 doi:10.20944/preprints201905.0331.v1

On the role of electric vehicles towards low-carbon energy systems: Italy and Germany in comparison

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ABSTRACT

Electric vehicles, being able to reduce pollutant and greenhouse gas emissions and shift the economy away from oil products, can play a major role in the transition towards low-carbon energy systems. 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 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 renewable shares not necessarily leads to a CO_2 emissions reduction. Different energy scenarios are simulated with the help of EnergyPLAN software assuming a progressive increase in renewable energy sources capacity and electric vehicles penetration. Results show that, for the German case, the additional electricity required leads to a reduction in CO_2 emissions only if renewable capacity increases significantly, whereas the Italian energy system benefits from transport electrification even at low renewable capacity. Smart charging strategies are also found to foster renewable integration; however, 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.

1 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, in response to Paris Agreement on climate change [1], energy strategies in different countries have put their focus on electricity generation [2] and transportation [3], that at present rely on fossil fuels respectively for 65 % and 96 % of their total energy consumption at a global scale [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, renewable power is forecast to grow by 36% over 2015-21 [6], however, according to International Energy Agency 2 °C Scenario (2DS), consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100, RES power is required to accelerate further by an additional 26% over 2021-25 and EV sales current growth rate (40 % in 2016 over the previous year) to remain unchanged in the future [6].

Constituting a key element of official energy policies, transport sector electrification is expected to play a key role in the progressive decarbonisation of energy systems in several ways. First, electrical motors can function as substitutes of fossil-fuelled engines to avoid climate-damaging combustion processes.

Second, the coupling of transport and electricity sector allows excess electricity from RES to be utilised to charge electric vehicles. Further, the aggregated battery capacity of EV is not only expected to provide negative balancing power in times of excess electricity but also to provide positive balancing power in times of high electricity demand and relatively low production through vehicle-to-grid strategies (V2G) [7]. Having regard to drivers' behaviour and given sufficient quality and quantity of data exchange between the infrastructural components of EV charging infrastructure and electricity network operation, grid operators can charge and discharge batteries of parked EV according to system requirements. The better the EV charging processes are harmonized with systemic requirements, the less electricity from RES needs to be curtailed and the less necessary is conventional electricity generation.

In general, previous studies have discovered the general sense of purpose of RES integration and relating EV diffusion [8], quantified the reduction in CO_2 emissions and RES curtailments [9], deduced optimal levels of EV and RES penetration [10] and designed mechansims for the incentivisation of those [11].

Although the mix of energy generation technologies was found to determine the benefits of EV penetration [12], energy system configuration, concerning the levels of RES integration and EV diffusion is mostly derived as an outcome variable. However, the benefits of electrification strongly depend on prior choices concerning the generation technology mix that underlies particular energy systems. In this context, this study aims to advance knowledge on the interaction between RES integration and transport sector electrification through the comparison of alternative energy system configurations and applies a bottom-up simulation approach that allows to assess the consequences of upfront modelled smart energy system design alternatives.

Consequentially, the first research question underlying this study can be stated as follows:

1. To what extent, in different energy system contexts, EV can positively interact with increasing levels of RES, absorb the otherwise-curtailed renewable surplus and consequently reduce CO_2 emissions?

For the present purpose, the energy sytems of Italy and Germany were both chosen as starting point for further modelling because, on the one hand, they presents features that are shared by several other developed European countries with high renewable potential and large oil products consumption in the transportation sector, on the other hand they significantly vary with regard to electricity supply mix. Specifically, Italy differs from Germany, and Nordic countries in general, in the availability of wind and solar energy, with this latter taking the lion's share among intermittent RES, as well as in the reliance on natural gas, rather than coal, for conventional electricity generation. Such differences become particularly important when electricity generation from RES is not available or not enough, depending on the installed capacity or the time of the year, and 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 [12] and making CO_2 savings potential greater where renewable contribution to the electricity mix is higher [13].

Consequentially, the second research question is:

2. To what extent, in different energy system contexts, the composition of the electricity generation sector affects the success of intermittent RES integration via transport sector electrification?

Moreover, a positive interaction between EV and RES also depends on the vehicle charge management. Forrest et al. [14] 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. Conversely, 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. However, some technical barriers still need to be addressed, including the battery duration and the need of additional grid connections for EV.

Previous research demonstrates that a smart charging approach supports solar power integration, doubling the utilization of photovoltaic generators when compared to uncontrolled charging strategy [10] and even leading to a 100 % renewable energy-based electricity supply under certain PV and EV combinations [15]. In addition, the integration of EV can worsen or lessen peak load depending on the charging strategy adopted [16].

The last research question can thus be defined as follows:

3. To what extent, in different energy system contexts, the charging strategy supports the synergy between EV and RES in different energy system contexts?

With a view to providing a detailed analysis of potential positive interactions between EV and RES, with reference to the capability of EV to act as an electricity storage system within different energy systems contexts and charging strategies, this work carries out an analysis that starts from a base-case scenario for Italy and Germany at 2016. Possible future projections with progressively increasing shares of RES and EV have been defined, analysed and compared with the help of EnergyPLAN software in order to evaluate the energy system response to an ever-growing renewable installed capacity and electrification of transport sector.

The focus of this analysis is on providing possible recommendation and a variety of technical solutions that policy makers can rely on to define the optimal path towards a sustainable and effective national energy strategy. In other words, instead of "following" a likely growth of renewable energy sources, that depends on several political and economic drivers and factors that are difficult, if not impossible, to forecast accurately especially on a medium-long time basis, this study aims to provide the base for a "backcasting" analysis by comparing different possible scenarios and investigate to what extent a rise of a given technology (RES and EV) affects crucial environmental and economic indicators such as CO_2 emissions, RES penetration, curtailments and costs. Such type of analysis could ultimately help policy makers in defining a strategic planning method that starts with choosing a desirable future, among the proposed scenarios, and then works backwards to identify actions and programs to connect that specified future to the present.

2 METHODS

This section describes the main logic of EnergyPLAN tool and lists input values for the definition of a base case and future scenarios for Italy and Germany, along with the related sources that have been used.

EnergyPLAN is an energy modelling tool that performs energy balances of a given energy system by simulating its operation throughout the year on an hourly basis. The software presents different tabs to be filled with input parameters so as to fully characterise the energy system; a detailed description of algorithms used in the tool can be also found in the user guide within the software, available as a freeware resource [17].

To perform an energy balance for a given country, a variety of input parameters are required. From demand side, they are represented by annual electricity, heating and cooling demand along with their hourly power distributions as well as yearly direct fuel consumption for transport, industry, residential and commercial sectors.

From supply side, power plants capacities, efficiencies and fuel shares for power generation must be provided, as well as hourly distributions of RES generation. Conventional power plants are classified as CHP (Combined Heat and Power) and PP (Power Plants) units. Heat supply is modelled through boilers for individual heating and CHP units for district heating and industrial processes.

Hourly distributions, which are required, as mentioned above, for energy demands and non-dispatchable RES generation supply, must be expressed as the ratio between the hourly-averaged power required at a particular hour and the yearly maximum value.

Details on all these input data are given in the following paragraphs.

2.1 Base case scenario definition

A base case scenario has been defined for both countries, represented respectively by the Italian and German energy systems at 2016, modelled 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). Input data for base case scenarios, resulting from the analysis presented in the followings, are available at an institutional repository [18].

2.1.1 Demand

From demand side, the Italian and German energy system have been described in terms of electricity, heating and cooling loads as well as direct fuel consumption for transport and industry sectors.

2.1.1.1 Electricity

Table 1 shows gross electricity loads for both countries at 2016, along with the sources where these data were taken from. The software allows electricity for heating, cooling and transportation to be set directly by the user: as a result, the remaining non-mentioned electrical loads are implicitly contained in the overall electricity demand (which also includes energy for auxiliary systems and losses). Annual net import/export electricity has been also inserted as an input parameter.

An hourly distribution must be associated with yearly electricity load and net import/export to ultimately let the software work out power plants generation on an hourly basis, thus performing the energy balance between electricity demand and supply throughout the year.

Hourly power distributions used to characterise electricity demand and import/export are shown in Figures A.1 and A.2 in the Appendix of this paper for the Italian and German case respectively.

Table 1. Electricity loads at 2016

	Consumption (TWh/year)		Source	
	Italy	*Germany*	*Italy*	*Germany*
Total national electricity demand	**326.80**	**598.59**	[19]	[20]
of which:				
Electricity for cooling	*6.42*	*0.96*	[21–23]	[23,24]
Electricity for heating (electric boilers)	*8.37*	*43.04*	[25]	[24]
Electricity for heating (heat pumps)	*18.63*	*5.82*	[26]	[27,28]
Electricity for transport	*11.16*	*11.73*	[22]	[29]
Import	43.18	28.34	[19]	[20]
Export	-6.15	-78.86	[19]	[20]
Net Import/Export	**37.03**	**-50.52**		

2.1.1.2 Heating and cooling

Fuel consumption for space heating and sanitary hot water for residential and commercial sectors is shown in Table 2 along with the average boiler efficiency; such parameters define what EnergyPLAN refers to as “individual heating”.

Table 2. Fuel consumption and efficiencies for individual heating at 2016

	Consumption (TWh/year)		Efficiency	
	Italy (Source: [21,22]*)*	*Germany (Source:* [29]*)*	*Italy (Source:* [30]*)*	*Germany (Source:* [30]*)*
Coal boiler	-	6.36	-	-
Oil boiler	29.19	214.61	0.90	0.90
Natural gas boiler	262.73	377.10	0.92	0.92
Solar thermal	1.73	8.74	0.90	0.90
Biomass boiler	79.44	95.04	0.85	0.85

With particular reference to the Italian case, a study carried out by “Gestore dei Servizi Energetici” (GSE), the company identified by the State to pursue and achieve environmental sustainability, provides a breakdown of residential and services overall energy consumption among end uses (as in space heating, space cooling, sanitary hot water, cooking etc.) and energy sources at 2015 [21]. From such subdivision, the consumption allocated specifically to space heating has been derived as a percentage of the total for each of the energy sources involved and the values have been rescaled to 2016.

As concerns the German case, in the absence of a detailed breakdown among end uses for residential and commercial sectors, the overall energy consumption has been entirely allocated to individual heating with the exception of electricity consumption, whose usage for heating and cooling purposes has been estimated from two external sources: the German energy models available at Heat Roadmap Europe database, a EU-funded project for the development of a low carbon and cooling strategy for 14 EU countries [24] and from the latest report concerning the development of Renewable Energy Sources in Germany provided by Federal Ministry for Economic Affairs and Energy [27].

