Positive interactions between electric vehicles and renewable energy sources in CO_2-reduced energy scenarios: the Italian case

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Abstract

Electric vehicles are progressively emerging in the light-duty passenger market as a promising alternative to oil-dependent road transport in the attempt to reduce greenhouse gas and pollutant emissions. However, it is necessary to investigate how a significant penetration of electric vehicles in the private transport fleet would affect the strategic planning of large scale energy systems.

This study evaluates the integration of electric vehicles in the Italian energy scenario and their synergy with electricity generation from renewable energy sources, identifying the impact in terms of CO_2 emissions, costs and curtailments on a medium-long term perspective.

The national energy system has been accurately characterized using currently available data and its operation simulated with the EnergyPLAN software through an integrated analysis method. Possible energy scenarios have been defined with increasing shares of electric vehicles and intermittent renewable energy sources.

Results assess the impact of electric vehicles in cutting private transport carbon emissions and the positive interaction with increasing levels of renewables under different vehicle charging strategies and the capability of electric vehicles to behave as an electricity storage system.

Keywords: EV, EnergyPLAN, integrated energy systems analysis, CO_2 emissions reduction, RES, curtailments

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1. Introduction

The level of carbon dioxide concentration in the atmosphere has been rising at an average rate of 2 ppm/year over the past decade [1] and is unequivocally responsible for the recent warming of the Earth's climate [2].

With the world energy consumption expected to grow by 30 % to 2040 [3], global negotiations and energy policies have become essential for the achievement of a sustainable development. A new technology framework in the energy sector, being alone responsible for approximately 60 % of global anthropogenic emissions [4], is essential to reach the goals of Paris Agreement [5]. Indeed, electricity and heat generation accounted for the largest share of global emissions (42 %) in 2015, followed by transportation producing 24 % of world CO_2 emissions [4]. Both sectors rely heavily on carbon-intensive fuels: in 2015, 39 % of electricity production was from coal while 94 % of world road transport fuel needs were still catered for by oil products [6].

With this respect, renewable energy sources (RES), energy efficiency and electric transport are regarded as key solutions to mitigate and prevent CO_2 emissions [7–9].

Renewable power generation has grown by more than 30 % over the period 2010–2015 and it is expected to expand by another 30 % between 2015 and 2020; electric vehicles (EV) sales registered a 40 % increase in 2016 over the previous year [10]. Nevertheless, according to the International Energy Agency, a 50 % chance of meeting Paris Agreement's emissions target requires an additional 40 % increase of energy generation by renewable sources over the period 2020–2025 and implies that the 2016 growth rate of EV sales remains unchanged in future years [10]. In addition, assuming a 30 % share of EV in the EU-28 in 2030 and an 80 % share in 2050, CO_2 emissions from road transport can be reduced respectively by 42 % and 84 % compared to 2010 levels, taking also into account the additional power sector emissions due to the related additional electricity demand [11, 12]. On the other hand, a large-scale integration of both intermittent RES and EV would pose technical challenges in the electricity grid management [11, 13].

Technical conditions to integrate ever-larger shares of intermittent RES into the electricity system have been widely explored in the literature, both at a European [14–16] and at a local scale [17–20], stressing the necessity of balancing measures such as curtailments, storage, backup power generation and demand-side management to ensure a reliable and low-cost supply. On the other hand, the impact of electric vehicles on national European grids has

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been investigated in many research studies proving that their overall impact on electricity systems highly depends on how vehicles are charged, as well as on the local context (quality of grid infrastructure and generation mix) [11, 21]. Without a proper EV charge management, an increasing EV penetration would have a negative impact on the grid infrastructure [22, 23], even at EV penetration rates of around 10 % [24–26] or in relatively well-developed national infrastructure [27]. In this context, smart charging management becomes essential to reduce both the intensity of vehicle charging and the additional electricity generation by conventional power plants.

Moreover, renewable sources and electric vehicles can effectively support each other. Indeed, EV can provide storage capacity for the electricity produced by intermittent RES exceeding demand, which would be otherwise curtailed, as well as supply energy to the grid during periods of peak demand and lack of RES production through a Vehicle-to-Grid (V2G) approach [28, 29], while RES could represent a cost effective and carbon-free way for EV energy supply [28].

Joining the Paris Agreement, Italy developed a new National Energy Strategy which sets a target of 39 % greenhouse gas emissions reduction by 2030 compared to 1990, an annual 1.5 % increase in energy efficiency, 28 % and 55 % of RES respectively in total and electricity consumption [30].

Implications related to renewable energy penetration within the Italian energy system have been explored in various research studies in terms of wholesale electricity price [31, 32], CO_2 average abatement costs [33], annual costs and curtailments [34] and emissions reduction at various levels of penetration [35–38]. A significant share of intermittent RES in the Italian electrical system cannot be achieved unless adequate operating thermal backup systems and energy storage capacity are included [37, 38]. Furthermore, with reference to the Italian case, since renewable energy has been widely deployed between 2008–2015 with priority of dispatchment, those utilities that invested in new high-efficiency combined cycles have been affected by a significant decrease of capacity factor that, in turn, reduced the overall efficiency of fossil fuel power plants. As a result, a significant RES penetration requires long-term policies and actions to improve the balance between electricity demand and supply so as to reduce the high volatility of electricity prices and restore opportunities for further investments [39].

In this regard, energy system modelling is an essential tool for a proactive planning of renewable and low-carbon energy policies to qualitatively understand and quantify potential benefits and drawbacks and ultimately

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advise policy makers. Different models based on different approaches have been implemented to this aim [34, 40, 41].

At present, only one study assessing the Italian energy scenario has been carried out with regard to strategies for RES optimal penetration that may include EV, but only up to a relatively modest penetration [38]. This study intends to provide an updated investigation of possible future scenarios for the Italian energy system including ever-larger shares of both RES and EV. In the case of RES, technical upper limits are taken into account for each technology, while EV penetration is increased up to the entire replacement of the oil-powered private vehicle fleet, aiming to establish to what extent a positive interaction between RES and EV exists. The capability of EV to act as electricity storage system, as well as the impact of a smart vehicle charging strategy to reduce RES curtailments, is also investigated. Resulting costs have been assessed and disaggregated to analyze the shift from fuel to investment costs, taking into account both current EV costs and possible (likely) future cost reduction.

The Italian energy system scenario has been modelled with reference to electricity data published by the grid operator Terna [42] for the year 2015. Simulation has been carried out with the help of EnergyPLAN computer tool [43], which uses a holistic approach to achieve a smart energy system in which the different sectors act in a synergic way [44, 45] and is widely used in the literature [46] for modelling complex energy system scenarios whether at a local [47–50] or at a wider scale [45, 51].

