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Impact and costs of proposed scenarios for power sector decarbonization: an Italian case study

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ABSTRACT

In the face of ever more ambitious global energy challenges, the European Union has set striving climate targets for 2030, planning to increase renewable energy penetration in the electricity generation as a key measure towards a clean energy transition. To respond to the challenge of keeping the increase in power sector costs, that inevitably arises when a profound reconfiguration of the electricity generation sector is expected, to the lowest possible, this paper aims to quantify the economic burden associated with the reduction of direct CO_2 emissions through a comparative assessment of various alternatives proposed for 2030 ranked in terms of their cost-effectiveness.
A sensitivity analysis is also applied to the main economic and energy parameters that make up CO_2 mitigation costs to include those uncertainties that characterise future projections. The impact of electricity generation shares on CO_2 mitigation costs is assessed thus providing a basis for the definition of alternative configurations for the Italian electricity sector capable to achieve the desired environmental performance with a limited economic impact.
Finally, results reveal that those scenarios based largely on natural gas and solar source are characterized by high mitigation costs, while energy efficiency is essential for a virtuous and clean electricity sector along with the use of all available sources in appropriate shares, both renewable and non-renewable, to pursue the highest environmental objectives in a cost-effective manner. Although related to the Italian case, the methodology provided in this study can be applied to any other electricity sector to ultimately evaluate the economic burden arising from possible different configurations.

KEYWORDS

Electricity generation mix, power sector decarbonisation, intermittent renewable sources, CO_2 mitigation cost, CO_2 emissions avoided

1. INTRODUCTION

The growing global concern about climate change is pushing all countries to plan energy policies targeted to ever less environmental impact. In this regard, the European Union has taken significant steps towards reaching challenging energy and climate objectives and adopted in 2009 the so-called "20-20-20 climate and energy package" (Directive 2009/28/EC) (European Commission, 2009a) focused on the promotion of the use of energy from renewable sources, complemented by a following one (Directive 2009/29/EC) (European Commission, 2009b) to improve and extend the greenhouse gas emission allowance trading scheme of the Community. In particular, the Directive sets ambitious goals for the entire Union: a 20% reduction in EU greenhouse gas emissions (from 1990 level), a 20% share of final energy consumption covered by renewable sources and a 20% improvement in energy efficiency.
With the Paris Agreement in 2015 (UNFCCC, 2015) and on track to meet its emissions reduction target for 2020 (European Commission, 2019a), the EU has committed itself to move further ahead aiming to a reduction in greenhouse gas emissions of at least 40% by 2030 compared to 1990. To respond to this challenge, the EU defined in 2019 an updated energy policy framework for the coming years, including key rules and legislative parameters (European Commission, 2019b).
As Parties of Paris Agreement, also member states have engaged themselves to present mid- and long-term greenhouse gas reduction proposals defining sophisticated future scenarios involving the energy system in all its energy sectors along with policies for energy strategies implementations and technologies evolutions (E3MLab and IIASA, 2016).

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Intergovernmental Panel on Climate Change drew up a report in which different scenarios, concerning the opportunities to limit warming to 1.5 °C above pre-industrial levels, were elaborated (IPCC, 2018): such scenarios were categorized according to climate targets, socio-economic assumptions and the capability of following Nationally Determined Contributions; these studies were also reviewed by (Committee on Climate Change, 2019) to recommend new emissions target for the UK. To comply with Paris Agreement, the UK produced a National Energy and Climate Plan (Department for Business, Energy & Industrial Strategy, 2019) and, in a similar way, future CO_2-reduced scenarios were designed specifically for Italy as well; in 2017, to manage and outline the transformation of the energy system, the Italian Government drew up a ten-year plan within a National Energy Strategy (NES) (Ministero dello Sviluppo Economico, 2017).

As greenhouse gas reduction goals become more ambitious, so do costs arising from the reconfiguration of fossil fuel-based power systems. As a result, it should be a key target for policymakers to maintain this increase to the lowest possible to comply with climate objectives with the least CO_2 mitigation costs (MC).

Although various strategies have been elaborated both at a European and at a national scale, the economic burden associated with the expected reduction of CO_2 emissions is seldom investigated using MC and even more rarely this crucial parameter is used to compare energy policies among them.

In this context, focusing on possible development pathways for the electricity generation sector, which is expected to go through substantial changes in the coming decade, this paper aims to analyse comparatively the economic impact of different possible scenarios for the Italian case in 2030, essentially investment costs incurred to install new generating capacity for non-programmable renewable sources along with variable costs related to fossil fuels consumption in conventional power plants. The proposed configurations for the power sector evolution are reviewed and compared by means of MC to ultimately quantitatively assess the cost-effectiveness of the alternatives considered in reducing CO_2 emissions; such parameter becomes crucial in the context of a comparative analysis providing a direct comparison of the CO_2 abatement cost that different scenarios measures entail.

Moreover, MC parameter is directly comparable with the CO_2 price provided by policymakers in each of the scenarios analysed. In fact, when direct CO_2 emissions reduction is considered, the economic burden of CO_2 abatement can be directly compared with the CO_2 price in the ETS: if no additional zero-emissions power plants are put in place, fossil fuels must be deployed to cater for additional electricity needs with the additional CO_2 emissions encumbered by the price of CO_2.

In addition, to identify which of the implemented scenarios variables have the greatest effect on MC, a dedicated sensitivity analysis is also carried out; MC variation is thus evaluated as a function of both cost parameters and electricity shares produced by the different technologies involved in the electricity generation mix.

This study describes and implements a methodology that allows a variety of future scenarios to be simulated and analysed in terms of crucial energy and economic indicators. Most importantly, by applying the proposed method, different new configurations for the Italian energy sector are suggested, starting from the scenarios initially available which are then reconfigured to provide the same amount of electric energy and specific CO_2 emissions. Such analysis allows new and considerable conclusions to be drawn based on different cost assumptions.

As a result, the work provides detailed information on the economic and environmental impact of possible strategic national choices in the electricity generation sector within a comparative assessment of official scenarios elaborated by state authorities and evaluates the effectiveness of other possible alternatives, suggested through the application of a proper method. All assessments are elaborated within a parametric analysis that takes into account uncertainties that inevitably come along with future projections. Besides performing a comparative evaluation of already available scenarios outlining future pathways for the Italian power sector, the ultimate aim of the study is to extend, and contribute to, the existing literature proposing novel innovative structures for the electricity generation sector, equally virtuous in environmental terms, but less impacting at an economic level.

Moreover, the method proposed in this paper can also be implemented elsewhere to propose specific structures for any electricity generation sector and to evaluate their impact and costs when these structures are devoted to decarbonise the electric sector analysed.

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2. LITERATURE REVIEW

Deep decarbonisation commitments can be met only provided that a profound energy system transition in the European Union is realised across all sectors of the EU economies and societies; in this regard, scenario-based studies become essential to quantitatively assess the impact of different low-carbon measures that CO_2 emissions reduction targets imply.

Hübler and Löschel (2013) focused on the EU Decarbonisation Roadmap, concluding that its successful realisation requires a wise and joint consideration of technology, policy design and sectoral aspects. Capros et al. (2018) provided an outlook of the EU energy system for the medium-long term through a comparative impact assessment of EUCO scenarios accompanying the submission of the policy package presented by EU institutions, revealing the key role of energy efficiency and renewable energy sources along with a shift from operating to capital expenses. Fragkos et al. (2017) demonstrated that restructuring the EU energy system induces changes in the energy mix and production with small effects on the European gross domestic product, but energy efficiency improvements, increasing penetration of renewables, fuel switching towards natural gas, and the technical progress in processes related to emissions abatement are identified as essential options. Different decarbonisation pathways, either driven by the effort of energy carrier suppliers or consumers or both, are also comparatively analysed for the EU energy system towards a sustainable transition by Korkmaz et al. (2020), results are provided in terms of energy consumption. The review of such different pathways is performed in order to explore the consequences deriving from the complying with the Paris Agreement: in order to do this, a model named BRAIN-Energy was developed by Barazza and Strachan (2020), comparing UK and Italy's possibilities; the results display that the two countries must act under the same logic of enhancing gas-based installed capacity and production.

Furthermore, aiming at raising ambitions further towards carbon neutrality, in recent years studies of a 100% renewable energy system have gained increasing attention, showing a predominant focus on the electricity sector for European countries (Hansen et al., 2019). Results demonstrate that large-scale renewable electricity systems can potentially be technologically feasible, and meet the criteria of reliability, security and affordability (Diesendorf and Elliston, 2018) especially under a smart energy system approach is deployed (Connolly et al., 2016), with a key role of flexible electricity generation, grid exchange and storage in supporting such transition (Child et al., 2019). According to Young and Brans (2017), a shift towards a 100% renewable energy system is only possible if the governance is "horizontally" devoted to this purpose, encouraging the participation of the local community in the decision-making process. Other authors (Sofia et al., 2020) applies cost-benefit analysis to evaluate the mitigation strategies adopted in Italy for 2030 under the decarbonization scenario from an environmental and social welfare perspective: they evaluate the potential benefits in terms of reducing major air pollutants (PM2.5, PM10, SOx, NOx, CO and VOC), mortality and morbidity. Other authors (Calise et al., 2017) proposed some possible future scenarios for the year 2050, able to achieve a deep decarbonization of the Italian energy system thanks to high electrification of transports and residential buildings and a shift towards public transport.

On the other hand, the implementation of stringent carbon-reduction measures inevitably results in additional power system costs; as a result, defining a proper policy framework and selecting appropriate measures to estimate the potential of CO_2 emission reduction through an MC-based approach becomes crucial to undertake a climate action plan in a cost-effective manner.

Hof et al. (2017) estimated the abatement costs of achieving the GHG emissions levels of energy policy proposals in 2030. This estimate covers all countries in the world and all energy sectors. Jägemann et al. (2013) evaluated the economic implications of alternative energy policies for Europe's power sector in over 36 scenarios finding that the costs of decarbonizing Europe's power sector by 2050 vary between 139 and 633 bn €2010. According to Liu and Feng (2018) CO_2 emissions could be reduced by 4482.28 Mt worldwide at a price of approximately 674–698 \$/t. These evaluations are reliable, bearing in mind the target of a cost-optimal power generation mix, only if curtailment of production from intermittent energy sources is taken into account (van Zuijlen et al., 2019).

Oshiro et al. (2017) studied implications of the target reduction in greenhouse gas emissions by 2030 in Japan, finding that the various scenarios studied incur carbon price hikes of over 160 $\$/t_{CO2}$ and need effective policy supports. Gillich et al. (2019) modelled different CO_2-reduced scenarios involving the evolution of German power sector to 2050 to assess MC under different modelling

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assumption (year-specific CO_2 caps with or without coal phaseout versus time-transcending carbon budget), demonstrating that average value of MC may vary between 106 and 83 €/t for the national German energy system. Li et al. (2018) used a multiobjective genetic algorithm to assess the potential and macroeconomic costs of CO_2 emission abatement in Beijing by means of in an integrated into an input-output analysis revealing abatement costs in the range 260–536 $/t at different rates of economic growth.

In this framework, this paper provides information on the economic burden associated with the forecasted national choices concerning the reconfiguration of the Italian power sector deploying an MC-based methodology, so far not been used in the existing literature having Italy as a case study. Furthermore, the work proposes interesting alternative options for the Italian power sector in 2030, equally virtuous in environmental terms, but less impacting at an economic level, providing a detailed comparative analysis evaluating cost-effectiveness of these alternative configurations of the national electricity sector in reducing direct CO_2 emissions.

3. CASE STUDY

Among the several energy pathways developed for 2030, four scenarios, applied to the Italian case, were chosen to be analysed and compared starting from the assumption that the objectives set for 2020 by the reference scenarios are met that, in details, can be summarised as follows (European Commission, 2016c):

- primary energy consumption: 153.9 Mtoe;
- final energy demand: 122.5 Mtoe;
- gross electricity generation: 316.5 TWh;
- total GHG emissions: 458.9 Mt of CO_2 eq. (a 12.6% decrease compared to 1990);
- CO_2 emissions from power generation sector: 121.6 Mt.