The overall thermal demand for individual heating can thus be evaluated, and it is equal to 643.46 and 394.23 TWh for Germany and Italy respectively. Heat pumps and electric boilers, whose electricity consumption has been previously set in Table 1, provide together for a thermal demand of 60.29 TWh for the German case and 57.37 TWh for the Italian case. The Seasonal Performance Factor (SPF, indicating the seasonally-averaged COP over the heating season) has been set to 2.95 and 2.63 for Germany [28] and Italy [21] respectively.

Once the annual fuel consumption is provided, annual CO_2 emissions related to individual heating can also be derived using fuel emission factors as reported in the following of this section.

As shown in Table 1, electricity consumption for cooling is respectively equal to 0.96 and 6.42 TWh for Germany and Italy; assuming a Seasonal Energy Efficiency Ratio (SEER, a commonly used measure of the average efficiency of cooling equipment that takes into account changes in operating conditions throughout the cooling season [31]) of 5.5 for both countries [23] cooling production is equal to 5.27 and 35.33 TWh for the German and the Italian case.

Hourly distributions of individual heating and cooling demand are also required and used by the software to simulate on an hourly basis electricity generation needed to fulfil demand for heat pumps and electric boilers. Individual heating demand distribution takes also into account demand for sanitary hot water. Such distributions are shown in Figures 15 and A.4 in the Appendix of this paper for Italy and Germany respectively.

With respect to Italy, heating distribution has been derived considering the overall national gas consumption considering that almost 70% of individual heating demand is fulfilled through natural gas. Its hourly distribution is provided by SNAM, the national society for natural gas transportation and storage, for the year 2016 [32]. Gas consumption for heating purposes only has been determined by subtracting industry, power plants and transportation usage.

As concerns the German case, heating and cooling distributions have been taken from Heat Roadmap Europe database [24]. Since the latest available models refer to the year 2015, it has been assumed that heating and cooling demand distributions stay the same in 2016.

Table 3. District heating and CHP heat demand (TWh/year) at 2016

	Italy (Source: [22]*)*	*Germany (Source:* [29]*)*
Energy industry own use	16.24	3.48
Residential and services	13.86	64.06
Industry	31.82	49.69
Total	**61.92**	**117.23**

District heating and heat demand for industrial processes have been also included, and values are listed in Table 3 for both countries. CHP and DH plants cater for such demand, as described in detail in the following (see section 2.1.2).

2.1.1.3 Industry and other fuel consumption

Fuel consumption in the industry and other sectors (agriculture, fishing, forestry, energy industry own use and various non-specified areas) have been included as well to account for CO_2 emissions also in these areas of the energy system. Data are shown in Table 4.
Besides fuel consumption, EnergyPLAN allows to insert fuel losses estimated as a percentage of the total fuel consumed at the end of the analysis. Such losses have been set to 1.04 % and 0.07 % for coal and oil in Germany [29] and equal to 0.5 % for natural gas in the Italian case [22].

Table 4. Industry and other sector fuel consumption (TWh/year) at 2016

	Industry		Other	
	Italy (Source: [22])	*Germany (Source: [33])*	*Italy (Source: [22])*	*Germany (Source: [33])*
Coal	11.16	70.41	0.05	9.55
Oil	30.94	27.35	61.08	66.65
Natural gas	97.23	226.62	27.35	14.62
Biomass and waste	7.64	45.43	73.22	6.22

2.1.1.4 Transport

With respect to the transport sector, energy demand has been modelled by including fuel and electricity consumption as listed in Table 5 for both countries. In the Italian case, fuel consumption projection for 2016 provided by "Istituto Superiore Per la Ricerca Ambientale" (ISPRA) [34] has been considered to derive how the overall consumption is distributed among fuels, and adjusted according to total energy consumption in the transport sector as provided by IEA for the same year [22]. As for Germany, transport-related energy consumption has been derived from data published by AGEB for the year 2016 [33].

Table 5. Transport sector fuel and electricity consumption (TWh/year) at 2016

	Italy (Source: [34])	*Germany (Source: [33])*
JP (Jet Fuel)	8.05	108.06
Diesel	262.63	423.94
of which biodiesel	*11.72*	*29.94*
Petrol	88.42	197.11
of which biopetrol	*0.29*	*0*
Natural gas	12.86	1.62
LPG	21.24	4.67
Electricity	11.16	11.74

Given the negligible share of EV in 2016, electricity consumption can be allocated to other means of transportation such as trains and electric trams. Moreover, since electricity demand for transportation is ultimately fulfilled by power plants, its distribution has to be included in the model. Figure A.5, reported in the Appendix of this paper, shows the distribution of electricity demand for transport [24], the same for both countries; only ten days have been displayed to highlight the daily pattern.

2.1.2 Supply

Energy supply has been modelled including the current technology mix deployed to satisfy power and thermal loads and ultimately achieve an hourly energy balance throughout the year.

2.1.2.1 Heat and electricity: conventional power plants

While individual heating demand has been already discussed in section 2.1.1.2, CHP and DH plants have been modelled to cater for district heating requirements for both countries. Among CHP plants, EnergyPLAN allows to select large CHP plants able to operate, if required, in electricity mode only. Such capacity is thus included in conventional power plants overall capacity (PP). Capacities and efficiencies are shown in Table 6.

Power plants fuel consumption has to be also considered to properly assess the overall CO_2 emissions related to electricity generation. With this regard, the software allows to set how the overall power plant energy consumption is distributed among fuels. Table 7 shows data used for Italy and Germany.

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Table 6. Conventional power and cogeneration plants: installed capacity and efficiency at 2016

	Italy *(Source:* [22,35]*)*			*Germany* *(Source:* [29,36]*)*		
	Capacity (GW)	η_{el}	η_{th}	*Capacity (GW)*	η_{el}	η_{th}
PP	58.95	0.43	-	86.82	0.40	-
CHP	26.25	0.39	0.22	51.16	0.39	0.30

Table 7. Conventional power and cogeneration plants: fuel distribution (TWh/year) at 2016

	CHP		**PP**	
	Italy *(Source:* [22]*)*	*Germany* *(Source:* [29]*)*	*Italy* *(Source:* [22,35]*)*	*Germany* *(Source:* [29]*)*
Coal	9.59	75.52	100.58	702.76
Oil	44.36	5.07	36.54	12.57
Natural gas	179.75	140.69	219.60	125.22
Biomass	39.02	98.07	62.50	66.27

District heating boilers are modelled to produce 35.83 TWh [29] and 1.14 TWh [22] of thermal energy for Germany and Italy respectively (with an overall efficiency equal to 0.77 and 0.71).

Finally, nuclear power plants have been included in the German energy scenario: the overall capacity has been set to 10.8 GW [36], with an electric efficiency of 0.33 [29].

2.1.2.2 Renewable electricity generation

Besides conventional power plants, electricity provided by renewable energy sources has to be modelled to completely define the technology mix to cater for national electricity demand. Their installed capacities are listed in Table 8.

RES hourly distribution is shown in Figures A.6 and A.7, in the Appendix section, for the Italian and German case respectively along with the related sources ([37], [38]).

Table 8. Renewable energy installed capacity (GW) at 2016

Technology	*Italy* *(Source:* [35]*)*	*Germany* *(Source:* [36]*)*
Onshore wind	9.41	45.28
Offshore wind	-	4.15
Photovoltaic	19.28	40.68
River Hydro	5.43	3.95
Dammed Hydro	18.72	1.54
Geothermal	0.82	0.04

2.1.3 Model validation

Base case scenarios have been validated comparing critical indicators against actual data at 2016 as displayed in Table 9. Variation with respect to actual data is within 2.3 %. Primary energy supply related to non-energy uses has 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 PP production and RES penetration is expressed as a percentage of total national electricity production.

Table 9. Model validation.

Country	Indicator	Model	Actual	Source	Difference
Italy	CO_2 emissions [Mt]	324.89	325.70	[4]	-0.25%
	TPES [Mtoe]	147.80	144.67	[4,29]	2.16%
	RES electricity (excl. biomass) [TWh]	90.34	90.34	[35]	0.00%
	PP electricity [TWh]	93.67	93.57	[35]	0.11%
	CHP electricity [TWh]	105.86	105.13	[35]	0.69%
Germany	CO_2 emissions [Mt]	724.08	731.60	[4]	-1.03%
	TPES [Mtoe]	295.17	288.62	[4,29]	2.27%
	RES electricity (excl. biomass) [TWh]	137.52	137.35	[39]	0.12%
	PP electricity [TWh]	301.49	295.97	[29]	1.87%
	CHP electricity [TWh]	125.51	125.51	[29]	0.00%

2.2 Future scenarios modelling

Future scenarios have been modelled in EnergyPLAN assuming progressively growing shares of RES, taking into account potential limits for renewable sources, and EV, up to an entire replacement of conventional vehicle fleet.

2.2.1 Electricity generation

As concerns electricity generation, renewable installed capacities for intermittent sources (iRES), as in wind and solar, have been linearly increased for the German case up to the maximum value derived according to 2050 energy policy target. Values are displayed for each source in Table 10 and lead to an overall increase equal to approximately 6 times the corresponding 2016 total installed capacity. With this respect, to provide an effective comparison among energy systems, the same increase in iRES capacity has been kept for the Italian case and divided among sources taking into account an upper limit for wind, conservatively set at 17.15 GW according to National Wind Energy Association (ANEV) projections at 2030 [40].

Table 10. iRES capacity values (GW)

Technology	Italy		Germany	
	iRES2016 (Source: [35])	6×iRES	iRES2016 (Source: [36])	6×iRES (Source: [41])
Onshore wind	9.41	16.00	45.28	198.00
Offshore wind	-	1.15	4.15	54.00
PV	19.28	150.66	40.68	275.00
Total	**28.69**	**167.81**	**90.11**	**527.00**

Assumptions have been also made with respect to fossil fuel consumption for electricity production and conventional power plants. The option of coal phase-out has been implemented for both countries, leading to a reduction in power capacity of 42.48 GW (28.89 GW for CHP and 13.59 GW for PP) for Germany [36] and 8.20 GW for the Italian case. Additionally, a nuclear phase-out has been implemented for the German case, which translates in the decommissioning of 10.8 GW of nuclear capacity.

Finally, with respect to import/export management, RES surplus has been considered to replace import for the Italian case.

2.2.2 Private transport

Future scenarios for transportation sector have been derived assuming a linear decrease in petrol and diesel cars combined with a simultaneous progressive replacement by EV up to a complete substitution of the conventional vehicle fleet, keeping the total number of vehicles stable at 2016 level (37.90 Million for Italy [42] and 45.06 Million for Germany [43]).

The impact of private transport only within the whole transportation sector needs to been estimated in terms of fuel consumption; conventional and electric vehicles were divided into different categories according to their market segment (as in small, medium and large) according to vehicles registrations over the last ten years for the Italian case [44] and using recent data on German road vehicles fuel consumption disaggregated by segment [45].

Average fuel economy for conventional cars has been derived from manufacturers' data and adjusted in each category to meet the more realistic overall higher value reported in Unione Petrolifera technical report [42].