First, this work identifies a base case scenario represented by the Italian energy system at 2015 and characterized in terms of its energy supply and demand, CO_2 emissions and primary energy consumption. Second, a parametric increase of intermittent RES capacity and EV penetration from 2015 level has been implemented and analyzed in terms of crucial environmental and socio-economic indicators and compared to the base case: CO_2 emissions, RES curtailments and annual costs. Instead of performing a forecasting analysis, based on current projections of a probable future, the purpose of this study is to provide the basis for a backcasting analysis that can direct policy makers to define a strategic planning that starts with identifying a desirable future, among the proposed scenarios, and then works backwards to implement actions and programs to connect that specified future to the present.

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2. Current National Energy System Definition

2.1. Demand

The Italian energy system has been modelled with the support of EnergyPLAN tool [43]. The software allows the characterization of a whole energy system with respect to a certain country and, according to the regulation strategy selected, optimizes its operation from a technical and/or economic perspective by defining a planning strategy that aims at minimizing the output from fossil fuel power plants so as to reduce both primary energy consumption and CO_2 emissions. Different scenarios can be created and compared with respect to energy and/or economical indicators by modifying input data related to the various energy sectors (e.g. installed capacity, fuel distribution, user demand, etc.). The Italian energy system has been characterized at 2015 in terms of energy demand and supply with reference to actual available data, as described in the following paragraphs. EnergyPLAN works on an hourly basis, therefore hourly power distributions (defined as the ratio between power demand at a particular hour and its yearly peak value) are required to describe electricity, heating, cooling and transport demands.

According to Terna, the grid operator for electricity transmission in Italy, the annual electricity gross demand (net of pumped storage plants consumption) was 327.94 TWh/year with a peak load of 60.49 GW in July [42]. The amount of imported electricity was 46.38 TWh/year [42]; electricity loads are displayed in Table 1 divided by end uses, as required by EnergyPLAN. The electricity hourly distribution has been derived from ENTSO-E (European Network of Transmission System Operators for Electricity) consumption data for 2015 [52].

Heating demand has been modelled with reference to GSE (Gestore dei Servizi Energetici) values, the agency responsible for managing energy services in Italy. Available data from 2013 [53] have been used to derive, for each type of fuel, a disaggregation of the whole energy consumption for private households and services sector so as to isolate, among the different end uses, the percentage of energy required for individual heating only. The same procedure has been applied to 2015 residential and tertiary sector overall consumption data as provided by IEA [54]. The usage of renewable energies for individual heating purposes has been evaluated according to GSE reports [55, 56]. Electricity demand for heat pumps has been set to 18.44 TWh/year [55]. The amount of electricity demand related to other electric heating devices has been derived by subtraction from the total electricity demand for

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Table 1: Italy electricity demand (TWh/year) at 2015

Electric cooling	13.08
Heat pumps	18.44
Other electric heating	10.56
Transport	10.85
Net import	46.38
Other loads	228.63
Overall gross demand	**327.94**

Table 2: Fuel consumption and electricity demand* (TWh/year) for individual heating at 2015

Oil	30.54
Natural gas	260.97
Biomass	72.19
Heat pumps*	18.44
Other electric heating*	10.56

space heating, equal to 29 TWh/year [57].

Energy demand for space cooling has been set to 34 TWh/year [57], that corresponds to 13.08 TWh/year of electricity consumption considering an average COP of 2.6 [38].

Heating and cooling power hourly distributions refer to a 2015 case study for the Italian energy system, developed within the EU-funded Heat Roadmap Europe project [58].

As for industry and other sectors (e.g. agriculture, fishing, non-heating uses for both residential and services sector, etc.), the overall energy consumption divided by fuel, as provided by IEA for 2015 [54], is reported in Table 3 along with primary energy losses, expressed as percentage of the total fuel consumed.

Transport sector energy consumption has been defined with reference to available data from ISPRA (Istituto Superiore per la Protezione e Ricerca Ambientale) and GSE [59, 60], as summarized in Table 4. Transport hourly distribution has also been derived from the above-mentioned Heat Roadmap

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Table 3: Primary energy consumption (TWh/year) at 2015 — industry and various sectors

	Industry	**Various**	**Losses**
Coal	14.81	0	0.0%
Oil	70.95	30.01	0.5%
Natural gas	109.20	13.04	0.5%
Biomass	7.66	0	0.0%

Table 4: Primary energy consumption (TWh/year) at 2015 — transport sector

	Fossil	**Biofuel**	**% of total**
Jet Fuel	7.46	0	2.01%
Diesel	256.86	13.28	64.51%
Petrol	95.26	0.29	22.82%
Natural gas	12.64	0	3.02%
LPG	21.13	0	5.05%
Electricity	10.85	0	2.59%
of which EV	*0.01*	*0*	*0%*

Europe project [58].

While diesel accounts for 64.51 % and petrol for 22.82 %, electric transport accounts only for 2.59 % of the total consumption. The amount of electricity consumed by EV for private transportation has been derived from their level of penetration at 2015. Given the overall EV sales over the period 2010–2016, the average battery capacity has been evaluated along with the driving range with reference to NEDC driving cycle for both battery (BEV) [61] and plug-in electric vehicles (PHEV) [62]. BEV and PHEV sales as well as technical specifications are displayed in Table 5 and 6 respectively; 2015 data have been used for the reference scenario while data up to 2016 has been considered to generate future projections.

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Table 5: BEV sales and technical specifications

Vehicle model	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Tot 2015**	**Tot 2016**	**Capacity [kWh]**	**Range [km]**
Fiat Panda	31	9	0	0	0	0	0	40	40	19.2	120
Fiat 500e	22	7	4	0	0	0	0	33	33	24	160
Renault Fluence	0	0	38	38	30	0	0	106	106	22	185
Nissan Leaf	0	5	146	323	336	390	473	1200	1673	24	199
Renault Zoe	0	0	0	204	156	328	210	688	898	22	210
Mercedes B 250e	0	0	0	0	0	80	90	80	170	28	200
Th!nk city	0	0	0	3	0	0	0	3	3	24	160
KIA soul	0	0	0	0	0	0	15	0	15	27	210
Bmw i3	0	0	0	34	124	111	91	269	360	22	190
Tesla Roadster	4	0	7	0	0	0	0	11	11	53	393
Tesla model X	0	0	0	0	0	0	23	0	23	90	414
Tesla Model S	0	0	0	19	55	134	218	208	426	60	390
Citroen C-Zero	0	87	146	55	15	164	145	467	612	14.5	150
Mitsubishi iMiev	3	36	14	0	0	0	0	53	53	16	160
Smart fortwo e-drive	33	80	37	155	252	115	0	672	672	16.5	135
Vw e-Up!	0	0	0	0	52	54	56	106	162	18	160
Peugeot iOn	0	59	116	17	25	0	26	217	243	14.5	150
Renault Kangoo	0	0	78	25	23	23	0	149	149	33	200
Fiat Doblò	12	6	0	0	0	0	0	18	18	43	150
Fiat (QUBO) Fiorino	10	4	0	0	0	0	0	14	14	23	200
Piaggio Porter	1	0	0	0	0	0	0	1	1	17	80
Total BEV Sales	**116**	**293**	**586**	**873**	**1068**	**1399**	**1347**	**4335**	**5682**		

