On integrating electric vehicles into Smart Energy Systems: Italy and Germany in comparison

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ABSTRACT

Over the last decade, electric vehicles have gained ever-increasing interest as a promising alternative to conventional road transport being able to reduce pollutant and greenhouse gas emissions and shift the economy away from oil products. Electric vehicles can play a major role in the transition towards Smart Energy Systems, thanks to the synergies that can be implemented with the other sectors, in particular in the challenges related to energy storage. However, the related increase in electricity demand inevitably affects the strategic planning of the overall energy system as well as the definition of the optimal power generation mix.
With this respect, the impact of electric vehicles may vary significantly depending on the country according to composition of both total primary energy supply and electricity generation. In this study, Italy and Germany are compared to highlight how a similarity in their renewables shares not necessarily leads to a CO_2 emissions reduction, when electric vehicles penetrate energy systems whose power generation sector relies heavily on carbon-intensive primary energy sources. Different energy scenarios are simulated with the help of EnergyPLAN software assuming a progressive increase in renewable energy sources capacity, up to 2050 projections, and electric vehicles penetration. Results show that, for the German case, the additional electricity required leads to an increase in CO_2 emissions if RES capacity is below a certain threshold, whereas the Italian energy system always benefits from EV. At the highest renewable capacity instead, CO_2 emissions can be reduced up to 23 and 25% for Italy and Germany respectively, when electric vehicles, recharged under a smart strategy, replace entirely the conventional fleet for private transportation. Despite featuring a decrease with electric mobility integration, power curtailments are still significant at high renewable capacity in the absence of large-scale energy storage systems.

KEYWORDS

Large-scale RES, curtailments, electric vehicles, EnergyPLAN, integrated energy systems analysis, CO_2 emissions reduction.

INTRODUCTION

Over the last decade, the ever-increasing level of carbon dioxide concentration in the atmosphere has called for a profound reconfiguration of the energy sector in order to cater for primary energy needs in the context of a sustainable development.

With this respect, global energy strategies have put their focus on electricity generation and transportation [1]–[3], that at present rely on fossil fuels respectively for 74 % and 96 % of their total energy consumption [4]. In this context, national policies agree upon the strategic role of renewable energy sources (RES) and electric vehicles (EV) in curbing CO_2 emissions [5]. Indeed, according to International Energy Agency, a 50 % chance of meeting Paris Agreement's emissions target requires RES share to reach 57–71 % of the total electricity production by 2050 and EV sales current growth rate (40 % in 2016 over the previous year) to remain unchanged in the future [6].

However, the integration of RES in the electricity market poses significant challenges on power grid management due to the intermittent nature of these sources, which may ultimately lead to a mismatch between power generation and electricity demand. As a result, the implementation of balancing measures becomes unavoidable to allow significant level of RES penetration without compromising grid stability requirements. Solutions such as curtailments, energy storage, backup power generation, demand-side management and power-to-gas have been widely explored in the literature to guarantee a reliable electricity supply despite RES volatility [7]–[14]. With this specific regard, EV can effectively behave as a storage system and absorb the potential surplus of intermittent RES power generation when this latter exceeds demand [15]. EV show potentials for optimal energy management and power quality improvement of the future distribution networks [16], being also able to replace gas power plants in balancing the grid nullifying the gas share in the electricity mix when 30 % of EV fleet provides for stabilization requirements [17]. However, a positive interaction between EV and RES strictly depends on the composition of the electricity generation sector and on the vehicle charge management. In fact, in the absence of a smart charge strategy, an increasing EV penetration may negatively affect network infrastructure reliability stressing the necessity of grid security-aware charging methods to improve grid well-being criteria and adequacy indices [18], [19] and to optimize renewable energy integration in smart grids context [20], [21]. Forrest et al. [22] found that, in order to meet high renewable utilization targets in large-scale energy systems, significant storage capacities need to be in place if EV charging is unregulated whereas, with EV smart charging, required power capacity drops from 60 to 16 % of the installed renewable capacity and with vehicle-to-grid (V2G) charging, storage systems are no longer required. In addition, curtailments can be mitigated with flexible loads, such as electric vehicle charging, if strategically shifted to coincide with high-resource periods of the day [23]. Previous research demonstrates that a smart charging approach supports solar power integration, doubling the utilization of photovoltaic when compared to uncontrolled charging strategy [24] and even leading a 100 % renewable energy based electricity supply under certain photovoltaics and electric vehicles combinations [25].

Moreover, when electricity generation from RES is not available or not enough depending on the installed capacity or the time of the year, the additional electricity demand has to be provided by conventional power plants, thus limiting or nullifying the environmental benefit of EV especially when such plants are powered by carbon-intensive fuels [26].

In this context, energy system modelling is essential for a proactive planning of low-carbon energy policies to assess future scenarios potential benefits and drawbacks and ultimately advise policy makers on the most effective options. An integrated holistic approach, that explores possible synergies among different energy sectors, becomes essential to achieve sustainable, affordable and achievable future solutions; such concept is referred to Smart Energy System and different models have been implemented under this perspective [27]–[30] proving that a Smart Energy system may feature lower energy consumption with comparable annual costs [29].

This study aims to assess the impact of EV on energy systems characterised by comparable shares of RES in the base case scenario, however featuring different composition in terms of total primary energy supply as well as different energy policies in the medium and long term. In particular, this work carries out an analysis in EnergyPLAN that starts from a base case scenario for Italy and Germany at 2015 and models possible future projections with progressively increasing shares of RES and EV. National energy policies for 2030 and 2050 to model the development of the electricity generation sector and different RES/EV combinations have been defined, analysed and compared to evaluate the impact on CO_2 emissions, curtailments, RES actual penetration in the energy system, primary energy supply and costs. We also evaluated if a positive interaction between RES and EV exists, and, if so, to what extent, with particular reference to the capability of EV to act as an electricity storage system within different energy systems contexts.

METHODOLOGY

Base case scenario definition

A base case scenario has been defined for both countries, represented respectively by the Italian and German energy systems at 2015, modelled with the help of EnergyPLAN software in terms of their energy supply and demand with reference to the most updated data from reliable sources (electric grid operators, International Energy Agency and EU-funded research projects).
Table 1 lists input values for electricity loads along with the related sources, for both countries, according to EnergyPLAN subdivision.

Table 1. Electricity loads at 2015

	Consumption (TWh/year)		**Source**	
	Italy	*Germany*	*Italy*	*Germany*
Electric cooling	13.08	2.46	[31], [32]	[33]
Electricity for heat pumps (individual)	18.44	3.98	[34]	[33]
Electric heating (individual)	10.60	37.44	[31]	[33]
Elec. for transport	10.85	11.29	[35]	[36]
Other electricity load	230.02	591.26	[37]	[38]
Total production	***282.99***	***646.43***		
Import	50.85	37.01	[39]	[38]
Export	-4.47	-85.29	[39]	[38]
Total domestic supply	***329.37***	***598.15***		

Fuel consumption for individual heating is provided in Table 2 along with thermal efficiencies.

Table 2. Fuel consumption and efficiencies for individual heating at 2015.