Projections to 2030 are then considered for each of the simulated alternatives. The reference scenario (named 2030-REF hereafter) provides for 2030 the following targets (European Commission, 2016c):

- primary energy consumption: 142.4 Mtoe;
- final energy demand: 115.9 Mtoe;
- gross electricity generation: 323.1 TWh;
- total GHG emissions: 393.4 Mt of CO_2 eq. (a 25.1% decrease compared to 1990);
- CO_2 emissions from power generation sector: 94 Mt.

As concerns policy scenarios, both EUCO (E3MLab and IIASA, 2016) and NES (Ministero dello Sviluppo Economico, 2017) objectives were considered. The targets set by EUCO scenarios are intended for EU member states as a whole and described in the following:

- 2030 EUCO27:
  - 40% GHG emissions reduction compared to 1990;
    - 43% GHG emissions reduction (compared to 2005) in the EU-ETS configurations;
    - 30% GHG emissions reduction (compared to 2005) in non-EU ETS configurations;
  - 27% reduction in primary energy consumption (down to 1369 Mtoe by 2030 in Europe and 136.4 Mtoe in Italy) as compared to what assumed by the reference scenario (PRIMES 2007 baseline), i.e. 1887 Mtoe in 2030;
  - a share of 27% in final energy consumption covered by renewable sources.
- 2030 EUCO40:
  - 47% GHG emissions reduction compared to 1990
    - 48% of greenhouse gas emissions (compared to 2005) in the EU-ETS configurations;
    - 39% GHG emissions reduction (compared to 2005) in non-EU ETS configurations;
  - 40% reduction in primary energy consumption (down to 1129 Mtoe by 2030 in Europe and 108.7 Mtoe in Italy);
  - a share of 28% in the final energy consumption covered by renewable sources.
- 2030 NES, that foresees for the Italian case a coal phaseout in the power sector for the years ahead. It is worth mentioning that today, 8 GW of coal-based capacity are installed producing 33 TWh in 2017 (Gestore dei Servizi Energetici, 2018) 11% of the overall gross generation.

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Along with this target, Italy is expected to reach a 55% share of renewables in electricity consumption by 2030 as well as:

- a reduction of GHG emissions in the following shares:
  - 57% decrease (compared to 2005) in the EU-ETS configurations
  - 33% decrease (compared to 2005) in non-EU ETS configurations
- a reduction of 42% in primary energy consumption (down to 135.9 Mtoe in 2030) as compared to what assumed by the reference scenario (PRIMES 2007 baseline), i.e. 232.6 Mtoe in 2030.

Table **Error! Reference source not found.** summarises the objectives in the aforementioned scenarios for the Italian case.

Table 1. Italy 2030 targets in the analysed scenarios.

	2030-REF (European Commission, 2016c)	2030 EUCO27 (E3MLab and IIASA, 2016)	2030 EUCO40 (E3MLab and IIASA, 2016)	2030 NES (Ministero dello Sviluppo Economico, 2017)
Primary energy (Mtoe)	142.4	136.4	108.7	135.9
Final energy demand (Mtoe)	115.9	112.0	88.8	108.0
Gross electricity (TWh)	323.1	318.9	261.5	304.0
Total CO_2 emissions (Mt)	393.4	359.7	305.1	332.0
CO_2 in electricity sector (Mt)	94.0	77.4	53.5	n.a.

4. METHODS

The method proposed in this study allows to estimate the economic impact associated with energy targets projected in different energy policies for any power sector by means of MC; such costs can then be compared with the price of CO_2 provided by different estimations on future energy scenarios. The proposed method allows also to analyse the influence of electricity production by fossil fuels and by renewable intermittent sources on MC.

Finally, this method can outline new possible cost-effective configurations for any power sector, once set an equivalent amount of both electricity generation and CO_2 emissions.

4.1 Definition of additional required parameters for the estimation of MC

To quantify MC, the following parameters are required input for each of the analysed scenarios and, consequently, need to be estimated when not explicitly reported:

- net generation capacity;
- fuel input to thermal power generation;
- CO_2 emissions from power generation sector.

Net generation capacity, in those scenarios that only refer to energy generation values for each power generation technologies, is evaluated based on the other scenarios, where capacity data are instead available, and starts with the calculation of the operating hours:

$$h_{i,j} = \frac{E_{i,j}}{P_{i,j}} \tag{1}$$

where $h_{i,j}$, $E_{i,j}$ and $P_{i,j}$ are respectively the equivalent operating hours, electricity generation and net power capacity for the *i*-th electricity generation technology within the *j*-th scenario.

Operating hours are then averaged over the different scenarios:

$$\bar{h}_i = \frac{\sum_j h_{i,j}}{n} \tag{2}$$

where *n* is the number of scenarios.

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As a result, net generation capacity $P_{i,k}$ can be derived for the different power generation technologies also in those *k* scenarios where such value is missing:

$$P_{i,k} = \frac{E_{i,k}}{\bar{h}_i} \tag{3}$$

Fuel input to thermal power generation can be also estimated based on electrical efficiency values, evaluated from the other scenarios where fuel input-related data are available:

$$\eta_{i,j} = \frac{E_{i,j}}{F_{i,j}} \tag{4}$$

where $\eta_{i,j}$ and $F_{i,j}$ are respectively the electrical efficiency and fuel input to thermal power generation for the *i*-th electricity generation technology within the *j*-th scenario.
Efficiencies are then averaged over the different *n* scenarios for each electricity generation technology *i*:

$$\bar{\eta}_i = \frac{\sum_j \eta_{i,j}}{n} \tag{5}$$

and applied to those *k* scenarios where fuel input to thermal power plants is not initially available:

$$F_{i,k} = \frac{E_{i,k}}{\bar{\eta}_i} \tag{6}$$

Direct CO_2 emissions can be thus evaluated based on fuel input values deployed for electricity generation for the *i*-th technology:

$$CO_{2,i} = EF_i \cdot F_i \tag{7}$$

where EF_i is the emission factor of the particular fuel used for electricity production.

4.2 Procedure used for the evaluation of mitigation cost

Based on the aforementioned data, the economic impact associated with measures forecast in the analysed scenarios can be evaluated through the cost of CO_2 emissions avoided; such costs are then compared with the price of CO_2 provided for 2030 in the different scenarios. To define this cost, the following procedure is used:

- focus is given to intermittent renewable sources (solar and wind) and on fossil fuels;
- in each scenario, the difference in electricity produced by each source in 2020 and in 2030 is calculated:

$$\Delta E_i = E_{i,2030} - E_{i,2020} \tag{8}$$

- to guarantee the electricity production foreseen in each of the analysed scenarios, the additional generating capacity is calculated in comparison with the installed generating capacity in 2020. If a reduction in electricity production from a source is expected, a decommissioning of the existing generating capacity is considered, without additional economic costs:

$$\Delta P_i = P_{i,2030} - P_{i,2020} \tag{9}$$

- cost of fossil fuels to generate the expected electricity in 2030 is assessed; dividing this cost by the expected electricity, the economic impact of each MWh of electricity produced in 2030 by fossil fuels in each *j* scenario is evaluated ($C_{1,j}$, €/MWh):

$$C_{1,j} = \left(\frac{\sum_i F_i \cdot C_{F_i}}{\sum_i E_i}\right)_{2030,j} \tag{10}$$

  where C_{F_i} is the cost of the *i*-th fuel in 2030;
- the economic impact of additional generating capacity from intermittent renewable sources is estimated and this cost is charged to 2030 with reference to an appropriate present annuity factor, Paf. Total cost must include also operation and maintenance costs; dividing this total cost for the expected electricity, the economic impact of each additional MWh, produced by intermittent renewable sources in each *j* scenario, is evaluated ($C_{2,j}$, €/MWh):

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$$C_{2,j} = \left(\frac{\sum_i \Delta P_i \cdot \left(\frac{C_{P_i}}{Paf} + C_{O\&M,P_i} \right)}{\sum_i (E_{i,2030} - E_{i,2020})} \right)_{2030,j} \quad (11)$$

where C_{P_i} and $C_{O\&M,P_i}$ are respectively the specific and the operation and maintenance costs of the *i*-th technology in 2030;

– based on the amount of fossil fuels used in 2030 and 2020, direct CO_2 emissions avoided can be estimated:

$$\Delta CO_2 = CO_{2,2030} - CO_{2,2020} \quad (12)$$

– the ratio between total annual costs (associated with additional generating capacity and the difference in fossil fuels used between 2020 and 2030) and the difference of CO_2 emissions between 2020 and 2030 provides the cost of CO_2 avoided. This parameter is indicated as mitigation costs (MC) and its application in a comparative analysis of scenarios represents the main contribution of the present paper as it is seldom adopted as a comparison criterion in the existing literature on this topic:

$$MC = \frac{\frac{C_{new\ generation\ capacity}}{Paf} + C_{O\&M,new\ generation\ capacity} + (C_{fossil\ fuels\ 2030} - C_{fossil\ fuels\ 2020})}{CO_{2,2020} - CO_{2,2030}} \quad (13)$$

where:

$$C_{new\ generation\ capacity} = C_{wind} \cdot (P_{wind,2030} - P_{wind,2020}) + C_{solar} \cdot (P_{solar,2030} - P_{solar,2020}) \quad (14)$$

$$Paf = \sum_{J=1}^{n} \frac{1}{(1+i)^j} = \frac{(1+i)^n - 1}{(1+i)^n \cdot i} \quad (15)$$

$$C_{O\&M,new\ generation\ capacity} = C_{O\&M,wind} \cdot (P_{wind,2030} - P_{wind,2020}) + C_{O\&M,solar} \cdot (P_{solar,2030} - P_{solar,2020}) \quad (16)$$

$$C_{fossil\ fuels,k} = (C_{solid} \cdot F_{solid} + C_{gas} \cdot F_{gas} + C_{oil} \cdot F_{oil})_k \quad (17)$$

$$CO_{2,k} = (EF_{solid} \cdot F_{solid} + EF_{gas} \cdot F_{gas} + EF_{oil} \cdot F_{oil})_k \quad (18)$$

where *C* stands for cost, *F* for fuel amount, CO_2 for carbon dioxide emission amount, *EF* for emission factor, *Paf* for present worth annuity factor, *i* for discount rate and subscript *k* refers to the considered year (i.e. 2020 or 2030).

The variety of scenarios considered are then modelled in Matlab and their impact evaluated quantitatively.

4.3 Influence of electricity generation shares on MC

Aiming to define virtuous configurations of the electricity sector, based on the scenarios analysed in the previous section, the influence of electricity production by fossil fuels and by renewable intermittent sources on MC has been also analysed.

The following parameters are assumed known in each of the analysed configurations:

- $E_{2030,k}$, the total electricity production in each *k* scenario in 2030;
- $E_{no\ int,2030,k}$, the electricity production by non-intermittent renewable sources (geo, bio and hydro) in each *k* scenario in 2030;
- $E_{int,2020,k}$, the electricity production by intermittent renewable sources in each *k* scenario in 2020.

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The remaining electricity generation is divided between fossil fuels and non-programmable renewable sources, starting from the case where the production is guaranteed by fossil sources only (lowest CO_2 emissions avoided) to the opposite situation where non-programmable renewable sources fulfil totally the national electricity needs (highest CO_2 emissions avoided):

$$\Delta E_{2030,k} = (E_{2030} - E_{no\ int,2030} - E_{int,2020})_k \tag{19}$$

$$\Delta E_{2030,k} = \left(E_{fossil\ fuel,2030} + E_{add\ int,2030}\right)_k \tag{20}$$

where $E_{add\ int,2030}$ is the additional electricity generation from intermittent renewable sources in each *k* scenario. Thus:

$$E_{int,2030,k} = (E_{int,2020} + E_{add\ int,2030})_k \tag{21}$$

$$E_{add\ int,2030} = \Delta E_{2030} - E_{fossil\ fuel,2030} = E_{2030} - E_{no\ int,2030} - E_{int,2020} - E_{fossil\ fuel,2030} \tag{22}$$

As the economic costs of each MWh of electricity produced in 2030 by fossil fuels (C_1, €/MWh) and intermittent renewable sources (C_2, €/MWh) are defined in the previous section, the impact of electricity production from fossil fuels and renewable intermittent sources on MC can be evaluated. This impact on MC in reference and policy scenarios has been assessed; in this case, in each *k* scenario, MC as a function of electricity production by fossil fuels is calculated as follows:

$$MC = \frac{C_1 \cdot E_{fossil\ fuels\ 2030} + C_2 \cdot E_{add\ int,2030} - C_{fossil\ fuels\ 2020}}{CO_{2,2020} - CO_{2,2030}} \tag{23}$$

MC can be expressed as a function of electricity production from either fossil fuels:

$$MC = \frac{E_{fossil\ fuels\ 2030} \cdot (C_1 - C_2) + C_2 \cdot \left(E_{2030} - E_{no\ int,2030} - E_{int,2020}\right) - C_{fossil\ fuels\ 2020}}{CO_{2,2020} - CO_{2,2030}} \tag{24}$$

or additional electricity production from intermittent renewable sources:

$$MC = \frac{E_{add\ int,2030} \cdot (C_2 - C_1) + C_1 \cdot \left(E_{2030} - E_{no\ int,2030} - E_{int,2020}\right) - C_{fossil\ fuels\ 2020}}{CO_{2,2020} - CO_{2,2030}} \tag{25}$$

while C_1 remains constant in each of the simulated scenarios, C_2 varies depending on the additional capacity installed from renewable sources.