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Table 6: PHEV sales and technical specifications

Vehicle model	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Tot 2015**	**Tot 2016**	**Capacity [kWh]**	**Range [km]**
Opel Ampera	0	3	62	19	0	0	0	84	84	16	56
Toyota Prius	0	0	39	8	87	0	0	134	134	4.4	23
Chevrolet Volt	0	0	38	38	0	0	0	76	76	16	56
Fisker Karma	0	0	6	0	0	0	0	6	6	20.1	51
Volvo V60 PHEV	0	0	0	135	59	0	0	194	194	11.2	43.5
Porsche Panamera	0	0	0	23	0	0	0	23	23	9.4	32
Mitsubishi outlander	0	0	0	0	85	133	0	218	218	9.8	52.8
Bmw i8	0	0	0	0	34	99	0	133	133	7.1	37
Vw Golf GTE	0	0	0	0	0	180	158	180	338	8.7	50
Audi A3 e-tron	0	0	0	0	0	86	0	86	86	8.8	50
Bmw 225xe	0	0	0	0	0	0	308	0	308	7.6	41
Bmw330e	0	0	0	0	0	0	107	0	107	7.6	25
Volvo XC90 PHEV	0	0	0	0	0	0	90	0	90	9	40
Others	0	0	0	9	76	242	654	327	981	4.4	23
Tot PHEV Sales	**0**	**3**	**145**	**232**	**341**	**740**	**1317**	**1461**	**2778**		

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Table 7: EV annual electricity consumption at 2015

Type	**Category**	**N.**	**Share**	**Avg capacity [kWh]**	**Avg range [km]**	**Annual cons. [GWh]**
BEV	Small	1515	35%	15.68	144.40	2.44
	Medium	2419	56%	23.17	198.66	4.18
	Large	219	5%	59.65	390.15	0.50
	Van	182	4%	33.13	194.40	0.46
Tot. BEV		**4335**				**7.57**
PHEV		**1461**		**8.56**	**40.23**	**4.60**
Tot. EV		**5796**				**12.17**

Electric vehicles have been divided in three main categories according to their battery capacity: small vehicles (capacity below 18 kWh), medium (18–28 kWh) and large (> 53 kWh). PHEV have been all considered medium vehicles. This type of subdivision will be needed for modelling future scenarios to allow a correct replacement of EV into the equivalent conventional vehicle category. The required energy for the year 2015 has been evaluated considering a weighted average for battery capacity and driving range, a commuting distance of 36.5 km/day (derived as an average value between diesel and petrol cars commuting distance as assessed by ISFORT [63]) and a charging efficiency of 90 % [26]. Values are displayed in Table 7: the resulting total annual consumption of 12.17 GWh/year shows that it represents a negligible part of the total amount of electricity required by the transport sector (10.85 TWh/year).

2.2. Supply

Thermal and electric energy supply has been modelled with reference to Terna technical report for 2015 [42]. The annual heat and electricity production has been distributed among the different energy systems according to EnergyPLAN subdivision. In particular, the software requires heat production to be partitioned into three main groups: individual boilers, district heating boilers (DHP), cogeneration power plants (CHP) and condensing power plants (PP). The latter category also includes large CHP extraction plants that can also operate on an electricity-only basis. In the model, CHP plants are equipped with auxiliary boilers able to provide for the full rated

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thermal power.

Table 8 lists thermal power plants main features derived from IEA and Terna annual reports [42, 54].

Table 8: Operating parameters and energy consumption for the conventional supply system at 2015

Operating parameters	**CHP**	**PP**
Installed capacity [GW]	26.569	66.858
Electric efficiency [%]	39.9	41.8
Thermal efficiency [%]	24.7	
Consumption [TWh/year]		
Coal	7.76	114.47
Oil	43.30	18.48
Natural gas	164.78	143.84
Biomass	38.4	66.6

Also, EnergyPLAN allows CHP to operate according to two different operating modes:

- balancing heat demands solely (H);
- balancing both heat and electricity demands (HE), so as to limit the excess of electricity production when possible.

As for intermittent RES, power distributions and capacities have been derived from hourly generation values available on Terna website [64] for the year 2015 that already include 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 9 shows installed capacity and actual maximum power. With regard to dammed hydro plants, a storage capacity of 75.51 GWh has been considered [58]. Dammed hydro power and geothermal plants have been modelled assigning a capacity of 18 732 and 824 MW respectively.

Annual electricity production divided by sources is showed in Table 10; at 2015 RES (excluding bioenergies) cover 32 % of electricity production.

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Table 9: RES installed capacity and actual maximum power generation (MW) in 2015

	Capacity	Actual maximum
Hydro	18 732	18 732
Geothermal	824	824
Onshore Wind	9126	6285
Photovoltaic	18 910	10 940
River hydro	5332	4875

Table 10: Domestic electricity production (TWh/year) divided by source at 2015

Source		**% of total**
Fossil fuel	172.66	61%
Hydro	46.97	17%
Geothermal	6.19	2%
Wind	14.84	5%
Solar	22.94	8%
Bioenergies	19.40	7%
Total	**281.57**	

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2.3. Model validation

The reference scenario for 2015 has been validated taking into account RES and PP production (which includes production from biomass), CO_2 emissions, TPES (Total Primary Energy Supply) as provided by IEA [54]. In particular, given that EnergyPLAN does not take into account the "non-energy use" of TPES, this amount has been subtracted from IEA TPES value for 2015 to allow a correct comparison. Such energy indicators are summarized and compared in Table 11. The difference between model results and actual values is acceptable (below 1.8 %).

For a further model validation, a duration curve has been derived from the output of the model and compared to the duration curve provided by Terna for 2015 [42] (see Fig. 8).

A technical minimum of 15.21 GW has been set for thermal power generation according to Terna technical report [42] and 25 % of total electricity production has been taken into account for grid stabilization requirements. In the base case scenario, all CHP units are operated following the heat demand.

