RENEWABLE ELECTRICITY IN THE PORTUGUESE ENERGY SYSTEM 2015-2050

GLOBAL REPORT

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PREAMBLE

This report refers to Product 2.4 (Global Report) in Point 2. Deliverables, as provided by the service provision agreement entered between APREN and FCT NOVA.

This report provides information about the study developed, in a brief but comprehensive manner, as described in Point 1. Object of the agreement, where 1.1. includes three components: 1) Establishment of all the necessary information and respective algorithms for the calculation of the LCOE (Levelized Cost of Electricity) values according to the best practices led by international bodies, related to electricity production technologies already under use in the Portuguese electricity system and which may be adopted in the future, by 2050; 2) Design of a user-friendly Excel application to be handled by APREN as a simulation, with free input parameters; 3) Establishment of a selected set of indicators to illustrate the value of renewable electricity production for the Portuguese energy system, namely the impact on the global cost of the electricity system, the savings/reductions on GHG emissions and the costs avoided with the purchase of permits in auctions, as well as the impact on the commercial balance of energy products and the level of energy dependency.

Component 2 includes an Excel application, which has already been delivered to APREN. Therefore, this Global Report is made up of 2 parts:

I. DESCRIPTION OF THE CALCULATION OF THE LCOE FOR RENEWABLE ENERGY PRODUCTION TECHNOLOGIES

II. PROSPECTIVE INDICATORS OF RENEWABLE ELECTRICITY IN THE PORTUGUESE ENERGY SYSTEM

I. DESCRIPTION OF THE CALCULATION OF THE LCOE FOR RENEWABLE ENERGY PRODUCTION TECHNOLOGIES

This section systematises the information and respective sources needed for the calculation of the LCOE (Levelized Cost of Electricity) figures related to electricity production technologies already under use in the Portuguese electricity system (since 2015) or which may be adopted in the future, until 2050. There is also a user-friendly Excel application developed to be handled by APREN as a simulation, with free input parameters.

APPROACH USED WHEN CALCULATING THE LCOE

The calculation of the LCOE is supported by cost curves until 2050, generating values (in Euros (2015) per unit of electricity produced) every 5 years by 2050. The following elements integrate the LCOE and contribute to its global value:

- Investment costs (€'15/kW);
- Fixed operation and maintenance costs (€'15/kW);
- Variable operation and maintenance costs, without fuel expenses (€'15/MWh);
- Costs of fuels used, when applicable (€'15/MWh);
- Costs with CO_2 permits, whenever applicable (€/tCO_2).

For the calculation of these LCOE values, it was necessary to consider the following technical and economic parameters:

- Thermal efficiency for net electricity generation (%) which considers the rate of self-consumption;
- Technical life span (no. of years);
- Hours of operation per year (no. of hours);
- Factors of CO_2 emissions (kt/MWh);
- Rate of CO_2 capture, when applicable (%);
- Update rate (%).

The calculations considered the following assumptions:

- The LCOE values are presented using costs from 2015;
- The cost values used are unitary, per unit of installed capacity (MW), per type of fuel (MWh) or per level of emissions (kt). Information is provided as to the dimension of the turbine/group for illustration purposes only;

- The cost values do not consider the costs involved in workmanship in a disaggregated manner;
- Network connection costs are not considered in the investment costs used. Reference shows a wide variety in terms of the inclusion or lack thereof in terms of these costs, while selected sources do not include this component;
- This exercise does not include plot rental values;
- Evolution profiles have been considered as costs and fuel for fossil fuels, according to the prices of fuel imports considered by the International Energy Agency (IEA) in its World Energy Outlook 2016. A forest biomass cost was assumed as corresponding to the cost of cutting, transporting and preparing the fuel. As far as the cost of Municipal Solid Waste (MSW) is concerned, it has been assumed that it corresponds to the cost of its collection, according to information provided by Valorsul. Finally, for biogas, it is assumed that there are no costs involved, since it is a waste from animal exploration which is always used by the producer.

This application has been developed for the 39 electricity generation technologies mentioned in Table 1, which include: 4 dedicated technologies for natural gas generation and one for cogeneration; 2 for oil products, 7 with coal, 4 with hydropower, 5 with wind, 3 using dedicated biomass generation technologies and one for cogeneration; 6 solar; 3 geothermal-based technologies; 1 with wave power; 1 biogas generation technology and finally, 1 technology fed by Municipal Solid Waste (MSW).