To perform such calculations, the variety of scenarios considered have been modelled in Matlab and their correctness validated in the context of the previous simulation of reference and policy scenarios.

4.4 Definition of new possible configurations for any power sector

As MC depend on the total electricity production estimated in the different scenarios, new configurations for any power sector, to be properly outlined, must be based on the same amount of overall electricity generation and projected reduction of CO_2 emission.

As a result, once the desired reduction in CO_2 emissions and the total electricity production is established, in each new configuration of the electricity sector the percentages of electricity production by each source and the associated MC can be estimated.

Applying this method to the Italian power sector, for this last assessment, it was assumed that CO_2 emissions avoided are 69 Mt/year (this value is forecast in the 2030 NES scenario) and total electricity production is 302 TWh (this is almost the average value of the predictions of the four scenarios analysed); therefore, each power sector mix exhibits the same specific CO_2 emissions (167.4 g/kWh).

The definition of the alternative configurations for the national power sector follows the procedure described in the following.

In all scenarios the following parameters are assumed known:

- $E_{2030,k}$, the total electricity production in 2030, which is assumed to remain unchanged in each of the new *k* configurations;
- $E_{no\ int,2030,k}$, the electricity production by non-intermittent renewable sources (geo, bio and hydro) in each scenario in 2030. Each *k* configuration of the power generation sector is assumed

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to be characterised by an amount of electricity generation derived according to what projected for 2030 in each scenario described in Section 3.1;

- $E_{int,2020,k}$, the electricity production by intermittent renewable sources in 2020 assumed to be the same in each *k* scenario;

Electricity generation from fossil fuels and the additional electricity from intermittent renewable sources are evaluated as follows:

- $E_{fossil\ fuel,2030,k}$, is estimated as the electricity generated from fossil fuels that ensures the projected reduction of CO_2 emissions for each *k* scenario and obtained using the same fossil fuel share assumed for 2030 in the scenarios described Section 2;
- $E_{add\ int,2030,k}$, is the remaining electricity generation which is covered by the additional amount of electricity generation from intermittent renewable sources and distributed between solar and wind using the same shares reported in the scenarios described in Section 2.

Defined electricity shares generated by each technology in the new power sector alternatives proposed, MC are evaluated according to the procedure followed in Section 4.2 while fuel input to thermal power generation is evaluated according to what described in Eq. (6) for each *i* electricity generation technology and *k* scenario.
Finally, for each new power sector configuration, the additional net capacity generation from solar and wind is evaluated as follows:

$$\Delta P_{i,k} = \left(P_{i,2030} - P_{i,2020}\right)_k = \left(\frac{E_i}{\bar{\bar{h}}_i} - P_{i,2020}\right)_k \qquad (26)$$

5. RESULTS

5.1 Net generation capacity in different scenarios

In this section, the methodology proposed in the previous section allows to estimate the economic impact associated with energy targets projected for the Italian power sector in the scenarios presented in section 3. All these analysed scenarios provide net generation capacity for the expected gross electricity generation, with the exception of 2030 NES, where the procedure described in Section 4.1 is used to elaborate the results shown in Table 2.

Table 2. Net generation capacity in different scenarios (MW)

Power (MW)	*OB-2020* (European Commission, 2016c)	2030-REF (European Commission, 2016c)	2030 EUCO27 (E3MLab and IIASA, 2016)	2030 EUCO40 (E3MLab and IIASA, 2016)	2030 NES (this paper)
P_{solar}	*20,057*	24,562	37,111	37,111	51,519
P_{wind}	*8,963*	15,577	15,715	13,520	19,071
P_{hydro}	*18,808*	18,939	18,885	18,805	19,113
$P_{biomass-waste}$	*5,388*	5,409	5,620	5,484	2,815
$P_{geothermal}$	*773*	773	773	773	871
P_{coal}	*8,858*	5,098	5,098	5,098	0
P_{gas}	*51,365*	41,739	41,719	40,721	48,233
P_{oil}	*8,629*	2,332	2,170	2,172	766

5.2 Fuel input to thermal power generation in different scenarios

Besides net generation capacity, fuel input to thermal generation is also estimated for 2030 NES following what described in Section 4.1. Data for the different analysed scenarios are summarised in Table 3.

Table 3. Fuel input to thermal power generation in different scenarios (ktoe)

Fuel input (ktoe)	*OB-2020* (European Commission,	2030-REF (European Commission,	2030 EUCO27 (E3MLab and IIASA, 2016)	2030 EUCO40 (E3MLab and IIASA, 2016)	2030 NES [this paper]

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	2016c)	2016c)			
F_{coal}	*14,694*	9,087	6,098	3,929	0
F_{gas}	*21,521*	20,871	18,762	13,000	20,458
F_{oil}	*1,675*	1,682	1,489	829	469

5.3 CO_2 emissions in power generation sector in different scenarios

CO_2 emissions in the power generation sector are estimated from data reported in Table 3 and the emission factors, *EF*, of each fuel, i.e. 102 tCO_2/TJ for coal, 77 tCO_2/TJ for oil (including refinery gas) and 57 tCO_2/TJ for gas (including derived gases) (ISPRA, 2019).The results obtained are shown in Table 4 and are consistent with data in the scenarios taken as a reference for this analysis.

Table 4. CO_2 emissions in power generation sector in different scenarios (Mt)

CO_2 emissions (Mt)	*OB-2020*	2030-REF	2030 EUCO27	2030 EUCO40	2030 NES
Coal	*62.8*	38.8	26.0	16.8	0.0
Gas (including derived gases)	*51.4*	49.8	44.8	31.0	48.8
Oil (including refinery gas)	*5.4*	5.4	4.8	2.7	1.5
TOTAL	*119.5*	*94.0*	*75.6*	*50.5*	*50.3*

5.4 Comparison of electricity generation in reference and policy scenarios

Based on data extrapolated from 2030 energy scenarios reported in the previous section, a first evaluation is conducted on the electricity generation in Italy in 2030; results for the different scenarios are shown in Fig. 1 and compared against 2015 and 2020.

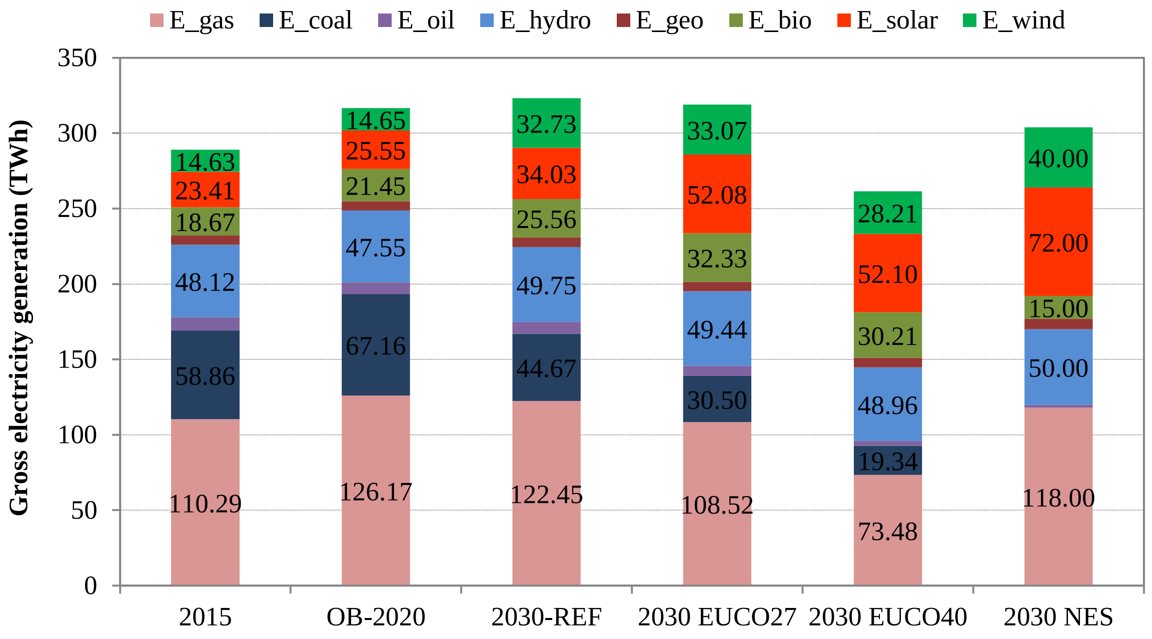

Fig. 1. Gross electricity generation in different scenarios

It is evident that the gross electricity generation has significantly different values depending on the particular scenario analysed: electricity generation in EUCO40 scenario appears relatively lower; indeed, this scenario forecast particularly ambitious energy efficiency policies in the residential, services and industrial sector. 2030 NES scenario also foresees a reduction in gross electricity production compared to 2020, however rather limited. The other two scenarios are characterized by almost equivalent, or at the most slightly higher, gross electricity production with respect to 2020.

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Besides gross electricity generation, it is also worth analysing how the different sources contribute to the overall production. To better analyse this aspect, in Fig. 2, the percentages of electricity generation from each source are reported. It clearly emerges that, starting from the reference scenario, there is an ever-decreasing contribution of fossil fuels to electricity production while, intermittent renewable sources, especially solar energy, supply an ever-increasing share of electricity. 2030 NES scenario records some differences compared to the other scenarios, precisely:

- total absence of coal in the electricity generation and use of natural gas to a rather large extent compared to the other two policy scenarios;
- massive reliance on solar source for electricity production;
- contraction of electricity production from biomass-waste.

These assumptions have significant consequences on costs required to reduce CO_2 emissions since natural gas has a high cost (higher than coal) and the conspicuous use of the solar source for electricity production will require the installation of a large additional generating capacity.

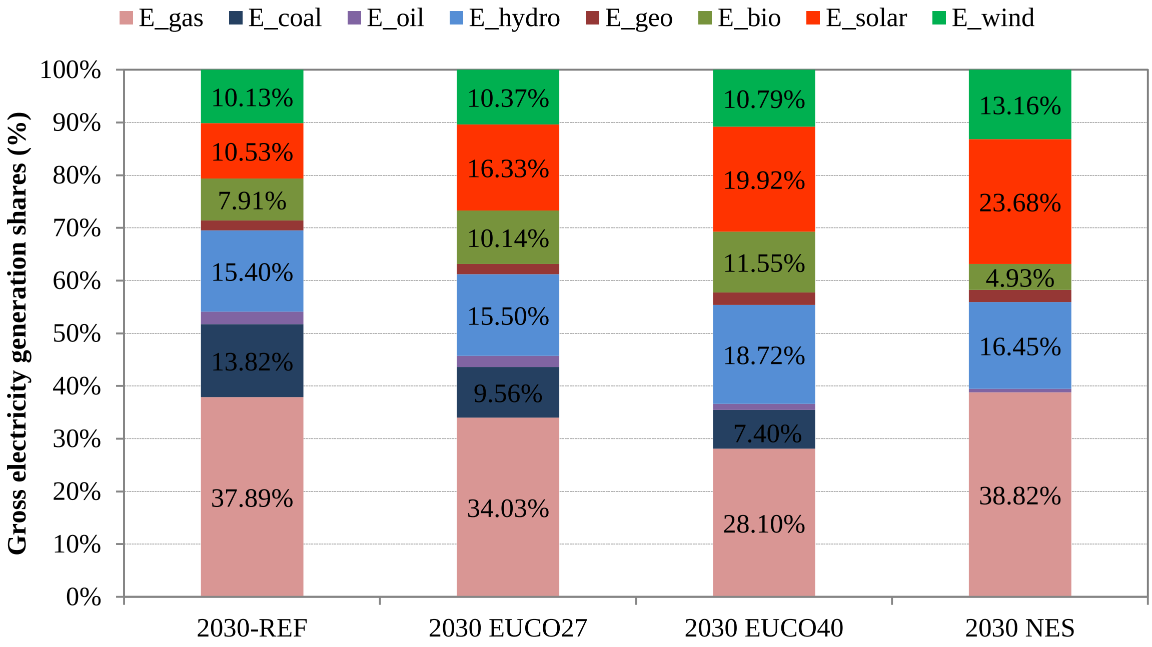

Fig. 2. Gross electricity generation shares in different scenarios

Other considerations can be drawn from CO_2 overall specific emissions for the analysed scenarios. OB-2020 shows a value equal to 377.6 $kgCO_2$/MWh, in line with what reported in the literature (Moro and Lonza, 2018) and close to the EU-28 average (340 $kgCO_2$/MWh). All the analysed 2030 scenarios feature a reduction of such parameter; 2030 NES, in particular, allows the lowest level of CO_2 specific emissions, i.e. 165.6 kg_{CO2}/MWh, due to the coal phaseout along with the significant deployment of natural gas and renewable sources in electricity generation. As for the other scenarios, 2030-REF, 2030 EUCO27 e 2030 EUCO40 show respectively 291.0, 273.1 and 193.0 kg_{CO2}/MWh.