Table 11: Model validation with reference to 2015 data

		Model	**Actual**		**Difference**
RES	[TWh/year]	90.47	89.51	[42]	1.1%
PP	[TWh/year]	195.55	192.06	[42]	1.8%
TPES	[TWh/year]	1682.23	1697.65	[54]	0.9%
CO_2	[Mt/year]	330.17	330.75	[54]	0.2%

3. Future scenarios definition

Different medium-long term scenarios have been defined for the Italian energy system assuming that the electricity demand (excluding demand for future EV) remains unchanged from 2015 level, i.e. 327.94 TWh/year, with a progressively higher penetration of both EV in the transport sector and RES capacity as concerns electricity production. We also assume the same transport demand (as in km/year, driving habits and number of total private

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vehicles) with respect to 2015. However, as EV progressively replace light-duty conventional cars, the overall energy demand for transport changes and energy consumption is shifted from petrol and diesel to electricity.

Installed power from the other plants stays the same along with individual heating and cooling demand. Different combination of EV and RES share have been simulated to assess, under different charging and technical simulation strategies, the impact on RES curtailments, CO_2 emissions and costs.

The model identifies Critical Excess Electricity Production (CEEP) as the production that exceeds the transmission line capacity (net of the electricity exported). Such parameter, which is unavoidable with RES significant penetration, is not allowed in real life, as this will cause a breakdown in the electricity supply in the absence of electricity storage systems, and it inevitably translates into energy curtailments. Scenarios have been modelled deploying proper CEEP regulation strategies when energy production exceeds demand. Scenarios have been simulated under the conservative assumption that production exceeding the electricity demand cannot be exported (whereas in 2015 electricity export was 4.65 TWh/year).

In these scenarios, both operating modes have been simulated for CHP units (i.e. to solely fulfill the heat demand (H), or according to both electricity and heat demand (HE) as described in section 2.2). However, due to the similarity of the results obtained, only HE-mode outcomes will be reported.

3.1. Renewable energy sources capacity

In the simulated scenarios, intermittent RES maximum power generation has been parametrically increased up to ten times the base case scenario values. Energy production from hydroelectric and geothermal power plants remains unchanged, having already almost reached their saturation level at 2015. Production linearly grows for photovoltaic (PV) and onshore wind power plants; concentrating solar power (CSP) and offshore wind plants are also taken into account in future scenarios. Wind technologies are increased up to their potential limits according to ANEV [65]. Table 12 displays the maximum capacity from intermittent RES as compared to 2015.

3.2. Electric vehicle penetration

In order to quantify the effect of EV penetration, energy consumption for transportation (Table 4) has been further disaggregated to quantify the impact of private transport within the whole sector. Petrol and diesel cars

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Table 12: Maximum power from intermittent RES for different scenarios (GW)

Source	**Max power at 2015 [GW]**	**Max potential capacity [GW]**
Onshore wind	6.285	20.000
Offshore wind	0	10.000
PV	10.940	99.575
CSP	0	42.675
Total	**17.225**	**172.250**

Table 13: Petrol and diesel cars annual fuel consumption at 2015

Category	**Share**	**Number (Mln)**	**Fuel economy (l/100 km)**	**Consumption (Mtep/year)**
Petrol				
Small ($< 1400\,\mathrm{cm}^3$)	45%	7.30	5.1	2.66
Medium (1400–2000 cm^3)	53%	8.57	6.0	4.07
Large ($> 2000\,\mathrm{cm}^3$)	2%	0.30	7.7	0.18
Total				**7.15**
Diesel				
Small ($< 1400\,\mathrm{cm}^3$)	1%	0.15	4.2	0.09
Medium (1400–2000 cm^3)	85%	12.33	4.9	8.93
Large ($> 2000\,\mathrm{cm}^3$)	14%	2.01	6.4	1.90
Total				**10.92**

have been divided into different categories according to their displacement capacity [66] and annual fuel consumption has been derived assigning an average fuel economy value, based on a mixed cycle [67] as shown in Table 13. The number of conventional vehicles has been derived from Unione Petrolifera technical report [68], which states that at 2015 petrol and diesel vehicles are equal to 16.27 and 14.48 millions. The annual travelled distance has been set to 10 120 km/year for petrol cars and to 16 505 km/year for diesel cars, according to ISFORT [63].

Private transport accounts for 83.15 and 126.95 TWh primary energy consumption respectively for petrol and diesel light-duty vehicles. Such figures, subtracted from total consumption values for transport (see table 4), give 12.11 and 129.91 TWh for other uses of petrol and diesel (e.g. heavy transport).

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Table 14: Petrol and diesel cars annual fuel consumption at 50 % EV replacement

Category	**Share**	**Number (Mln)**	**Fuel Economy (l/100km)**	**Consumption (TWh/year)**
Petrol				
Small ($< 1400\,\mathrm{cm}^3$)	45%	3.65	5.1	17.02
Medium (1400–2000 cm^3)	53%	4.29	6.0	23.51
Large ($> 2000\,\mathrm{cm}^3$)	2%	0.15	7.7	1.04
			Total	**41.57**
Diesel				
Small ($< 1400\,\mathrm{cm}^3$)	1%	0.07	4.2	0.53
Medium (1400–2000 cm^3)	85%	6.17	4.9	51.90
Large ($> 2000\,\mathrm{cm}^3$)	14%	1.00	6.4	11.05
			Total	**63.48**

Table 15: EV annual electricity consumption at 50 % EV replacement

Category	**Share**	**Number (Mln)**	**Battery capacity (kWh)**	**Electricity consumption (TWh/year)**	**Battery storage (GWh)**
Small	24%	3.72	15.64	8.61	58.24
Medium	68%	10.45	12.37	19.13	129.34
Large	8%	1.15	61.33	10.46	70.73
			Total	**38.21**	**258.31**

In this study, it has been assumed that vehicles in each category of conventional cars (both petrol and diesel) decrease linearly at the same rate while being progressively replaced by EV from the corresponding category until their complete replacement. Tables 14 and 15 display energy consumption for private transport when EV replace 50 % of the fleet.

For each EV penetration scenarios, two different options have been analyzed according to the implemented battery charging strategy:

- Dump charge: EV charge without regulation, depending on the demands or habits of the consumers;
- 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.

PHEV are considered able to work in full-electric mode when performing

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relatively short daily commutes. However, fuel consumption has been also included in the analysis when they work in mixed-mode, which is likely to occur when PHEV are used to travel over longer distances (e.g. holidays or non-working days). More specifically, an average consumption of 1.92 l/100 km has been applied to a travelled distance of 1001 km, which is the average distance travelled by Italians on holidays [69]. Also, electric vans have been incorporated into the medium vehicle category for replacement.

