both from residual generation reduction and ICE vehicle substitution. If a hypothetical 2040 scenario without BEVs (case 2040 BEV0) is calculated, the result is an additional 10 Mt/y CO_2 reduction in residual generation. Comparing this hypothetical benefit with the 38 Mt/y CO_2 avoided thanks to BEVs in 2040, the advantage is clear.

Moreover, a BEV charging strategy that prioritizes central daytime hours, such as the simple PC − 7 h adopted, could represent an additional improvement of 2–3 Mt/y CO_2 due to RES overgeneration recovery (mainly from photovoltaic plants).

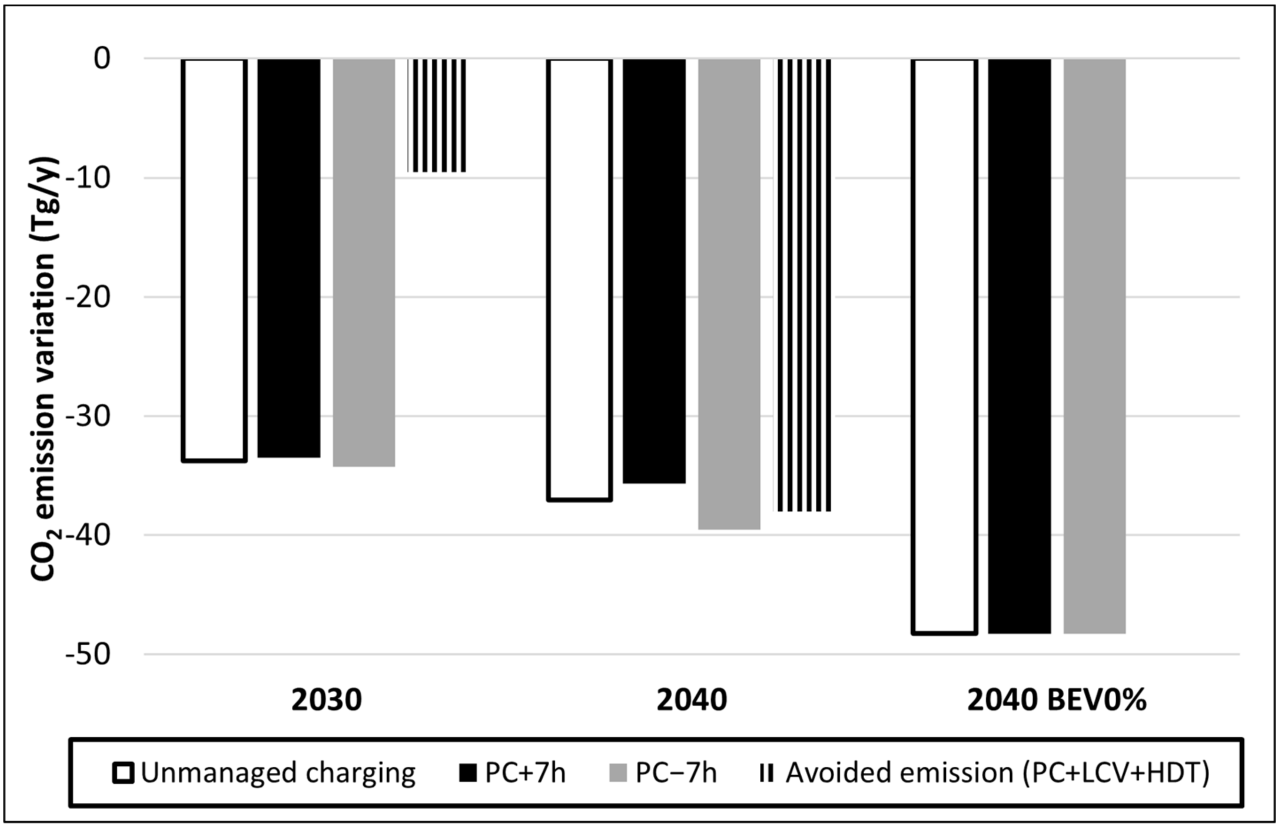

Figure 9. Annual balance of CO_2 emission variation in 2019.

5. Discussion

5.1. General

We have seen significant qualitative advantages, especially in synchronizing PV generation with BEV recharging through time-shifting of the charging profiles. As detailed earlier, we imagine a time shift for passenger cars only.

It is very important to find a way to make them quantitative and understand the economic benefits of these strategies, which, in turn, could be used to incentivize BEV users to perform, when possible, shift toward times of the day in which charging is beneficial for the grid.

It is felt that a lot of personal car users can charge their cars at home or work around noon. It is slightly less convenient than charging during evenings and nights and, therefore, they will need to obtain incentives to make this shift.

We quantify three advantages, which can be summed up to find a global evaluation of the charging time shift. They are quantitatively evaluated considering the 2040 scenario, in which we expect to have a BEV stock of 40% of the total cars. The evaluation has only a first orientation value, just to have a broad idea of the cost–benefit relationship.