TABLE 1 | LIST OF GENERATION TECHNOLOGIES CONSIDERED FOR THE LCOE

No.	Code used in the application	Name of the technology	Illustrative dimension of the group/turbine (MWel)	Illustrative dimension of the station/farm (MWel)
1	GasCC	Conventional Combined Cycle Gas	550	1100
2	GasCCAdv	Advanced Combined Cycle Gas	500	1000
3	GasCCCCSpost	Combined Cycle Gas with post-combustion CO2 capture	550	1100
4	GasOGCC	Advanced Open Cycle Gas (Peaker) (OGCC)	200	400
5	OilSupercri	Fuel Oil Steam Turbine (Supercritical)	40	80
6	DieselPeaker	Advanced Diesel Turbine (Peaker)	40	80
7	CoalConv	Subcritical Coal (Conventional)	300	600
8	CoalSuperc	Supercritical Coal	300	600
9	CoalFluid	Fluidised bed combustion of coal	300	600
10	CoalGCCCCSpre	Combined cycle coal with integrated gasification (IGCC)	300	600
11	CoalGCCCCSpre	IGCC coal with pre-combustion CO_2 capture	300	600
12	CoalCCSpost	Supercritical Coal + Post-combustion CO_2 capture	300	600
13	CoalOxyCCS	Supercritical Coal + CO_2 oxy-fuel capture	300	600
14	CHPgas	Cogeneration of natural gas in a combined cycle of condensation (medium)	50	100
15	CHPbio	Cogeneration in a combined cycle with integrated gasification using biomass	100	200

No.	Code used in the application	Name of the technology	Illustrative dimension of the group/turbine (MWel)	Illustrative dimension of the station/farm (MWel)
16	HydroRoRS	Hydropower with reduced water flow	7	14
17	HydroRoRL	Hydropower with large water flow	20-50	50
18	Hydro	Hydropower with dam	250	500
19	HydroPmp	Hydropower with pump	250	500
20	GeoHDR	Enhanced Geothermal System (hot dry rock)	20	40
21	Geoflash	Hydrothermal Geothermic with flash	50	100
22	GeoBin	Binary Cycle Geothermal *Organic Rankine Cycle*	50	100
23	WindOff	Floating Offshore Wind	5	60
24	Wind1	High Onshore Wind IEC Class I	3	60
25	Wind2	Medium Onshore Wind IEC Class II	3	60
26	Wind3	Low Onshore Wind IEC Class III	3	60
27	Wind4	Very High Onshore Wind IEC Class S	3	60
28	Wave	Waves - Generic Technology	5	60
29	PvroofRSD	Roof Solar Panel (crystalline silicon) - Residential	0.01	0.01
30	PvRoofCOM	Roof Solar Panel (crystalline silicon) - Commercial	0.01-0.25	0.25
31	PVplant	Centralised solar photovoltaic (PV) (crystalline silicon)	>0.25	250
32	CPV	High Concentration Solar Photovoltaic	5	50
33	CSPparab	Parabolic Through Collector Solar Concentrator system (reference station with 7.5 hours of storage in molten salt)	30	60
34	CSPtower	Solar Tower Solar Concentrator (reference station with 9 hours of storage in molten salt)	30	60
35	Stbio	Solid biomass steam turbine (conventional)	200	200
36	IGCCbio	Biomass integrated gasification (IGCC)	100	200
37	IGCCbioCCS	CO_2 capture biomass integrated gasification (IGCC)	100	200
38	Stwaste	Incineration of Municipal Solid Waste with energy recovery	50	100
39	STbiogas	Anaerobic digestion of biogas	3	30

It should be noted that the renovation of hydropower stations for pumping are not considered as a separate technology, since pumping is not generation in its strict sense. It has been considered that the 4 types of onshore wind technologies reflect the different turbine designs that enable working more hours with less wind. Therefore, we get:

- Very High Yield Onshore Wind (Very High Onshore Wind IEC, Class S), i.e., operating even with IEC class S (*very low wind* approximately 30 m/s of reference speed for the wind) and which operates at a maximum of 3,780 hours/year with a CAPEX of 1194 €'15/MW;

- High Yield Onshore Wind (Low Onshore Wind IEC, Class III), i.e., operating even with wind speeds from IEC Class III or bigger (*low wind* approximately 37.5 m/s of reference speed for the wind) and which operates at a maximum of 2,800 hours/year with a CAPEX of 980 €'15/MW;
- Medium Yield Onshore Wind (Medium Onshore Wind IEC Class II) which operates only with wind speeds from IEC class II (*medium wind* approximately 42.5 m/s of reference speed for wind) and which operates for a maximum of 2,016 hours/year with a CAPEX of 912 €'15/MW (the investment values were swapped with technology III on the file);
- Low Yield Onshore Wind (Low Onshore Wind IEC Class III) which operates only with high wind speeds, i.e. IEC class I (high wind, approximately m/s of reference speed for wind) which operates for a maximum of 1,792 hours/year with a CAPEX of approximately 1,126 €'15/MW.

STRUCTURE OF THE LCOE APPLICATION

The LCOE tool or application is structured as follows (Figure 1 and following):

A) ***Reference Values***: Systematisation of the base data used to estimate the LCOE - this sheet is read-only and as such, cannot be modified

B) ***LCOE Dashboard***: Graphic presentation of the LCOE values, global or only for a certain component, for all the technologies under a ranking for a certain year (the year should be selected in the box on the right hand-side). To view the ranking made through the global LCOE value or one of its components, please select it from the boxes below the graph above. The graph below shows the same ranking, which is recalculated when the reference values in the Technology Dashboard (s. D) are altered;

C) ***Technology Dashboard***: Graphic presentation of the LCOE, disaggregating each cost component for two selected technologies, allowing for its comparison (the technologies should be selected under the graphs). Simulations can be made, altering the reference values for new values inserted by the user for the following parameters: investment, fixed O&M, variable O&M, hours worked, life span, fuel cost and CO_2 permit prices.