5.5 MC in reference and policy scenarios

To quantify the MC, appropriate assumptions must be made about the costs of power plants and fuels in 2030. Conversions between US dollars and euros refer to the dates declared in the publications (where available); for the predictions to 2030, ratios of data in 2020 and 2030 have been considered. The data of the various sources have been made homogeneous, assuming, where necessary, the same basic assumptions.

With respect to fossil fuels price, Table 5 summarizes the main data available in the technical literature on the subject and used in these simulations. It is worth mentioning that fossil fuel costs do not take into account emissions costs in the ETS context.

Table 5. Fossil fuels price in different scenarios (€/GJ)

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Fuel price (€/GJ)	*'20-'30* (World Bank Group, 2019)	*'20-'30* (Eurostat, 2019)	*'20-'30* (Knoema, 2019)	*'20-'30* [this study]
Natural gas, C_{gas}		9.0 - /		9.0 - 10.5
Oil, C_{oil}	13.6 - 14.6			14.0 - 14.0
Coal, C_{coal}	3.2 - 2.1		3.0 - 2.0	3.0 - 2.5

With respect to solar and wind power plants, data available in the literature significantly differ greatly from each other as displayed in Table 6.

Table 6. New generating capacity costs (2030) in different scenarios (€/kWe)

Investment cost (€/kWe)	(IEA and NEA, 2015)	(EIA, 2016)	(EIA, 2019)	(IRENA, 2019a, 2019b)	(JRC, 2018)	(Heat Roadmap Europe, 2018)
Solar PV (tracking), C_{solar}	1600	2500	1700	760-310	950-430	640
Onshore wind, C_{wind}	1550	1800	1500	1230-730	1060-840	830

To take into account the variability in costs related to renewable sources generating capacity, three different models are considered:

- low-cost model (model 1): this model assumes the lowest costs for solar and wind technologies, respectively equal to 310 and 730 €/kWe;
- medium-cost model (model 2): this model is based on the median of solar and wind costs from the different available sources, resulting in 855 and 1145 €/kWe respectively for solar and wind technologies;
- high-cost model (model 3): in this model the highest costs for both technologies are taken into account, 2500 and 1800 €/kWe for solar and wind respectively.

In all the analysed scenarios, useful life is assumed equal to 30 years and the discount rate is set equal to 10%.
However, to take into account uncertainties related to these costs, a sensitivity analysis is carried out as shown in the next section to evaluate the effect of each parameter on MC.
Based on the data provided in the previous section, MC are calculated, and results are reported in Table 5 together with the CO_2 price in the various scenarios proposed.
When direct CO_2 emissions reduction is considered, the economic burden of CO_2 abatement can be directly compared with the CO_2 price in the ETS: if no additional zero-emissions power plants are put in place, fossil fuels must be deployed to cater for additional electricity needs and the additional CO_2 emissions would be encumbered by the price of CO_2.

Table 5. MC and CO_2 prices in different scenarios (€/t)

		2030-REF	2030 EUCO27	2030 EUCO40	2030 NES
	Model 1	43.72	11.42	-	17.18
MC	Model 2	65.38	40.65	-	49.91
	Model 3	114.3	119.1	23.30	139.4
Price of CO_2		34	42	14	-

It is worth mentioning that the lowest costs associated with solar and wind technologies lead to values of MC that, except for 2030-REF scenario, appear to be not congruent with the price of CO_2 estimated in the analysed scenarios. For instance, MC for in EUCO40 configuration is zero: in other words, the additional cost arising from the instalment of additional generation capacity is lower than the savings related to the decrease in fossil fuel deployment for electricity generation. On the other hand, the highest cost assumptions for solar and wind technologies lead to an overestimation of MC with respect to the price of CO_2 reported in the different scenarios.

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As a result, the following discussion is based on model 2 and 3 only although the effect of the other cost models is considered in the sensitivity analysis.
It is evident (model 2) that costs for reducing CO_2 emissions are much higher than the expected price of CO_2 in 2030-REF scenario (+92%) while they are aligned in 2030 EUCO27 configuration. 2030 NES is characterised by an elevated MC but lower than what featured in 2030-REF alternative.
Results can be discussed analysing Fig. 3 that displays both the numerator (on main y-axis) and the denominator (on secondary y-axis) of MC for each scenario. From this representation the role of each contribution to the total annual costs can be immediately inferred and compared to 2020 related both to the additional wind and solar generating capacity (in green and red respectively) and the reduction/increase of fossil fuels (coal in blue and gas and oil, together, in pink). The secondary y-axis shows the CO_2 emissions avoided (cyan line), compared to 2020, in the four scenarios analysed.

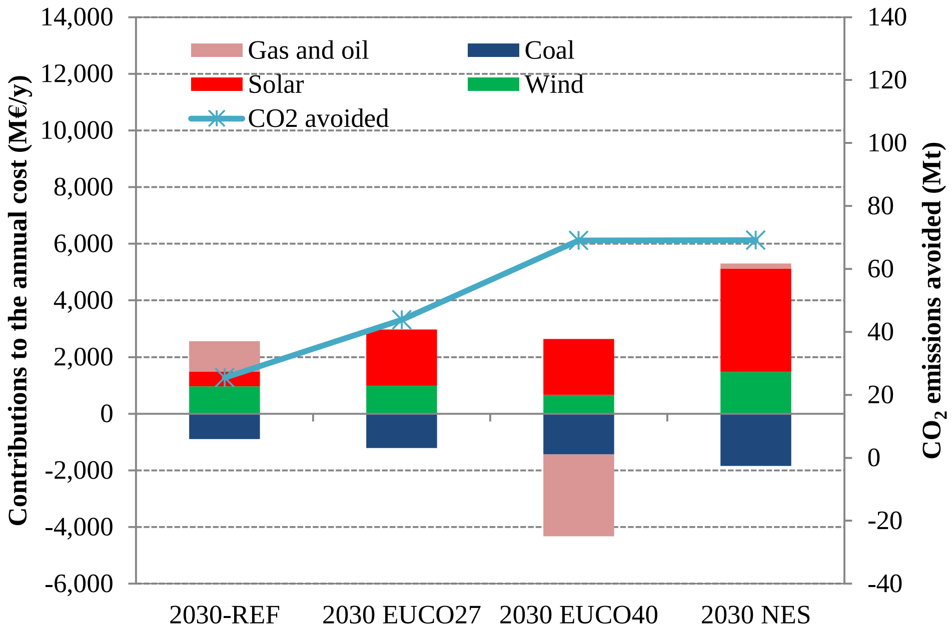

Fig. 3. Annual costs and CO_2 emission avoided in the different scenarios (model 2)

It immediately emerges that in all scenarios, with the exception of EUCO40, savings associated with fossil fuels (negative contributions) are quite limited; the 2030 NES scenario, while completely renouncing coal, presents savings, entirely associated with coal, comparable to that of the 2030 EUCO40 scenario, but it exhibits a cost, even if very limited, associated with natural gas; the overall saving is far lower than that of the 2030 EUCO40 scenario.
At the same time, economic costs associated with the installation of new generating capacity and with natural gas (where present) are higher than savings related to fossil fuels in all scenarios, except for EUCO40. Excluding 2030 EUCO40 from the analysis, 2030-REF scenario exhibits the lowest overall cost, almost evenly divided among new solar and wind generating capacity and natural gas. On the other hand, 2030 NES scenario exhibits the highest cost, attributable, for the most part, to the additional solar generating capacity, but also to natural gas, even if this share is much smaller than the case of 2030-REF scenario.
The secondary y-axis shows CO_2 emissions avoided compared to 2020: the 2030 EUCO40 and 2030 NES scenarios are particularly virtuous, as they allow CO_2 emissions to be reduced by around 70 Mt per year; the 2030 REF scenario, on the other hand, shows the least reduction in CO_2 emissions, amounting to just over 25 Mt per year.
In Fig. 4, MC are shown together with CO_2 emissions avoided and annual costs to be incurred to produce electricity by the amount forecast for the different scenarios in model 2.

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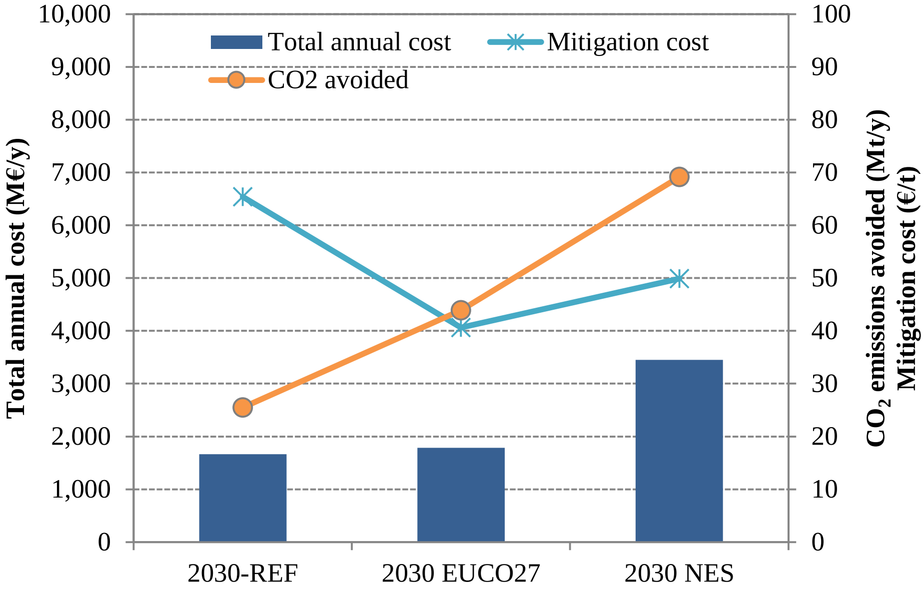

Fig. 4. Mitigation costs (MC) in different scenarios (model 2)

2030 EUCO 40 is not included in Fig. 4 since, as previously mentioned, such scenario shows cost savings with respect to 2020. 2030 NES scenario shows a value of MC equal to 50 €/t located in an intermediate position in terms of MC; indeed, despite requiring a considerable economic effort (the highest among the analysed scenarios), CO_2 emission reduction is the highest among the alternatives considered.
In Fig. 5, MC are shown together with CO_2 emissions avoided and annual costs related to the electricity production forecast for the different scenarios when model 3 is implemented.