The kinds of savings obtained by time shifting the vehicle charge are the following:

1. National power peak reduction;
2. Overgeneration reduction;
3. GHG emissions reduction.

Even though we provide incentives to time-shift charges, it is expected that only a fraction of PC users will adhere to the incentive. If the incentive is significant, however, significant proportions will shift. We have numerically evaluated these three benefits at different percentages of vehicles in the target year: 33%, 66%, and 100%. Our numerical results show that for these percentages, all the three numerical values are proportional to the percentage itself. Therefore, it is acceptable to make computations imagining that 100%

of all the future vehicles in the years 2030 and 2040 will time shift. In case of a smaller percentage, the per-vehicle advantage, and, therefore, incentives, will stay constant.

Below, we will show computations in detail for the 2040 scenario; in Tables 7 and 8, numbers are shown for the 2030 case.

The time-shifted energy per year is the total energy charged by the expected 16 million vehicles in 2040, which corresponds to $10,400 \text{ km/y} \times 150 \text{ Wh/km} \times 16 \times 10^6 = 25 \text{ TWh/y}$.

Regarding point 1 above, the capital and running cost of peak (turbo gas) units could be accounted for. We can assume 300 EUR/kW for capital and discounted running costs globally. In Table 6, we see that we have a residual generation peak reduction of $47.4 - 40.3 = 7.1$ GW, which will translate into a total benefit of $7.1 \times 10^6 \text{ kW} \times 300 \text{ EUR/kW} = 2.1$ GEUR. This advantage is to be applied throughout the life of the considered turbo gas units; if we consider, for simplicity's sake, a 20-year timespan, the yearly advantage is 2100/20 = 105 MEUR/y. Then, the benefit per time-shifted kWh becomes as follows:

$$\frac{105 \text{ MEUR/y}}{25 \text{ TWh/y}} = 0.42 \text{ cEUR/kWh (National Power Peak reduction advantage)}$$

Regarding point 2 above, we can consider that the avoided overgeneration becomes energy that can be supplied to load at market price. According to what is stated in Section 2.4, at 2019 money value, we count energy at 120 EUR/MWh, i.e., 12 cEUR/kWh.

In Table 6, we see that we have an overgeneration reduction of $64.4 - 57.66 = 6.74$ TWh, which corresponds to yearly and per kWh savings S_y and S_{kWh} :

$$S_y = 0.12 \frac{\text{EUR}}{\text{kWh}} \times 6.74 \frac{\text{TWh}}{\text{y}} = 0.809 \frac{\text{GEUR}}{\text{y}}; \text{ thus}$$

$$S_{kWh} = \frac{0.809 \text{ GEUR/y}}{25 \text{ TWh/y}} = 3.2 \text{ cEUR/kWh (overgeneration reduction advantage)}$$

The discussion of point 3 is more complex and will be performed in the next section.

5.2. Incentive for GHG Emissions Reduction

To reach an economic estimate of GHG emissions reduction due to BEV charging time shifting, we could use two different approaches:

a. The Emission Trading System UE (ETS) market. In this market, the CO_{2eq} price has grown dramatically since January 2020 from 20 EUR/tonne to 80–100 EUR/tonne in 2023 [27]. It is difficult to forecast future evolutions of this price, but it appears likely that it will further grow as soon as the pressure on climate concerns evolves. Here, a value of 100 EUR/Mg has been used.

b. The penalty of CO_{2eq} emissions on vehicles in the EU. The EU requires some monetary penalties from car manufacturers in case their fleet of GHG emissions exceed an ever-reducing cap [22]. For the years 2020 to 2024, the cap for cars is 95 g/km, while for the years 2030 to 2034, which is the farthest period with stated caps for cars, the cap value is 49.5 g/km. The set penalty for excess emissions is EUR95 per g/km of target exceedance.

The economic advantage of a time-shifting BEV charge according to point (a) is straightforward. In this scenario, we have 16 million passenger cars that time shift their charge (Table 3). This will imply a reduction in CO_2 emissions of 2.5 Tg/y (2.5 million tonnes, Figure 9), which corresponds to an ETS benefit in B_y and B_{kWh} per year and per kWh, respectively:

$$B_y = 2.5 \text{ Tg/y} \times 100 \text{ EUR/Mg} = 250 \text{ MEUR/y}$$

$$B_{kWh} = \frac{250 \text{ MEUR/y}}{25 \text{ TWh/y}} = 1.0 \text{ cEUR/kWh}$$

Translating the cap in point (b) in a value per time-shifted kWh requires some reasoning. The average yearly mileage of a passenger car in Italy is 10,400 km (Table 3). Assuming a useful life of 15 years, for each extra g/km of CO_2, each car will emit 156 kg of CO_{2eq} throughout its life

For those exceeding emissions, the manufacturer will pay 95 EUR, which corresponds to 95/0.156 = 609 EUR per tonne of CO_2. In principle, the same mechanism could be used to reward virtuous behavior from users, i.e., time shifting their recharge to allow system benefits.