These simulations can be made in two ways:

1) The user inserts absolute values in the boxes on the left/right hand-side of the two graphs (or only one) and presses the "Update" button, or

2) The user changes the reference values in percentage terms using the bars below the two graphs.

The modified values for a certain year are extrapolated by 2050, assuming the same percentage difference. The alterations are viewed in the lower graph on the LCOE Dashboard. To return to the reference values, please press the "Reset" button. It is not possible to make changes on values referring to 2015.

D) **List of Technologies**: A list of the electricity generation technologies considered and the respective code used for viewing, according to Table 1.

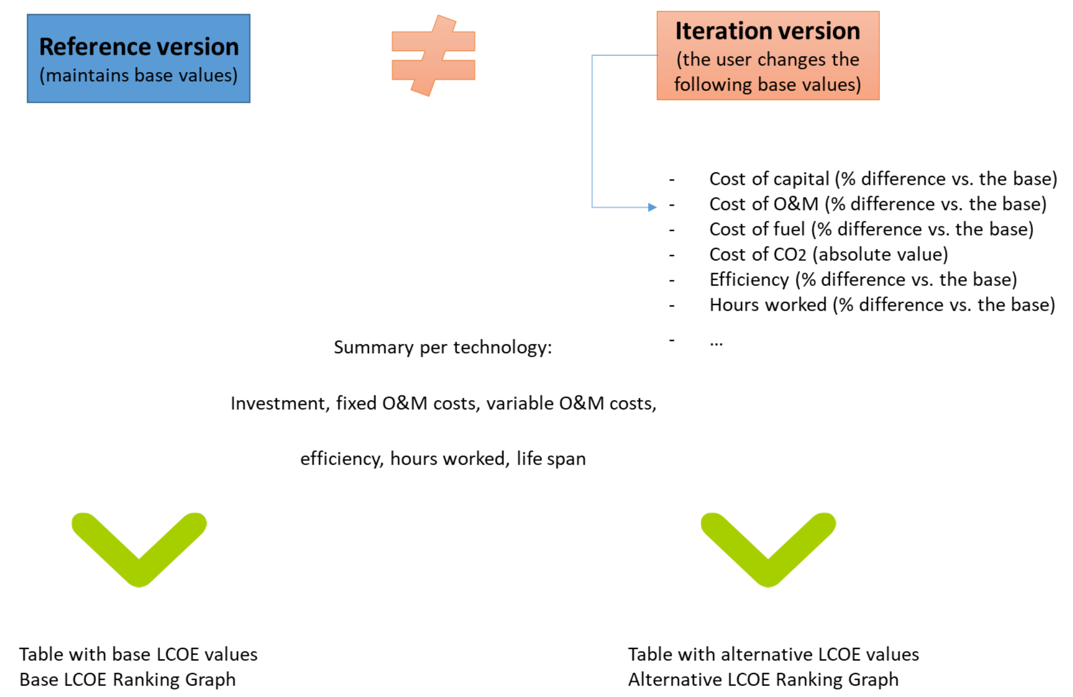

FIGURE 1 | POSSIBILITIES OF INTERACTING WITH THE LCOE TOOL

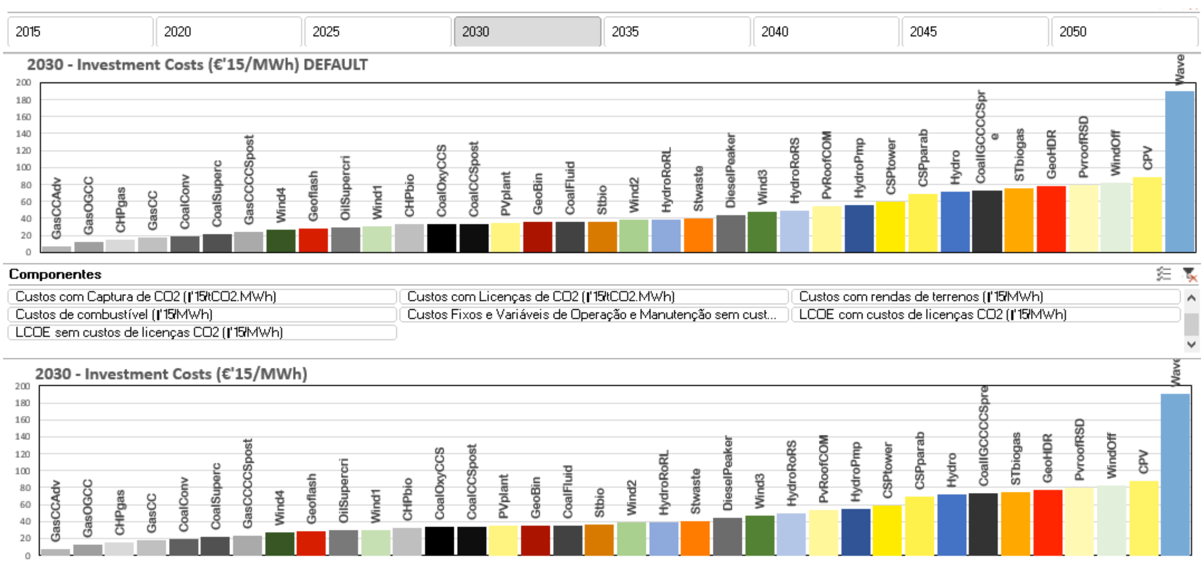

FIGURE 2 | LCOE TOOL DASHBOARD

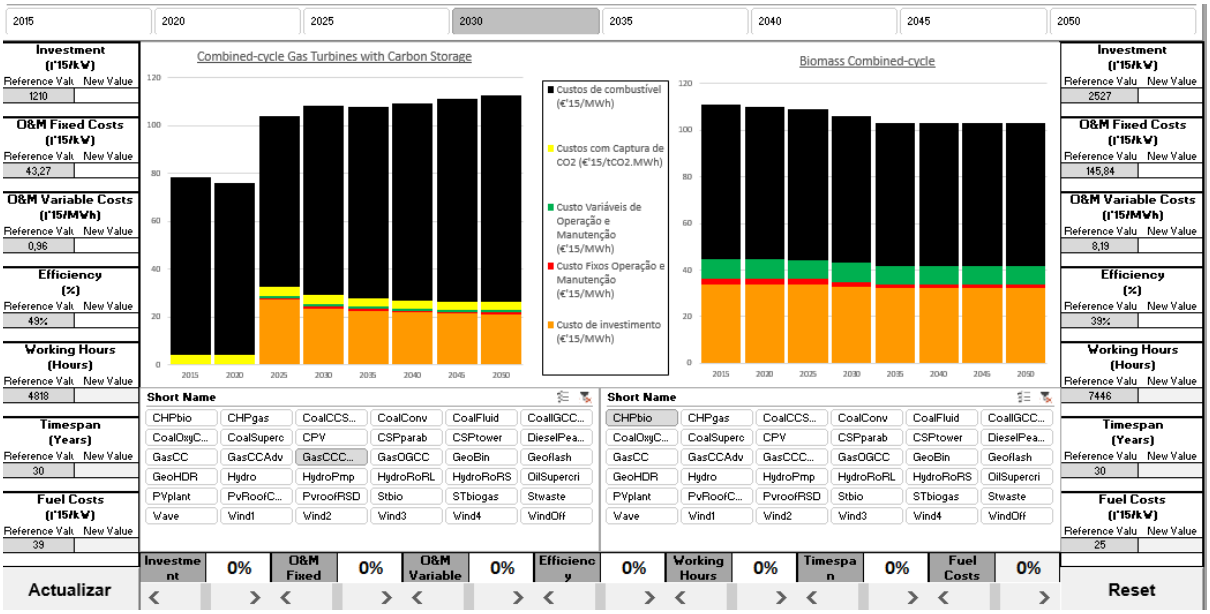

FIGURE 3 | TECHNOLOGY TOOL DASHBOARD

SOURCES OF INFORMATION

The following sources of information have been considered to obtain the values used when estimating the LCOE:

- Fraunhofer ISE (2015a). Current and Future Cost of Photovoltaics. Fraunhofer Institute for Solar Energy Systems. Available: https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf
- IRENA (2014). Renewable Power Generation Costs in 2014. International Renewable Energy Agency. Innovation and Technology Centre. Bonn, Germany. Available on: http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf
- IRENA (2015). Renewable Power Generation Costs in 2014. International Renewable Energy Agency. Innovation and Technology Centre. Bonn, Germany. Available on: http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf
- JRC (2013). The JRC-EU-TIMES model - Assessing the long-term role of the SET Plan Energy Technologies. Joint Research Centre. European Commission. Available on: http://publications.jrc.ec.europa.eu/repository/handle/JRC85804
- NREL (2016). U.S. Solar Photovoltaic, System Cost Benchmark: Q1 2016. National Renewable Energy Laboratory. USA. Available on: http://www.nrel.gov/docs/fy16osti/67142.pdf
- OECD/IEA and IRENA IRENA (2017). Perspectives for the Energy Transition - Investment Needs for a Low-Carbon Energy System. 204 pp. Available at:

http://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf

- Sigfússon, B. and Uihlein, A. (2015). 2014 JRC Geothermal Energy Status Report. Technology, market and economic aspects of geothermal energy in Europe. JRC Science and Policy Reports number JRC93338. ISBN 978-92-79-44614-6. doi:10.2790/460251
- Randall, T. (2016) World Energy Hits a Turning Point: Solar That's Cheaper Than Wind. Bloomberg Technology. December, 15.2016. Available on: https://www.bloomberg.com/news/articles/2016-12-15/world-energy-hits-a-turning-point-solar-that-s-cheaper-than-wind
- REN21 (2016). Renewables 2016 Global Status Report. Paris. ISBN 978-3-9818107-0-7. Available on: http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf
- WWEA (2016). Small Wind World Report. World Wind Energy Association. Available on: http://www.wwindea.org/small-wind-world-market-back-on-track-again/
- JRC (2014). ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. JRC Science and Policy Reports number JRC92496, ISBN 978-92-79-44403-6, doi: 10.2790/057687
- Torres, A. (2017). Comunicação pessoal a Sofia Simões da Direção Técnica da Valorsul sobre custos médios de recolha de RSU. October 2017.