	Consumption (TWh/year)		**Efficiency**	
	Italy (Source: [40]*)*	*Germany (Source:* [41]*)*	*Italy (Source:* [33]*)*	*Germany (Source:* [33]*)*
Coal boiler	-	9.2	-	0.65
Oil boiler	30.5	186.8	0.83	0.80
Natural gas boiler	261.0	352.0	0.84	0.85
Biomass boiler	72.2	112.6	0.75	0.65

Heat from CHP plants is equal to 60.47 TWh [40] and 91.06 TWh [36] and district heating boilers provide for 3.06 TWh [42] and 36.15 TWh [36] respectively for Italy and Germany.
As for industry and other sectors (e.g. agriculture, fishing, non-heating uses for both residential and services sector), the overall energy consumption divided by fuel is reported in Table 3. For the Italian case, primary energy losses for oil and natural gas have been taken into account and set equal to 0.5 % of total fuel consumed [40]; as for Germany, natural gas losses are negligible while coal and biomass losses account respectively for 0.68 % and 0.08 % [43].

Table 3. Industry and other sector fuel consumption (TWh/year) at 2015.

	Industry		**Various**	
	Italy (Source: [40]*)*	*Germany (Source:* [36]*)*	*Italy (Source:* [40]*)*	*Germany (Source:* [36]*)*
Coal	14.81	113.97	0	9.17
Oil	70.95	15.10	30.01	290.78
Natural gas	109.20	223.56	13.04	57.85
Biomass and waste	7.66	1.05	0	6.08

Table 4 displays fuel consumption for transport sector for both countries.

Table 4. Transport sector fuel consumption (TWh/year) at 2015

	Italy (Source: [35]*)*	*Germany (Source:* [36]*)*
JP (Jet Fuel)	0	100.69
Diesel	270.14	412.24
of which biodiesel	*13.28*	*29.87*
Petrol	95.55	201.61
of which biopetrol	*0.29*	*0*
Natural gas	12.64	2.06
LPG	21.13	5.27
Electricity	10.85	11.29

In order to derive consumption for private transport only, conventional and electric vehicles have been divided in three different categories according to displacement or battery capacity. Battery capacity for small, medium and large EV are considered respectively: <18 kWh, 18–24 kWh, >24 kWh. PHEV have been all considered medium vehicles. For conventional cars, small, medium and large vehicles feature respectively displacements of <1200 cm^3, 1200–1400 cm^3, >1400 cm^3.

The latest data on EV fleet composition have been included in the appendix of this study.

A weighted average in terms of consumption has then been derived assuming an annual commuting distance of 10120 km and 16505 km for petrol and diesel cars in Italy [54], and of 10800 km and 19500 km in Germany [55]. EV are assumed to perform daily commutes of 36.47 km and 41.51 km (average distance covered by conventional cars) in Italy and Germany respectively.

Consumption and operating parameters are reported in Table 5-Table 8 for conventional and EV cars. With regard to conventional vehicles, reasonable fuel economy values have been derived from data related to the most common vehicles in use [56]; Eurostat data have been used to break down cars in different categories according to the displacement size [57].

Table 5. Petrol vehicles number and consumption at 2015

	Italy			*Germany*		
Vehicle category	No. of vehicles (Millions)	Fuel economy (l/100 km)	Consumption (TWh)	No. of vehicles (Millions)	Fuel economy (l/100 km)	Consumption (TWh)
Small	7.30	5.1	34.03	14.89	5.1	74.10
Medium	8.57	6	47.03	12.32	6	72.13
Large	0.30	7.7	2.09	2.60	7.7	19.54
Total	16.17		83.15	29.81		165.76

Table 6. Diesel vehicles number and consumption at 2015

	Italy			*Germany*		
Vehicle category	No. of vehicles (Millions)	Fuel economy (l/100 km)	Consumption (TWh)	No. of vehicles (Millions)	Fuel economy (l/100 km)	Consumption (TWh)
Small	0.15	5.1	34.03	0.35	5.1	74.10
Medium	12.33	6	47.03	10.54	6	72.13
Large	2.01	7.7	2.09	4.21	7.7	19.54
Total	14.49		83.15	15.09		165.76

Table 7. EV annual electricity consumption at 2015 - Italy

		No. of vehicles	Share by size	Capacity (kWh)	Range (km)	Consumption (GWh)
BEV	Small	1742	31%	15.64	125.58	3.21
	Medium	3298	58%	23.33	145.71	7.81
	Large	460	8%	61.33	185.75	2.25
	Van	182	3%	33.13	194.40	0.46
Total BEV		5682				13.73
PHEV		1461		7.46	36.22	4.45
Total EV		7143				18.18

Table 8. EV annual electricity consumption at 2015 - Germany

		No. of vehicles	Share by size	Capacity (kWh)	Range (km)	Consumption (GWh)
BEV	Small	11530	34%	7.69	62.33	23.94
	Medium	18648	54%	23.74	130.12	57.27
	Large	3893	11%	59.96	242.35	16.21
	Van	182	1%	33.11	173.08	0.59
Total BEV		34253				13.73
PHEV		18666		7.50	38.66	60.95
Total EV		52919				18.18

As concerns the supply section, the software requires CHP plants to be partitioned in three different groups depending on their size. Typically, large CHP plants, able to operate in electricity only mode, belong to Group 3, while Group 2 involves CHP plants working in back-

pressure mode. In this work, all CHP plants have been included in Group 2 (referred to as CHP2), while Group 3 (named PP1 hereafter) is assumed to be made up of both large CHP plants (typically combined cycle and condensing power plants) and conventional power plants.
Installed capacities, fuel consumption, efficiencies for both power plants and relative auxiliary boilers are reported in Table 9-Table 12.

Table 9. Power plants capacity (GW) at 2015.

	Italy *(Source:* [37],[33]*)*	*Germany* *(Source:* [44]*)*
PP1	66.86	103.44
CHP2	26.57	56.64
Aux. boilers	18.11	15.07

Table 10. Power plants average efficiency at 2015.

	Italy *(Source:* [37],[33]*)*	*Germany* *(Source:* [33], [45]*)*
PP1 (η_{el})	0.42	0.43
CHP2 (η_{el}/η_{th})	0.40/0.25	0.40/0.35
Aux. boilers	0.9	0.9

Table 11. Power plants fuel consumption (TWh/year) at 2015.

	PP1		**CHP2**	
	Italy *(Source:* [37]*)*	*Germany* *(Source:* [36]*)*	*Italy* *(Source:* [40]*)*	*Germany* *(Source:* [36]*)*
Coal	113.9	627.8	7.8	84.4
Oil	9.0	3.9	43.3	14.0
Natural gas	244.5	6.7	164.8	181.0
Biomass	65.1	17.6	38.4	115.9

Table 12. District heating boilers fuel consumption (TWh/year) at 2015.

	Italy *(Source:* [40]*)*	*Germany* *(Source:* [36]*)*
Coal	0	4.83
Oil	0	1.38
Ngas	2.53	25.33
Biomass and waste	0.63	10.49

As concerns RES, power distributions have been derived from hourly generation values available on Terna and Fraunhofer ISE website for the year 2015 [37], [46], already including power curtailments. Therefore, annual electricity from intermittent RES has been modelled using the actual maximum power generated throughout the year instead of the installed capacity.