For the Italian case, the annual driving distance was set to 7280 and 13650 km/year respectively for petrol and diesel cars [46]. With respect to the German case, annual distance covered by petrol and diesel vehicles has been set to 10260 and 18525 km/year, derived as a projection to 2016 from historical data for Germany reported in [47].

EV technical specifications were evaluated as a weighted average of the actual circulating fleet composition for both countries considering new registrations from 2015 onwards [44,48] including also electricity consumption for auxiliary systems and real driving conditions based on the latest EV models available data [49]. Petrol consumption was also taken into account for hybrid plug-in electric vehicles (PHEV) when exceeding the full-electric range. PHEV are also assumed to represent 30% of the EV medium and large size vehicle segment in future scenarios. Final electricity consumption for EV and PHEV was calculated considering a 90% charging efficiency. EV are assumed to cover an average distance between petrol and diesel, i.e. 10367and 13027 km/year for Italy and Germany respectively. An example, referring to a 50 % replacement of the conventional fleet, is shown in Tables 11–14.

Table 11. Conventional vehicles fuel consumption at 50 % replacement - Italy

	Size	*Share*	*Initial vehicles ($\times 10^6$)*	*Remaining vehicles ($\times 10^6$)*	*Consumption (l/100 km)*	*Consumption (TWh/year)*
Petrol	Small	0.86	13.75	6.87	6.19	27.90
	Medium	0.13	2.04	1.02	6.79	4.54
	Large	0.01	0.12	0.06	9.38	0.37
	Total		**15.91**	**7.95**		**32.81**
Diesel	Small	0.35	5.27	2.63	4.79	16.87
	Medium	0.61	9.06	4.53	5.56	33.71
	Large	0.04	0.64	0.32	8.09	3.44
	Total		**14.96**	**7.48**		**54.02**

Table 12. EV electricity and PHEV fuel consumption at 50% replacement - Italy

Size	*Share*	*Consumption (kWh/100km)*	*Vehicles ($\times 10^6$)*	*Electricity consumption (TWh/year)*	*Battery storage (GWh)*	*PHEV fuel consumption (TWh/year)*
Small	0.62	16.39	9.51	17.95	154.57	-
Medium	0.36	18.44	5.55	11.79	155.53	0.54
Large	0.02	22.11	0.38	0.96	26.01	0.08
Total			**15.43**	**30.70**	**336.11**	**0.62**

Table 13. Conventional vehicles fuel consumption at 50 % replacement - Germany

	Size	*Share*	*Initial vehicles ($\times 10^6$)*	*Remaining vehicles ($\times 10^6$)*	*Consumption (l/100 km)*	*Consumption (TWh/year)*
Petrol	Small	0.32	9.59	4.80	6.19	27.44
	Medium	0.58	17.39	8.69	6.79	54.53
	Large	0.10	3.00	1.50	9.38	13.00
	Total		**29.97**	**14.99**		**94.97**
Diesel	Small	0.09	1.36	0.68	4.79	5.90
	Medium	0.70	10.49	5.24	5.56	52.97
	Large	0.21	3.24	1.62	8.09	23.84
	Total		**15.09**	**7.54**		**82.71**

Table 14. EV electricity and PHEV fuel consumption at 50% replacement - Germany

Size	*Share*	*Consumption (kWh/100km)*	*Vehicles ($\times 10^6$)*	*Electricity consumption (TWh/year)*	*Battery storage (GWh)*	*PHEV fuel consumption (TWh/year)*
Small	0.24	16.72	5.47	13.25	90.13	-
Medium	0.62	18.40	13.94	37.11	368.62	3.99
Large	0.14	22.20	3.12	10.03	215.25	1.73
Total			**22.53**	**60.24**	**671.80**	**5.72**

With reference to charging strategy two different options have been taken into account:

- Dump charge: Vehicles are charged exclusively according to driver's needs/habits;
- Smart charge: EV charge during low-power demand in order to meet drivers' needs to recharge the vehicle at a certain time as well as to avoid grid overloading.

The graphs displayed in the Results and discussion section refer to the smart charge option.

2.2.3 Cost structure

As concerns costs, economic data are based on projections to 2050 from the EU-funded Heat Roadmap Europe project [24], Tables 15 and 16 display data relevant to the analysis, i.e. RES costs and fuel price.

Table 15. Intermittent RES related costs at 2050 (Source: [24])

Country	*Technology*	*Investment ($M€/MW_e$)*	*Period (Years)*	*O. & M. (% of Inv.)*
Italy	Onshore wind	0.86	30	3.41
	Offshore wind	1.39	30	1.93
	Photovoltaic	0.66	40	1.11
Germany	Onshore wind	0.91	30	3.40
	Offshore wind	1.47	30	1.93
	Photovoltaic	0.70	40	1.11

Table 16. Fuel price (€/GJ) (Source: [24])

Fuel	*Price*
Coal	2.4
Fuel Oil	9.7
Diesel fuel	12.1
Petrol/JP	12.1
Natural gas	9.3
LPG	13.4
Biomass	8.6

A weighted average price for EV has been considered from the current vehicle fleet composition. Medium and large EV price has been evaluated considering such category made up of 30 % BEV and 70 % PHEV. As concerns petrol and diesel cars, for both countries purchase costs have been derived from manufacturers' prices for the most common vehicles for each category, chosen as representative of the particular segment. Resulting data are summarized in Table 17.

Table 17. Conventional and EV purchase costs (k€)

Country	*Category*	*Petrol*	*Diesel*	*EV*
Italy	Small	12.39	13.45	29.81
	Medium	23.40	21.00	37.03
	Large	62.65	58.17	88.33
Germany	Small	13.60	16.20	24.96
	Medium	23.40	26.40	36.43
	Large	62.65	60.43	87.68

Given the foreseen decrease in battery costs in the medium-long term future [50,51], a parametric analysis has been also undertaken with respect to EV price, evaluating the effect of possible reasonable future price reductions for EV as compared to conventional vehicles. In particular, cost analysis has been carried out under three different EV purchasing cost assumptions:

- EV price @2016: EV price is stable at 2016 level;
- EV price reduced: average between current EV and conventional car price;
- EV=Conventional: EV price equals that of conventional cars.

3 RESULTS AND DISCUSSION

The variety of scenarios defined according to the above-mentioned assumptions have been compared using environmental and techno-economic indicators as CO_2 emissions variation, RES penetration and surplus. In particular, CO_2 emissions variations have also been evaluated with respect to the primary energy supply (defined as the total amount of primary energy used by the energy system in a particular scenario) with and without RES (labelled respectively as TPES and $PES_{excl.RES}$). RES penetration and surplus have been evaluated with respect to the domestic electricity production.

3.1 RES and EV positive interactions

Figures 1 and 2 display how the increase in iRES capacity with respect to 2016 (labelled as iRES capacity growth factor) affects two crucial energy indicators, namely CO_2 emissions and RES surplus, for the German and the Italian case respectively; EV are assumed to be charged under a smart strategy.

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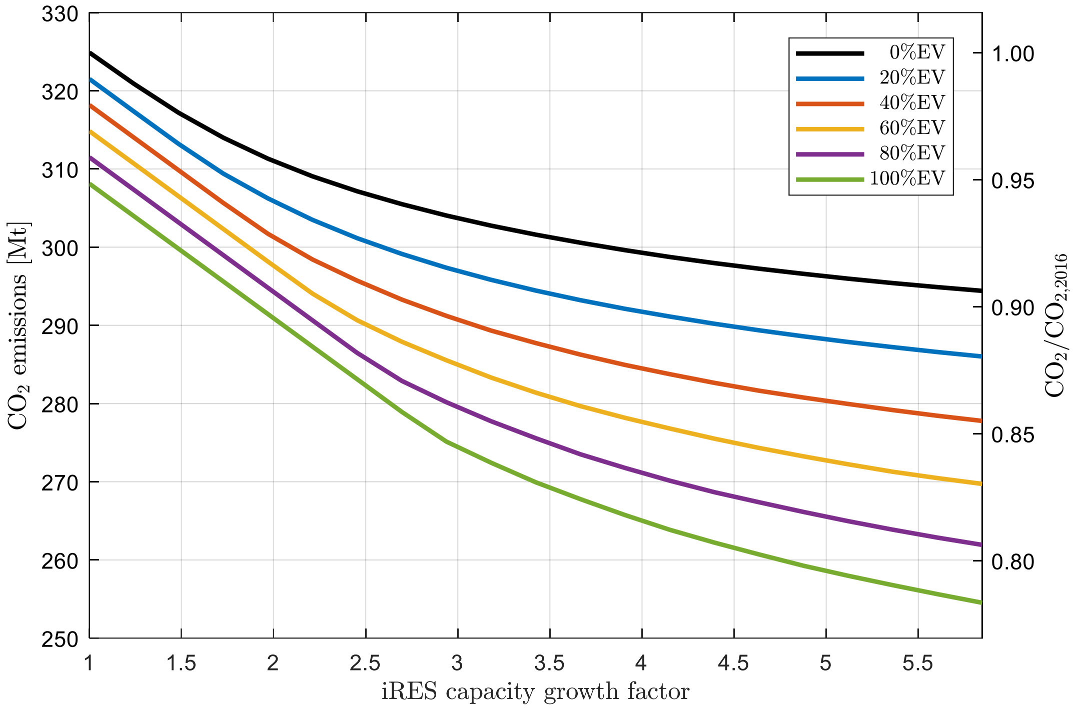