EnergyPLAN allows the implementation of V2G technology that models the possibility to reverse the electric power flow from the vehicle to the grid, controlled in part by electric grid needs (e.g. to provide peaking power).

A preliminary analysis has been carried out to assess the impact of an increase in grid recharging power and of the V2G option. A variation in grid-to-vehicle recharging power from 4 to 19.2 kW (fast-recharge) [70] does not affect CO_2 emissions but only grid-related investments. Same goes for the implementation of V2G technology, in line with recent research results [71]. Therefore, a recharging power of 4 kW has been conservatively considered and the V2G option has been disregarded in this study.

3.3. Cost structure

For the economic analysis, costs data have been derived from the Italian baseline model, developed within the EU-funded Heat Roadmap Europe project [58], which provides values for all cost categories required by the EnergyPLAN tool (including an interest rate of 3 %).

Road vehicles costs have been inputted as a weighted average of actual manufacturers' price for each category as displayed in Table 16. EV costs refer only to purchase costs and not to total life cycle; for both conventional and electric cars the investment period and the interest rate have been set at 5 years, in line with common discounting periods for private vehicle purchases. We also extended the period to 10 years so as to evaluate the sensitivity of the model to this parameter.

Table 16: Conventional and electric vehicles prices (€ × 10^3)

Category	**Petrol**	**Diesel**	**Electric**
Small	12.02	16.20	29.81
Medium	20.15	20.35	27.29
Large	58.15	58.80	88.33

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4. Results and discussion

Scenarios have been compared with respect to three different indicators: annual CO_2 emissions, RES energy curtailments and costs. Results are shown in Figs. 1–3 for CHP plants operating in HE mode and vehicles charged through a smart strategy (see section 3.2). Intermittent RES total capacity (onshore and offshore wind, PV and CSP) grows tenfold from its 2015 level, that is from 17.225 GW to 172.25 GW. As for CO_2 emissions and RES electricity production, the dotted line in Figs. 1 and 3 represents the threshold values required by the National Energy Strategy for the year 2030.

For a given RES capacity, as EV penetration grows CO_2 emissions decrease, at a higher rate for scenarios with increased shares of RES (Fig. 1). This, however, comes at the price of significant energy curtailments when RES capacity grows significantly in the absence of appropriate storage systems (Fig. 2). At a given EV share, curtailments rise almost linearly with RES capacity, while CO_2 emissions exhibit an exponentially decreasing trend, with a lower rate of reduction as RES capacity increases. In other words, CO_2 emission reduction potential rapidly reaches its saturation level in the absence of suitable large-scale storage systems. Lacking such storage capacity, the difference between potential RES generation and energy demand unavoidably results in curtailments rather than fossil fuel displacement, and curb the achievement of 2030 objectives (i.e. 233.58 Mt).

As fig. 3 shows, RES share of total domestic electricity production clearly grows, for a given EV share, however at a remarkably decreasing rate because of curtailments, as discussed above. As EV penetration grows, instead, RES share of electricity production decreases for relatively low values of RES installed capacity: this happens because all the electric energy produced from RES already covers a fraction of the overall demand, therefore there is no excess (curtailments) to provide for EV charge. As soon as RES curtailments arise in the energy scenario, an increase in EV allows RES share of electricity production also to increase and to reach 55 % of electricity production as pursued by the National Energy Strategy for 2030.

Table 17 lists results obtained for a RES capacity equivalent to ten times as compared to the base case scenario for different shares of EV penetration under dump and smart charging strategies. Variations refer to the 2015 base case scenario.

Results differ depending on the charging strategy adopted; when RES capacity is set to the maximum value, CO_2 emissions can be reduced by

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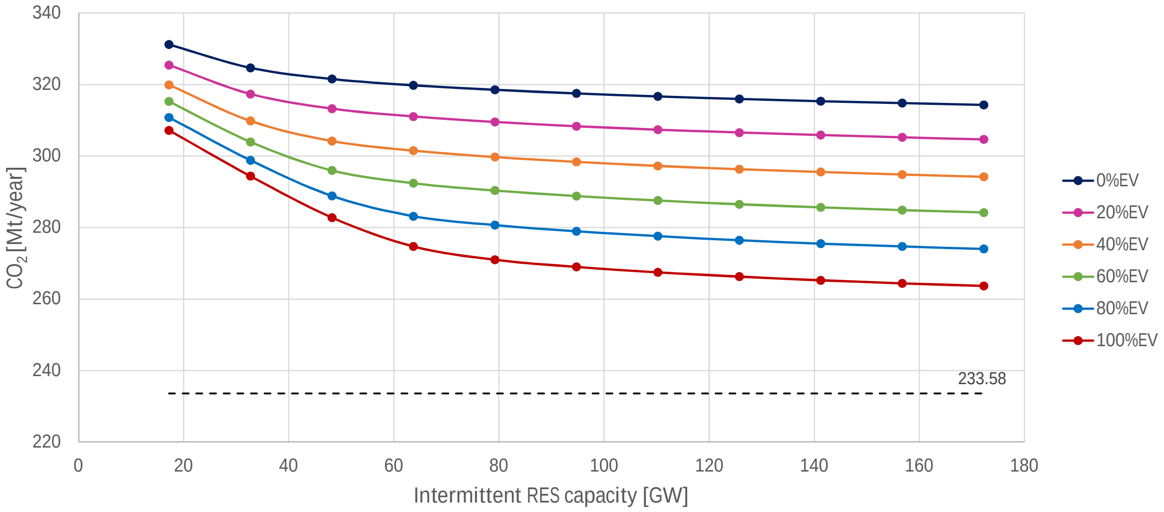

Figure 1: CO_2 emissions for increasing intermittent RES capacity and EV penetration