II. PROSPECTIVE INDICATORS OF RENEWABLE ELECTRICITY IN THE PORTUGUESE ENERGY SYSTEM

SCOPE AND OBJECTIVE

In the end of 2015, the Paris Agreement was signed with the main goal of strengthening the global response to climate change and reinforcing the countries' capacity to adapt to its risks and impacts. A total of 195 countries, including Portugal, pledged to "keep the rise in the global average temperature below 2º C above pre-industrial levels and drive efforts to restrict the temperature rise to up to 1.5º C above pre-industrial levels".

The Paris Agreement will thus demand a deep decarbonisation of the economy, focused mainly on its energy sector. The investment on energy efficiency and low/neutral carbon electricity, namely renewable electricity, has been pointed out as the main strategy to assure deep cuts in greenhouse gas emissions.

Currently, Portugal already counts on a high percentage of renewable sources in terms of electricity generation (54% in 2016), and significantly increasing this proportion would require a well-pondered strategy, which represents a significant challenge since it brings the need to change behaviours and paradigms. Following the national pledge to reach carbon neutrality by the first half of the century, it is crucial to understand the importance of renewable electricity in the decarbonisation of the Portuguese energy system.

What are the costs/benefits of a transformation into a power-producing system with a high proportion of renewable energies? What is the optimal technological profile, i.e. cost-effective, of this power-producing system? These are also fundamental issues raised by political decision-makers and investors and which are generally responded to using a common metric to estimate and compare the costs involved in electricity generation per technology - the LCOE. However, a simple analysis of the LCOE ignores several aspects of the total value of the system, namely costs and benefits of an integration of renewable technologies (Ueckerdt et al., 2013), including: i) The "profile" costs (linked to the costs involved in the variability of renewable energy throughout the day and/or year); ii) "Stabilisation" costs (the output of renewables is uncertain and this needs to be taken into account when planning the configuration of a power-producing system so as to assure a safe supply), iii) Network costs (different technologies and locations associated to different network costs, generally ignored by a simple analysis of the LCOE).

Therefore, this component intends to go beyond a simple LCOE analysis, encompassing in its analysis (sustained by an energy model of optimisation), the cost/benefit balance of the integration of renewables at the systemic level.

Therefore, the study aims to analyse the role of renewable electricity and establish a selected set of indicators to illustrate the value of renewable electricity production for the Portuguese energy system, namely the impact on the global cost of the electric system, savings/reduction in GHG emissions and costs avoided with the purchase of permits in auction, the impact on the commercial balance of energy products and the degree of energy dependency.

METHODOLOGY: THE TIMES_PT MODEL

The TIMES_PT is a linear optimisation technological model that results from the implementation of the economy-energy optimisation models generator in Portugal in a TIMES environment developed by ETSAP (Energy Technology Systems Analysis Programme), from the International Energy Agency (IEA). The generic structure of the TIMES may be adapted by each user to simulate a specific energy system, at a local, national or multi-regional scale. The main objective of any TIMES model is to satisfy the demand for energy services at the smallest cost possible. To this end, investment options and the operation of certain technologies, sources of primary energy and energy imports and exports are simultaneously considered, according to the following equation (Loulou, et al., 2005a, 2005b):

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \bullet ANNCOST(r, y)$$

NPV: net present value of total costs

ANNCOST: total annual cost

d: update rate

r: region

y: years

REFYR: reference year for updating purposes

YEARS: set of years for which there are costs (all the costs included in the model, plus past years with costs defined for past investment plus a number of years after the technology's life span in case dismantling costs are also considered)

For each year, the TIMES model calculates the updated sum of the total costs, minus the income. The TIMES_PT model considers investment, operational and maintenance (fixed and variable) costs for the various energy production and consumption technologies. The income generally considered in the TIMES model includes subsidies and material recovery, which are not considered in the TIMES_PT model. More information may be obtained about the development of the TIMES and respective equations on Loulou, et. al., (2005a, 2005b).

The TIMES_PT model represents the Portuguese energy system from 2005 to 2050, including the following sectors: offer of primary energy (refining and production of synthetic fuel, imports and endogenous resources); power generation; industry (cement, glass, ceramics, steel, chemistry, paper pulp and paper, lime and other industrial materials); residential; tertiary; agriculture and forestry, fisheries (only the energy consumption component) and transportation. Each sector models in detail the monetary, energy and material flows associated to the various energy production and consumption technologies, including mass balance for some industrial sectors. The simplified structure of the TIMES_PT model is shown in Figure 4.