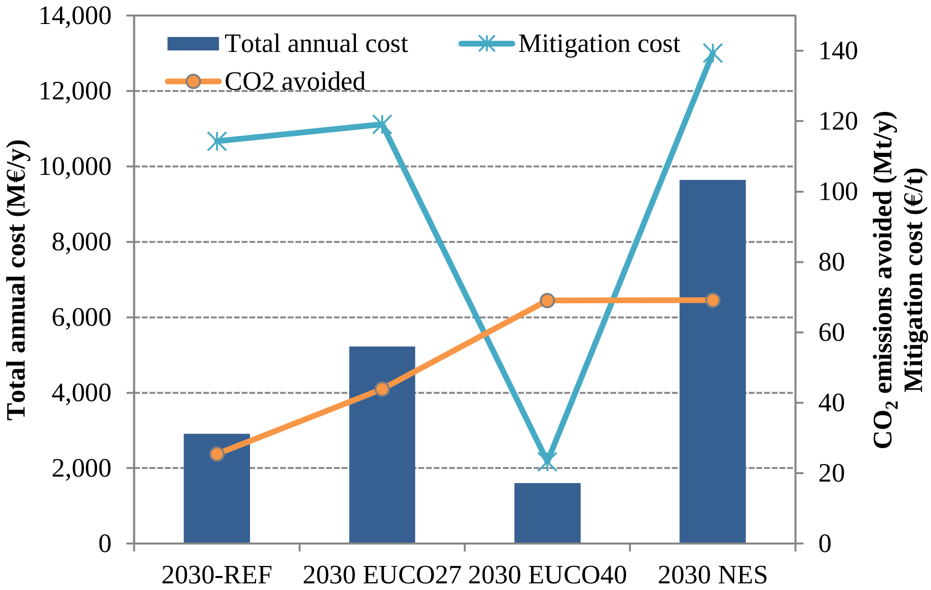

Fig. 5. MC in different scenarios (model 3)

From Fig.5 it can be inferred that, based on model 3 assumptions, 2030 EUCO40 scenario is the most virtuous one: the substantial energy savings (which allows to limit gross electricity production to around 260 TWh) allow to increase the share of electricity production by non-programmable renewable sources, thus significantly reducing CO_2 emissions; the consequence is a particularly low value of MC. It is also

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worth noting that 2030 NES scenario, while achieving high environmental performance (same level as 2030 EUCO40), entails the highest costs (almost 140 €/t): gross electricity production amounts to 304 TWh and savings linked to coal phase-out are relatively small when compared to the costs incurred to increase electricity generation by intermittent renewable sources and generate the estimated electricity production via natural gas-fired power plants; the consequence is an extremely high value of MC.

5.6 MC in reference and policy scenarios: sensitivity analysis

To assess the influence of all assumptions adopted for the evaluation of MC, a sensitivity analysis was conducted considering model 2 for costs assumptions and the following variations for the starting values of the parameters that make up MC (see Section 5.5):

- specific cost of solar generating capacity in the range -65%/+200%;
- specific cost of wind generating capacity in the range -40%/+60%;
- cost of natural gas in the range -30% / + 30%;
- cost of coal fuel in the range -40% / + 50%;
- discount rate in the range -50% / + 50%.
- useful life years in the range -50% / + 50%.

It is worth pointing out that the sensitivity analysis allows the price of CO_2 to be included (ETS): considering the higher assumption for CO_2 price in 2030 (42 €/t) the increase in natural gas cost would be approximately 2.2% and slightly higher than 17% for coal. Results can thus be used also to take ETS into account.

Results are summarised in Fig. 6; the following considerations can be drawn for the various parameter involved:

– investment cost related to solar capacity has the highest impact on 2030 NES scenario where, under model 3 assumptions (i.e.+200%), MC can be as high as 130 €/t. 2030 EUCO27 starts from a lower MC level with respect to 2030 NES showing however a similar variation (MC vary in the range 18–111 €/t). On the other hand, 2030-REF scenario starts from a higher MC value but features a more limited variation range, between 55 and 100 €/t approximately. In 2030 EUCO40 configuration, MC remain at relatively low values (below 30 €/t) and become significant only when solar technology costs grow above 2000 €/kW;
– wind technology cost shows a lower impact on MC with respect to solar. In 2030-REF and 2030 EUCO27 scenarios MC variation is the range -20%/+30% with respect to values reported in Table 7, while 3030 NES appears to be less influenced (MC range between -15% and +20%) and 2030 EUCO40 scenario is not affected at al by the variation of such parameter. Overall, as wind technology varies in the range -40%/+60%, MC, apart from 2030 EUCO40, change between 32 and 84 €/t;
– the price of natural gas shows a higher impact on 2030 REF configuration; assuming a 30% increase with respect to the value reported in Table 5, MC can be as high as 170 €/t. A lower variation is displayed in 2030 EUCO27 scenario, where the highest value for MC is 100 €/t; 2030 NES reports the lowest MC change (between 11 and 90 €/t) while 2030 EUCO 40 is not affected at all.
– coal price has a lower impact on MC than natural gas; MC vary in the range -23%/+30% for 2030-REF scenario and between -14% and +18% in 2030 EUCO27. Since 2030 NES is characterised by a complete elimination of coal is influenced at all by any variation in the price of coal and the same goes for 2030 EUCO40 scenario;
– the change in the interest rate has a rather limited impact on MC; with the exception of 2030 EUCO40 scenario that is not affected by the variation of such parameter, MC vary between 20 and 86 €/t over the entire range of interest rate percentage variation;
– the length of useful life has an opposed effect on MC as compared to the other parameters analysed: as useful life increases MC shows a decreasing trend although at a moderate rate. MC show an overall variation in the range 38–77 €/t.

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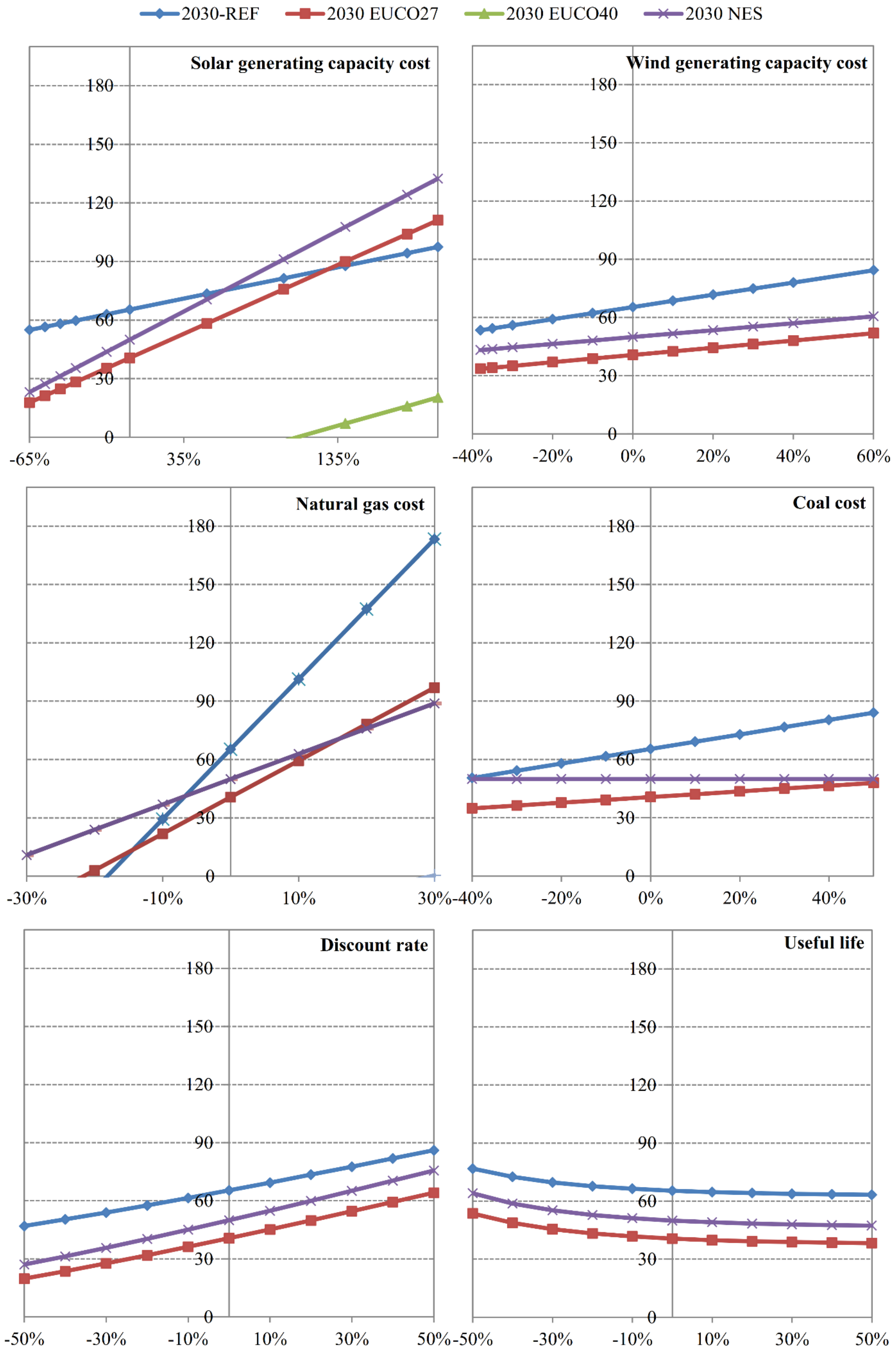

Fig. 6. MC in different scenarios (€/t): sensitivity analysis

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Analysing each of the proposed scenarios, MC assume the maximum values in the 2030 REF scenario (under the highest assumed natural gas price) and in the 2030 NES scenario (with the highest cost related to solar technology), reaching almost 180 €/t in the former and above 130 €/t in the latter configuration; the minimum values of MC are close to zero and are obtained only in the 2030 EUCO40 scenario. Overall, the following considerations can be made:

- 2030 REF scenario is particularly influenced by the price of natural gas; while indeed all the other parameters lead to a MC in the range 47–97 €/t (the more noticeable effects are due to the solar generating capacity cost and the most modest ones to useful life years), the cost of natural gas significantly influences MC since in this scenario over 126 TWh, of a total of 323 TWh, are produced by this fuel (i.e. approximately 38% of total electricity production is produced by natural gas);
- 2030 EUCO27 scenario is particularly affected both by the cost of solar generating capacity and, albeit to a lesser extent, by natural gas; while costs of wind generating capacity and of coal lead to a MC between 30–50 €/t, the cost of solar generating capacity lead to a maximum MC over 110 €/t, since in this scenario 52 TWh of a total of 319 TWh are produced by solar source (i.e. approximately 16%) with a doubling of electricity production by solar source compared to 2020;
- 2030 NES scenario is particularly influenced by the cost of solar generating capacity and the price of natural gas; coal cost obviously has no influence (given that in this scenario there is no electricity production by coal), while the influence of wind generating capacity is less than that of the other parameters. Indeed, this scenario, while completely renouncing to coal, foresees a conspicuous increase, compared to 2020, in electricity production by solar source (which becomes almost three times the corresponding 2020 value) and keeps electricity production by gas almost constant. Total gross production is not very different from that in 2020 and, therefore, in addition to the strong increase in electricity production by solar source, there is also an increase in electricity production by wind, however, since all the scenarios estimate an increase in equivalent operating hours of wind farms, the impact of the new wind generating capacity is less evident. Useful life years show a quite limited impact.

5.7 MC in reference and policy scenarios: influence of electricity generation share

This section analyses MC as a function of electricity generation shares from fossil fuels and renewable sources (this latter is evaluated as the additional generation with respect to 2020). These results are reported in Figg. 7 and 8, taking into consideration model 2 for costs estimates. Electricity produced by fossil fuels, related to the MC reported in Table 5, is highlighted in Fig. 7 with a dashed line for each scenario.