Table 13. RES capacity (GW) at 2015

	Italy (Source:[37]*)*	*Germany (Source:* [46]*)*
Onshore wind	6.29	37.76
Offshore wind	-	0.99
Photovoltaic	10.94	37.45
River Hydro	4.88	4.57
Dammed Hydro	18.73	8.27
Geothermal	0.82	0.03
Nuclear	-	12.23

EnergyPLAN works on an hourly basis, as a result hourly power distributions need to be provided to perform the simulation throughout the year. Table 14 lists the sources used for each distribution implemented.

Table 14. Sources used for hourly distributions

	Italy	*Germany*
Electricity demand	[47]	[47]
Fixed Import/Export	[48]	[48]
Heat demand	[49]	[33]
Cooling demand	[33]	[33]
Electricity for transport	[33]	[33]
Wind	[37]	[46]
Photovoltaic	[37]	[46]
River Hydro	[37]	[46]
Geothermal	[33]	[46]
Nuclear	-	[46]

As concerns grid stabilisation, a minimum power of around 20 % of total PP1 installed capacity has been assigned to PP1 power plants, resulting in 14.12 GW and 20.7 GW for Italy and Germany respectively.

Model validation

Base case scenarios have been validated comparing critical indicators against actual data at 2015 as displayed in Table 15-Table 16. Variation with respect to actual data is within 2 %. As for TPES, non-energy uses have been subtracted from the actual value, as they are not included in the energy system model; RES electricity production does not include biomass, which is instead included in PP1 production.

Table 15. Model validation - Italy

	Model	***Actual***	***Source***
CO_2 emissions [Mt]	330.75	330.75	[50]
TPES [Mtoe]	145.16	146.00	[50]
RES electricity (excl. biomass) [TWh]	90.38	90.94	[37]
PP1 electricity [TWh]	195.80	192.05	[37]

RES penetration [%]	31.58	32.14
CO_2 /PES_f [t/toe]	2.40	2.39
CO_2 /TPES [t/toe]	2.28	2.27

Table 16. Model validation - Germany

	Model	*Actual*	*Source*
CO_2 emissions [Mt]	743.68	744.33	[36]
TPES [Mtoe]	301.37	295.73	[36], [43]
RES electricity (excl. biomass) [TWh]	131.76	133.87	[46]
PP1 electricity [TWh]	512.85	512.56	[36]
RES penetration [%]	20.38	20.71	
CO_2 /PES_f [t/toe]	2.56	2.62	
CO_2 /TPES [t/toe]	2.47	2.52	

Future scenarios modelling

Future scenarios have been modelled in EnergyPLAN assuming progressively increasing shares of RES and EV in the energy system and compared using environmental and techno-economical indicators.

Electricity supply

As concerns electricity generation, two specific scenarios have been highlighted with reference to actual energy policies:

- RES capacity increases up to 2030 level projections (RES2030)
- RES capacity increases up to 2050 level projections (RES2050)

Maximum RES capacities are displayed in Table 17-

Table 18 for both countries, along with 2015 values (RES2015). Precisely, for Italy the required RES capacity has been derived using the same power distribution as 2015 and increasing the power from base case scenario level until the expected amount of electricity generation was reached. Also, wind capacity remains unchanged in RES2050 having already reached its maximum potential in RES2030.

Table 17. Maximum RES capacity (GW) – Italy

	RES2015 (Source: [37]*)*	*RES2030 (Source:* [51]*)*	*RES2050 (Source:* [51]*)*
Onshore wind	6.29	15.80	15.80
Offshore wind	-	1.15	1.15
PV	10.94	32.63	97.89
CSP	-	2.00	6.00

Table 18. Maximum RES capacity (GW) – Germany

	RES2015 (Source: [46]*)*	*RES2030 (Source:* [52]*)*	*RES2050 (Source:* [53]*)*

Onshore wind	37.76	52.51	198.00
Offshore wind	0.99	6.49	54.00
PV	37.45	62.00	275.00

Assumptions have been also made with respect to fossil fuel consumption for electricity production and conventional power plants. As for Italy, a decrease of 10 GW is assumed for PP1 capacity by 2030. With respect to the German case, nuclear power plants are assumed to be completely dismissed by 2030 [51], along with a decline in coal and natural gas (-14 % and -29 % respectively) and a doubling of biomass consumption for electricity generation [52].
With regard to import-export, the net import showed by Italian case is assumed to be gradually replaced by RES production as this latter grows; Germany, instead, features a net export towards neighbouring countries that is assumed to remain unchanged as generation from RES increases.

Private transport

In the modelled future scenarios, EV penetration linearly grows until replacing entirely conventional vehicles fleet.
The replacement of conventional cars with EV occurs assuming a progressive decrease of conventional vehicles (the same percent reduction in each category) keeping the total number of cars stable at 2015 level (37.9 Million and 45.8 Million [57]). The number of hybrid and LPG vehicles remains unchanged with respect to 2015. In future scenarios, EV are charged using two different strategies, as follows:

- Vehicles are charged exclusively according to driver’s needs/habits (Dump)
- Vehicles are charged with the aim to absorb potential RES surplus thus minimizing grid overloading (Smart)

As concerns costs, latest data from a EU-funded project [33] have been used, including also the weighted average price for conventional cars and EV as shown in Table 19 andTable 20 different for Italy and Germany as EV fleet has been fully characterised considering specific vehicle models. Medium EV price has been evaluated considering such category made up of 30 % BEV and 70 % PHEV. As concerns petrol and diesel cars, purchase costs only have been derived from the manufacturers prices for common vehicle for each category, chosen as representative.

Table 19. Conventional and EV purchase costs (k€) - Italy

	Petrol	*Diesel*	*EV*
Small	12.39	13.45	29.81
Medium	23.40	21.00	37.03
Large	62.65	58.17	88.33

Table 20. Conventional and EV purchase costs (k€)- Germany

	Petrol	*Diesel*	*EV*
Small	13.60	16.20	24.96
Medium	23.40	26.40	36.43
Large	62.65	60.43	87.68

Finally, results from different scenarios have been compared with respect to crucial indicators: CO_2 emissions, RES share and RES surplus (CEEP). As concerns primary energy supply, two different options have been considered: primary energy supply from fossil fuels only and excluding RES (PES_f) and total primary energy supply including RES (TPES).

RESULTS AND DISCUSSION

Figure 1 displays the variation of crucial energy indicators with respect to RES capacity for the German and Italian case respectively, when EV are charged under a smart strategy.
While the Italian energy system always benefits from EV, in Germany the additional electricity required leads to an increase in CO_2 emissions if RES capacity is below a certain threshold. In particular, for the German case, the projected RES2030 installed capacity is not adequate to allow a sustainable EV integration resulting in higher emissions whereas, at higher level of RES penetration (approximately double the base case capacity), the interaction between RES and EV proves to be beneficial. As for the German case in particular, the discontinuity in the CO_2 emission trend at RES2030 can be linked to the nuclear power plants phase-out. In fact, on one hand the progressive nuclear power capacity reduction limits emissions reduction, on the other hand, once such power plants are dismissed completely, RES become the only carbon-free competitor to fossil fuels in the electricity generation sector and their impact becomes more visible as a result.
The rate of reduction of CO_2 emission exhibits a plateau for both countries that starts at a RES capacity level that is around 3-4 times higher than the base case one; additional installed power directly translates into surplus of potential production without affecting CO_2 emissions due to both the mismatch between potential generation and demand as well as conventional power plant base load, necessary for grid stabilisation requirements in the absence of large-scale energy storage systems.