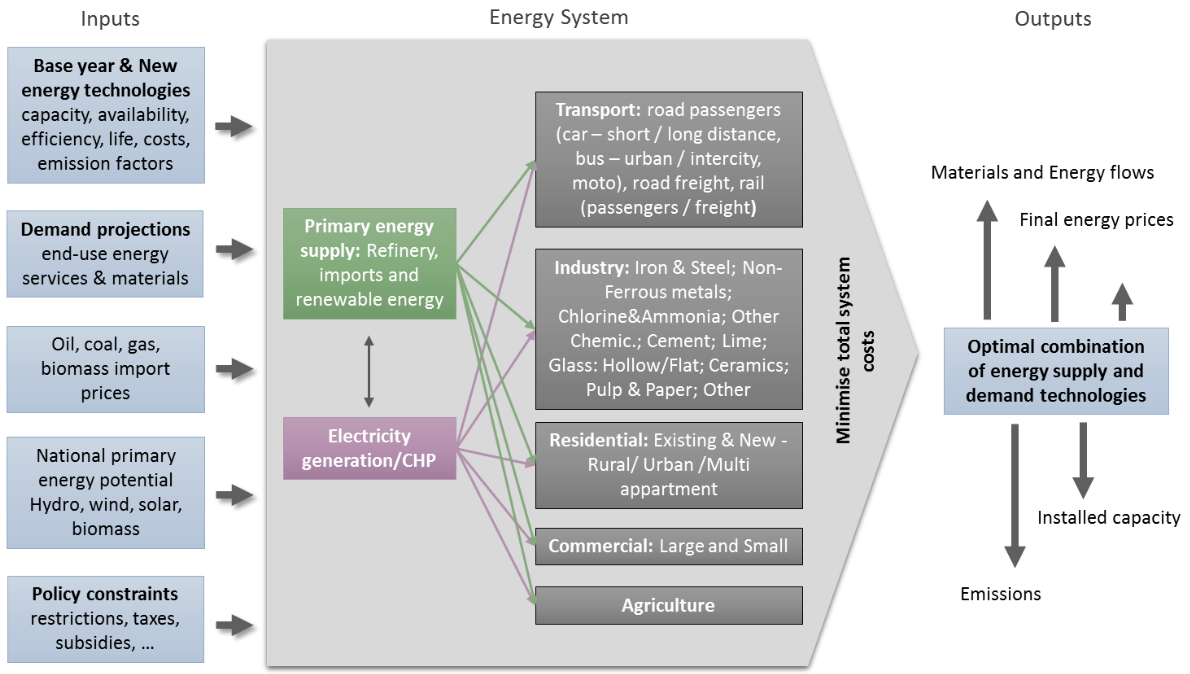

FIGURE 4 | SCHEMATIC REPRESENTATION OF THE TIMES_PT MODEL

The implementation of the TIMES_PT requires the specification of a set of exogenous inputs, namely: demand for energy services, the technical and economic features of the energy demand and supply technologies, the potential for the use of endogenous energy resources, imports and respective costs and restrictions in terms of the energy and climate policy, such as restrictions on greenhouse gas emissions or renewable final energy consumption objectives. A detailed description of the inputs considered in this study is shown in the following section.

The model also generates a series of outputs, including: the costs of the energy system, energy flows linked to each sector, technological options, namely installed capacity in the power-producing system, energy imports and exports, use of endogenous resources and sectorial emissions. The emissions considered by the model include greenhouse gas emissions generation in combustion and industrial processes, and do not include escaping emissions associated with the production, storage and distribution of fossil fuels and fluorinated gases (F-gases).

Although the model handles information sequentially, the results are only shown for 5-year periods (e.g. 2005, 2010, 2015,... 2040, 2045, 2050). Each year is divided into 12 time periods which represent an average day. Energy supply and demand is thus disaggregated among the night, day and peak periods for each of the four seasons: spring, summer, autumn and winter (e.g. spring daytime period, spring peak period, summer night period, etc.) (Table 2). This disaggregation enables the differentiation between the various electricity demand periods (more intense during peak periods and less intense during the night period) and capture the daily and seasonal variability of the different electricity generation technologies with a renewable base (e.g. solar PV technology is not available during the winter peak period; it is more available over the periods associated with spring compared to winter). Therefore, this disaggregation allows for the consideration of "profile" costs of renewable technologies, albeit in a superficial manner when compared to an hourly-based model.

TABLE 2 | TIME DISAGGREGATION OF THE TIMES_PT MODEL

	Season duration	Day periods duration		
		Day	Night	Peak
Spring	21 Mar - 20 Jun	7 AM - 11 AM Noon - 9 PM	9 PM - 7 AM	11 AM - Noon
Summer	21 June - 21 Sept	7 AM - 11 AM Noon - 9 PM	9 PM - 7 AM	11 AM - Noon
Autumn	22 Sept - 20 Dec	7 AM - 9 AM	8 PM - 7 AM	7 PM - 8 PM
Winter	21 Dec - 30 Mar	7 AM - 9 AM	8 PM - 7 AM	7 PM - 8 PM

It is also worth noting that, because it is a model of partial balance, TIMES does not consider economic interactions outside the energy sector, such as implications on the activity of other sectors of the economy (e.g. Impact of the expansion of wind power in the metalworking sector). Also, the model does not consider irrational aspects that limit the investment in new technologies, namely preferences motivated by aesthetics or social status which may occur mainly during the acquisition of end use technologies. Therefore, the TIMES model assumes that the stakeholders have perfect knowledge of the market, both present and future. Finally, it is important to highlight that the technological base models like the TIMES_PT, do not accommodate for market decisions based on price, taking options based on cost, both in terms of technologies and energy resources. For this reason, the solutions found translate the best options in terms of cost-efficiency.

