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Electrification of transport and residential heating sectors in support of renewable penetration: scenarios for the Italian energy system

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Abstract

The integration of significant shares of renewable energies poses remarkable issues related to the intermittent nature of these sources. Nonetheless, solutions in support of renewables integration exist and become particularly effective if conceived under a smart energy system perspective, to exploit potential synergies among different energy sectors. With this respect, shifting programmable consumption from fossil fuels to electricity represents one measure to exploit otherwise-curtailed renewable generation. In this study, the impact of electrification of both private transport and space heating is assessed for the Italian energy system with the help of EnergyPLAN software and quantified in terms of critical environmental and techno-economic indicators, evaluating to what extent increasing the electricity demand supports the development of renewables. Results confirm that both transport and heating electrification can lead to significant reductions in CO_2 emissions, around 25–30 % if pursued independently. However, smart charge allows managing transport electricity demand more flexibly than heating demand, which makes the former more effective than the latter in fostering an increased renewable penetration, unless additional technologies are deployed to enhance flexibility in the heating sector. A techno-economic optimisation identifies possible optimal scenarios capable to reduce emissions by up to 47 % with an increase in annualised costs of 34 %.

Keywords: Smart energy system, Renewable energy sources, Electrification, CO_2 emissions, Electric vehicles, Heat pumps

1. Introduction

Over the period 1971—2017, Total Primary Energy Supply (TPES) increased by almost 2.5 times worldwide, up to 13 972 Mtoe in 2017 [1]. Such growth, however, occurred without a significant change in TPES structure; fossil fuels, in fact, still take the lion's

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share in 2017, representing 81 % of total TPES that compares with 86 % in 1971. In addition, in terms of power generation, fossil fuels provide for 65 % of the total electricity produced globally, with coal accounting for the largest share (38.5 % in 2017), with its share increased again in 2017 after a three-year decrease [1].

An energy system that relies heavily on fossil fuels is commonly recognised to have a detrimental impact on the environment, ranging from air pollution, responsible in turn for millions of premature deaths each year, to climate change issues, by raising the level of carbon dioxide in the atmosphere.

Moreover, with global energy demand foreseen to increase by more than 25 % by 2040 [2], the decarbonisation of the energy system becomes essential for the achievement of a sustainable development. In this context, the ratification of the Paris Agreement [3] and the calls to meet the United Nations Sustainable Development Goals [4] showed a common global intent to tackle environmental concerns through a profound transformation of the current energy sector.

Increasing electricity generation from Renewable Energy Sources (RES) together with a deeper electrification of energy sectors currently dominated by fossil fuels, such as transport and heating, are widely recognised as key measures towards a more sustainable energy system [2], particularly in the context of a smart energy system that tries to make the most from the synergies among different energy sectors [5]. However, the intermittent and stochastic nature of RES generation also requires operational flexibility measures to help the power system deal with the uncertainty of large renewable generation [6, 7]. Such measures become particularly effective if potential interactions among different energy sectors are fully exploited, viewing the entire energy system as a whole rather as the mere sum of different sectors [8].

Several studies explored different sector coupling strategies in various contexts [9], assessing the role of renewables in establishing positive interactions with the transport [10, 11] and heating sectors [12, 13], or included both heating and transport in the context of the transition towards a heavily-decarbonised or 100 %-renewable energy sector [14, 15]. However, at present, a thorough comparison between transport and heating electrification is still lacking. Within this framework, this study proposes two different modelling techniques: a parametric analysis and a multi-objective expansion capacity optimisation. In the literature, some studies already exist on the development of an optimisation tool starting from EnergyPLAN simulation software. Bjelic et al. developed an energy system optimisation tool based on EnergyPLAN and the single-objective optimisation program GenOpt [16]. Mahbub et al. coupled EnergyPLAN to a Multi-Objective Evolutionary Algorithm (MOEA) written in Java to evaluate the Pareto front of best configurations of the energy system [17]. M. G. Prina et al. developed the EPLANopt model with a particular focus on the heating sector, including energy efficiency of buildings within the optimisation through the introduction of a cost-curve describing costs versus energy savings [18]. This paper, by means of a similar optimisation method, aims at inspecting and identifying the impacts and opportunities resulting from different levels of electrification in the heating and transport sectors.

Italy features one of the highest shares in terms of renewable power generation in Europe, and, although hydroelectric power plants are the largest among RES, intermittent renewables' contribution is expected to grow significantly according to the Italian draft National Plan for Energy and Climate (PNEC) medium- and long-term objectives [19]. Previous studies examined the impact of large RES capacity on the Italian energy system,

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showing that their integration within the energy system cannot be achieved fully unless adequate operating thermal backup systems and energy storage capacity are included [20, 21] or a transition towards a smart energy system is established [12, 22].

In 2016 transport and space heating in Italy accounted respectively for 30 % and 27 % of total final energy consumption and relied heavily on fossil fuels (96 % and 73 % of total for transport and space heating respectively) [1, 23]. Therefore, a shift in consumption towards electricity, in the context of high renewable shares in power generation, appears to be an interesting solution to decarbonise those sectors. For instance, previous studies on the Italian energy system found that CO_2 emissions could be reduced by 20–30 % as compared to today's level when Electric Vehicless (EVs) are included under progressively increasing RES capacity [11, 14]. The excess of renewable electricity production resulting from a large Intermittent Renewable Energy Sources (IRES) capacity could be conveniently exploited by increasing electricity demand further. With this regard, electrification of space heating could theoretically represent an additional measure to absorb the otherwise-curtailed renewable power by means of Heat Pumps (HPs).

With the help of EnergyPLAN software [24] and starting from a reference scenario validated at 2017, this study aims to establish to what extent an increasing RES capacity can potentially fulfil the additional electricity demand arising from progressive growing shares of EVs and HPs in private transport and individual heating respectively, taking also into account a feasible level of heat savings. EV penetration is assumed to grow up to the complete replacement of conventional vehicles, while heating demand supplied by HPs is projected to increase up to twice the goal set by PNEC at 2030. Heating and transport progressive electrification are first analysed separately and the corresponding results are compared by means of relevant energy and environmental indicators, such as CO_2 emissions, curtailments and RES penetration. It is shown that the additional electricity demand required to replace a unit of fossil fuel consumption is similar for private transport and space heating, making this comparison particularly interesting and effective. Then, a multi-objective techno-economical optimisation of the national energy scenario, based on a holistic integrated approach and aimed at minimising energy-related CO_2 emissions and costs, is presented to investigate beneficial interconnections among electricity generation, private transportation and space heating.

2. Methods

A base case scenario was defined for the Italian energy system with reference to the year 2017 according to updated available data from reliable sources. The national energy system was modelled using the latest version of EnergyPLAN software following the approach described thoroughly in previous works of the authors and validated against annual energy indicators; simulations were carried out considering a medium and long-time perspective and compared against relevant environmental and technical features.

2.1. Reference scenario

EnergyPLAN performs energy balances to simulate the operation of an energy system on an hourly basis and requires several input parameters to fully describe energy demand and supply. The software is an input/output model and includes a wide range of technologies allowing a synergic interaction among different energy sectors. Data relevant

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Table 1: Model validation.

Indicator	Units	Model	Actual	Difference	Source
CO_2 emissions	Mt	325.0	321.5	1.1 %	[27]
TPES	Mtoe	143.1	145.5	−1.7 %	[27]
RES electricity*	TWh	86.3	86.4	0.0 %	[28]
PP electricity	TWh	99.6	98.7	0.9 %	[28]
CHP electricity	TWh	110.2	110.1	0.1 %	[28]

*Excl. bioenergies

to the modelling procedure are recalled in Appendix and qualitatively described in the following of this section; full details and a more extensive description of the base case scenario are given in a document available on the open-access repository Zenodo [25].

Power generation technologies were defined in terms of installed capacity and efficiencies as well as fuel consumption distribution for conventional plants (Tables A.1–A.3).