Figure 1. CO_2 emissions at increasing iRES capacity - Italy

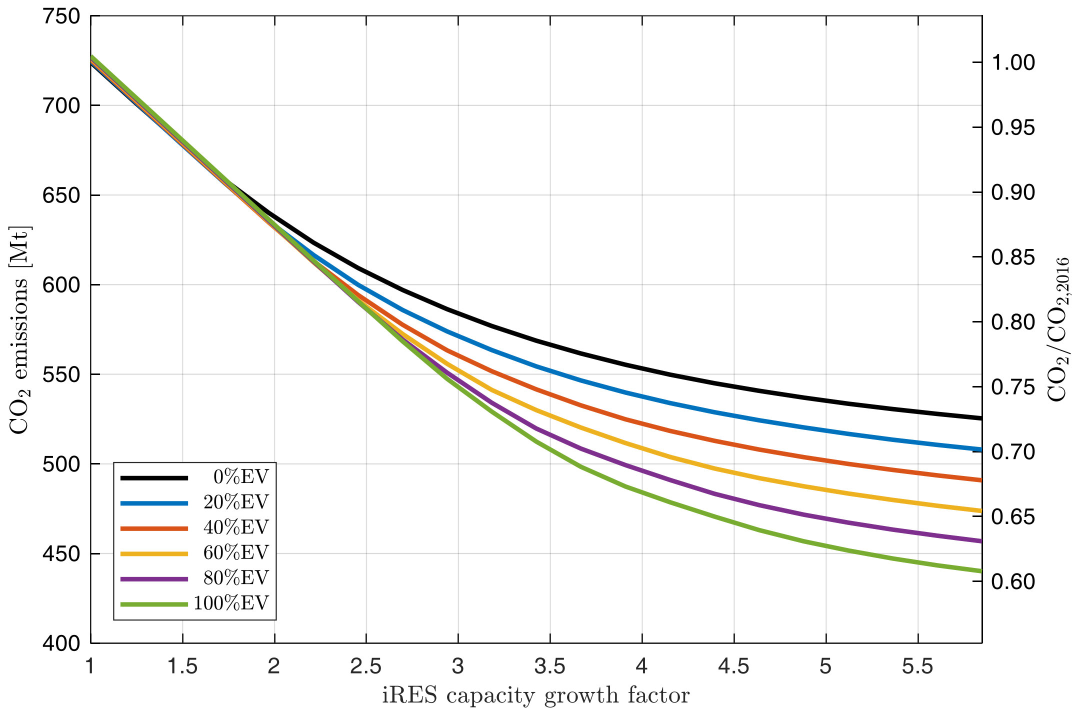

Figure 2. CO_2 emissions at increasing iRES capacity - Germany

While the Italian energy system always benefits from EV, in Germany the additional electricity required for EV charging leads to a different trend in CO_2 emissions, so that, when iRES capacity is below a certain threshold, emissions remain almost unchanged irrespective of EV penetration (and actually slightly increase). Moreover, as discussed in Section 3.3, for the German case, the overall installed capacity for electricity generation is not adequate to fulfil the increase in electricity demand that arises under significant EV penetrations, thus requiring additional electricity to be imported from neighbouring countries (or, possibly, additional increase of existing installing capacity). For such scenarios, CO_2 emissions equivalent to additional import have been calculated as if they were produced by national PP capacity, that is, German PP specific CO_2 emissions have been applied to the additional import.

On the other hand, at higher levels of RES penetration (approximately twice the base case capacity), the interaction between RES and EV proves to be beneficial for both countries, even more effective in the German case where RES replace a more carbon-intensive electricity generation sector. In particular, without including the electrification of transport sector, if RES are increased up to 6 times the overall 2016 capacity, CO_2 emissions can be reduced by 9 % and 27 % for Italy and Germany respectively. At the highest RES level, EV allow a further reduction of CO_2 emissions down to 22 % and 39 % for Italy and Germany respectively by absorbing the otherwise-curtailed renewable surplus, which is reduced from 29 % to 15 % of total electricity production for Italy and from 50 % to 28 % for Germany (Tables 18 and 19).

Nonetheless, it is worth mentioning that curtailments cannot be effectively reduced unless the deployment of renewable sources is extended, besides transportations, also to other sectors of the energy system to maximise the positive effects of sector coupling [52], or suitable grid-scale electricity storage systems become available and widely used [53].

3.2 Impact of charging strategy

Tables 18 and 19 and show CO_2 variations (with respect to 2016 base-case), RES penetration and surplus (both expressed as a percentage of the total production) for increasing EV penetrations comparing dump and smart charging strategies at the highest RES level.

For both countries, shifting from dump to smart strategy results in a positive effect on CO_2 emissions; when a smart charge is implemented Italy features a higher percentage variation than Germany with respect to results obtained using a dump charge. This is due to the particular uneven distribution of the Italian RES potential generation throughout the day; conversely, the charging strategy shows a lower effect for the German case where potential RES surplus, more uniformly distributed, lessens the negative impact of dump charge. In fact, 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 mostly during the day due to the higher solar power share. As a result, in terms of percentage change, RES penetration variation, and subsequent RES surplus, is higher for the Italian case when a smart charge is applied as a relatively higher share of renewable power can be incorporated in the energy system.

Table 18. CO_2 variations, RES penetration and surplus at 6×iRES - Italy

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-9.4%	-10.8%	-12.3%	-13.1%	-12.9%	-14.2%
Smart	-9.4%	-12.0%	-14.5%	-17.0%	-19.4%	-21.7%
Variation	**0.0%**	**11.2%**	**17.6%**	**30.1%**	**50.3%**	**52.7%**
RES penetration [% of tot. prod.]						
Dump	51.5%	50.1%	49.3%	47.0%	46.7%	45.5%
Smart	51.5%	52.7%	53.8%	54.6%	55.3%	55.7%
Variation	**0.0%**	**5.3%**	**9.2%**	**16.3%**	**18.5%**	**22.3%**
RES surplus [% of tot. prod.]						
Dump	28.9%	27.1%	25.2%	24.8%	25.0%	23.9%
Smart	28.9%	25.7%	22.6%	19.7%	17.0%	14.6%
Variation	**0.0%**	**-5.0%**	**-10.2%**	**-20.3%**	**-32.0%**	**-38.9%**

Table 19. CO_2 variations, RES penetration and surplus at 6×iRES - Germany

	0%EV	20%EV	40%EV	60%EV	80%EV	100%EV
CO_2 [%]						
Dump	-27.4%	-28.6%	-29.5%	-30.3%	-31.1%	-31.9%
Smart	-27.4%	-29.8%	-32.2%	-34.6%	-36.9%	-39.2%
Variation	**0.0%**	**4.3%**	**9.0%**	**13.9%**	**18.7%**	**23.1%**
RES penetration [% of tot. prod.]						
Dump	59.9%	60.2%	59.5%	58.7%	57.8%	56.9%
Smart	59.9%	61.2%	62.4%	63.5%	64.5%	65.4%
Variation	**0.0%**	**1.7%**	**4.9%**	**8.3%**	**11.7%**	**15.0%**
RES surplus [% of tot. prod.]						
Dump	49.8%	46.8%	43.7%	41.1%	38.9%	37.1%
Smart	49.8%	44.7%	40.0%	35.6%	31.5%	27.7%
Variation	**0.0%**	**-4.4%**	**-8.4%**	**-13.3%**	**-18.9%**	**-25.3%**

This phenomenon is visible in Figures 3 and 4 that show boxplots related to electricity demand normalized distributions throughout the 24 hours for the whole year considering dump and smart charge at 6×iRES and EV entirely replacing the conventional vehicle fleet (100%EV). Electricity demand distribution is reshaped from dump to smart strategy according to the availability of RES surplus, shifting night-hour load to day hours characterised by an abundance of renewable power. The contribution of conventional power plants and RES surplus can thus be partly reduced as shown in Figures 5–8, representing, for the Italian and the German case respectively, hourly demand and supply by RES and conventional sources for approximately ten days of February, in which it can be also observed how the higher share of wind generation may reduce issues related to an unregulated EV charge.

The variation of CO_2 emissions divided by energy sectors is displayed in Figures 9–14 for base-case and for iRES2016 and 6×iRES at the highest EV share.

When EV replace entirely conventional cars, CO_2 emissions in the transport sector can be reduced by 13 and 12 percentage points respectively for Italy and Germany at the price of a rise in total electricity generation emissions (11 and 13 percentage points respectively) when RES are kept at 2016 level. As discussed previously (section 3.1), full transport electrification results in an overall decrease in emissions in Italy, while it leads to a slight increase in Germany, due to the carbon-intensive electricity generation sector of this country.

An increase in iRES capacity up to 6 times 2016 level allows a reduction in CO_2 emission within the electricity generation, leading to a level that is comparable to the total 2016 emissions for the Italian case (30 % of the overall emissions) and even lower for Germany (22 %), that entails however a huge amount of RES surplus (as described previously). Emissions due to transportation are still significantly affected by other means of transportation other than light-duty vehicles (heavy-duty vehicles, boat and air transport, etc) whose contribution, for both countries, represents 20–21 % of the overall emissions in the best-case scenario. Such figure could be curbed by replacing petrol and diesel supply with electrofuels, these latter generated out of electricity (possibly from RES surplus), hydrogen and biomass [52]. At the present stage, however, electrofuels have not been included in the analysis.

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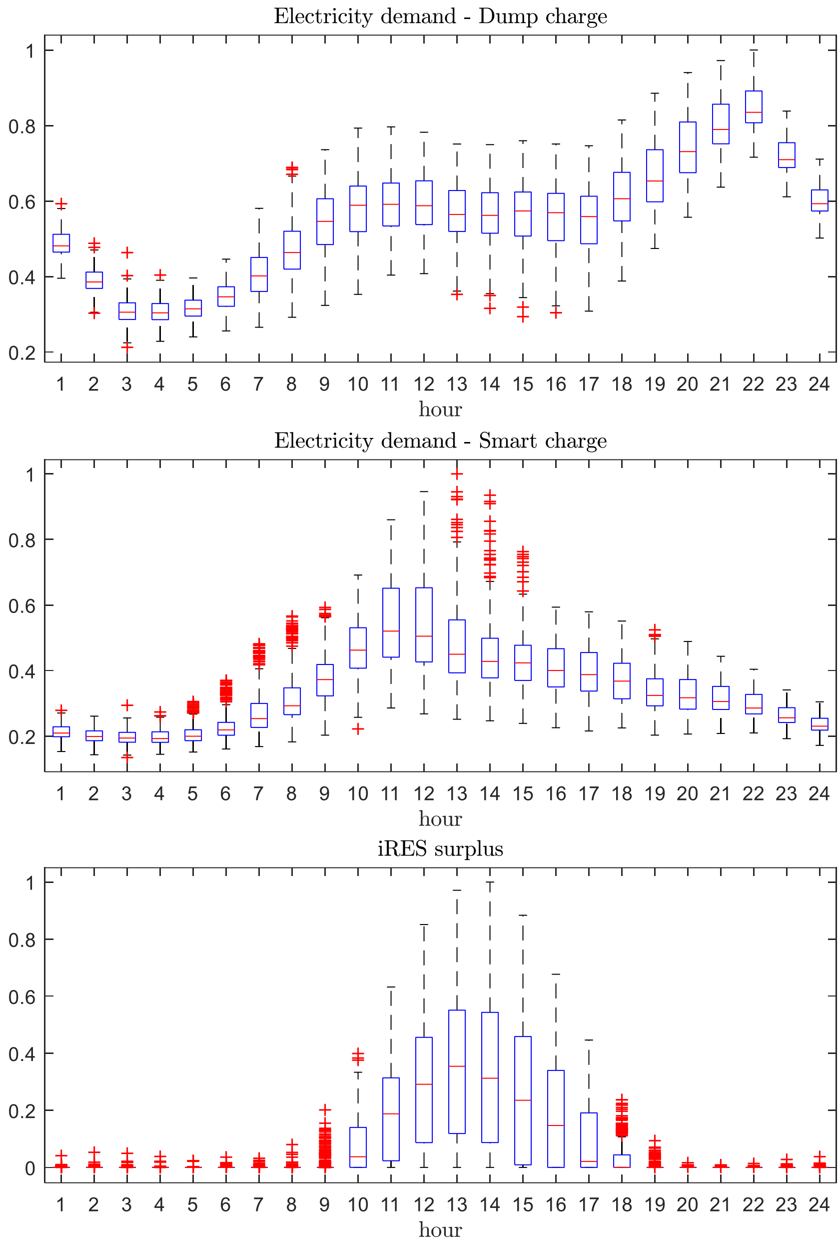

Figure 3. Daily distributions for the whole year of electricity demand under dump (top) and smart (center) EV charge and RES surplus (bottom). 6×iRES and 100%EV scenario - Italy.