The total emission reduction, as already said, is equal to 2.5 Mt/y, with the incentive mechanism corresponding to $2.5 \times 10^6 \times 609 = 1.52$ GEUR/y or, considering that the shifted energy is 25 TWh/y, to 6.1cEUR/kWh. In Table 7 are reported also 2030 results.

Table 7. Economic evaluation of charging time shifting by BEVs using incentives similar to disincentives in [27].

Year	Number of Time-Shifting BEVs	CO_2 Reduction (Mt/y)	Potential Incentive (GEUR/y)	Yearly Shift (TWh/y)	Potential Charge Shift Incentive (cEUR/kWh)
2030	4×10^6	0.5	0.30	6.3	4.8
2040	16×10^6	2.5	1.52	25.0	6.1

5.3. Summary

The results of the above discussion are summarized in Table 8.

Table 8. Summary of economic benefits of time-shifting BEV recharge (cEUR/kWh).

Year	Yearly Peak Reduction	Over Generation Reduction	ETS-Based Emission Reduction	Incentive-Based Emission Reduction	TOTAL
2030	0.4	2.7	0.8	4.8	3.9–7.9
2040	0.4	3.2	1.0	6.1	4.6–9.7

The evaluation of ETS-based emission reduction somehow computes the benefit "commercially", while the incentive-based evaluation is more "political" since it gives CO_2 a larger value to push politically toward stronger reductions.

Given the final fork of 4–10 cEUR/kWh, we can say that there is enough room to incentivize time shifting, considering that the total energy value (Section 2.4) is around 20 cEUR/kWh. So, the incentive can reach a discount over a purchase price between 20 and 50%.

Based on this result, the hypothesis of being able to convince a large share of personal car users to operate time shifting, for instance by rewarding them in well-tailored flexibility markets, appears realistic. This "ad hoc" remuneration is crucial since it is not obvious that the energy market, even when the abundance of PV generation will reduce the electricity price in the solar hours of the day, will provide enough economic signals to synchronize a significant share of the recharging demand with PV production profiles.

It could be finally envisaged that part of the monetary value of the benefits be used to feed the capacity markets, helping them to constantly foster the needed PV investments, even in market scenarios characterized by a strong reduction in energy revenues in solar hours.

6. Conclusions

This paper's research question was to evaluate the potential impact of large numbers of BEVs on the future electric grid and whether exploiting the partial flexibility that loads have in the choice of the time of the day for recharging can induce enough system benefits to remunerate BEV users for the change in recharging pattern they are requested to adopt.

The considered scenario refers to the Italian context and what might occur in a 15-year time, with increases in PV and wind generation of factors of around four and three, respectively, in comparison to the 2019 values. Although this study is made taking as reference the Italian load diagram, its results can be applicable, with minor differences, to several EU countries.

This paper has first shown that the future impact of increasing the penetration of battery electric vehicles is compatible with the expected growth of generation from renewable energy sources. It has also given an estimate of CO_2 emission reduction, considering an unmanaged charge profile, and two different managed profiles, with the displacement of the car's charging period toward hours of the day where they not only do not negatively impact the grid but even favor effective RES exploitation.

Then, we evaluated the economic benefits of displacing private car charging toward the times of the day when the grid obtains its maximum advantages; these benefits range from 4 to 10 cEUR/kWh and could be used as tariff incentives (discounts between 20 and 50% of energy price) to obtain this displacing in recharging time. The results obtained show that the benefits of time-shifting BEV recharge create enough economic advantages to fund incentives able to drive large shares of users to time shift.

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Nomenclature

BEVs	Battery Electric Vehicles
B_{HDT}	BEV heavy duty truck load
B_{LCV}	BEV light commercial vehicle load
B_{PC}	BEV passenger car load
DE	Distributed Energy Scenario
EV	Electric Vehicle
FCEVs	Fuel Cell Vehicles
FF55	Fit For 55
GA	Global Ambition Scenario
GHGs	Greenhouse Gases
G_r	Residual electricity generation
G_{res}	Renewable electricity generation
G_o	Overgeneration from renewables
HDTs	Heavy Duty Trucks
HVAC	Heating Ventilation and Air Conditioning
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
k_{HDT}	BEV heavy duty truck fleet multiplier
k_{LCV}	BEV light commercial vehicle fleet multiplier
k_{PC}	BEV passenger car fleet multiplier

k_{PV}	Photovoltaic generation multiplying factor respect 2019
k_W	Wind generation multiplying factor respect 2019
L_b	Electricity load from battery electric vehicle recharge
LCVs	Light Commercial Vehicles
L_s	Stationary electricity load
NZE	Net Zero Emission Scenario
NECP	National Energy and Climate Plan
PCs	Passenger Cars
PV	Photovoltaic
RES	Renewable Energy Sources
STEPS	Stated Policies Scenario
TSO	Transmission System Operator
V2G	Vehicle to Grid

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