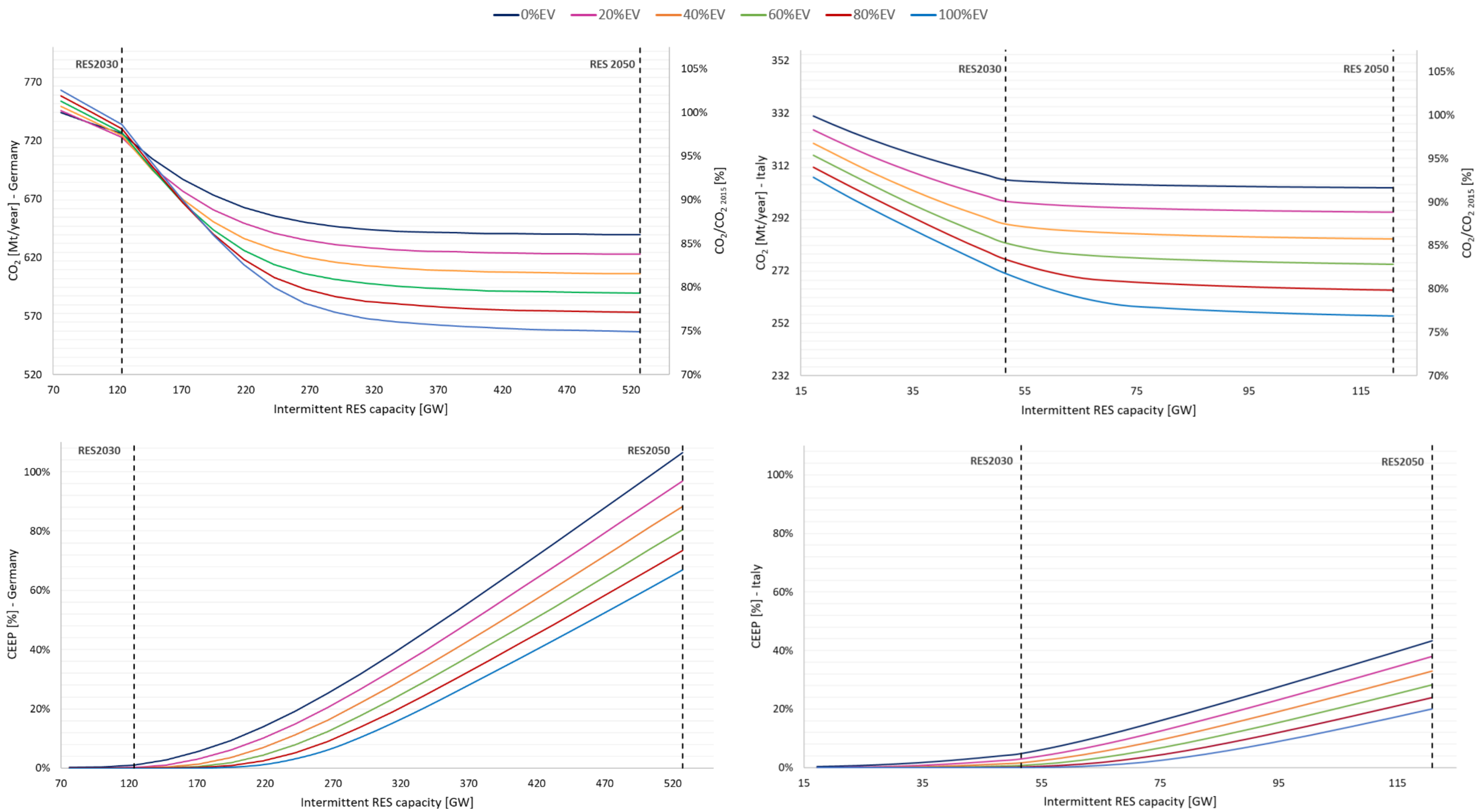

Figure 1. CO_2 emissions and CEEP variation at increasing intermittent RES capacity and EV penetration

Table 21 toTable 24 show CO_2 variation (with respect to the base case), RES penetration and CEEP (both expressed as a percentage of total production) for increasing EV penetration at both RES2030 and RES2050 comparing dump and smart charging strategies.

As concerns Germany, CO_2 emission reduction worsen with EV increasing share under dump charge at RES2030, while a slight/comparable decrease (down to 2.9 % in the best case) occurs if EV are smart-charged and for a relatively small EV share (between 20 % and 40 %). It is worth observing that, despite a percentage decrease (although negligible), CO_2 emissions feature an increase with respect to 2015 level when related to primary energy supply, PES_f in particular, as a result of the shift from petrol and diesel to coal for EV electricity generation demand.

On the contrary, the Italian case is positively affected by EV penetration at RES2030: in particular, when a smart type of charge is implemented, emissions can be reduced down to 18 % as compared to 2015 level. Due to the predominant share of natural gas in the electricity generation energy supply, CO_2/PES_f and CO_2/TPES feature decreasing trend as EV penetration grows.

For both countries, RES penetration reduces with EV, meaning that the contribution of conventional power plants cannot be disregarded when the electrification of the energy system rises. For instance, as for the German case, a 15 % reduction in PP installed capacity (same as the Italian case for RES 2030) would lead to the necessity of external energy import to satisfy the additional electricity demand when EV share becomes higher than 80 %, thus justifying the stance of energy policy makers in this regard [58]. CEEP level is still acceptable at 2030, slightly higher for Italy under dump charge however adsorbed when smart charging strategy is implemented.

When RES capacity is increased up to RES2050 level, the share of electricity production covered by RES grows up to 69 % and 58 % respectively for Germany and Italy at 100%EV that however is accompanied by a significant amount of CEEP. In particular, in the highest RES scenarios, the excess of production can be as high as 107 % and 44 % respectively for the German and Italian case when EV are not included in the system. In this respect, the additional electricity demand introduced by EV may play a major role reducing the surplus from RES down to 68 % and 22 % in Italy and Germany at 100%EV. At 0 % EV, despite a reduction in primary energy supply at the highest RES level, emissions register the same variation as RES2030 when related to PES_f, due to the percent increase of coal among fossil fuels usage for the German case, and a decrease when emissions are referred to TPES due to the higher amount of RES in the supply mix.