Energy demand was modelled in terms of annual electricity loads, that can be further subdivided in the contributions for cooling, heating and transport (Table A.4), energy consumption for individual heating (Table A.5), other derived heat demands (Table A.6), transport (Table A.7) and industry (Table A.8). In this study, particular attention was given to heating demand: its distribution is derived from the overall national gas consumption, considering that almost 70 % of individual heating demand was fulfilled through Natural Gas (NG). NG hourly distribution was derived from Snam, the national society for NG transportation and storage, for the year 2017 [26]. Gas consumption for heating purposes only was determined by subtracting industry, power plants and other usage.

The software works out an hourly balance in which total electricity demand is supplied by both RES and conventional power plants. Given the stochastic nature of IRES generation, hourly power distributions for each IRES technology must be given as input. Sources used to derive hourly distributions for energy demand and renewable generation are listed in Table A.10.

The model was validated against the most significant energy indicators showing an acceptable difference (below 2 %) with respect to 2017 actual references, as shown in Table 1. Non-energy uses were subtracted from values given by the International Energy Agency [27]. RES electricity generation excludes bioenergies as EnergyPLAN estimates such production within thermoelectric power plants generation.

2.2. Future scenarios definition

A variety of possible future scenarios were defined assuming, from supply side, a growing RES installed capacity and, from demand side, an increasing electrification of both heating and transport sector, with conventional cars and boilers being progressively replaced by EVs and HPs respectively.

2.2.1. Electricity generation

The modelled energy scenarios considered an increase in IRES installed capacity up to values close to the corresponding potential, as illustrated in the followings. Only

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Photovoltaic (PV) and wind power plants were taken into account, because these are the technologies which the PNEC mostly relies on to increase RES penetration, with other RES kept at the same installed capacity as in 2017. Hydropower is a long-established source that has already basically reached its potential in Italy; concentrated solar power is currently negligible and PNEC projects its installed capacity at just 880 MW in 2030; finally, electricity generation from bioenergy is even expected to decrease by the PNEC [19]. Indeed, electricity generation from biomass is affected by a lower power density compared to PV and wind and could also conflict under some circumstances with food and feed production [29]; moreover, other uses for biomass could be more efficient than electricity generation, such as providing carbon in Power-to-Gas (P2G) and Power-to-Liquid (P2L) technologies to produce electrofuels, enhancing renewable penetration in the energy system [22].

A literature review was conducted to assess PV and wind potential in Italy. Tables 2 and 3 show potentials for annual generation and installed capacity, respectively, from different authors. The most recent and complete data were provided by Tröndle et al. [29, 30], even though this source seems to overestimate offshore wind potential in Italy: the ratio of potential capacity to PNEC goals at 2030 is around four for both PV and onshore wind (more precisely, 4.1 for PV and 3.9 for onshore wind), while it leaps to an apparently unrealistic value of 51.6 for offshore wind.

It must be highlighted that data taken from Tröndle et al. [30] refer to what the authors define as technical-social potential, that is "a socially and ecologically constrained potential", which prohibits "the use of environmentally protected surfaces", allows open-field PV to be be built only "on bare and unused land", and where only "10 % of all available surface area can be used for renewable power generation" [29]. Regarding building-integrated PV, the authors did not consider any constraints and take the technical-social potential to be equal to the technical potential; however, they admit that in most energy scenarios generation from rooftop PV is below 40 %, and consequently discussed results obtained when taking into account a 40 % ceiling on building-integrated PV as a share of total IRES generation. Correspondingly, in Table 2 the building-integrated PV generation for [30] takes into account this limit, and in Table 3 the corresponding capacity potential is limited by the same ratio.

Ultimately, in this study the increase in IRES installed capacity was constrained by the maximum values given in Table 4, resulting from an increase by a factor of around four with respect to 2030 PNEC goals, in accordance with Tröndle et al. [30]. The relative increase in IRES capacity, with respect to 2017, is 9.5. These maximum values for PV and wind capacity were used in two ways: first, to generate different energy scenarios in a parametric analysis of the impact of EVs and HPs penetration on the energy system, with capacity in each IRES technology linearly increasing from 2017 levels up to such maximum values; then, as upper boundaries in a techno-economic multi-objective optimisation of the national energy system.

Finally, as concerns electricity generation from fossil fuels, coal phase-out was included in all energy scenarios in accordance to PNEC targets, by implementing the decommissioning of 7.89 GW coal power plants installed capacity [31], partially replaced by additional 3.4 GW capacity of NG power plants [19, p. 93].

EnergyPLAN allows also to select, among Combined Heat and Power (CHP) plants, large cogeneration plants that are able to operate, if required, in electricity-only mode. This option was used by the authors in modelling future scenarios to provide the energy

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Table 2: Annual PV and wind generation (TWh): PNEC goals for 2030 and technical potentials.

Source		PNEC [19]	[32]	[33]	[34]	[30]
PV	building-integrated	-	126.9	-	110.0	196.4
	open-field	-	-	-	-	63.7
	total	74.5	126.9	-	110.0	260.0
Wind	onshore	-	-	89.8	-	141.1
	offshore	-	-		-	89.8
	total	40.1	-	89.8	-	230.9

Table 3: PV and wind capacity potential (GW): PNEC goals for 2030 and technical potentials.

Source		PNEC [19]	[33]	[35]	[30]
PV	building-integrated			260.8	162.4
	open-field				42.9
	total	50.0			205.3
Wind	onshore	17.5	49.1	98.4	68.5
	offshore	0.9		4.3	46.4
	total	18.4		102.7	114.9

system with additional flexibility, under the assumption that large CHP plants (such as large combined cycle plants or condensing turbines) might be able to support conventional power plants in fulfilling electricity demand.

2.2.2. Private transport: EV penetration

Future assumptions for the transport sector were modelled according to previous works by the authors [36] assuming a linear replacement of petrol and diesel vehicles by EVs up to a complete substitution of these vehicles. Both driving habits (as in driven km/year) and total number of vehicles were kept unchanged with reference to 2017 (see section 3.1). Values were updated with respect to current EV features resulting in slightly different average electricity consumption and battery capacity, equal to 173.6 Wh/km and

Table 4: Maximum IRES installed capacity (GW) considered in the energy scenarios, compared to 2017 values [28] and PNEC targets [19].

Source	2017	PNEC	max
Photovoltaic	19.7	50.0	200.0
Onshore wind	9.8	17.5	68.5
Offshore wind	-	0.9	3.6
Tot. IRES	29.5	68.4	272.1

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Table 5: Oil, NG and HP heating demand (TWh/year): current and future scenarios.

Technology	2017	Individual HP demand share					
		20 %	30 %	40 %	50 %	54 %	77 %$^+$
Oil boilers	24.3	0.0	0.0	0.0	0.0	0.0	0.0
NG boilers	243.9	240.4	201.6	162.9	124.1	107.9	12.5
Biomass boilers	61.8	61.8	61.8	61.8	61.8	61.8	43.2
Electric boilers	8.1	8.1	8.1	8.1	8.1	8.1	5.7
Individual HP	49.8	77.6	116.3	155.1	193.9	210.1	210.1
Tot. heat demand	387.8	387.8	387.8	387.8	387.8	387.8	271.5

26.9 kWh respectively.

2.2.3. Heating: HP penetration

Future scenarios for the heating sector were defined assuming a progressive electrification by means of a widespread usage of HPs for individual heating. All simulated scenarios foresee oil consumption to be entirely phased out, consistently with the steadily decreasing trend observed in the residential sector in the last 40 years, when it fell from a share of 75 % in 1973 to just 7 % in 2016 [1]. Consumption mostly shifted to NG, as oil products were more expensive and environmentally harmful (the same shift has been observed in the power sector).

In the modelled scenarios, NG boilers were progressively replaced by individual HPs, whose share was increased up to twice the PNEC goal, that set to 5.6 Mtoe the target for renewable energy consumption by HPs for 2030 [19] (Table 5). Assuming a Seasonal Performing Factor (SPF) unchanged with respect to 2017, i.e. equal to 2.63 [37], this gave a projected heat demand covered by HPs equal to 210.1 TWh/year; such assumption led to a maximum HP share of 54 % keeping the total heat demand, as well as the demand covered by biomass and electric boilers, stable with respect to 2017 (see also Table A.5).