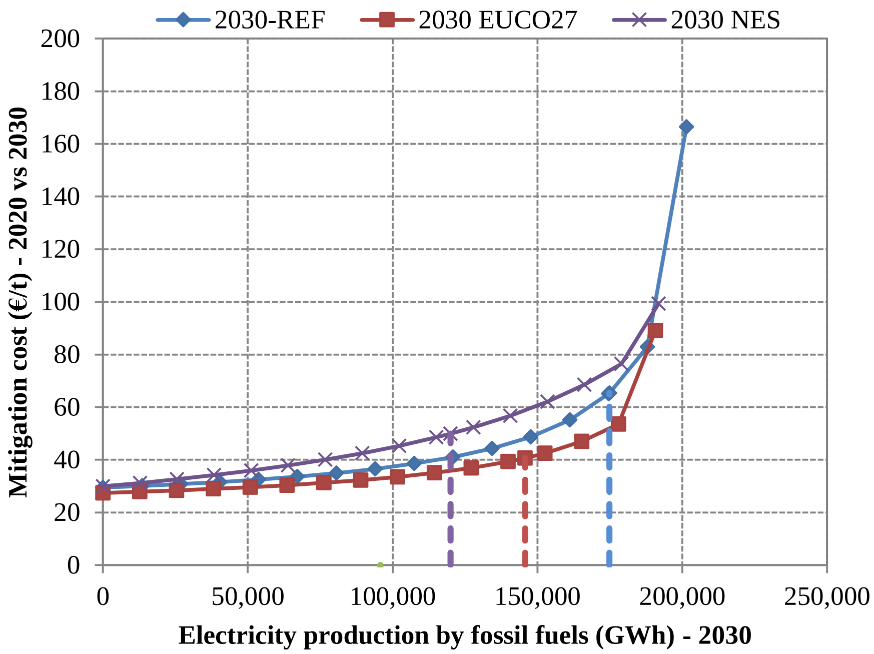

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Fig. 7. MC as a function of electricity production by fossil fuels in the original three scenarios (model 2)

As shown in Fig. 7, as electricity generation from fossil fuels grows, so do MC that appear to be very similar when production is below 50 TWh. In fact, the decreasing trend of MC is justified by the fact that the reduction in additional annual costs is lower than the reduction of CO_2 emissions, under the assumptions adopted with respect to costs (relatively low) related to solar and wind technologies. Beyond 50 TWh, MC differences become more significant.
With reference to each of the analysed scenario, the following conclusions can be made:

- 2030-REF is characterised by the highest value of additional electricity generated and by the lowest value of C_1 which is higher, however, than C_1 in OB-2020 (63.54 €/MWh versus 54.38 €/MWh due to the higher level of electricity generated from coal in OB-2020); C_2 varies from a minimum of 38.48 €/MWh and a maximum of 71.73 €/MWh with an average value of 65.59 €/MWh, the lowest value among the analysed scenarios. This leads high annual costs and low CO_2 emissions avoided resulting in significant MC (above 165 €/t, where all the additional electricity generated is produced by fossil fuel);
- EUCO27 shows a lower value of additional electricity generated as compared to 2030-REF, however with a higher value of both C_1 and C_2 (66.95 versus 63.54 €/MWh for C_1 and 68.20 versus 65.59 €/MWh for the average value of C_2). The higher value of C_2 is related to the increase of electricity generation by solar and wind sources with respect to 2020 (more than double when electricity from fossil fuels is approximately equal to 146 TWh) that leads to a significant cost related to the instalment of new generating capacity; as a result, as electricity generated from fossil source increases, annual cost decreases at a higher rate with respect to the previous scenario while CO_2 emissions avoided follow a similar decreasing trend;
- 2030 NES features the higher MC throughout the entire range of electricity generated from fossil fuels. In this scenario, the additional electricity generated is similar to 2030 EUCO27 configuration that, however, comes along with a higher value of both C_1 and C_2 (77.24 versus 66.95 €/MWh for C_1 and 69.75 versus 65.59 €/MWh for the average value of C_2). The higher values of C_2 are linked to the significant amount of electricity generated from intermittent renewable sources as compared to 2020 that nearly triples when production from fossil fuels is around 120 TWh resulting in remarkable costs related to additional generating capacity to be installed; moreover, the deployment of natural gas for electricity production as the sole fossil source for electricity generation leads to a higher value of C_1 this resulting in higher MC despite the most significant reduction in CO_2 emissions.

Fig. 8 reports MC as a function of additional electricity generated from intermittent renewable sources, whose trend, opposed to that of Fig. 7, can be directly explained based on the considerations made above.

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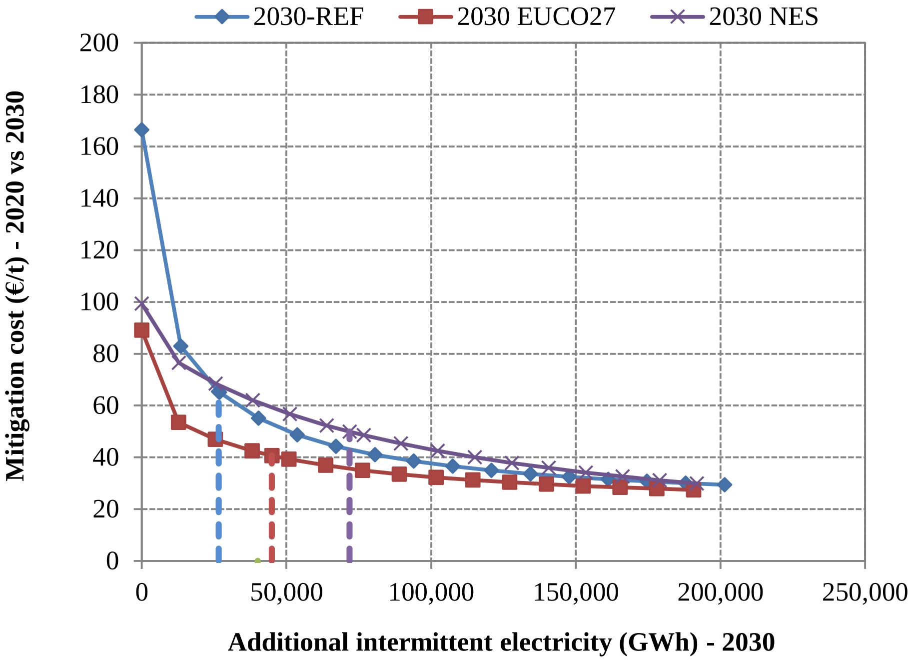

Fig. 8. MC as a function of additional electricity production by renewable intermittent sources in the original three scenarios (model 2)

When the additional electricity generated by intermittent renewable sources becomes significant, MC tend to a similar value for all the scenarios considered, i.e. 30 €/t with a generation of 190 TWh.

Fig. 9 shows results obtained when model 3 is implemented; as opposed to the previous case, the value of MC decreases as electricity generated from fossil fuels grows. In fact, additional costs with respect to 2020 decrease at a faster rate with respect to the reduction in CO_2 emissions, under the assumptions adopted with respect to costs (relatively high) related to solar and wind technologies.

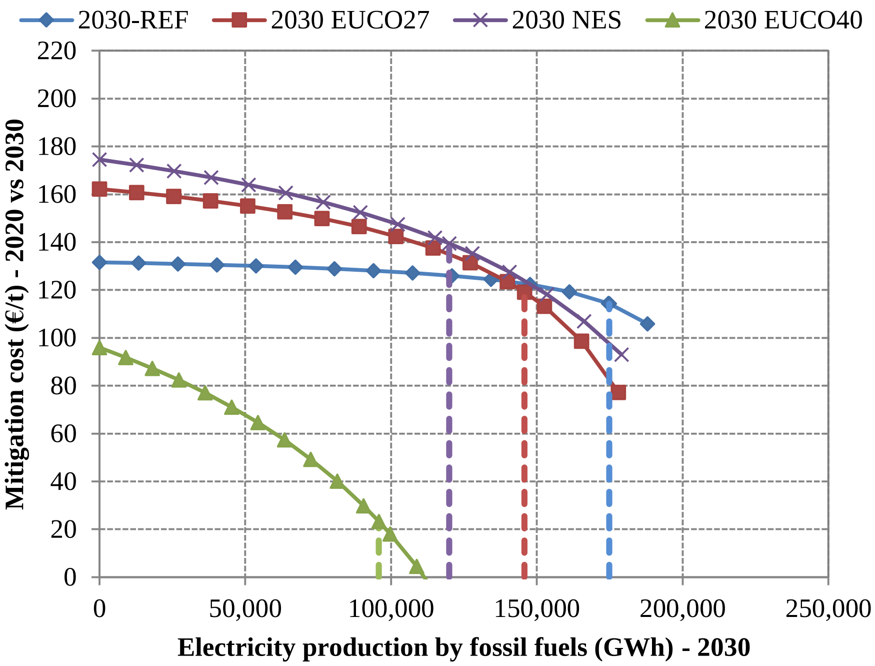

Fig. 9. MC as a function of electricity production by fossil fuels in the original three scenarios (model 3)

The following conclusions can be inferred from the graph:

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- in 2030 REF scenario, MC remain at a higher level as compared to model 2 alternative, precisely in the range 100–130 €/t; for electricity generation by fossil fuels below approximately 150 TWh MC are also lower than 2030 EUCO27 and 2030 NES scenarios;
- As for 2030 EUCO27, MC vary between 80 and 160 €/t and is below 2030 NES throughout the whole range of variation of electricity generated from fossil fuels;
- 2030 EUCO40 option exhibits the lowest value of additional electricity production and C_1 and the average value of C_2 are rather similar to those of the previous scenario. For these reasons, when the additional electricity is completely produced by intermittent sources, the annual cost is the lowest while CO_2 emissions avoided are equal to those of the other scenarios resulting in the lowest MC;
- 2030 NES scenario exhibits the highest MC, at least when electricity production by fossil fuels is below 150 TWh, beyond this threshold 2030 REF scenario becomes the most expensive. Indeed, 2030 NES scenario shows significant costs related to the conspicuous deployment of solar and wind sources as well as natural gas for electricity generation. As a result, even if this scenario exhibits the greatest reduction in CO_2 emissions, MC are the highest among the proposed scenarios.

Fig. 10 displays MC variation as a function of additional electricity generated by intermittent renewable sources in 2030.

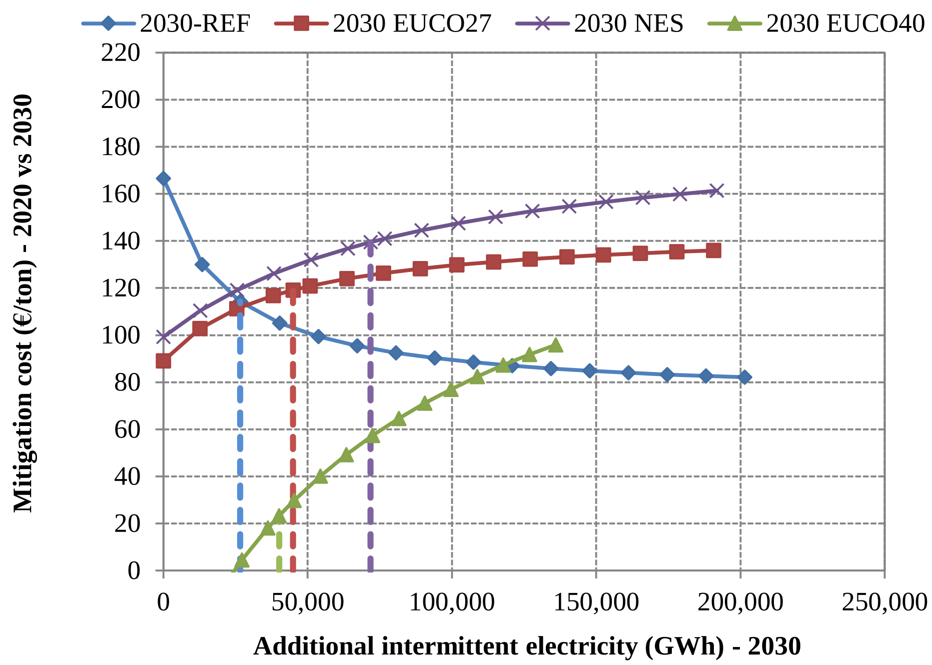

Fig. 10. MC as a function of additional electricity production by renewable intermittent sources in the original three scenarios (model 3)

In 2030 REF scenario, the trend of MC is opposed to that in all the other scenarios: MC increase as additional electricity production by intermittent sources increases. Indeed, this scenario exhibits the highest value of additional electricity production and the lowest value of C_1 and C_2, however, the value of C_1 in this scenario is higher than that in OB-2020 scenario (63.54 €/MWh versus 54.38 €/MWh since electricity production by coal is higher in OB-2020 scenario); this leads to high annual costs and low CO_2 emissions avoided resulting in considerable MC.
The other trends can be explained based on the considerations made above.