Table 21. CO_2 variation, RES penetration and CEEP at RES2030 - Germany

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-2.4%	-2.1%	-1.7%	-1.3%	-1.0%	-0.6%
Smart	-2.4%	-2.9%	-2.7%	-2.3%	-1.9%	-1.4%
CO_2/PES_f [%]						
Dump	6.4%	6.5%	6.6%	6.8%	7.0%	7.7%
Smart	6.4%	6.3%	6.4%	6.5%	6.7%	6.9%
CO_2/TPES [%]						
Dump	3.0%	3.1%	3.2%	3.4%	3.6%	4.2%
Smart	3.0%	2.7%	2.8%	3.0%	3.2%	3.4%
RES [% of tot. prod.]						
Dump	35.4%	33.9%	32.5%	31.1%	29.9%	29.0%
Smart	35.4%	34.5%	33.1%	31.8%	30.5%	29.3%
CEEP [% of tot. prod.]						
Dump	1.0%	0.8%	0.7%	0.6%	0.6%	0.6%
Smart	1.0%	0.3%	0.1%	0.0%	0.0%	0.0%

Table 22. CO_2 variation, RES penetration and CEEP at RES2030 - Italy

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-7.3%	-9.1%	-10.8%	-12.1%	-13.3%	-15.1%
Smart	-7.3%	-9.8%	-12.4%	-14.6%	-16.5%	-18.1%
CO_2/PES_f [%]						
Dump	0.1%	-0.6%	-1.4%	-2.2%	-3.0%	-4.0%
Smart	0.1%	-0.9%	-1.9%	-2.9%	-4.0%	-5.0%
CO_2/TPES [%]						
Dump	-5.0%	-5.1%	-6.2%	-7.1%	-7.9%	-8.9%
Smart	-5.0%	-6.1%	-7.3%	-8.4%	-9.5%	-10.5%
RES [% of tot. prod.]						
Dump	51.5%	48.0%	46.6%	44.9%	43.2%	42.3%
Smart	51.5%	51.1%	50.5%	49.6%	48.1%	46.5%
CEEP [% of tot. prod.]						
Dump	5.7%	3.7%	3.5%	3.4%	3.2%	2.4%
Smart	5.7%	3.8%	2.2%	1.1%	0.6%	0.3%

Table 23. CO_2 variation, RES penetration and CEEP at RES2050 - Germany

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-14.0%	-16.2%	-18.4%	-20.3%	-21.9%	-23.0%
Smart	-14.0%	-16.3%	-18.5%	-20.7%	-23.0%	-25.2%
CO_2/PES_f [%]						
Dump	6.4%	6.0%	5.6%	5.2%	4.9%	4.7%
Smart	6.4%	6.0%	5.6%	5.2%	4.8%	4.3%
CO_2/TPES [%]						
Dump	-3.7%	-5.3%	-6.8%	-8.2%	-9.4%	-10.3%
Smart	-3.7%	-5.3%	-6.8%	-8.4%	-10.1%	-11.7%
RES [% of tot. prod.]						
Dump	63.0%	64.5%	65.6%	66.3%	66.4%	65.9%
Smart	63.0%	64.5%	65.9%	67.0%	68.1%	69.0%
CEEP [% of tot. prod.]						
Dump	107.1%	97.5%	89.2%	81.7%	75.5%	70.4%
Smart	107.1%	97.7%	89.2%	81.4%	74.3%	67.8%

Table 24. CO_2 variation, RES penetration and CEEP at RES2050 - Italy

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-8.2%	-10.6%	-12.4%	-13.8%	-15.0%	-17.2%
Smart	-8.2%	-11.0%	-14.1%	-17.0%	-19.9%	-22.9%
CO_2/PES_f [%]						
Dump	0.2%	-0.5%	-1.4%	-2.2%	-3.0%	-4.0%
Smart	0.2%	-0.8%	-1.8%	-2.8%	-3.9%	-5.0%
CO_2/TPES [%]						
Dump	-12.1%	-12.1%	-13.2%	-14.1%	-15.0%	-16.0%
Smart	-12.1%	-13.2%	-14.5%	-15.7%	-17.0%	-18.4%
RES [% of tot. prod.]						
Dump	55.2%	53.0%	51.7%	50.0%	48.2%	48.1%
Smart	55.2%	55.9%	56.5%	57.0%	57.6%	58.1%
CEEP [% of tot. prod.]						
Dump	43.7%	37.7%	35.5%	33.8%	32.3%	29.2%
Smart	43.7%	38.6%	34.0%	29.8%	25.8%	22.2%

The variation of CO_2 emissions divided by energy sectors is displayed in Figure 2 for base case, RES2030 and RES2050 with respect to both countries. When EV replace entirely conventional cars, CO_2 emissions in the transport sector ca be reduced by 13 and 11 percentage points respectively for Italy and Germany at the price of a rise in the electricity generation emissions (6 and 10 percentage points respectively). An increase in RES capacity up to RES2050 projections allows a reduction in CO_2 emission within the electricity generation, leading to a level that is comparable to 2015 for the Italian case (34 % of the overall emissions) and even lower for Germany (26 %) that entails however a huge amount of CEEP (as described previously). Emissions related to transportation are still significantly affected by heavy-duty vehicles, whose contribution represent 15-17 % of the overall emissions. Such figure could be however curbed replacing petrol and diesel with electrofuels, these latter generated out of electricity (possibly CEEP from RES), hydrogen and biomass [59].

As previously observed, the adoption of smart charge allows higher CO_2 emissions reduction as compared to dump charge, in particular for the Italian case where, at RES2050, additional 6 percentage points of emissions reduction can be achieved. The charging strategy shows a lower effect for the German case (a difference of just 2 % exists between dump and smart charge options in terms of CO_2 emissions); this is due to a more even distribution of CEEP throughout the day that lessens the negative impact of dump charge. Vehicle charged at evening/night time can still exploit some RES power related to wind electricity generation, as opposed to Italy where renewable production occurs mainly during the day hours due to the higher solar power share. This phenomenon is clearly visible in **Errore. L'origine riferimento non è stata trovata.** that compares smart and dump charge for Germany and Italy at RES2050 during a few spring days. CEEP variation throughout the 24 hours and its annual cumulative curve are respectively shown in Figure 4 andFigure 5 for Italy and Germany; the higher variation between night and day as well as winter and spring months for the Italian case can be clearly observed.

However, despite a relatively small added benefit in terms of CO_2 emissions reduction for the German case, smart charge contributes to reduce the frequency of electricity peaks on the grid as compared to dump charging strategy as shown by the load duration curve in Figure 6.