A possible reduction in heating demand was also taken into consideration, as foreseen by PNEC and other studies [38, 39]. In particular, Hansen et al. identified economically feasible levels of heat savings and heat production for various European countries [39]: feasible balances between saving and supplying heat were assessed, by projecting a future development of the building stock in terms of retrofit measures, new building and demolition rate and evaluating the associated costs. For the Italian case, heat savings up to 30 % of heat demand were deemed feasible, as compared to the business-as-usual scenario. Correspondingly, a further heating scenario was built taking into account a 30 % reduction in total heat demand as well as in heat generation from biomass and electric boilers, with HP generation again equal to twice the PNEC goal, and NG boilers providing the remaining demand: the resulting values are given in the last column of Table 5, and the corresponding scenario is labelled as 77 %$^+$.

2.3. Cost structure

As concerns costs, in line with previous works of the authors [36] economic data were mainly obtained from 2050 projections in the EU-funded Heat Roadmap Europe project

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Table 6: Projected investment and O&M costs of IRES technologies [40].

Technology	Inv. costs EUR/W	O&M fraction % of inv.	Inv. period years
Onshore Wind	0.86	3.41	30
Offshore Wind	1.39	1.93	30
Photovoltaic	0.67	1.11	40

Table 7: Fuel costs (EUR/GJ) [40].

Fuel	Cost
Coal	2.4
Fuel Oil	9.7
Diesel fuel	12.1
Petrol/JP	12.1
NG	9.3
LPG	13.4
Biomass	8.5

[40] and are summarised in Tables 6 and 7.

With specific reference to HPs, costs were again derived from the Heat Roadmap database [40] and listed in Table 8, where average unit investment costs are given for the purchase of a single heating device (NG boiler or HP).

Total annual costs for heat savings were implemented according to the relationship between heat savings and annualised costs reported by Hansen at al. for the Italian case [39], in order to take into account how costs of heat savings vary for different levels of heat demand reduction. The investment period for heat savings-related costs was set to 30 years.

With respect to purchasing price for EVs and conventional cars, values were set respectively equal to 33.84 and 16.96 kEUR. A weighted average price for EVs was considered from the current vehicle fleet composition, in line with a previous work by the authors [36]. As concerns petrol and diesel cars, purchase costs were derived from manufacturers' prices for the most common vehicles for each category, chosen as representative of the particular segment. Finally, costs related to EV infrastructure were included within the techno-economic optimisation in the form of a linear dependency between EV penetration and annualised costs related to the necessary infrastructure for EV charging, as follows:

$$C_{\mathrm{EVinfrastructure}} = (10^4 \times EV_{share} + 50)\,\mathrm{MEUR} \tag{1}$$

This cost trend was derived from a report drawn up by Enel foundation and Politecnico di Milano [41], which evaluated costs related to EV charging infrastructure both at urban and extra-urban scales under increasing penetration of electric mobility. Discount period for infrastructure investments was taken as 30 years.

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Table 8: Projected investment and O&M costs of individual heating devices [40].

Technology	Inv. costs kEUR/unit	O&M fraction % of inv.	Inv. period years
NG boilers	3.86	4.95	20
Heat pumps	7.78	2.05	16

2.4. Techno-economic optimisation

In addition to defining a single scenario and assessing its impact on the energy system through a parametric analysis, a techno-economic optimisation was carried out to ultimately let the algorithm select a variety of possible optimal configurations for the Italian energy system, acting on different parameters related to heat and transport electrification. Precisely, the tool used in this study performed a multi-objective optimisation by means of MATLAB® MOEA function *gamultiobj* [42], which finds a Pareto front for multiple-objective functions using a controlled, elitist genetic algorithm (a variant of NSGA-II [43]). The MOEA allowed to find the best energy mix in terms of selected objectives based on a given set of decision variables. In this particular case, the selected objectives, to be both minimised, were total annual costs and CO_2 emissions. For each decision variable a range of potential values was defined within a minimum and a maximum bound as displayed in Table 9.

Table 9: Decision variables in the multi-objective optimisation.

	Variable	Minimum	Maximum
x_1	LDV diesel consumption (TWh)	0	94.5
x_2	LDV gasoline consumption (TWh)	0	58.7
x_3	Onshore wind capacity (MW)	9.7	68.5
x_4	Offshore wind capacity (MW)	0	3.6
x_5	PV capacity (MW)	19.7	200.0
x_6	NG consumption (TWh)	0	265.1
x_7	Heat savings	0	50%

It is worth noting that in the optimisation analysis the powertrain efficiency of conventional cars was also increased according to Unione Petrolifera projections for 2030 [44] and consumption was set respectively to 51.3 and and 45.7 kWh/100km for gasoline and diesel cars respectively. EV electricity consumption was held constant at 17.4 kWh/100km. As concerns heating demand, oil consumption was completely phased out in all simulated scenarios.

Transport demand for light-duty vehicles, set in terms of vehicle-kilometres (D_{LDV}), was left unchanged at 32.13×10^{10} km and EV electricity consumption was estimated as follows so as to ensure that transport demand stayed the same:

$$E_t = (D_{\mathrm{LDV}} - x_1/\bar{c}_d - x_2/\bar{c}_g) \times \bar{c}_{el} \tag{2}$$

Here, $\bar{c}$ denotes average energy consumption, while subscripts d, g and el indicate diesel, gasoline and electric vehicles respectively.

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Heating demand (H_{tot}), reduced with respect to the base case when heat savings were introduced, was assumed to be satisfied by biomass (H_{bm}) and electric (H_{el}) boilers in the same percentage as the base case, while NG could be potentially reduced, with HPs catering for the remaining share of demand (H_{HP}). NG boiler average efficiency η_b was kept unchanged with respect to the base case:

$$H_{HP} = (1 - x_7)\, H_{tot} - [\eta_b\, x_6 + (1 - x_7)\,(H_{bm} + H_{el})] \tag{3}$$

3. Results and discussion

3.1. Additional electricity demand from transport and heating electrification

In this section the additional electricity demand required to replace a unit of energy consumption from fossil fuels in transport and heating is estimated. In particular, NG is the fossil fuel replaced by electricity in the heating sector, while gasoline and diesel are those considered in the transport sector.

Heating demand supplied by NG boilers is $\Delta H = \eta_b\, \Delta F$, where η_b is the average efficiency of NG boilers equal to 0.92 (Table A.5) and ΔF is the amount of NG energy that is to be replaced by electricity. The same demand must be supplied by HPs, requiring an addition electricity consumption $\Delta E = \Delta H/\text{SPF}$, where $\text{SPF} = 2.63$ is the Seasonal Performance Factor (Table A.5), therefore the additional electricity demand required to replace NG consumption for individual heating is:

$$(\Delta E/\Delta F)_h = \eta_b/\text{SPF} = 0.350 = 4.07\,\text{MWh/toe} \tag{4}$$

In the case of private transport, the average energy consumption of the national fleet of private vehicles must first be evaluated. For gasoline-fuelled vehicles, in 2017 their total number was $N_g = 15.73 \times 10^6$, their average distance travelled in a year was $\bar{D}_g = 7280\,\text{km}$, and the overall energy consumption was $F_g = 5.58\,\text{Mtoe}$; for diesel-fuelled vehicles, the same parameters were $N_d = 15.15 \times 10^6$, $\bar{D}_d = 13\,650\,\text{km}$, $F_d = 9.41\,\text{Mtoe}$ [36, 44]. Consumption for private transportation only is derived from total consumption for transport according to the procedure used in a previous work [36]. Average energy consumption is thus:

$$\bar{c}_{d,g} = \frac{F_g + F_d}{N_g \bar{D}_g + N_d \bar{D}_d} = 1.95\,\text{MJ/km} \tag{5}$$

Average EV electricity consumption is $\bar{c}_{el} = 174\,\text{Wh/km}$ (section 2.2.2), so the additional electricity demand required by EVs to cover the same distance as conventional vehicles is:

$$(\Delta E/\Delta F)_t = \bar{c}_{el}/\bar{c}_{d,g} = 0.320 = 88.9\,\text{Wh/MJ} = 3.72\,\text{MWh/toe} \tag{6}$$

This assessment shows that, although comparable in terms of electricity required to replace 1 toe of fossil fuel consumption, transport electrification appears to be more efficient than the electrification of heating sector, with a difference of 8 % for the Italian energy system in 2017. In spite of the fact that, in the context of electricity supplied exclusively by RES, a difference in electric efficiency loses its importance in terms of CO_2 emissions reduction, higher energy efficiency might still be an advantage if conventional generation is still required to occur to compensate for renewable power unpredictability.