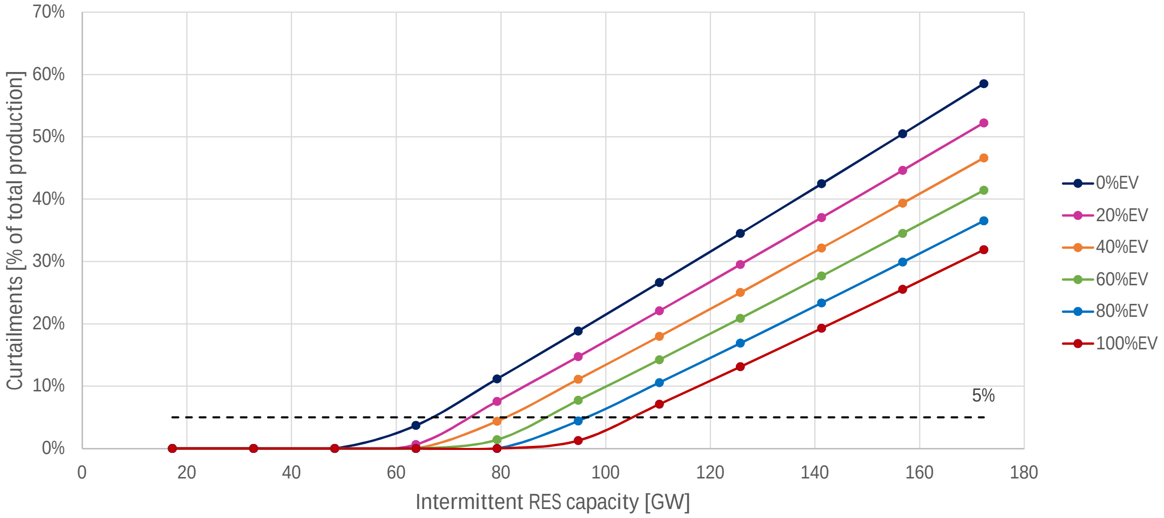

Figure 2: Energy curtailment for increasing intermittent RES capacity and EV penetration

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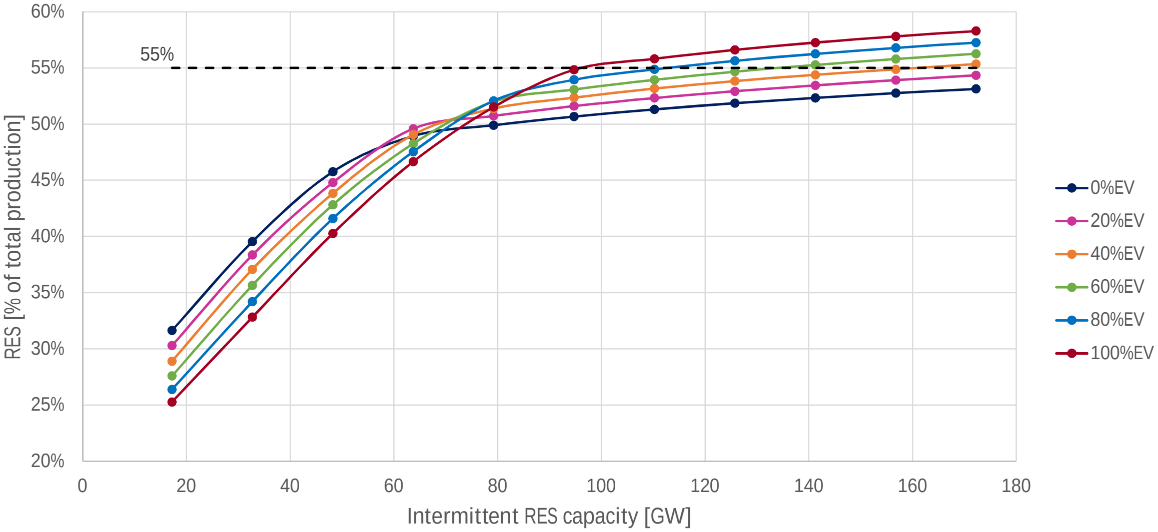

Figure 3: RES share of total domestic electricity production for increasing intermittent RES capacity and EV penetration

Table 17: Change in CO_2 emissions with reference to 2015 base case scenario, RES share and curtailment percentage of total domestic electricity production at maximum RES capacity

EV penetration	0%	20%	40%	60%	80%	100%
Change in CO_2 emissions						
Dump charge	-5.10%	-7.20%	-9.18%	-10.76%	-12.16%	-13.46%
Smart charge	-5.10%	-8.01%	-11.17%	-14.19%	-17.27%	-20.39%
RES share						
Dump charge	57.42%	52.63%	51.52%	50.15%	48.70%	47.23%
Smart charge	57.42%	54.34%	55.34%	56.26%	57.26%	58.28%
Curtailments percentage of total electricity production						
Dump charge	53.13%	53.05%	49.70%	46.96%	44.61%	42.56%
Smart charge	53.13%	51.30%	45.79%	40.74%	35.93%	31.38%

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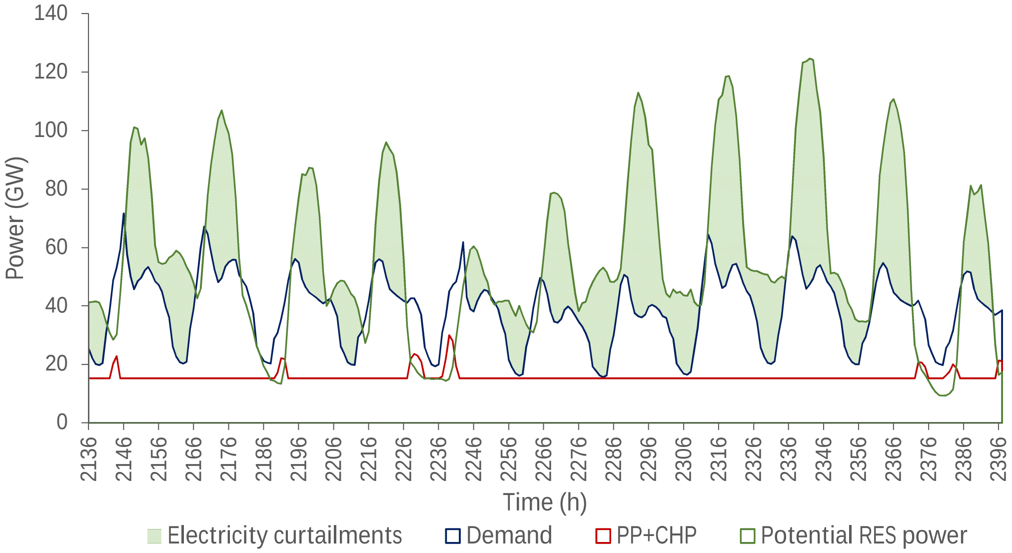

Figure 4: Power generation and demand at 100% EV and maximum RES capacity

20.39 % with smart charge, and only by 13.46 % with dump charge. Charging strategy also positively affects curtailments that are reduced from 42.56 % to 31.38 % of national electricity production respectively for dump and smart charge strategy.

Despite a tenfold increase in intermittent RES capacity, the overall electricity produced from RES not even doubles (58 % vs. 32 %, Fig. 3) and curtailments can be as high as 43 % of the overall domestic energy production. This is due to the already mentioned lack of suitable large-scale storage systems in the model. The amount of energy curtailed can be clearly appreciated in Fig. 4 for approximately ten days at the beginning of April.