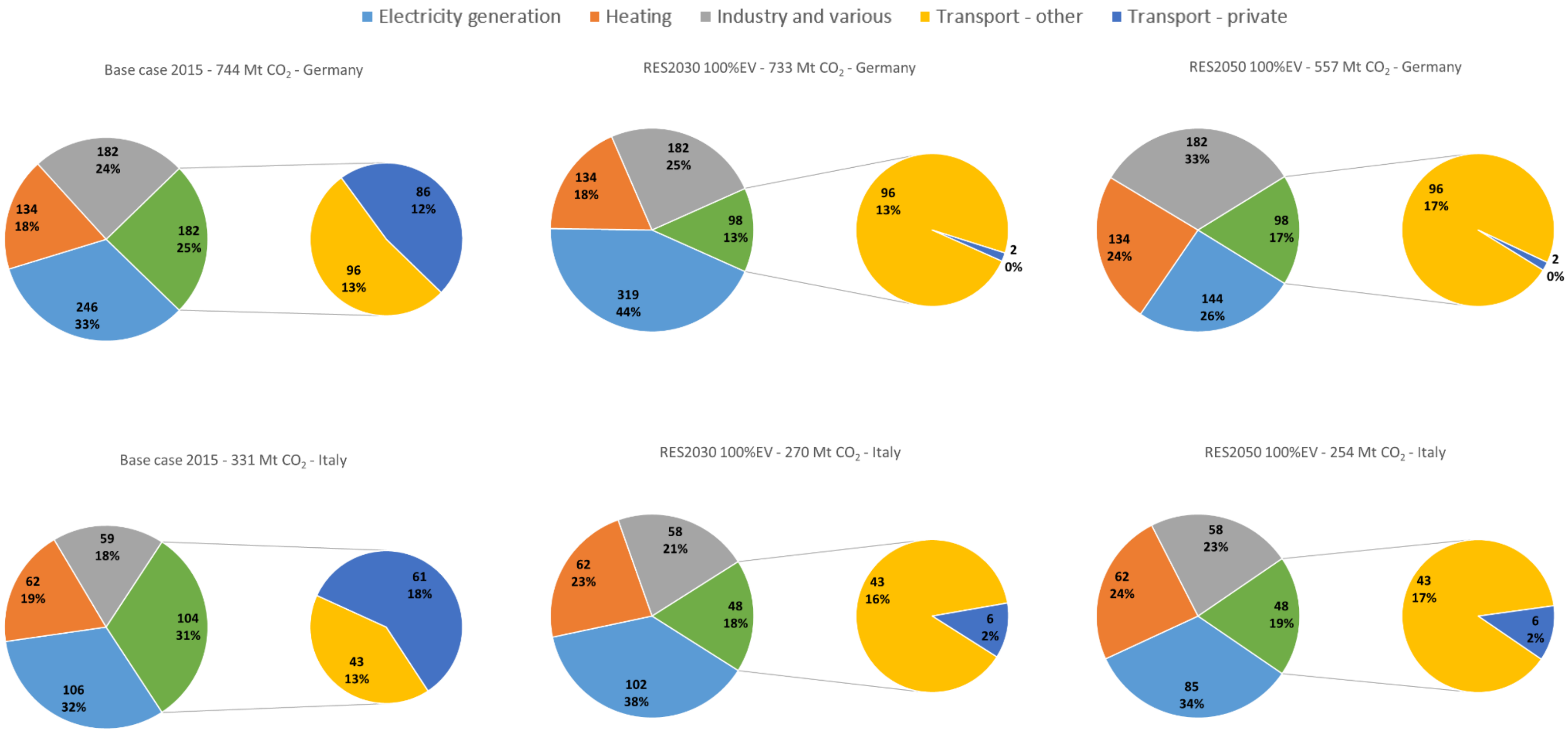

Figure 2. CO_2 emissions divided by sector for Germany and Italy – base case, RES2030 and RES2050

Figure 3. Power generation and demand at 100% EV and RES2050 capacity

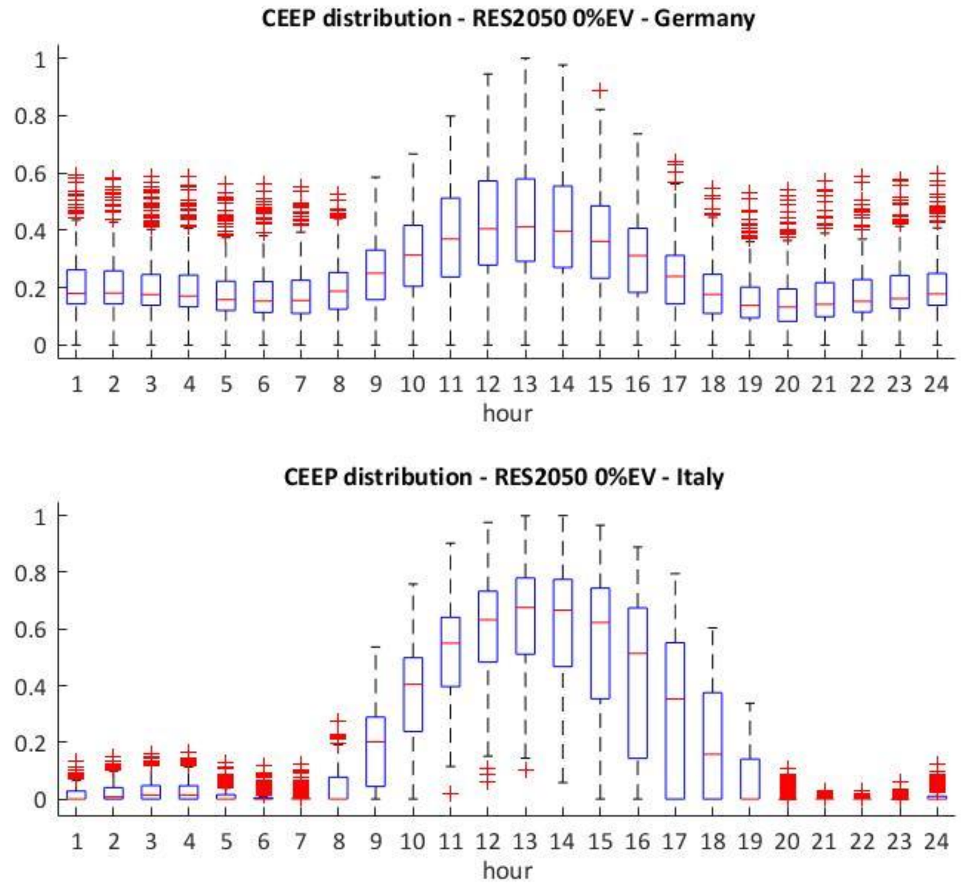

Figure 4. CEEP distribution throughout the day

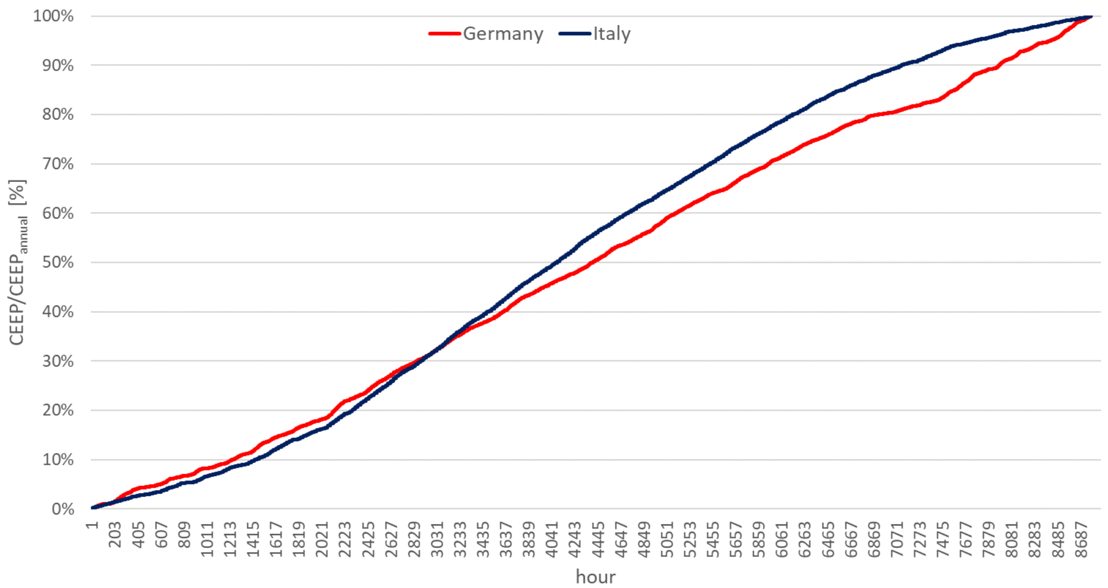

Figure 5. CEEP annual cumulative (normalized with respect to total annual value) curve at RES2050