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On the other hand, it is worth noting that $\bar{c}_{el}$ is based on the most recent EV models, while SPF results from a seasonal average of the current HP stock performance. If this latter is projected to increase at a higher rate than EV powertrain efficiency, a parity in terms of electric efficiency can be reasonably achieved between heating and transport sectors.

However, when discussing emissions it must be remembered that fossil fuels used in private transport are significantly more carbon-intensive than NG: replacing 1 toe of NG with carbon-free electricity would reduce CO_2 emissions by 2.4 t, while the ratio is 3.2 t/toe for the replacement of oil-derived products. CO_2 emission factors were derived according to the latest available national data [45] and are listed in Table A.9.

3.2. Analysis of EV and HP penetration

This section presents the results obtained with a parametric analysis of national energy scenarios with different levels of EV and HP penetration. Results have been analysed in terms of crucial energy indicators such as CO_2 emissions and RES penetration, and have been extensively discussed for the Italian case under the aforementioned assumptions and in relation with the existing literature reporting similar analyses.

Fig. 1 shows CO_2 emissions trends when IRES installed capacity grows under a progressively increasing penetration of EVs (Fig. 1a) and HPs (Fig. 1b). The reduction in emissions observed even at current IRES capacity and EV and HP penetration levels, compared to 2017, is due to the phase-out of coal for electricity generation, which is replaced by the less carbon-intensive NG (see section 2.2.1).

The most interesting result of this comparative analysis is that the replacement of fossil-fuelled vehicles with EVs for private transportation is more effective at reducing CO_2 emissions as compared to the substitution of NG boilers with HPs. In fact, both technologies bring about an increase in energy efficiency when compared to conventional alternatives (slightly higher for transportation rather than heating), and the additional electricity demand is very similar; nonetheless, NG is less carbon-intensive than gasoline and diesel, and EVs can quite easily benefit from a smart type of charge that partly regulates transport electricity demand according to IRES surplus availability, something that is not available in the heating sector unless large seasonal thermal storage or P2G technologies are included in the system [46]. As a result, EVs allow a larger renewable penetration compared to HPs that, as shown in Fig. 2, can rise well above 65 % of the overall national production at the maximum EV penetration when IRES capacity is increased to its maximum value discussed in section 2.2.1. In particular, it is possible to observe that, once a certain IRES capacity threshold is reached (above four times the current level under the assumptions of this study), an increase in EV penetration leads to higher RES shares (Fig. 2a), as already observed in previous works [11]. On the contrary, for relatively low-capacity scenarios, fossil-fuelled power plants must supply a significant share of the additional electricity demand arising from EV increasing penetration, thus resulting in the observed decrease in RES share.

On the other hand, the reduction in CO_2 emissions associated to a progressive penetration of HPs replacing NG boilers is mainly due to an increase in energy efficiency, rather than to a larger contribution from renewables; in fact, as a result of the mismatch between demand and potential supply, IRES generation share actually decreases as HPs penetrate the heating sector, as displayed in Fig. 2b.

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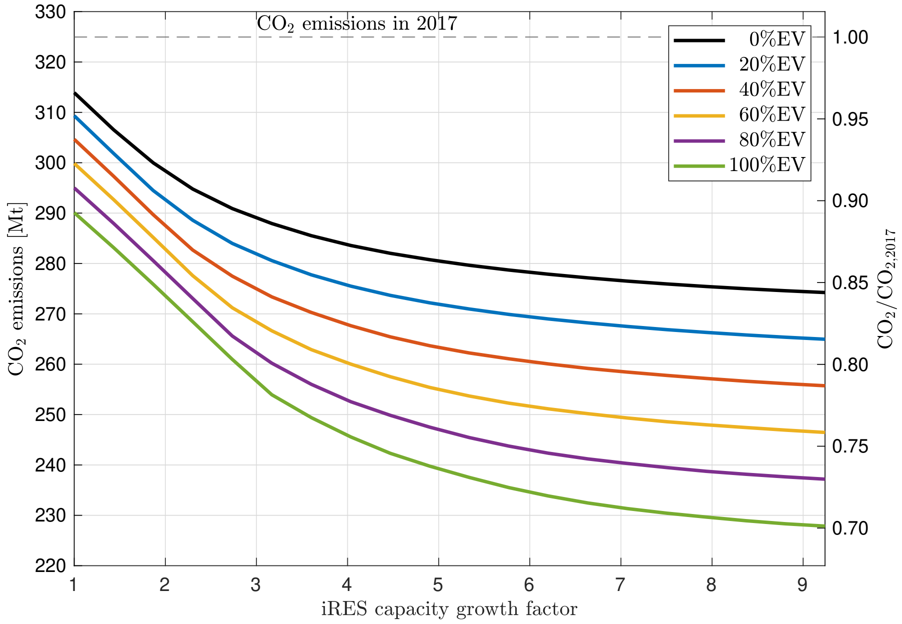
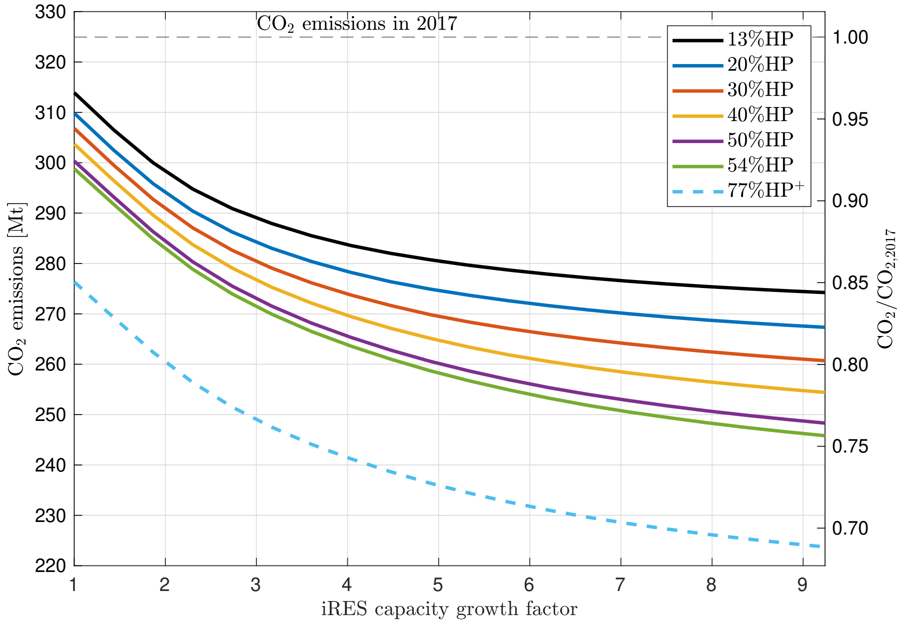


(a) Influence of increasing IRES capacity and EV penetration.



(b) Influence of increasing IRES capacity and HP penetration.

Figure 1: CO_2 emissions for increasing IRES capacity, EV and HP penetration.