The main conclusion of this analysis is the following: the greater the reduction in expected electricity production (EUCO 40 scenario compared to all the other alternatives) the lower are the MC; on the other hand, in the case of comparable electricity production (all scenarios except for the EUCO 40

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scenario), two aspects must be considered: (i) type and quantity of electricity production by intermittent renewable sources; (ii) type and quantity of electricity production by fossil fuels.
To make the values shown in Figg. 7-10 comparable, MC should be recalculated in these four configurations of the electricity sector assuming the same overall electricity production (while the other assumptions, already introduced in the previous section, can be maintained valid). Results, shown in Fig. 11 and associated with an electricity generation of 323 TWh, demonstrate that:

- when electricity generation becomes significant even 2030 EUCO40 shows MC higher than zero;
- MC are in the range 30–180 €/t;
- once the electricity production from fossil sources has been fixed (i.e. the electricity sector has been fixed), the economic ranking of the different scenarios, regarding MC, changes. More in detail, even if 2030 NES scenario remains the most expensive, REF-2030 becomes the cheapest (at any rate for electricity production by fossil fuel lower than about 100 TWh), followed by 2030 EUCO27 that shows a rather similar MC trend; 2030 EUCO40 exhibits high MC however lower than 2030 NES.

Consequently, Fig. 11 demonstrates that the most virtuous configuration of the electricity sector is the one based on 2030-REF scenario (or 2030 EUCO27 which is rather similar) while the most expensive configuration is that based on 2030 NES scenario; hence, the complete elimination of coal, as forecast by NES, is not as beneficial as other configurations from a cost perspective.

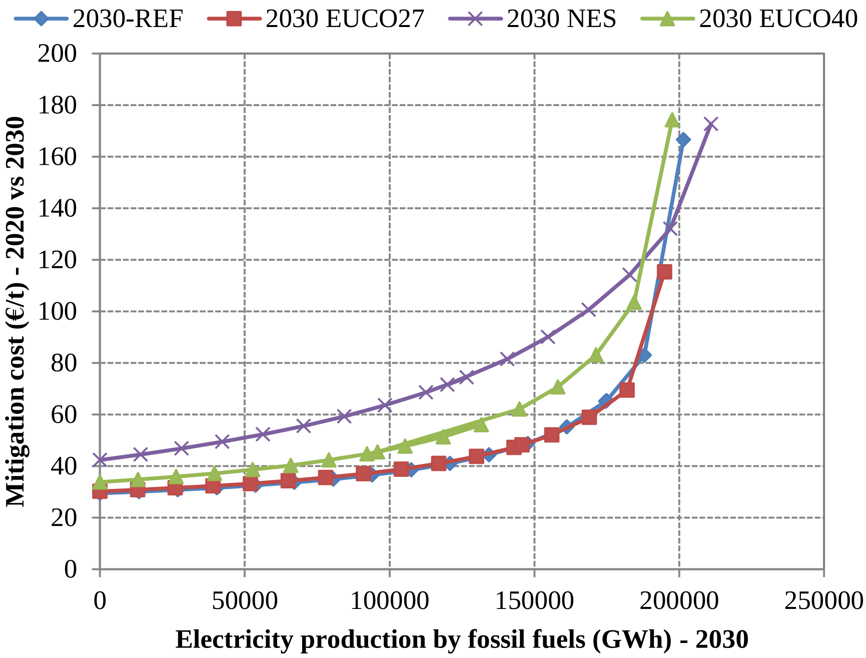

Fig. 11. MC as a function of electricity production by fossil fuels (assuming the same overall electricity production - model 2)

5.8 Proposal of new configurations for the electricity sector

Finally, once the desired reduction in CO_2 emissions and the total electricity production are established, in each new configuration of the electricity sector it is possible to calculate the percentages of electricity production by each source and the associated MC using model 2 for cost assumptions (Fig. 12).
For this latest assessment, it was assumed that CO_2 emissions avoided are 69 Mt/year (value forecast in 2030 NES scenario) and total electricity production is 302 TWh (this is almost the average value of the predictions in the four analysed scenarios); therefore, each power sector mix exhibits the same specific CO_2 emissions (i.e. 167.4 g/kWh). The results obtained are shown in Fig. 12 and they lead to the following conclusions:

- in the new REF-2030 scenario, the economic impact for CO_2 mitigation is the lowest: in this configuration, 68.9% of electricity is produced by clean sources (27% non-intermittent renewable source, i.e. bio, geo and hydro; 41.9% intermittent renewable sources: solar 17.6% and wind 24.3%) and the remaining 31.1% is produced by natural gas, 23.2%, and coal, 7.9%; MC amount

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to 13.8 €/t. In this scenario, production by intermittent renewable sources is remarkable and this situation poses two issues: (i) the stability of the electric grid and (ii) the feasibility of the necessary wind farms. While, in fact, electricity production by solar source is lower than that estimated by the original NES 2030 scenario (-24.6%), the production of electricity by wind source would be significantly higher (1.876 times);

- 2030 EUCO27 features a higher economic impact for CO_2 mitigation: in this scenario, 67.7% of electricity is produced by clean sources (29.1% non-intermittent renewable source, i.e. bio, geo and hydro; 38.6% intermittent renewable sources: solar 23.4% and wind 15.2%) and the remaining 32.2% is produced by natural gas, 25.5%, and coal, 6.7%; MC amount to almost 14.1 €/t. In this case electricity production by solar source is similar to that estimated in the original NES 2030 scenario, while electricity production by wind source is higher (1.174 times);
- the new 2030 EUCO40 lead to very similar considerations to the previous alternatives; in this case, the lower electricity production by non-intermittent renewable sources and by fossil fuels is compensated for by solar source with an increased value of MC equal to 21.5 €/t;
- the highest economic impact for CO_2 mitigation is registered by the new 2030 NES scenario: 60.1% of electricity is produced by clean sources (23.8% non-intermittent renewable source, i.e. bio, geo and hydro; 36.3% intermittent renewable sources: solar 23.3% and wind 13.0%) and the remaining 39.9% is produced only by natural gas; MC amount to more than 47.7 €/t. The complete elimination of coal makes this configuration of the electricity sector not as beneficial as other scenarios from an economic point of view.

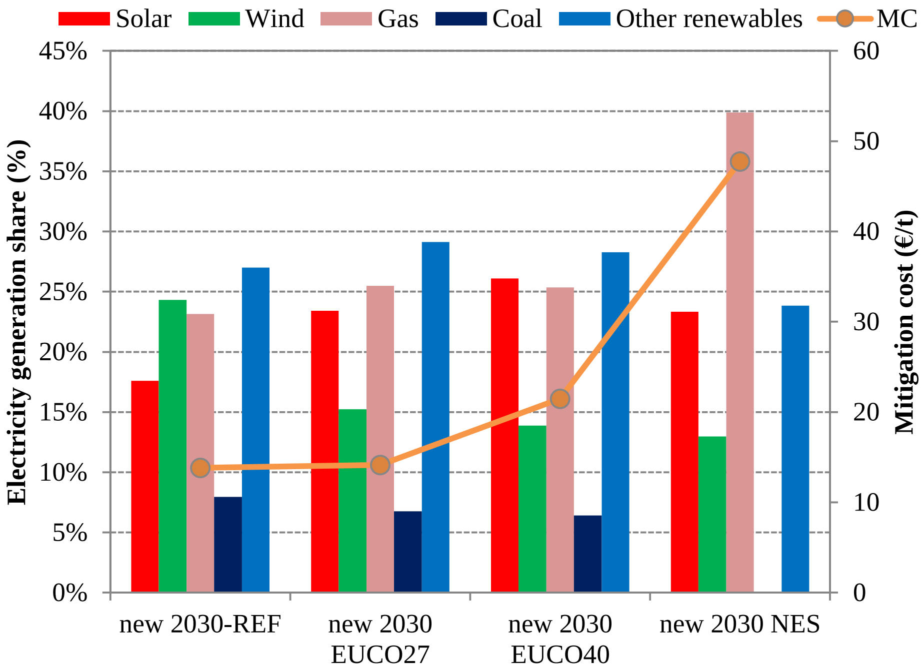

Fig. 12. Percentage shares of electricity by sources and MC in the new scenarios (model 2)

Fig. 13 shows MC when model 3 is deployed for cost assumptions, thus considering the highest costs for solar and wind technologies. The share of electricity generated by the different sources involved remains unchanged while MC reach higher values, between 86.2 and 134.3 €/t.

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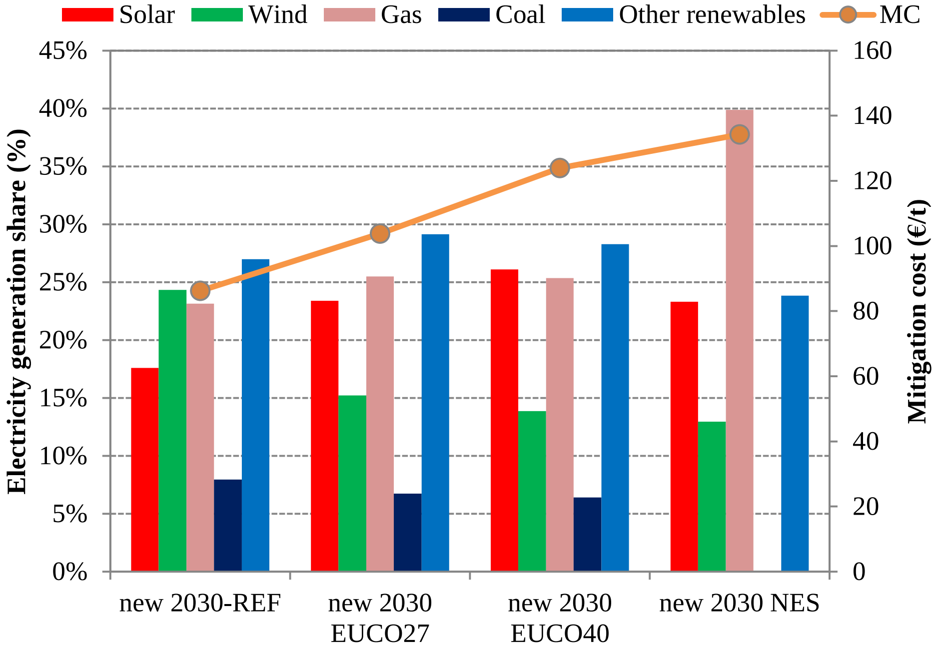

Fig. 13. MC and percentage shares of electricity by sources in the new scenarios (model 3)

In conclusion, it is evident that the larger the use of gas (new 2030 NES) and the production of electricity from solar source (new 2030 EUCO40), the higher are the MC.
Moreover, the key parameter for achieving high environmental performance is improvement of energy efficiency and reduction of energy consumption; in this context, a virtuous and clean electricity sector is the one which boasts an energy configuration where all sources, both renewable and non-renewable, are used appropriately for achieving the highest environmental objectives at the lowest cost.

6. DISCUSSION

MC for the proposed 2030 scenarios concerning the Italian power sector appear to be highly dependent on the assumptions adopted for intermittent renewable (as in solar and wind) and fossil fuels costs. To accommodate the broad variation of such costs featured in the available literature, three different models were deployed. The outcome of the analysis (described in Section 5.5) allows the following conclusions to be drawn:

- model 1 leads to extremely low MC, with the exception of 2030-REF. Although desirable, the actual realisation of such a situation is doubtful when considering the estimated price of CO_2 in some of the analysed scenarios;
- when model 2 is deployed, MC register a variation that ranges from a minimum of 40 €/t to a maximum value of 65 €/t. The scenario that shows the lowest additional economic impact is 2030-REF that, however, is also the configuration that leads to the lowest value of CO2 emissions avoided resulting in the highest MC among the proposed alternatives. On the other hand, 2030 EUCO27, despite a higher economic impact with respect to 2030-REF due to the increased deployment of solar and wind technologies for electricity production, shows an increased reduction in CO_2 emissions leading to the lowest value of MC among the proposed configurations;
- model 3 leads to particularly high MC in all the variety of scenarios considered. With respect to model 2, scenarios are ranked differently based on MC and those foreseeing significant amounts of electricity from solar and natural gas sources appear to be disadvantaged in this regard (i.e. 2030 EUCO27 and 2030 NES featuring respectively 109/52 TWh and 118/72 TWh from natural gas and solar source respectively). Such a situation should be obviously averted, moreover, considering the estimates of CO_2 prices reported in some of the analysed scenarios the actual possibility of achieving such costs is unlikely.