INPUTS & SCENARIOS

The main inputs of the TIMES_PT model, which are common to all the modelled scenarios under the scope of this study, include:

A. **Demand for energy services.** The estimate of energy services (useful energy per type of service and within national circumstances), materials and mobility by the various activity sectors is determined through a prospective scenario for the Portuguese economy and demography, using differentiated methodologies for the various activity sectors. A detailed description of the methodology to determine the demand for energy services can be found in Fortes et al. (2015). Additionally, the estimate of the demand for energy services and others (e.g., cement production) also considers the expectations of the economic stakeholders consulted in some previous modelling exercises. The social and economic context considered in the present study is based on an intermediate estimate of growth based on historic trends and forecasts by various entities. The values considered for the social and economic characterisation by 2050 are presented on Table 3. It should be noted that no type of rupture has been assumed regarding the structure of the current economic model.

TABLE 3 | SOCIAL AND ECONOMIC INDICATORS

	2005	2010	2015	2020	2030	2040	2050
GDP (M€$_{2011}$)*	174,038	179,445	171,343	182,102	211,337	245,265	284,640
Population (thousands)**	10,503	10,573	10,358	10,339	10,203	9,974	9,559
GDP Per capita (M€$_{2011}$/pa)	16.6	17.0	16.5	17.6	20.7	24.6	29.8

*IMF projections by 2020 (FMI, 2016); from 2020: 1.5%/year; **high scenario growth projections from the United Nations (UN, 2016).

B. **Technical and economic features of the existing technologies** over the baseline year, as well as future technologies. The technological database of the TIMES_PT model is made of approximately 2,800 technologies (current and future). The technologies are characterised by representative parameters like efficiency, technical life span, availability, investment costs and operation and maintenance costs. The technological database which supports the TIMES_PT model started to be developed during the NEEDS European project (2008) and was expanded and updated throughout the last 10 years during various international projects (e.g. RES2020, COMET, CCS Roadmap, INSMART,) and national projects (e.g., Roteiro Nacional de Baixo Carbono, Programa Nacional para as Alterações Climáticas, Contributo da Eletricidade na Descarbonização da Economia Portuguesa). Under the scope of this study, electricity generation technologies, especially those based on renewable energy sources, were subject to an update and posterior validation process by APREN. The technical and economic data and respective sources of information are presented on the LCOE (Section i). As referred in the previous chapter, the availability of the renewable electricity generation technologies shows a time disaggregation divided among 12 time periods to simulate its seasonal and daily variability. Additionally, the uncertainty associated to renewable resources is captured in a simplified manner through factors that contribute to the peak and which reflect, for a high level of probability of occurring, the percentage of installed capacity per technology that is available to satisfy peak periods. Table 4 shows "peak contribution" factors, which have been validated by national stakeholders.

TABLE 4 | CONTRIBUTION FACTORS OF THE RESOURCE/TECHNOLOGY FOR PEAK CAPACITY

Resource/Technology	Factor
Natural gas-powered thermal power plants	93%
Coal-powered thermal power plants	91%
Fuel-powered thermal power plants	78%
Biomass, biogas or waste-powered plants	50%
Large hydropower plant with pump	70%
Large hydropower plant without pump	60%
Small hydropower plant	38%
Onshore wind farm	7%
Solar PV	0%
Offshore wind farm	10%
CSP	20%
Geothermal	50%
Waves	50%
Cogeneration	57%

The TIMES_PT model also accommodates the costs of the transportation and distribution network and the study considered the high tension values (above 150 kV) of the report by ENTSO-E (European Network of Transmission System Operators for Electricity): ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2010 (ENTSO-E, 2011). In this sense, the following cost variables are assumed for the transmission and distribution network: High: 9.7 $€_{2011}$/MWh; Average: 21.4 $€_{2011}$/MWh and Low: 12.3 $€_{2011}$/MWh.

C. **Primary energy sources** available, current and future, including: i) Potential endogenous energy resources with technical viability and expectation of economic feasibility, ii) Primary energy imports and iii) Respective costs. The present study considered the potential endogenous resources according to the information provided in the national low carbon roadmap (Roteiro Nacional de Baixo Carbono (Seixas et al., 2012)) (Table 5), except for the potential in terms of solar energy, which has been subject to an update based on the best information available and the exponential technical and economic progress of the technology verified over the last years.

As far as fossil primary energy imports are concerned, the prices from the New Policies of the World Energy Outlook 2016 published by the International Energy Agency prolonged to 2050 (IEA, 2016) (Table 6)were assumed. In its turn, the evolution of bio-energy import prices follows the same assumptions, considered on the RNBC (Seixas et al, 2012), i.e.:

- Evolution of the price of biodiesel and oil for the production of biofuel indexed to the evolution of the price of diesel;
- Evolution of the price of bioethanol indexed to the price of gasoline;

- Evolution of the price of biomass indexed to the evolution of the price of natural gas, as it considers various energy commodities which compete among them. This relation was considered for the fact that there is no converging information published regarding the evolution of the prices of biomass.