Costs have been disaggregated in investment and fuel costs; results for the highest RES capacity (172.25 GW) are shown in Fig. 5 for increasing EV shares.

Total annual costs variation, with respect to base case scenario, almost linearly increase with EV penetration. In particular, when EV share grows from 0 to 100 % of the total fleet for private transportation, investment costs increase up to 83 %, while fuel costs decrease down to 21 % as compared to 2015, thus partially mitigating total costs rise.

Table 18 shows, in absolute values, both annual costs and and their varia-

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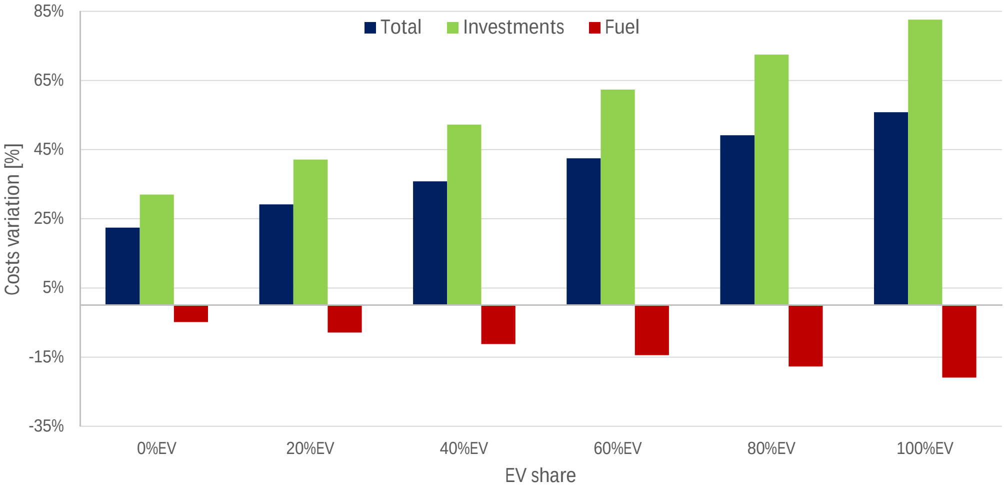

Figure 5: Costs variation with respect to base case scenario for increasing EV shares with maximum RES capacity

tion against CO_2 emission reduction (ΔCosts/ΔCO_2) at different EV shares when RES capacity is set to its maximum level.

When EV replace entirely private transport vehicles and RES capacity is set to its maximum level, the cost per tonne of CO_2 avoided is 1671 €/t adopting a smart charge strategy. The main driver for this extremely high unitary cost is the price difference between electric and conventional vehicles, which is still large even under the above-mentioned assumption on price reduction (see table 16), rather than the avoided CO_2 emissions. Indeed, at 2015, EV still represent an emerging technology with relatively high purchasing prices. More specifically, EV price should fall significantly in particular in the small vehicle category, where the price difference is substantial (around 100 percent), in order to bring unitary cost down to an acceptable level.

Therefore, another analysis has been carried out to include a realistically possible price reduction, linearly increasing with EV share, up to a purchasing cost for EV equal to the cost of a conventional car (i.e. 35 % of reduction). Moreover, if one considers the actual EV life time equal to 10 years, the impact on CO_2 emission reduction can be extended for additional 5 years beyond the investment period. However, as shown in Table 18 (smart *plus* scenarios), in the highest RES power scenario under smart charge, annual costs increase by 37 133 M€, and if measured against CO_2 emission reduction

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Table 18: Total annual annual unitary costs: variations with respect to 2015 base case scenario for dump and smart charge and for smart charge under EV price reduction (smart *plus*)

EV penetration	0%	20%	40%	60%	80%	100%
ΔCosts [M€]						
Dump charge	45 373	59 300	73 207	87 260	101 353	115 473
Smart charge	45 373	58 946	72 388	85 906	99 388	112 844
Smart *plus*	45 373	50 021	51 016	48 997	44 253	37 133
ΔCosts/ΔCO_2 [€/t]						
Dump charge	2687.66	2487.83	2406.86	2448.99	2516.09	2590.18
Smart charge	2687.66	2221.95	1956.91	1828.33	1738.04	1670.87
Smart *plus*	2687.66	1885.52	1379.15	1042.80	773.87	549.83

the cost per tonne of CO_2 avoided is still substantial (550 €/t).

In any case, it is useful to observe that not only does a large EV adoption help in reducing CO_2 emissions, but it also contributes to improve air quality, which is an ever-increasing problem particularly in cities [72], and to increase energy security. In this respect, this study only focuses on investment and fuel costs variations; however, further analysis should be dedicated to include the above-mentioned beneficial actions so as to assess the actual overall costs of EV penetration from a wider technical and socio-economic perspective.

It is worth mentioning that private transport and thermal power plants are respectively responsible for 18 and 32 % of total CO_2 emissions at 2015 (Fig. 6): therefore, changes to how electricity is generated and private transport demand fulfilled can only affect approximately half the overall energy-related CO_2 emissions (fig. 1).

Fig. 7 shows CO_2 emissions by sector at 100% EV and maximum RES capacity. Since LPG and hybrid private cars will not be replaced by EV in future scenarios as perceived as low-emissions solutions, private transport CO_2 emissions cannot be entirely avoided. Moreover, as EV share progressively increases so does EV electricity demand (up to 76.42 TWh/year at 100 % EV), which cannot be totally fulfilled by renewable energies due to the mismatch between generation and demand that, in turn, can only be partly overcome by means of a smart charging strategy. This results in a relatively small reduction of CO_2 emissions (in absolute values) from thermal power generation with respect to reference scenario (Fig. 7). Moreover, CO_2 emis-

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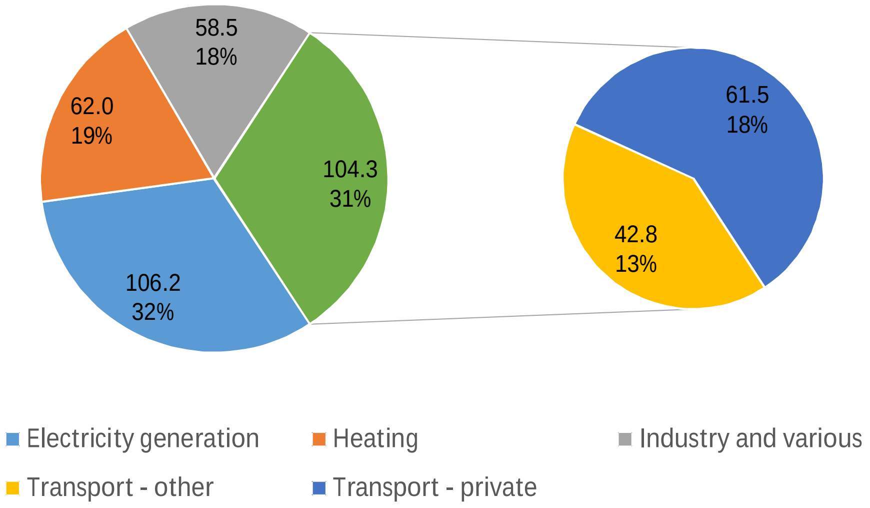