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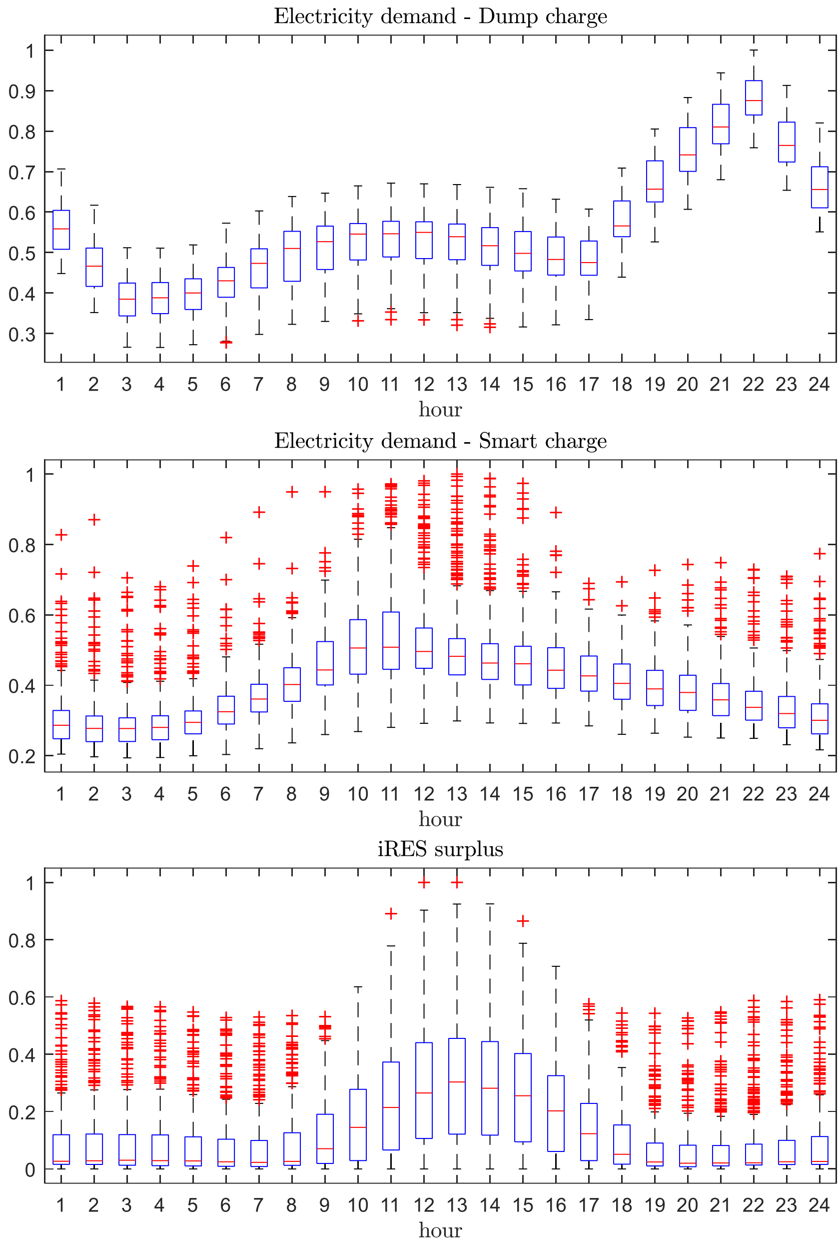

Figure 4. Daily distributions of electricity demand under dump (top) and smart (center) EV charge and RES surplus (bottom). 6×iRES and 100%EV scenario - Germany.

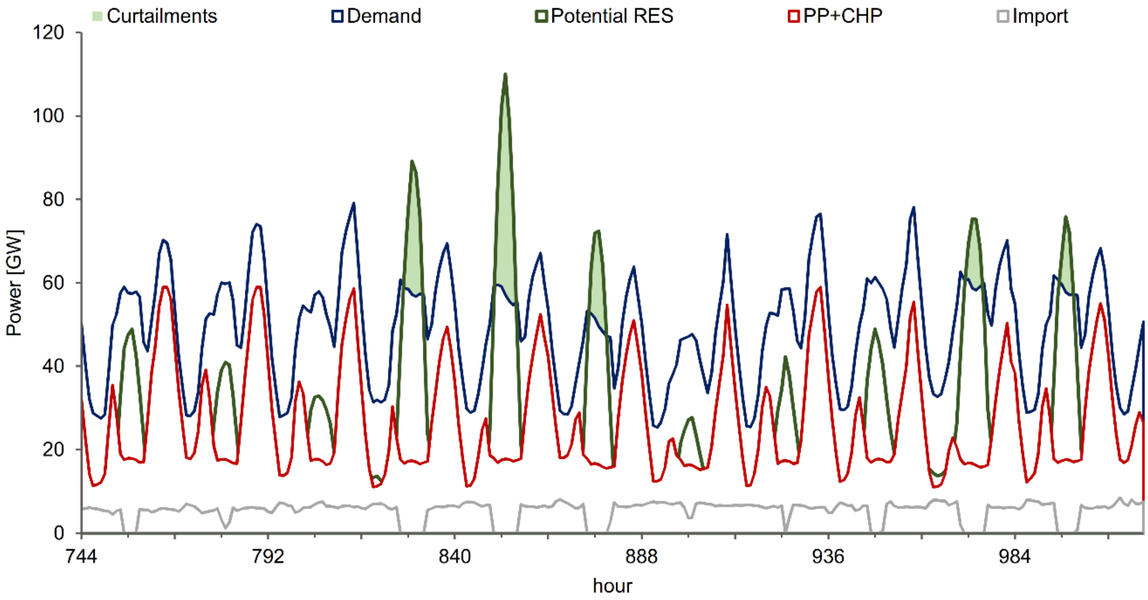

Figure 5. Power generation and demand at 100% EV and 6×iRES (Dump Charge) – Italy

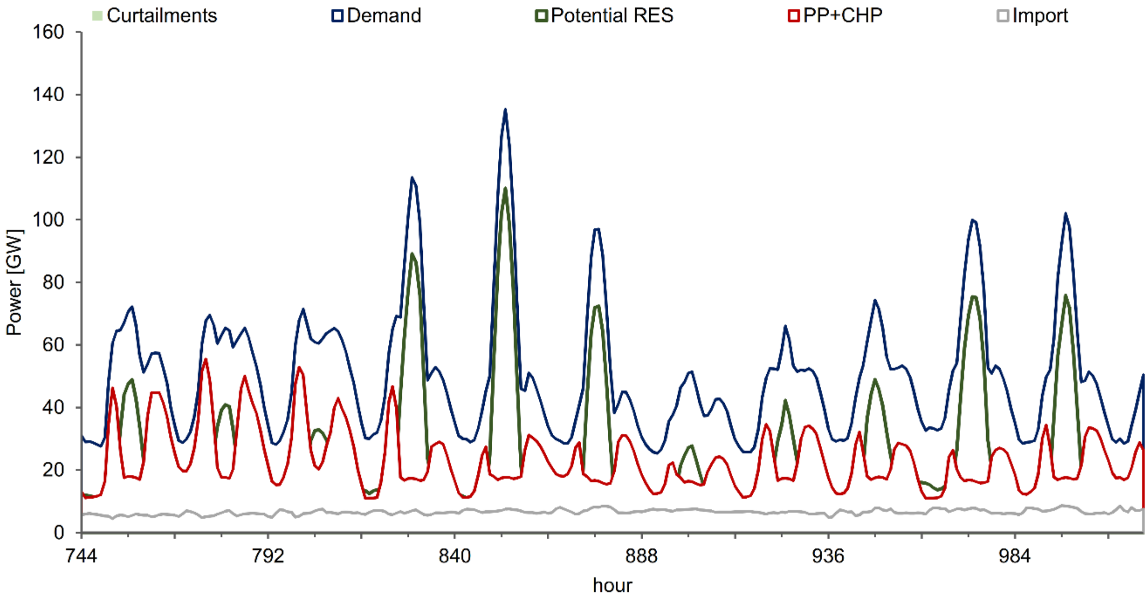

Figure 6. Power generation and demand at 100% EV and 6×iRES (Smart Charge) - Italy

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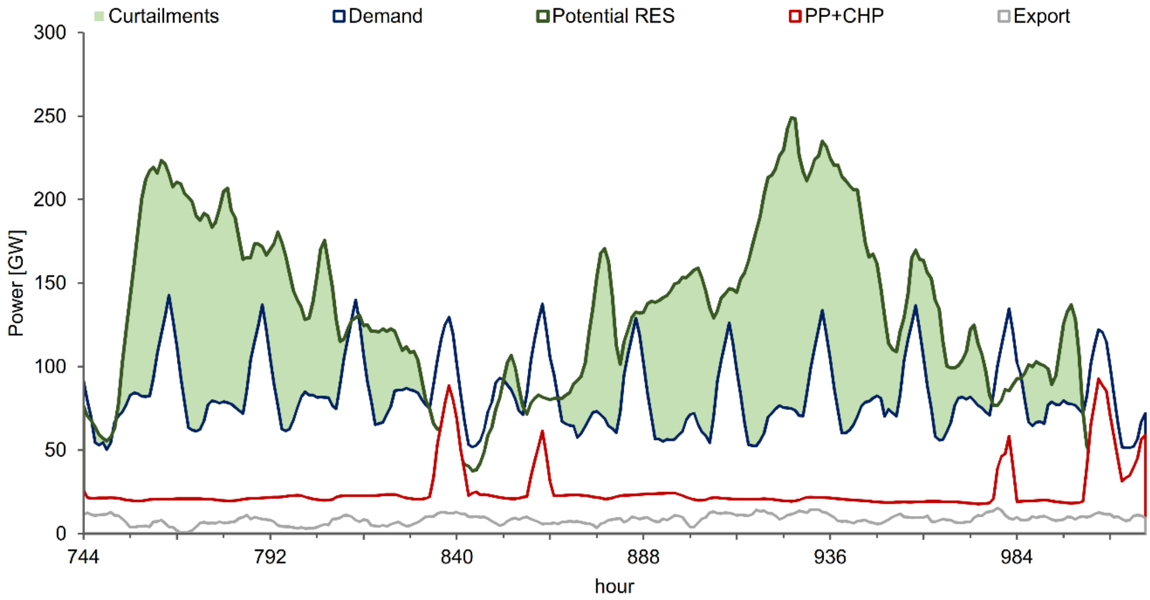