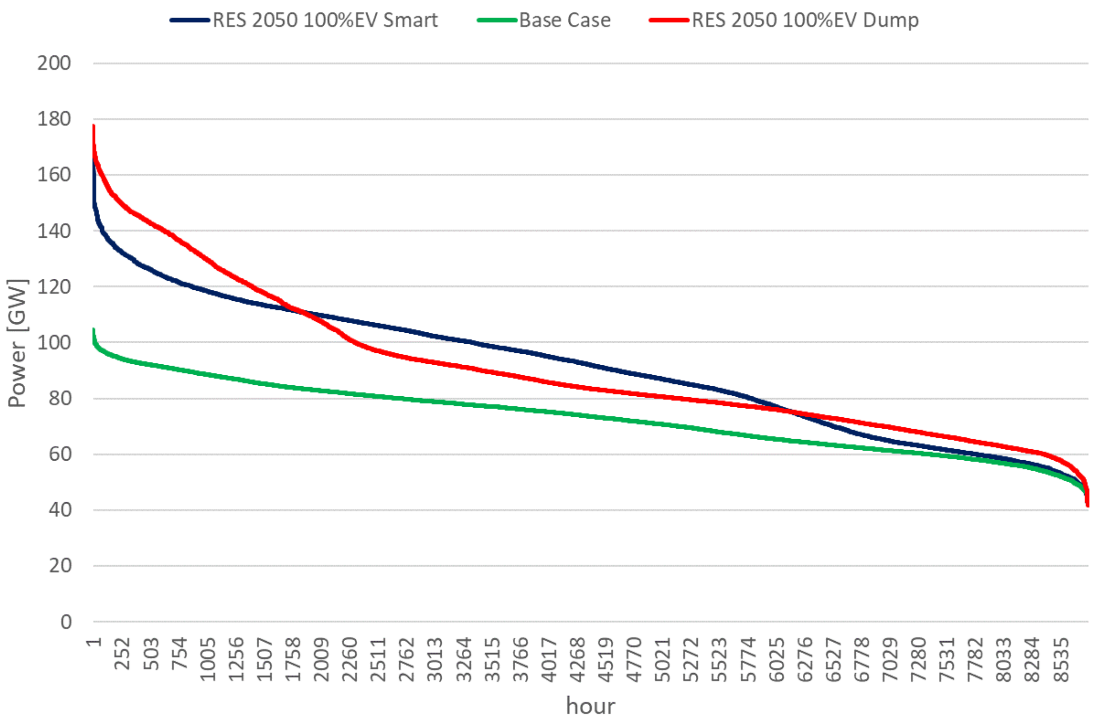

Figure 6. Germany load duration curves - base case, RES2030 and RES2050

Finally, a preliminary cost analysis has been conducted; results are displayed in Table 25 and Table 26 at RES2050 at increasing EV shares. The positive effect of smart charge on CO_2 emissions directly reflects on variable costs reduction (in a range between 23 % and 27 %) due to lower fuel consumption. On the other hand, the higher installed RES capacity and EV purchasing price lead to an increase in investment costs, up to 93 % for the Italian case. Such increase can however be reduced foreseeing a reduction in EV price, in this case conservatively kept unchanged with respect to 2015 level. The combined effect of variable and fixed costs opposite trend result in an increase in total annual costs up to approximately 50 % as compared to 2015 base case scenario.

Table 25. Variable, investment and total costs variation at RES2050 – Germany

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
Variable costs [%]						
Dump	-11.0%	-14.0%	-16.9%	-19.7%	-22.2%	-24.5%
Smart	-11.0%	-14.0%	-17.0%	-20.0%	-23.0%	-25.9%
Investment costs [%]						
Dump/Smart	32.9%	43.2%	52.4%	61.6%	70.8%	80.0%
Total costs [%]						
Dump	15.9%	21.0%	25.5%	30.1%	34.7%	39.5%
Smart	15.9%	21.0%	25.5%	30.0%	34.4%	38.9%
ΔCosts/ΔCO_2 [€/t]						
Dump	392.4	449.2	480.3	513.1	549.3	594.3
Smart	392.4	446.3	477.0	501.3	518.7	535.2

Table 26. Variable, investment and total costs variation at RES2050 – Italy

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
Variable costs [%]						
Dump	-8.77%	-11.70%	-14.58%	-17.07%	-19.43%	-22.61%
Smart	-8.77%	-12.28%	-16.16%	-19.84%	-23.55%	-27.25%
Investment costs [%]						
Dump/Smart	16.22%	31.52%	46.81%	62.11%	77.41%	92.71%
Total costs [%]						
Dump	7.85%	16.86%	26.07%	35.41%	44.79%	53.90%
Smart	7.85%	16.85%	25.72%	34.66%	43.59%	52.53%
ΔCosts/ΔCO_2 [€/t]						
Dump	365.8	612.5	806.9	986.5	1145.6	1199.0
Smart	365.8	586.7	700.5	781.9	838.5	880.7

Policy recommendations

Electrification of transport is a priority in the European Community Research Program, due to several advantages related to EVs, including higher "tank-to-wheel" efficiency with respect to traditional combustion engines, no tailpipe emissions of CO_2 and pollutants at the point of use, and lower impacts in terms of noise and vibrations. Moreover, a key aspect is the possibility of increasing the share of RES in the transport sector through electricity generation, as deeply analyzed in this paper.

This last aspect is particularly of interest in Germany and Italy, where RES shares in electricity mixes are already reaching interesting values. Both countries are currently supporting EVs by providing tax incentives to EV's owners, and Germany is also supporting the diffusion of EVs with an environmental bonus for the buyers. Both countries are also investing in the development of a charging infrastructure, which will be a crucial point for the diffusion and use of EVs.

The results of this paper provide some valuable insights for the further development of EV supporting policies. The electricity generation mix is a crucial parameter for the success of reducing CO_2 emissions throughout the diffusion of EVs in any country. The comparison of Germany and Italy clearly highlights that a threshold exists in RES electricity share for an effective reduction of CO_2 emissions. For this reason, an integrated energy policy is needed to couple the increase of EVs diffusion to a parallel development of electricity generation from RES.

Again, as confirmed by the results of this work, without a careful support of RES electricity generation, the strong increase of EVs penetration could potentially lead to an unwanted increase of CO_2 emissions in the transport sector. Attention must be paid also to the electricity profiles, to guarantee the optimal coupling between the RES generation and the EVs charging logics. A support to smart charge could increase the benefits in terms of overall efficiency and CO_2 emissions reduction.