Figure 6: CO_2 emissions by sector at 2015

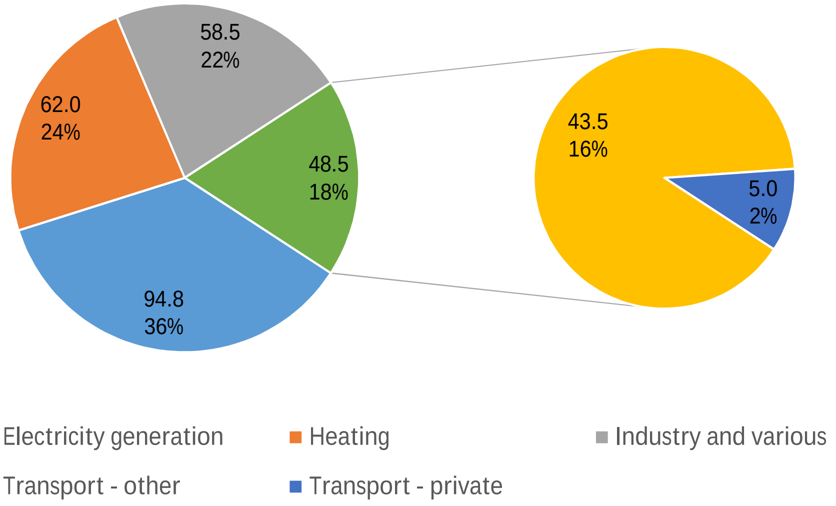

Figure 7: CO_2 emissions by sector at 100% EV and maximum RES capacity

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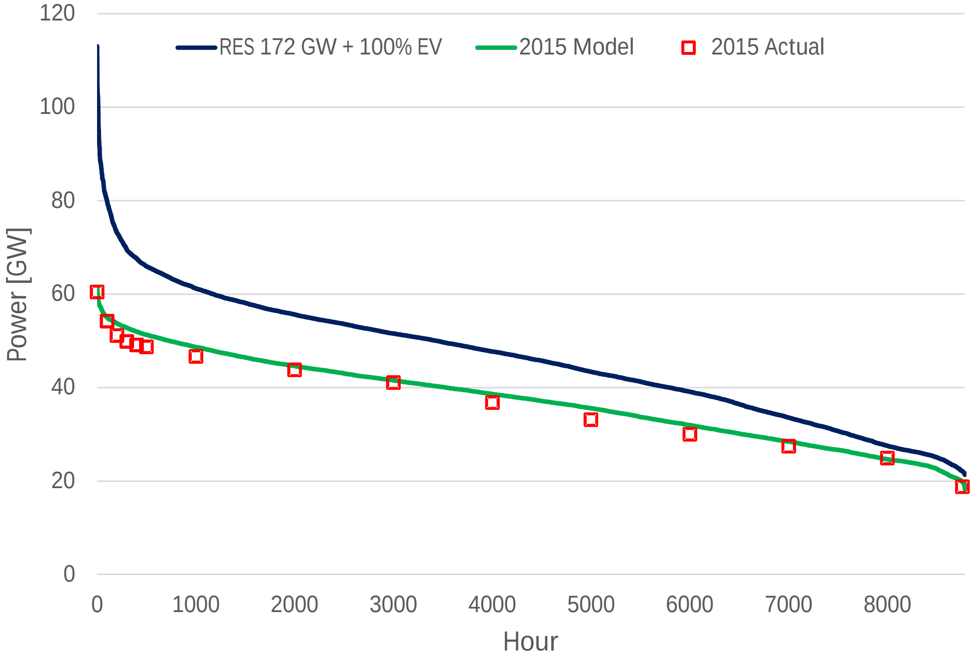

Figure 8: Load duration curve

sions due to transport halves, but they still account for a substantial share of total emissions (18 %); this analysis in fact only focuses on private transport while all other means of transportation, such as heavy-duty vehicles, remain unchanged.

The increase in electricity demand due to EV significant penetration inevitably leads to higher electrical power on the grid and related infrastructure investments in turn. Fig. 8 shows the duration curve for the highest RES and EV share with respect to 2015 base case scenario. Despite the adoption of a smart EV charge strategy, the increase in maximum power is substantial, almost twice as much as in 2015 (113 against 60 GW): in order to avoid such a significant increase in grid capacity, a *smart grid* approach becomes necessary to sustain a large EV penetration [73].

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5. Conclusions

This study aimed to assess the impact of progressively increasing shares of EV in scenarios with different level of production from intermittent renewable sources, using different technical and charging strategies. Results have been compared with respect to three different indicators: CO_2 emissions, annual costs and RES curtailments.

With a tenfold increase in RES potential power generation (with reference to 2015) and a complete replacement of oil-powered private transport vehicles with EV, CO_2 emissions can be reduced by 20 % as compared to 2015 level. This, however, comes at the price of curtailments that can be as high as 43 % of the total domestic electricity production in absence of energy storage solutions and that can be partly reduced by means of a smart EV charging strategy.

Total annual costs, although partially benefiting from fuel costs reduction, increase with EV penetration and RES capacity up to 56 % as compared to 2015 level. At maximum RES penetration, unitary costs (per unit of tonnes of CO_2 avoided) are substantial, but decrease with EV penetration, even further if a reasonable future price reduction for EV is taken into account.

Overall, the optimization of the different energy sources involves economical, technical and environmental issues and requires a smart energy system to be in place to effectively reduce curtailments that inevitably occurs with significant RES capacity, such as suitable energy storage systems, proper management strategy of transmission lines, shifting energy consumption for individual heating from natural gas toward electric energy, and in general a larger electrification of different energy sectors.

With this respect, a further development for this type of analysis could be achieved by coupling the EnergyPLAN software with a multi-objective optimization algorithm, such as *EPLANopt* [74], assessing the actual overall life-cycle costs of EV from a wider technical and socio-economic perspective including their positive impact on different important issues such as, for example, urban air pollution and national energy security.

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