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The sensitivity analysis conducted (see Section 5.6) shows that, among the different parameter that make up MC, the deployment of solar source and natural gas has the greater impact. Although natural gas allows reduced CO_2 emissions with respect to coal, the higher cost of fuel lead to an increased economic impact. Electricity generation from solar technology is remarkable in all the analysed scenarios and goes from a minimum of 34 TWh (2030 REF) to a maximum of 72 TWh (2030 NES). Considering that in 2020 electricity generation from solar source is approximately equal to 25.6 TWh, additional capacity is to be installed to fulfil the foreseen generation target. The effect related to the deployment of wind technology on MC is less pronounced as, even all scenarios forecast an increase in electricity generation from wind, such increment is lower than what projected for solar technology. The role of coal on MC is limited to the fact that all the analysed scenarios forecast various degrees of reduction of electricity produced from this fossil source, entailing a direct advantage on CO_2 emissions.

The influence of the variation in the shares of electricity produced by fossil and renewable sources (for these latter the additional production with respect to 2020) on MC was assessed associating such variation with C_1 and C_2, parameters that quantify, for each scenario, the economic burden linked to the electricity generated from fossil and intermittent renewable sources respectively (see Section 5.7). Being MC also influenced by the overall amount of electricity generation, it was shown how the larger the reduction in expected electricity consumption (EUCO 40 scenario compared to all other scenarios) the lower are the MC. However, in the case of comparable electricity production (all scenarios except for the EUCO 40 scenario), MC are influenced by (i) type and amount of electricity production by intermittent renewable sources; (ii) type and amount of electricity production by fossil fuels.

Finally, new configurations of the electricity sector are defined, based on the scenarios analysed, establishing in all the scenarios the same desired reduction in CO_2 emissions (69Mt/year) and the same total electricity production (302 TWh); in these scenarios (see Section 5.8) it is possible hence to calculate the percentages of electricity production by each source and the associated MC. The final finding is that the larger the use of gas (the new 2030 NES scenario) and the production of electricity from solar source (the new 2030 EUCO40 scenario), the higher are MC. The scenario where economic impact is the least is the new REF-2030 scenario: 68.9% of electricity is produced by clean sources (27% non-intermittent renewable source, i.e. bio, geo and hydro; 41.9% intermittent renewable sources: solar 17.6% and wind 24.3%) and the remaining 31.1% is produced by natural gas, 23.2%, and coal, 7.9%; the MC amounts to almost 13.8 €/t in model 2 and 86.3 €/t in model 3. The scenario where economic impact is the highest is the new 2030 NES: in this scenario 60.1% of electricity is produced by clean sources (23.8% non-intermittent renewable source, i.e. bio, geo and hydro; 36.3% intermittent renewable sources: solar 23.3% and wind 13.0%) and the remaining 39.9% is produced only by natural gas; the MC amounts to about 47.7 €/t in model 2 and above 130 €/t in model 3. The complete elimination of coal makes this configuration of the electricity sector not as beneficial as other scenarios from an economic perspective.

In conclusion, in order to achieve high environmental performance, energy efficiency must be increased and energy consumption must be reduced; it is worth underlining that this work refers to future projections on electricity generation and power sector configurations in Italy in 2030 without analysing the development of final uses within the energy system. In this context, a virtuous and clean electricity sector with low CO_2 emissions is the one which boasts an energy configuration where all sources, both renewable and non-renewable, are used appropriately for achieving the highest environmental objectives at the lowest cost. It is also worth mentioning that an environmentally-friendly energy system brings about additional benefits related for instance to a reduced particulate emissions improving citizen health; moreover, a balanced and diversified deployment of all the available sources could also improve the national trade balance by reduced fuel imports being Italy a net importer of fossil fuels.

CONCLUSIONS

The main objective of the paper is providing a methodology that allows a variety of future electric scenarios to be simulated and analysed in terms of crucial energy and economic indicators. Applying this methodology in Italy gives detailed information on the economic burden associated with strategic national choices concerning future configurations for the Italian electricity generation sector in 2030. A comparative assessment evaluates the cost-effectiveness of possible alternatives based on mitigation costs to quantify the economic burden associated with the projected reduction of CO_2 emissions in the proposed scenarios.

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The outcome of the analysis reveals that MC vary widely, from being null up to 140 €/t, depending on the assumptions adopted and structure of the configurations proposed for 2030.
Finally, the analysed scenarios were also rescaled to produce the same amount of overall electricity generation and desired reduction in CO_2 emissions, new power sector configurations were thus created obtaining additional results on the impact of different cost assumptions on MC.
The final finding is that the larger the use of gas (new 2030 NES scenario) and electricity generation from solar source (new 2030 EUCO40 scenario), the higher are MC. Moreover, new 2030 NES scenario exhibits the highest MC meaning that the complete phaseout of coal is not as beneficial as other scenarios from an economic perspective. Furthermore, it can be concluded that when high environmental performance are to be achieved, energy efficiency must be increased and energy consumption must be reduced; in this context, a virtuous and clean electricity sector is the one which boasts an energy configuration where all sources, both renewable and non-renewable, are used appropriately for achieving the highest environmental objectives at the lowest cost.

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REFERENCES

Barazza, E., Strachan, N., 2020. The co-evolution of climate policy and investments in electricity markets: Simulating agent dynamics in UK, German and Italian electricity sectors. Energy Res. Soc. Sci. 65, 101458. https://doi.org/10.1016/j.erss.2020.101458
Calise, F., Dentice D'Accadia, M., Barletta, C., Battaglia, V., Pfeifer, A., Duic, N., 2017. Detailed Modelling of the Deep Decarbonisation Scenarios with Demand Response Technologies in the Heating and Cooling Sector: A Case Study for Italy. Energies, 10, 1535; doi:10.3390/en10101535
Capros, P., Kannavou, M., Evangelopoulou, S., Petropoulos, A., Siskos, P., Tasios, N., Zazias, G., DeVita, A., 2018. Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. Energy Strategy Rev. 22, 255–263. https://doi.org/10.1016/j.esr.2018.06.009
Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew. Energy 139, 80–101. https://doi.org/10.1016/j.renene.2019.02.077
Committee on Climate Change, 2019. Net Zero - The UK's contribution to stopping global warming.
Connolly, D., Lund, H., Mathiesen, B.V., 2016. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew. Sustain. Energy Rev. 60, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025
Department for Business, Energy & Industrial Strategy, 2019. THE UK'S DRAFT INTEGRATED NATIONAL ENERGY AND CLIMATE PLAN (NECP).
Diesendorf, M., Elliston, B., 2018. The feasibility of 100% renewable electricity systems: A response to critics. Renew. Sustain. Energy Rev. 93, 318–330. https://doi.org/10.1016/j.rser.2018.05.042
E3MLab, IIASA, 2016. Technical report on Member State results of the EUCO policy scenarios.
EIA, 2019. Annual Energy Outlook 2019.
EIA, 2016. Capital Cost Estimates for Utility Scale Electricity Generating Plants.
European Commission, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, OJ L 140, p. 16–62.
European Commission, 2009b. Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community, OJ L 140, p. 63–87.
European Commission, 2019a. Report from the commission to the European parliament and the council - Preparing the ground for raising long-term ambition - EU Climate Action Progress Report 2019.

European Commission, 2019b. Clean energy for all Europeans.
European Commission, 2016c. EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050.
Eurostat, 2019. Natural gas price statistics [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics#Natural_gas_prices_for_non-household_consumers (accessed 3.30.20).
Fragkos, P., Tasios, N., Paroussos, L., Capros, P., Tsani, S., 2017. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy 100, 216–226. https://doi.org/10.1016/j.enpol.2016.10.023
Gestore dei Servizi Energetici, 2018. Rapporto Statistico 2017.
Gillich, A., Brodecki, L., Hufendiek, K., 2019. Impacts of complementing goals besides emission targets on CO2 mitigation cost: A model-based analysis. Energy Strategy Rev. 26, 100395. https://doi.org/10.1016/j.esr.2019.100395
Hansen, K., Breyer, C., Lund, H., 2019. Status and perspectives on 100% renewable energy systems. Energy 175, 471–480. https://doi.org/10.1016/j.energy.2019.03.092
Heat Roadmap Europe, 2018. Energy Models.
Hof, A.F., den Elzen, M.G.J., Admiraal, A., Roelfsema, M., Gernaat, D.E.H.J., van Vuuren, D.P., 2017. Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. Environ. Sci. Policy 71, 30–40. https://doi.org/10.1016/j.envsci.2017.02.008
Hübler, M., Löschel, A., 2013. The EU Decarbonisation Roadmap 2050—What way to walk? Energy Policy, Special section: Long Run Transitions to Sustainable Economic Structures in the European Union and Beyond 55, 190–207. https://doi.org/10.1016/j.enpol.2012.11.054
IEA, NEA, 2015. Projected Costs of Generating Electricity.
IPCC, 2018. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.
IRENA, 2019a. Future of Solar Photovoltaic - Deployment, investment, technology, grid integration and socio-economic aspects.
IRENA, 2019b. Future of Wind - Deployment, investment, technology, grid integration and socio-economic aspects.
ISPRA, 2019. Fattori di emissione atmosferica di gas a effetto serra nel settore elettrico nazionale e nei principali Paesi Europei.
Jägemann, C., Fürsch, M., Hagspiel, S., Nagl, S., 2013. Decarbonizing Europe's power sector by 2050 - Analyzing the economic implications of alternative decarbonization pathways. Energy Economics, 40 622–636, http://dx.doi.org/10.1016/j.eneco.2013.08.019
JRC, 2018. Cost development of low carbon energy technologies.
Knoema, 2019. Coal Prices Forecast: Long Term, 2018 to 2030.
Korkmaz, P., Gardumi, F., Avgerinopoulos, G., Blesl, M., Fahl, U., 2020. A comparison of three transformation pathways towards a sustainable European society - An integrated analysis from an energy system perspective. Energy Strategy Rev. 28, 100461. https://doi.org/10.1016/j.esr.2020.100461
Li, Y., Wei, Y., Shan, S., Tao, Y., 2018. Pathways to a low-carbon economy: Estimations on macroeconomic costs and potential of carbon emission abatement in Beijing. J. Clean. Prod. 199, 603–615. https://doi.org/10.1016/j.jclepro.2018.07.093
Liu, J.-Y., Feng, C., 2018. Marginal abatement costs of carbon dioxide emissions and its influencing factors: A global perspective. J. Clean. Prod. 170, 1433–1450. https://doi.org/10.1016/j.jclepro.2017.09.216
Ministero dello Sviluppo Economico, 2017. Strategia Energetica Nazionale.
Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp. Res. Part Transp. Environ., The contribution of electric vehicles to environmental challenges in transport. WCTRS conference in summer 64, 5–14. https://doi.org/10.1016/j.trd.2017.07.012
Oshiro, K., Kainuma, M., Masui, T., 2017. Implications of Japan’s 2030 target for long-term low emission pathways. Energy Policy 110, 581–587. https://doi.org/10.1016/j.enpol.2017.09.003

M. Vellini, S. Bellocchi, M. Gambini, M. Manno, T. Stilo, Impact and costs of proposed scenarios for power sector decarbonisation: An Italian case study, Journal of Cleaner Production 274 (2020) 123667, https://doi.org/10.1016/j.jclepro.2020.123667.

Sofia, D., Gioiella, F., Lotrecchiano, N., Giuliano, A., 2020. Cost-benefit analysis to support decarbonization scenario for 2030: A case study in Italy, Energy Policy, 137, February 2020, 111137, https://doi.org/10.1016/j.enpol.2019.111137

UNFCCC, 2015. Paris Agreement.

van Zuijlen, B., Zappa, W., Turkenburg, W., van der Schrier, G., van den Broek, M., 2019. Cost-optimal reliable power generation in a deep decarbonisation future. Appl. Energy 253, 113587. https://doi.org/10.1016/j.apenergy.2019.113587

World Bank Group, 2019. Commodity Markets Outlook.

Young, J., Brans, M., 2017. Analysis of factors affecting a shift in a local energy system towards 100% renewable energy community. J. Clean. Prod., Experimentation for climate change solutions 169, 117–124. https://doi.org/10.1016/j.jclepro.2017.08.023

M. Vellini, S. Bellocchi, M. Gambini, M. Manno, T. Stilo, Impact and costs of proposed scenarios for power sector decarbonisation: An Italian case study, Journal of Cleaner Production 274 (2020) 123667, https://doi.org/10.1016/j.jclepro.2020.123667.