CONCLUSIONS

This study aims to assess the impact of EV on energy systems characterised by a different supply mix for the electricity generation sector but with comparable intermittent RES share in the base case. Current projections for 2030 and 2050 renewable energy capacity have been implemented along with progressively increasing shares of EV up to a total replacement of conventional vehicle fleet. Results reveal that EV penetration in the energy system worsen CO_2 emissions for the German case unless renewable installed capacity is increased up to a certain threshold (around double the base case scenario) while electric private mobility proves to be always sustainable in the Italian system even at the current RES capacity.

At the highest RES capacity with a complete replacement of conventional cars by EV, CO_2 emissions can be reduced by 25% and 23% for Germany and Italy respectively at the price of a significant amount of curtailments (respectively 68% and 22% of the total production). Smart charge positively contributes to emissions reduction, more significantly for the Italian case due to the more uneven distribution of potential RES power throughout the day and the year with respect to Germany.

The higher installed capacity and EV penetration in the energy system result in higher investment costs whose impact on total costs is however mitigated by a variable costs reduction related to lower fuel consumption, thus leading to a total cost increase up to 50% at the highest RES capacity when EV totally replace conventional fleet.

APPENDIX

Table 27. BEV annual sales and technical specifications – Italy (Source:[60])

BEV model	2010	2011	2012	2013	2014	2015	2016	Tot 2016	Capacity (kWh)	Range (km)
Fiat Panda	31	9	0	0	0	0	0	40	19.2	120
Fiat 500e	22	7	4	0	0	0	0	33	24	160
Renault Fluence	0	0	38	38	30	0	0	106	22	185
Nissan Leaf	0	5	146	323	336	390	473	1673	24	199
Renault Zoe	0	0	0	204	156	328	210	898	22	210
Mercedes B 250e	0	0	0	0	0	80	90	170	28	200
Th!nk city	0	0	0	3	0	0	0	3	24	160
KIA soul	0	0	0	0	0	0	15	15	27	210
Bmw i3	0	0	0	34	124	111	91	360	22	190
Tesla Roadster	4	0	7	0	0	0	0	11	53	393
Tesla model X	0	0	0	0	0	0	23	23	90	414
Tesla Model S	0	0	0	19	55	134	218	426	60	390
Citroen C-Zero	0	87	146	55	15	164	145	612	14.5	150
Mitsubishi iMiev	3	36	14	0	0	0	0	53	16	160
Smart fortwo ED	33	80	37	155	252	115	0	672	16.5	135
Vw e-Up!	0	0	0	0	52	54	56	162	18	160
Peugeot iOn	0	59	116	17	25	0	26	243	14.5	150
Renault Kangoo	0	0	78	25	23	23	0	149	33	200
Fiat Doblo	12	6	0	0	0	0	0	18	43	150
Fiat (QUBO) Fiorino	10	4	0	0	0	0	0	14	23	200
Piaggio Porter	1	0	0	0	0	0	0	1	17	80
Tot BEV Sales	116	293	586	873	1068	1399	1347	5682		

Table 28. PHEV annual sales and technical specifications – Italy (Source:[61])

BEV model	2010	2011	2012	2013	2014	2015	2016	Tot 2016	Capacity (kWh)	Range (km)
Opel Ampera	0	3	62	19	0	0	0	84	16	56
Toyota Prius	0	0	39	8	87	0	0	134	4.4	23
Chevrolet Volt	0	0	38	38	0	0	0	76	16	56
Fisker Karma	0	0	6	0	0	0	0	6	20.1	51
Volvo V60 PHEV	0	0	0	135	59	0	0	194	11.2	43.5
Porsche Panamera	0	0	0	23	0	0	0	23	9.4	32
Mitsubishi outlander	0	0	0	0	85	133	0	218	9.8	52.8
Bmw i8	0	0	0	0	34	99	0	133	7.1	37
Vw Golf GTE	0	0	0	0	0	180	158	338	8.7	50
Audi A3 e-tron	0	0	0	0	0	86	0	86	8.8	50
Bmw 225xe	0	0	0	0	0	0	308	308	7.6	41
Bmw330e	0	0	0	0	0	0	107	107	7.6	25
Volvo XC90 PHEV	0	0	0	0	0	0	90	90	9	40
Others	0	0	0	9	76	242	654	981	4.4	23
Tot PHEV Sales	0	3	145	232	341	740	1317	2778		

Table 29. BEV annual sales and technical specifications – Germany (Source:[62])

BEV model	2010	2011	2012	2013	2014	2015	2016	Tot 2016	Capacity (kWh)	Range (km)
Nissan Leaf	0	0	213	855	0	948	1121	3137	24	199
Renault Zoe	0	0	0	1019	1498	1787	2804	7108	22	210
KIA soul	0	0	0	0	0	3839	1384	5223	27	210
Bmw i3	0	0	0	413	1246	0	1521	3180	22	190
Tesla Roadster	23	0	0	0	0	0	0	23	53	393
Tesla Model S	0	0	0	0	814	1582	1474	3870	60	390
Citroen C-Zero	3	200	454	276	0	0	0	933	14.5	150
Mitsubishi iMiev	11	683	0		0	0	0	694	16	160
Smart fortwo ED	106	283	734	2146	1589	0	1325		16.5	135
Vw e-Up!	0	113	0	0	0	0	750	863	18	160
Peugeot iOn	0	0	0	0	1354	1031	0	2385	14.5	150
Renault Kangoo	1	208	263	0	0	0	0	472	33	200
Fiat Doblo	0	0	78	25	23	23	23	172	43	150
Fiat (QUBO) Fiorino	0	6	0	0	0	0	0	6	23	200
Piaggio Porter	0	4	0	0	0	0	0	4	17	80
Tot BEV Sales	144	1497	1742	4734	6524	9210	10402	28070		

Table 30. PHEV annual sales and technical specifications – Germany (Source:[62])

BEV model	2010	2011	2012	2013	2014	2015	2016	Tot 2016	Capacity (kWh)	Range (km)
Opel Ampera	0	241	828	335	0	0	0	1404	16	56
Toyota Prius	0	0	321	424	0	0	0	745	4.4	23
Chevrolet Volt	0	25	23	0	0	0	0	48	16	56
Fisker Karma	0	0	52	0	0	0	0	52	20.1	51
Volvo V60 PHEV	0	0	8	340	394	0	0	742	11.2	43.5
Porsche Panamera	0	0	0	210	0	0	0	210	9.4	32
Mitsubishi outlander	0	0	0	0	1068	2138	1436	4642	9.8	52.8
Bmw i8	0	0	0	266	1392	1331	1342	4331	7.1	37
Vw Golf GTE	0	0	0	0	0	2062	1264	3326	8.7	50
Audi A3 e-tron	0	0	0	0	460	1854	1615	3929	8.8	50
Bmw 225xe	0	0	0	0	0	1001	1256	2257	7.6	41
Others	0	0	0	81	1087	2725	6470	10363	4.4	23
Tot PHEV Sales	0	266	1232	1656	4401	11111	13383	32049		

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