Figure 7. Power generation and demand at 100% EV and 6×iRES (Dump Charge) – Germany

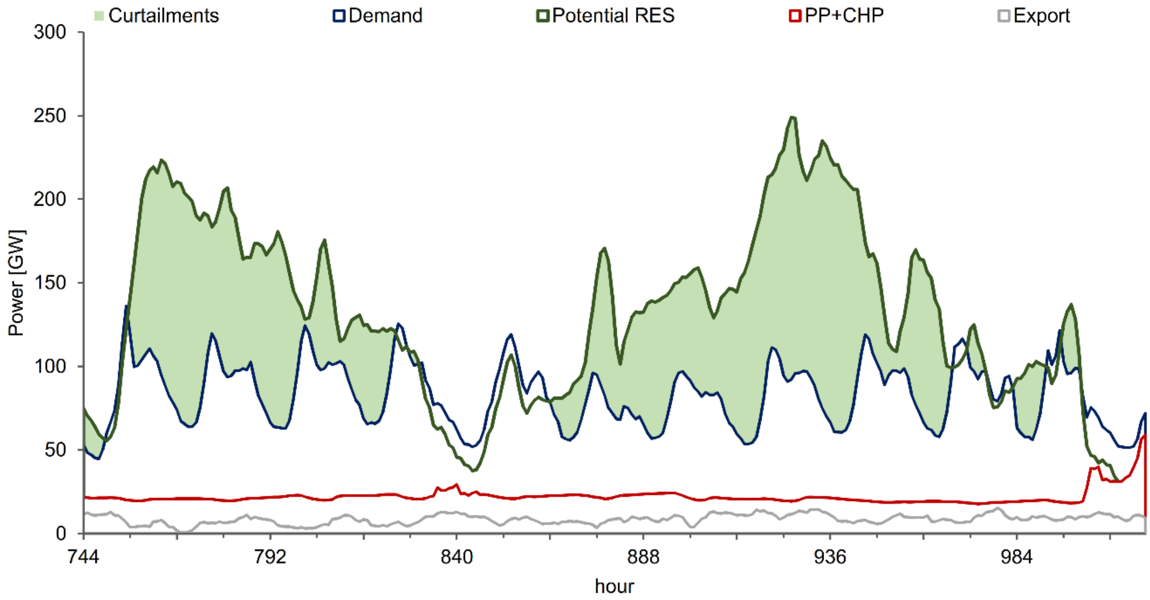

Figure 8. Power generation and demand at 100% EV and 6×iRES (Smart Charge) – Germany

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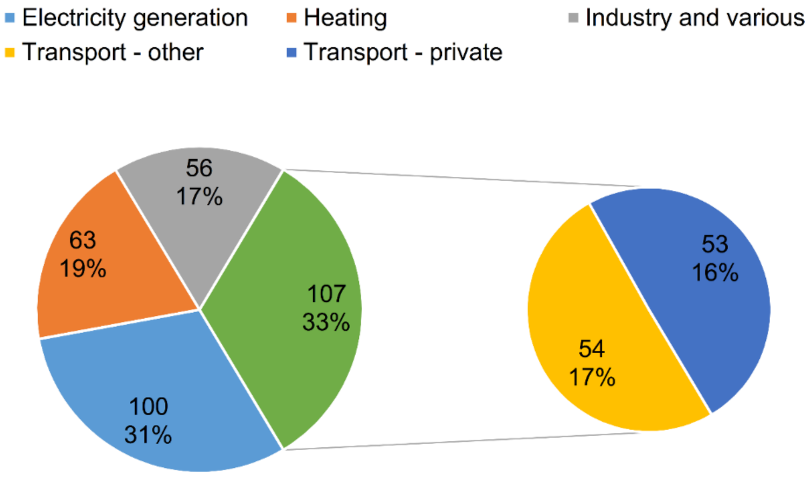

Figure 9. CO_2 emissions (Mt) divided by sector (base-case) - Italy

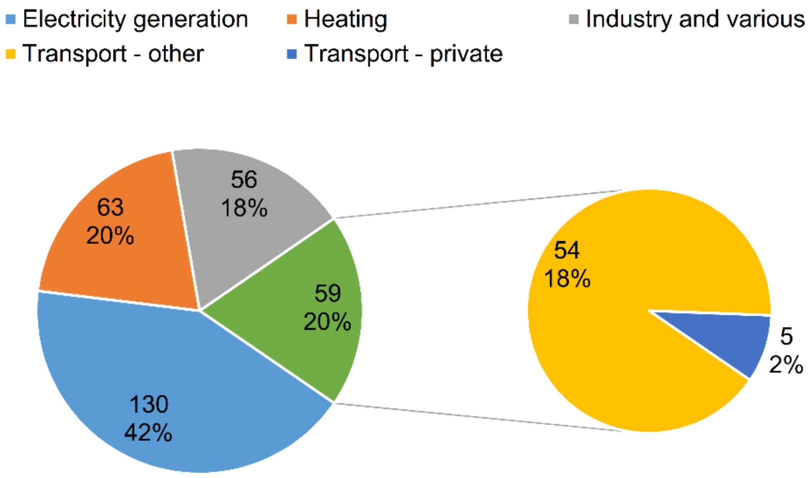

Figure 10. CO_2 emissions (Mt) divided by sector (iRES2016 and 100%EV) - Italy

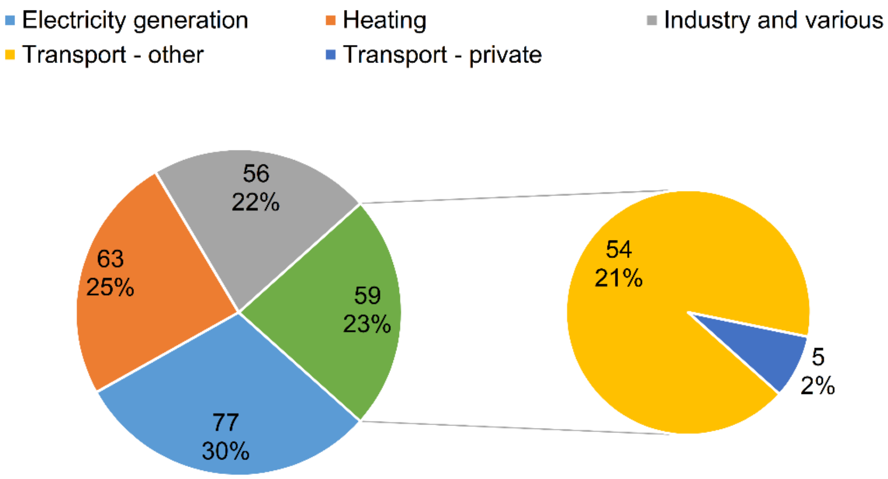

Figure 11. CO_2 emissions (Mt) divided by sector (6×iRES and 100%EV) - Italy

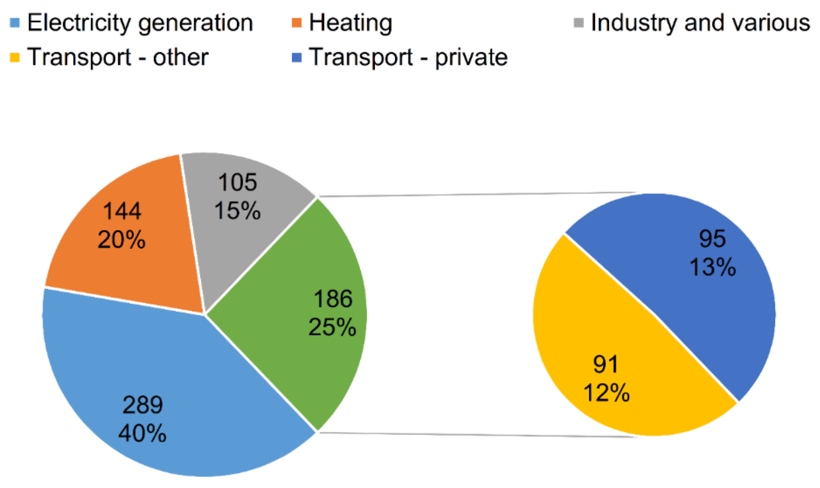

Figure 12. CO_2 emissions (Mt) divided by sector (base-case) - Germany

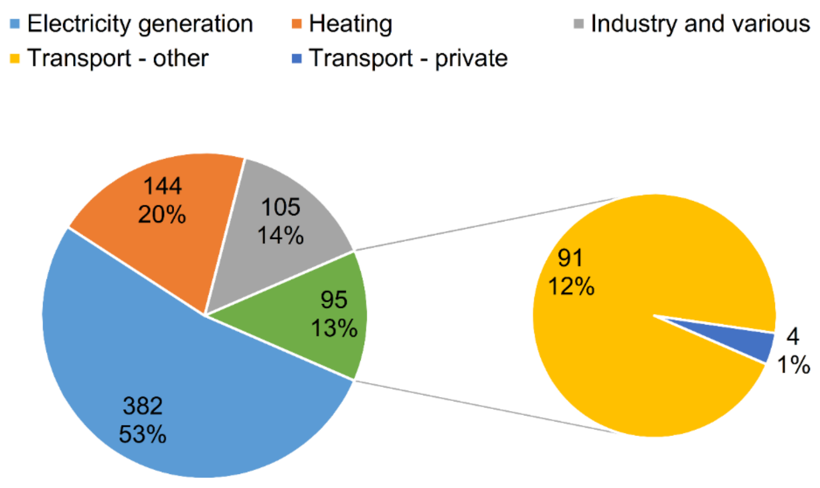

Figure 13. CO_2 emissions (Mt) divided by sector (iRES2016 and 100%EV) - Germany

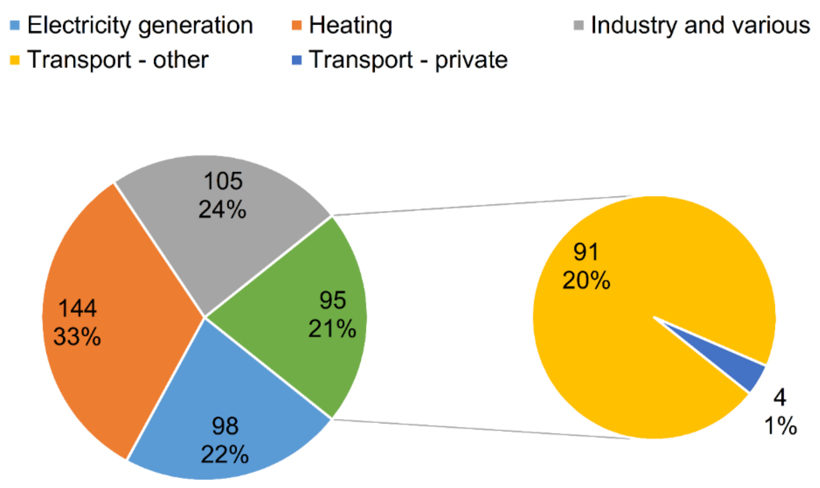

Figure 14. CO_2 emissions (Mt) divided by sector (6×iRES and 100%EV) – Germany

3.3 Coal and nuclear phase-out

The effect of coal phase-out included in the energy strategies of both countries [54,55] has been also assessed; results are shown in Table 20 when EV entirely replace the conventional vehicle fleet at the lowest and highest iRES installed capacity. The reduction of CO_2 emissions is remarkable when coal is phased out from the German energy system; however, it occurs at the price of a considerable electricity import as the projected installed capacity is not adequate to cater for an increase in electricity demand. Import has been assumed to be fulfilled by PP by virtually increasing their available capacity, and corresponding emissions taking into account German PP specific emissions.