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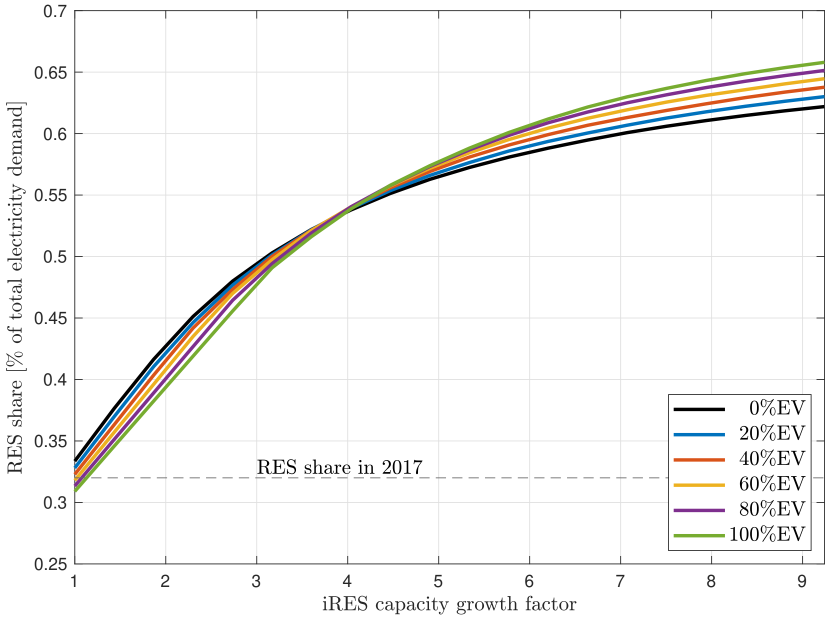
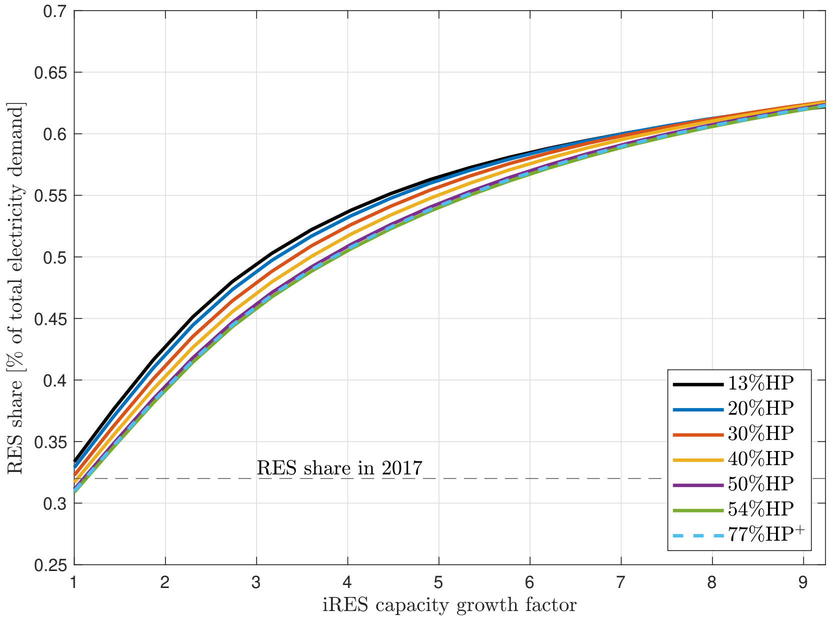


(a) Influence of increasing IRES capacity and EV penetration.



(b) Influence of increasing IRES capacity and HP penetration.

Figure 2: RES share of total electricity demand for increasing IRES capacity, EV and HP penetration.

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It is also instructive to compare the emission reduction at maximum IRES capacity between the baseline scenario (black curves in Fig. 1, identified as 0%EV and 13%HP) and those with maximum EV or HP penetration (green lines, identified as 100%EV or 54%HP). Emissions decrease by 46.4 Mt for a complete electrification of private transport (Fig. 1a), which is very close to 47.8 Mt, that is the value that should be expected if current energy consumption would be replaced by carbon-free electricity: the difference is just −2.9 % (the decrease in fuel energy consumption is $E_g + E_d - E_{\mathrm{PHEV}} = 14.9$ Mtoe, with $E_{\mathrm{PHEV}} = 0.1$ Mtoe). On the other hand, the decrease in heating demand supplied by NG between these scenarios is 136 TWh (Table 5), which means a decrease in NG consumption by 12.7 Mtoe, that amounts to 30.7 Mt of CO_2 emissions: the actual reduction calculated at maximum IRES capacity is 28.4 Mt (Fig. 1b) (a difference of −7.3 %), therefore even at such a large capacity renewable sources cannot supply the whole additional demand due to the hourly mismatch between heating demand and potential RES supply.

Finally, the HP scenario including heat savings (identified as 77%HP$^+$, dashed line in Fig. 1b) underlines the importance and effectiveness of energy efficiency in achieving a sustainable energy system: in this case NG consumption is dramatically reduced (by 21.6 Mtoe), and energy-related CO_2 emissions can decrease by more than 30 % with respect to 2017, confirming that energy efficiency should be the "first fuel" to deploy in any energy transition [47, 48].

The non-contemporaneity between potential IRES surplus and heating demand is clearly observable in Figs. 3 and 4 in terms of hourly and monthly distributions throughout the year. While EV smart charging is regulated to exploit IRES generation throughout the day and shows an almost constant pattern over the year, heating demand distribution is at its highest in both hours and months characterised by relatively lower amount of IRES potential generation.

3.3. Techno-economic optimisation

Results related to the techno-economic optimisation are summarised in Figs. 5 and 6 for the different areas of the energy system involved. CO_2 emissions reduction trend starts at approximately 30 % with respect to the base case scenario with a small reduction on annualised costs. This result can be achieved by increasing IRES capacity up to approximately 60–80 % of the maximum value for wind and 48 % for PV, with EVs replacing a negligible share (3 %) of Light-Duty Vehicles (LDV) fleet and HPs catering for 78 % of heating demand. The opposite side of the Pareto front identifies the maximum possible reduction of CO_2 emissions, that can reach 47 % at the expense of an increase in annual costs equal to 34 %. The increase in annual costs is mainly driven by EV purchasing price when EVs start to replace significant shares of conventional cars. On the other hand, costs related to heat savings clearly influence total costs variation when heat savings become higher than approximately 40 % as the related costs curve shows its highest slope [39].

Overall, as concerns transport (Fig. 5), the optimisation analysis reveals that EVs play a key role in reducing CO_2 emissions; however, their current purchasing price is the major cause of annual costs increase throughout the Pareto front when EV share increases. Taking as a reference what is reported in the International Energy Agency 2018 World Energy Outlook, where the EV share is set up to 67 % in the European Union in the "Future is Electric" Scenario [2, pp. 426–427], CO_2 emissions could be potentially

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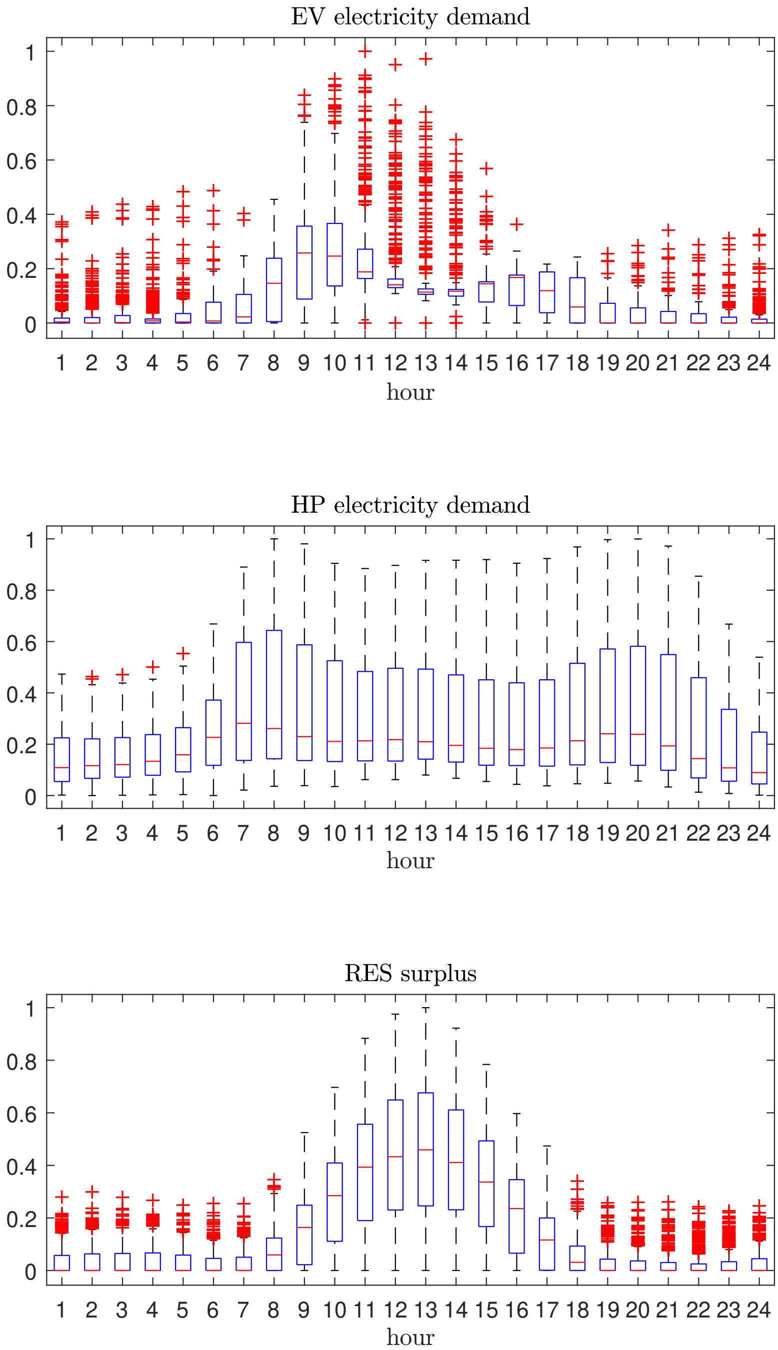

Figure 3: Transport and heating electricity demand compared to RES surplus: hourly distribution.

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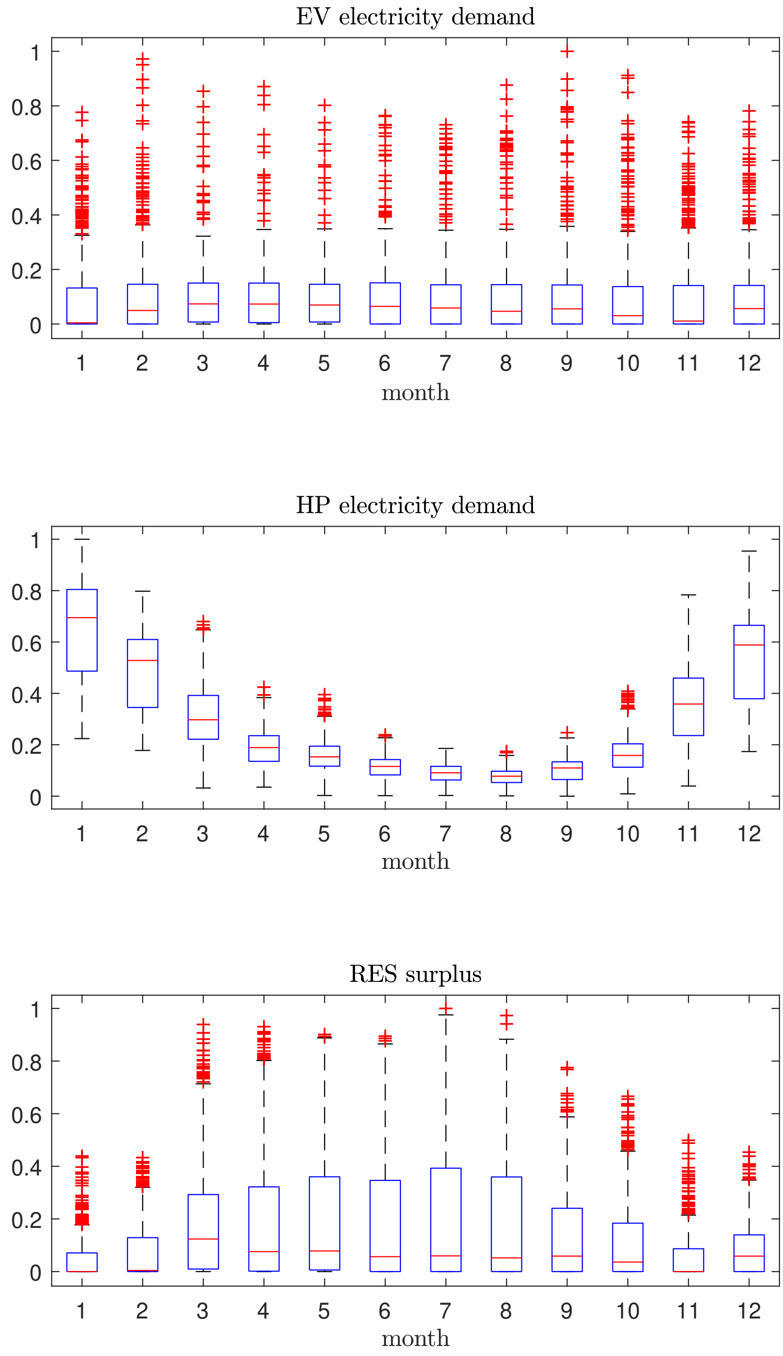

Figure 4: Transport and heating electricity demand compared to RES surplus: monthly distribution.

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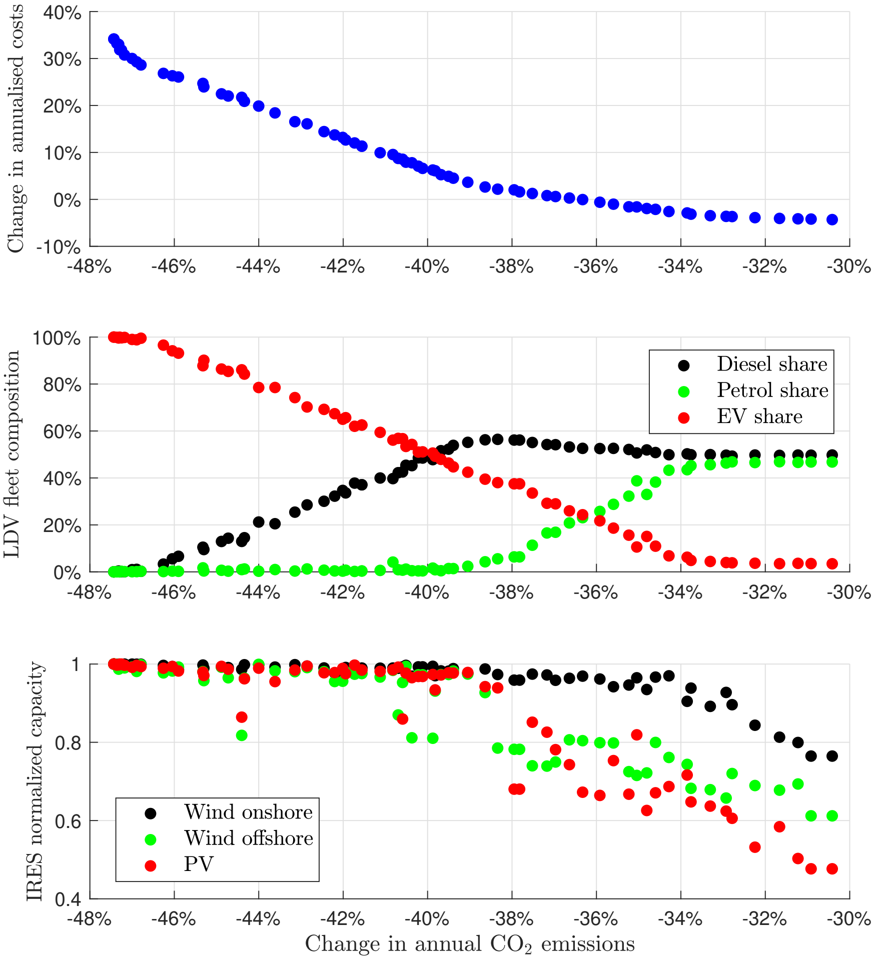

Figure 5: Effect of IRES capacity and measures in the LDV sector on annualised costs and CO_2 emissions.