In this regard, while almost negligible for the Italian case, import can be as high as 44 % of the total national production for the German case if RES capacity is kept at 2016 level. As a result, the energy mix of the country from whom electricity is imported highly affects the overall sustainability of both coal and nuclear phase-out strategies.

Table 20. CO_2 emissions and import – effect of coal and nuclear phase-out.

	Italy		*Germany*	
	iRES2016	*6×iRES*	*iRES2016*	*6×iRES*
CO_2 [%]				
No phase-out	-5.2%	-21.7%	0.5%	-39.2%
Coal phase-out	-8.3%	-23.5%	-26.5%	-45.1%
Coal and nuclear phase-out	-	-	-22.3%	-43.8%
Additional import [% of total production]				
No phase-out	0.0%	0.0%	1.2%	0.0%
Coal phase-out	0.4%	0.1%	26.0%	0.7%
Coal and nuclear phase-out	-	-	43.5%	1.9%

3.4 Cost analysis

A preliminary cost analysis was undertaken breaking down total annual costs in investments and variable costs according to EnergyPLAN subdivision.

Tables 21 and 22 report cost composition for iRES2016 and 6×iRES at 100%EV, compared with the base case scenario assuming the different EV purchasing costs. Set to 100 total costs for the reference case, variable and investment costs were normalized accordingly:

$$C_{i\,norm} = C_i / C_{tot\,2016} \times 100$$

Table 21. Total, investments and variable normalized costs at 2016 (base case) and iRES2016 and 6×iRES at 100%EV - Italy

	Base case 2016	100%EV iRES2016	100%EV 6×iRES
Variable costs	49.8	46.7	41.0
of which CO_2 emissions costs	8.3	7.9	6.5
Investments and O&M (EV price @2016)	50.2	86.1	89.2
Investments and O&M (EV price reduced)	50.2	63.3	71.3
Investments and O&M (EV=Conventional)	50.2	45.4	53.4
Total costs (EV price @2016)	100.0	132.8	130.1
Total costs (EV price reduced)	100.0	114.8	112.2
Total costs (EV=Conventional)	100.0	99.8	94.3

Table 22. Total, investments and variable normalized costs at 2016 (base case) and iRES2016 and 6×iRES at 100%EV - Germany

	Base case 2016	100%EV iRES2016	100%EV 6×iRES
Variable costs	40.7	37.2	28.1
of which CO_2 emissions costs	10.0	10.1	6.1
Investments and O&M (EV price @2016)	59.3	82.3	90.5
Investments and O&M (EV price reduced)	66.7	70.8	79.1
Investments and O&M (EV=Conventional)	66.7	59.3	67.6
Total costs (EV price @2016)	100.0	119.5	118.6
Total costs (EV price reduced)	100.0	108.0	107.1
Total costs (EV=Conventional)	100.0	96.5	95.6

For both countries, the increase investment costs due to both new RES installed capacity and EV is partly offset by a reduction in variable costs leading to an overall increase in total costs in the range 19–33 % with respect to the base case scenario when EV price remains unchanged from 2016 level. As EV purchasing cost decreases so do investments costs ultimately leading to a reduction in total costs up to around 5 % when the difference in EV and conventional cars' price is eventually evened out.

3.5 Policy recommendations

Electrification of transport is a priority in the European Community Research Program, due to several advantages related to EV, 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 remarkable values. Both countries are currently supporting EV by providing tax incentives to EV owners, and Germany is also supporting the diffusion of EV with an environmental bonus for 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 EV.

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 EV 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 EV 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 EV penetration could potentially lead to an unwanted rebound effect, i.e. an increase of CO_2 emissions in the transport sector. Attention must be paid also to the electricity profiles, to guarantee the optimal coupling between RES generation and EV charging logics and avoid the necessity of additional electricity import and/or conventional generation to offset the mismatch between RES potential production and increased electricity demand. A policy support to smart charging solutions could increase the benefits in terms of overall efficiency and CO_2 emissions reduction.

4 CONCLUSIONS

This study aims to assess the impact of EV on energy systems characterised by a different supply mix for the electricity generation sector in the framework of a progressive increase of RES capacity. Projections for possible future increase of renewable energy capacity have been implemented along with linearly growing shares of EV up to a total replacement of conventional vehicle fleet.

Results confirm that the electricity generation mix is a crucial parameter for the success of reducing CO_2 emissions throughout the diffusion of EV in any country. In particular, EV penetration in the energy system curbs CO_2 emissions for the German case provided that renewable installed capacity is increased up to a certain threshold (approximately twice the base case capacity) 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 22 % and 39 % for Italy and Germany respectively at the price of a significant amount of curtailments (respectively 15 % and 28 % of the total national 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 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 in the range 19–33 % with respect to the base case scenario under the conservative assumption that EV price stays the same with respect to 2016 level.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

DECLARATIONS OF INTEREST

None.

APPENDIX

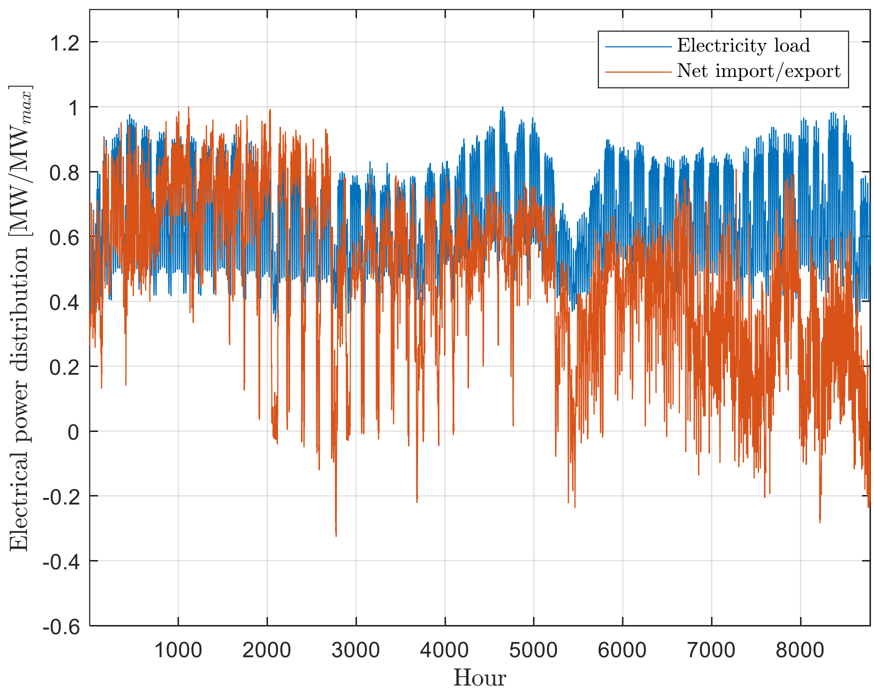

Figure A.1. Electricity demand and net import/export hourly distribution: Italy at 2016 (Source [38,56])

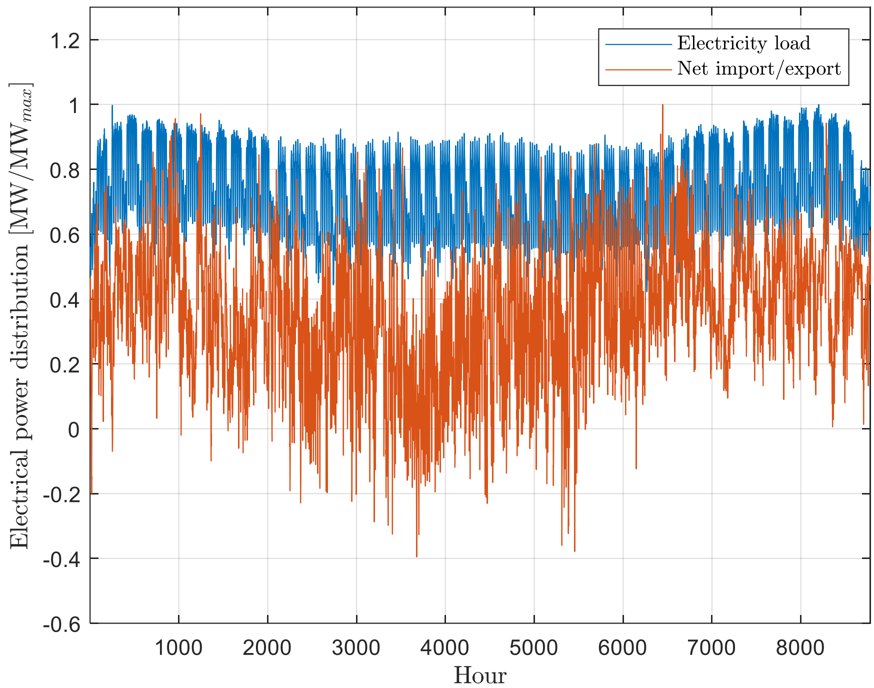

Figure A.2. Electricity demand and net import/export hourly distributions: Germany at 2016 (Source: [57,58])