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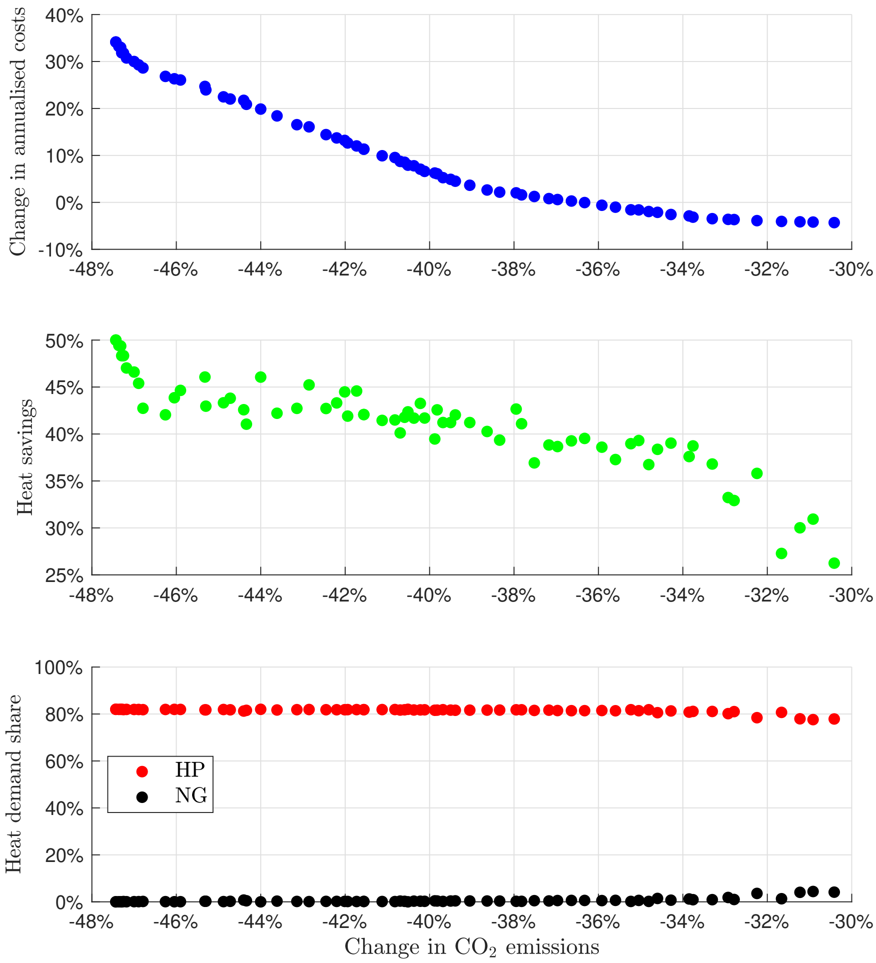

Figure 6: Effect of measures in the heating sector on annualised costs and CO_2 emissions.

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reduced by approximately 43 % with respect to the base case. It is also worth mentioning that results could be highly influenced by the purchasing cost trend of EVs in the future years, which are forecast by some to achieve cost parity with conventional vehicles in the medium term [49, 50]. Furthermore, diesel vehicles are preferred by the optimisation algorithm to gasoline alternatives due to the higher powertrain efficiency, and this is in contrast with national and local policies designed to limit diesel share within LDV fleet in future years, particularly in urban environments.

With regard to the heating sector (Fig. 6), the role of HPs proves to be beneficial not only in terms of CO_2 emissions reduction but also of annualised costs, being all scenarios on the Pareto front characterised by a HP share almost constant at 80 %. In fact, the increase in investment costs related to HP penetration is amply offset by a reduction in variable costs related to the higher efficiency and to the possibility of exploiting renewable power when in phase with heat demand.

Finally, among IRES technologies, the solver leans towards a faster saturation of wind power rather than PV since the former has a lower potential, but also because its generation is more uniformly distributed throughout the day and the year and can be more conveniently coupled with the increasing electrification of the energy system.

3.4. Comparison with the existing literature using EnergyPLAN for similar analyses in other countries

Although results of this type of analysis may vary significantly depending on the particular energy system object of the study, as well as on assumptions made for future energy scenarios, it is worth discussing results available in the existing literature on similar topics involving other countries and based on EnergyPLAN as energy planning tool, so as to highlight analogies and differences as well as possible pathways for future developments.

Novosel et al. analysed the impact of EVs on the Croatian energy system and showed that the electrification of 50 % of road transport could potentially reduce fuel consumption by 12.3 % and CO_2 emissions by 14.6 % as compared to 2011 level [51]. Similarly to the analysis presented in this work, scenarios were created assuming progressively higher penetration of both RES and EVs showing positive interactions between the two, thus confirming the capability of EVs to reduce the excess electricity (that becomes significant for a wind penetration higher than 10 % or PV higher than 15 %) and increasing the potential for a further penetration of intermittent RES. Synergies between RES and EVs for the Croatian energy system were also confirmed by Pfeifer et al. who showed that the introduction of electric vehicles, along with a moderate introduction of heat storage in CHP plants and flexible operation of power plants, enabled the integration of additional PV capacity up to 2000 MW keeping electricity surplus from solar and wind power below 5 % [52].

The key role of the electricity generation mix on transport electrification was discussed by the authors in a previous work, which compared Italian and German energy systems assuming a progressive growth of IRES installed capacity and EV penetration [36]. Results showed that the German energy system, highly dependent on coal, can only benefit from EVs if IRES grows up to approximately two times as compared to toady's level, unlike the Italian system, whose energy generation currently mostly rely on efficient natural gas-fired power plants.

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Nunes et al. quantitatively defined, for the Portuguese energy system, the positive interactions between a high penetration of PV and EVs, using a smart charging strategy to conveniently exploit the surplus of PV generation [53]. The substantial solar resource availability represents an interesting analogy with the Italian case, and, in fact, similar qualitative conclusions are drawn. At a given PV penetration, as EV share grows, CO_2 emission, along with excess of PV generation, is progressively reduced confirming the ability of EVs to assist intermittent RES integration. Noteworthy is the fact that, likewise the proposed study, the marginal benefit of additional EV share became higher at higher RES scenarios, as it can be inferred from the increase in vertical distance of CO_2 curves at growing RES installed capacities. On the other hand, much deeper RES penetration and CO_2 emission reduction were reached (leading to an almost complete decarbonisation of the Portuguese energy system) as other critical assumptions were made including, among others, both coal and oil phase-outs as well as a significant increase in wind and hydropower generation.

Prina et al. developed an optimisation tool coupled with EnergyPLAN to select the best techno-economic transition pathway between a 2015 baseline and a possible 2050 scenario, acting only on the electricity sector [14]. Their best-case alternative led to a cumulated CO_2 emission reduction of 24 %, while the additional introduction of EVs, covering 60 % of demand, led to a further emission reduction of just about 5 %. In fact, without implementing a regulated charge, most of the increase in electricity demand mainly occurs during night hours, when RES generation is at its lowest as PV modules are not generating, thus calling for conventional thermal plants to cater for EV additional electricity needs.