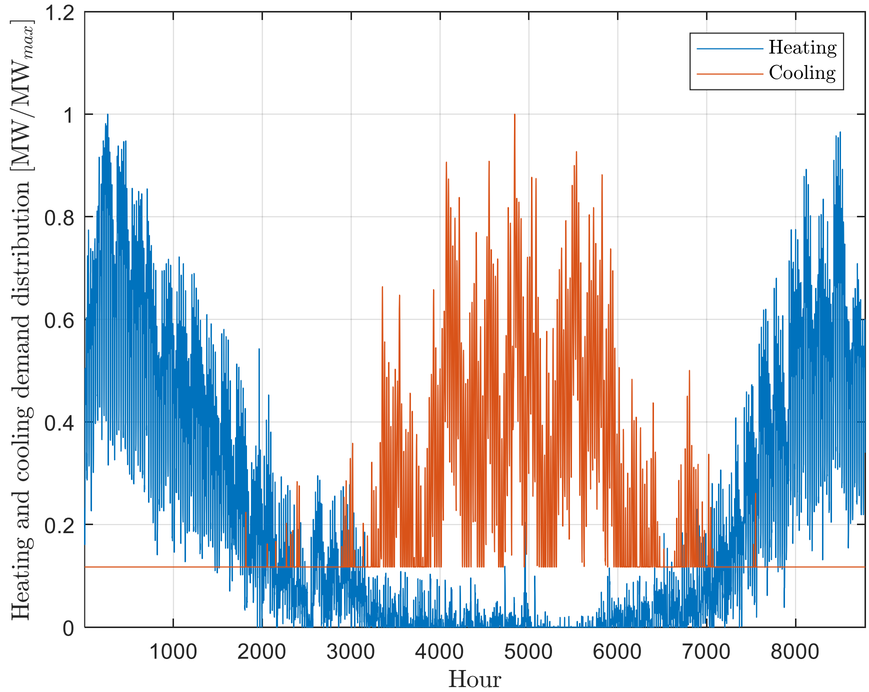

Figure 15. Heating and cooling demand hourly distributions: Italy at 2016 (Source: [59])

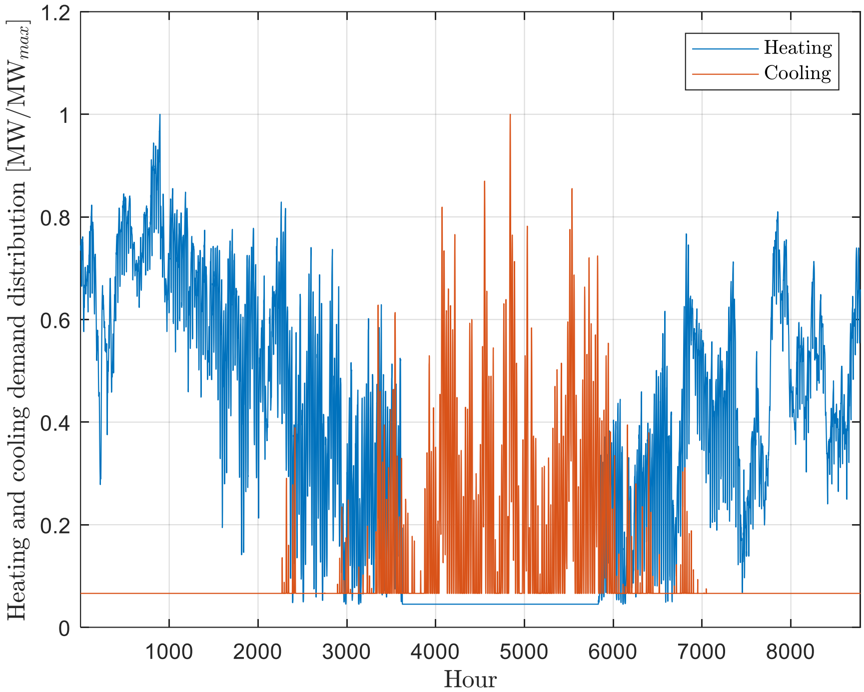

Figure A.4. Heating and cooling demand hourly distributions: Germany at 2016 (Source: [24])

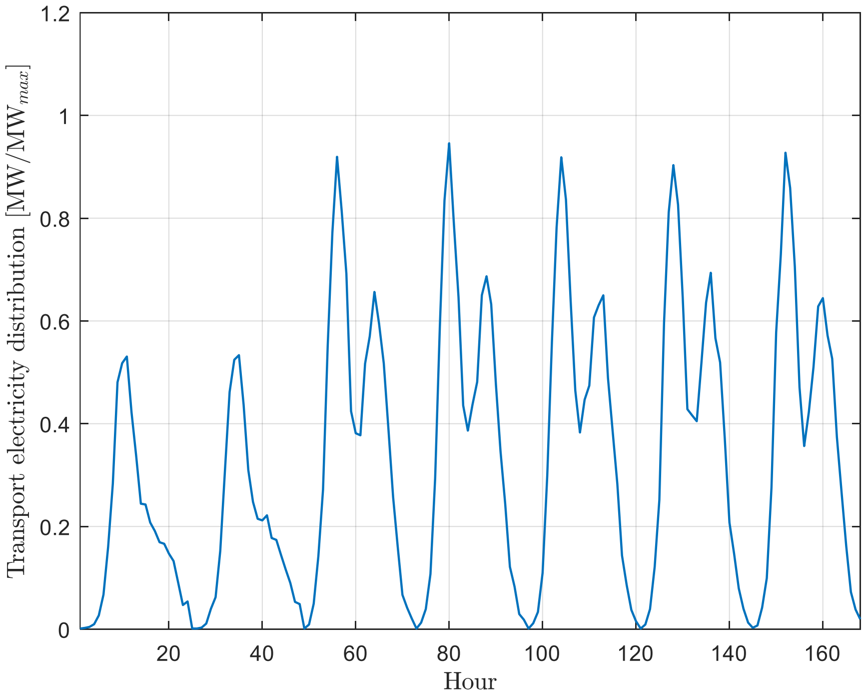

Figure A.5. Hourly distribution of electricity demand for transport, valid for both Germany and Italy.

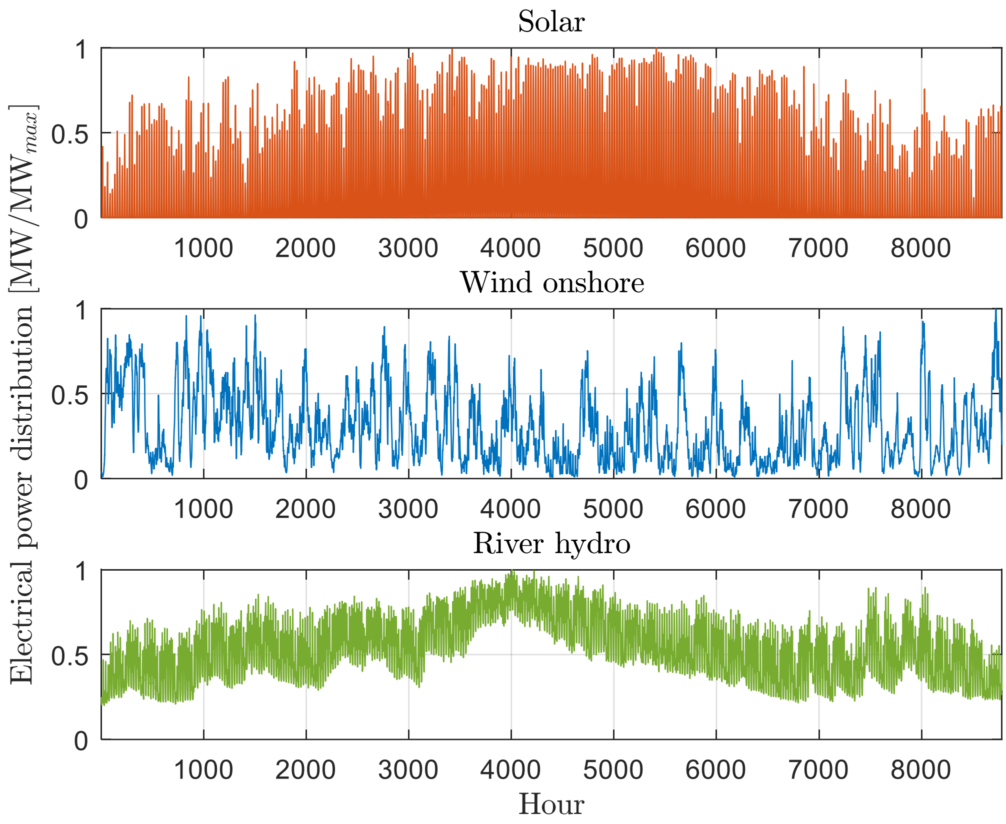

Figure A.6. Distribution of renewable electricity generation: Italy at 2016 (Source: [38])

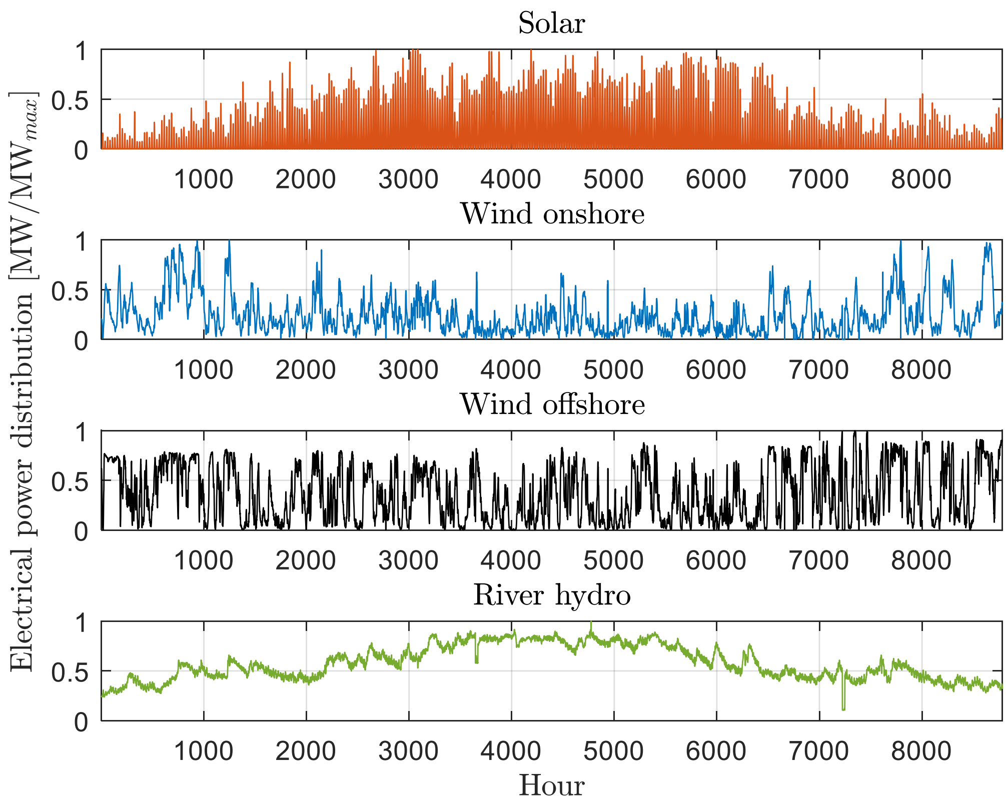

Figure A.7. Distribution of renewable electricity generation: Germany at 2016 (Source: [37])

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