Lund and Kempton analysed the role of EVs in integrating wind power into the Danish energy system, including also the effect of the charging strategy adopted providing a comparison between night charging and smart charging [54]. The impact of EVs, that were assumed to fully replace the conventional vehicle fleet, was evaluated for a range of wind power growing from zero to approximately 100 % of the electricity demand. EVs improved the ability to integrate wind power and reduce CO_2 emissions. For instance, in the 50 % wind scenario, shifting from conventional to EVs under a smart charging strategy was found to reduce excess electricity production by one half and CO_2 emissions by 15 %. However, EVs with night charge performed better than in the Italian case and the incremental benefit to smart charging was small; such difference may lie in the different hourly distribution between the major IRES of the two energy systems, i.e. wind and solar respectively, as the authors also pointed out in a comparison between Italy and Germany [36]. RES excess and CO_2 emissions curves also show the same trend: an exponential growth for the excess of production and a saturation for CO_2 reduction, which becomes almost flat at 75 % wind. A preliminary analysis was also conducted in this study to demonstrate that combining building and transportation end-uses through EVs, HPs, heat storage and CHP represents an effective solution to support IRES integration (e.g. at 100 % wind scenario the electrification of transport and heating sector could reduce by one-third the excess from wind). With respect to the Danish case, Lund et al. performed another advanced energy system analysis acting on the heating sector only, where conventional boilers were assumed to be replaced by a variety of possible alternatives [55, 56]. To achieve a future 100 % renewable energy scenario, this study demonstrated that individual HPs and district heating are preferable from both an energy and economic perspective; such alternatives are also able to absorb the excess

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of wind power arising from the increase in its installed capacity. In particular, with HPs covering entirely individual heat demand, energy consumption was halved as compared to the conventional boilers option.

Connolly and Mathiesen used a 2020 Irish energy system forecast as a case study to define a transition towards a 100 % renewable energy system, acting on the supply side of the energy system through subsequent key stages that included the installation of small and large-scale HPs as well as EVs [57]. Despite analysing a different national energy system (due to Ireland's climate conditions wind power is the primary form of IRES), results confirmed that heat and transport electrification could reduce primary energy supply since both HPs and EVs are more efficient than their conventional alternatives. As a result of a combination of these measures, under the assumption of 37 % of buildings heat demand covered by district heating, primary energy supply could be reduced by 25 % with respect to the reference scenario.

As a result, findings herein discussed extend the previously mentioned literature providing an insight on how possible CO_2-reduced future scenarios could look like where RES are assumed to grow progressively along with EVs in the private transport including also HPs in the individual heating sector. Their effect is analysed first individually (Figs. 1 and 2) and then jointly (Figs. 5 and 6). Results may provide the basis for a "back-casting" type of analysis that compares different possible scenarios and could ultimately help policy makers in defining a strategic planning method that starts with choosing a desirable future, among the proposed ones, and then works backwards to identify actions and programs to connect that specified future to the present.

4. Conclusions

This study assessed the impact of transport and heating electrification on the Italian energy system, first by comparing the effects of progressively increasing shares of EVs and HPs replacing conventional alternatives, in the context of an increase in IRES capacity; then with an analysis of optimal scenarios presenting the best trade-offs between annual CO_2 emissions and total costs, taking as decision variables IRES capacity, EV and HP penetration and energy savings in the heating sector. IRES capacity was allowed to increase up to maximum values related to technical-social potentials for PV, onshore and offshore wind.

Results show that, when IRES capacity grows up to approximately 9.5 times its 2017 level, CO_2 emissions can be reduced significantly by both transport and heating electrification, down to approximately 70–75 % of the 2017 level, with an overall renewable penetration reaching approximately 65 % of national electricity demand. More specifically, private transport electrification supports the incorporation of higher IRES within the national electricity generation mix, while heating electrification actually leads to a decrease in RES penetration, due to the mismatch between hourly profiles of heating demand and IRES supply. This happens because heating demand is at its highest when potential RES supply is relatively low, both on a daily and seasonal basis, thus the contribution of conventional plants in supplying the additional electricity demand for heating purposes is not negligible and leads to the observed decrease in RES share. Nonetheless, the relatively high efficiency of NG power plants, combined with the inherent efficiency of HPs, allow a reduction in CO_2 emissions compared with the reference case.

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A techno-economic analysis applied to the Italian case, including a variety of possible measures for the decarbonisation of the national energy system, confirms the key role that EVs and HPs could play in curbing CO_2 emissions together with increased IRES generation. However, while the parametric analysis highlights the higher beneficial effect of EV penetration on CO_2 emissions reduction compared to HPs, in the context of a techno-economic optimisation the genetic algorithm heavily leans towards HPs thanks to the significant variable costs savings achievable, while EV penetration appears to be hindered by current relatively high costs. With this specific regard, results could significantly vary if EV cost reductions, which are widely expected to occur, are implemented.

Acronyms

CHP Combined Heat and Power

EV Electric Vehicles

HP Heat Pump

IRES Intermittent Renewable Energy Sources

LDV Light-Duty Vehicles

LPG Liquefied Petroleum Gas

MOEA Multi-Objective Evolutionary Algorithm

NG Natural Gas

P2G Power-to-Gas

P2L Power-to-Liquid

PNEC National Plan for Energy and Climate

PV Photovoltaic

PP Power Plant

RES Renewable Energy Sources

SPF Seasonal Performing Factor

TPES Total Primary Energy Supply

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Nomenclature

$\bar{c}$	Vehicle average energy consumption (kWh/km)
C	Costs (EUR)
D	Transport demand (km)
E	Electric energy consumption (TWh)
F	Fuel energy consumption (TWh)
H	Heat demand (TWh)
N	Number of vehicles
x	Decision variable
η	Average efficiency

Subscripts

b	boiler
bm	biomass
d	diesel
el	electric
g	gasoline
h	gasoline
t	heating

Appendix A. Reference case scenario: national energy system data in 2017

Table A.1: CHP and Power Plant (PP) installed capacity and efficiency (Sources: [28, 58]).

Group	Capacity (GW)	η_{el}	η_{th}
PP	37.88	44.52%	
CHP	26.16	39.14%	21.71%

Table A.2: RES installed capacity (GW) (Source: [28]).

Technology	Capacity
Onshore wind	9.77
Offshore wind	-
Photovoltaic	19.68
Hydro	22.84
Geothermal	0.82

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Table A.3: Power plants fuel consumption (TWh/year) (Sources: [28, 58]).

Fuel	PP	CHP
Coal	83.80	8.40
Oil	5.83	42.59
NG	100.23	190.30
Biomass	31.81	40.05

Table A.4: Electricity loads (TWh/year).

Load	Consumption	Source
Electric cooling	8.91	[59, 60]
Electricity for HPs (individual)	18.93	[37]
Electric heating (individual)	8.07	[61]
Electricity for transport	11.38	[62]
Other electricity loads	286.30	[28]
Total demand (gross)	*333.59*	
Net import	-37.76	[28]
Total domestic production (gross)	295.83	

Table A.5: Fuel/electricity consumption, heat demand (TWh/year) and efficiency for individual heating.

Technology	Consumption (Sources: [23, 58])	Efficiency/SPF (Sources: [63, 37])	Demand
Oil boilers	27.02	0.90	24.32
NG boilers	265.08	0.92	243.87
Biomass boilers	82.33	0.75	61.75
Electric boilers	8.07	1.00	8.07
Heat pumps	18.93	2.63	49.79
Total demand			387.80

Table A.6: Derived heat gross demand (TWh/year; source: [58]).

Residential and services	14.10
Energy industry own use	16.31
Industry	33.42
Others	0.30

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Table A.7: Transport sector fuel consumption (TWh/year; sources: [62]).

Fuel	Consumption
JP (Jet Fuel)	8.44
Diesel	244.04
of which biodiesel	11.97
Petrol	86.43
of which biopetrol	0.38
NG	12.37
LPG	21.30
Electricity	11.38

Table A.8: Industry and various sector fuel consumption (TWh/year; source: [58]).

Fuel	Industry	Energy industry own use	Agriculture and others
Coal	8.22	0.65	0
Oil	22.72	35.60	29.83
NG	103.15	16.48	13.84
Biomass and waste	7.27	21.13	0.89

Table A.9: CO_2 emission factors by fuel (Source: [45]).

Fuel	kg/GJ
Coal	93.89
Oil	76.69
NG	57.62
LPG [40]	59.64

Table A.10: Sources used for hourly distributions.

Electricity demand	[64]	Cooling demand	[40]
Fixed Import/Export	[65]	Electricity for transport	[40]
District heating demand	[66]	Wind power	[65]
Individual heating demand	[26, 67]	PV generation	[65]
Industrial CHP heating demand	[40]	River Hydro power	[65]
Industry gas demand	[26]	Geothermal power	[65]

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