TABLE 5 | TECHNICAL POTENTIAL OF ENDOGENOUS RESOURCES

Resource/Technology	Unit	Current Situation	Maximum Potential			Source
		2015	2020	2030	2050	
Hydric (dam)	**GW**	6.03	4.27	6.29	9.83	PNBEPH
Hydric (water flow)	**GW**		3.43			PNBEPH
Onshore Wind Farm	**GW**	5.03	6.50		7.50	RNBC (LNEG)
Offshore Wind Farm	**GW**	N/A	4.00		10.00	RNBC (LNEG)
Wave	**GW**	N/A	5.00		7.70	WaveC
PV (decentralised)	**GW**	0.45	2		13	IEA, 2002
PV (centralised) Solar Concentrator (CPV) CSP	**GW**		2		12*	Own calculations
Municipal Solid Waste	**PJ**	2.13	9.10	7.50	9.50	PNAC
Biogas	**PJ**	1.07	2.90	2.20	0.40	PNAC
Geothermal	**GW**	0.03	0.05	0.08	0.23	RNBC (Luís Neves)
Geothermal (hot dry rock)	**GW**			0.10	0.75	RNBC (Luís Neves)
Biomass - forest	**PJ**	8.61	17.67	30.87		RNBC (CELPA)
Biomass - waste from agriculture and the wood industry	**PJ**			5.93		
Bioethanol	**PJ**			19.50		RNBC (GPPAA – Ministry of Agriculture
Biodiesel	**PJ**			9.99		RNBC (GPPAA – Ministry of Agriculture)

TABLE 6 | PRIMARY ENERGY IMPORT PRICES.

		2015	2020	2025	2030	2035	2040	2045	2050
Oil	$2015/bbl	51.0	79.0	95.5	111.0	118.0	124.0	128.8	132.7
Natural Gas	$2015/MBtu	7.0	7.1	8.7	10.3	10.9	11.5	12.0	12.3
Coal	$2015/t	57.0	63.0	68.5	74.0	75.5	77.0	79.1	81.3

Source: IEA (2016).

Although it is not a source of energy, CO_2 storage potential is also seen as an endogenous resource in terms of low carbon options. Therefore, onshore and offshore potential were considered as well as its respective costs from the CCS Roadmap for Portugal project (Seixas *et al*., 2015).

D. **Policy Assumptions**, such as rates, greenhouse gas emission restrictions or end energy consumption goals from renewable sources. All the scenarios considered the tax on oil and energy products (ISP), circulation tax (IUC) and road tax, according to values from July 2016 assumed as a constant by 2050. VAT has not been considered. Additionally, incentives to the production of renewable electricity, namely current incentives (feed-in tariffs, or FITs) have not been considered as the aim is to assess their cost-efficiency in the absence of any incentives and also because the perspective for these incentives by 2050 is not known. The policies on energy and climate assumed in each scenario are listed in the description of the scenarios, and each has different presumptions.

In energy system optimisation models like the TIMES_PT model, the demand for energy services may be satisfied by numerous technological options that are cost-effective, depending on the predefined assumptions, especially in terms of curbing greenhouse gas emissions. It is worth noting that the technological modelling supported by the TIMES_PT does not consider other external factors, usually associated to electricity production technologies, such as the loss of value in land incoming from its increasing or decreasing occupation and the respective landscape value and biodiversity, or the gain in the quality of air from a rise in the usage rate of renewable energy sources.

To assess the role of renewable electricity in the decarbonisation of the national energy system, we have considered the following scenarios:

- **Conservative RES-E scenario**, considered as a baseline for the decarbonisation scenarios. This scenario assumes the fulfilment of the current energy/climate policy goals for 2020 as well as keeping them until 2050, in percentage terms of the gross energy consumption. Additionally, it restricts centralised renewable electricity up to 60% of the value associated to the national target for 2020.
- **Mitigation scenarios - 60%**, which establish a linear reduction of GHG emissions from the energy sector and industrial processes until it reaches -60% in 2050, compared to 1990. This scenario does not define any restriction to the entrance of renewable electricity.
- **Mitigation scenarios - 75**, which establish a linear reduction of GHG emissions from the energy sector and industrial processes until it reaches -75% in 2050, compared to 1990, with an interim target of -60% in 2040 compared to 1990. This scenario also does not define any restriction to the entrance of renewable electricity.

Table 7 presents the main policy criteria considered in each scenario.

TABLE 7 | DESCRIPTION OF THE POLICIES CONSIDERED IN EACH OF THE 3 SCENARIOS

	Energy Policy	Climate Policy	Other Assumptions
Conservative FER-E	**2020**: Energy production from renewable sources: 31% of the total consumption of end use energy according to the Directive 2009/28/CE of the European Parliament and Council, from April 23, 2009. **2020**: Energy efficiency: maximum limit to the consumption of primary energy in 2020 (based on PRIMES forecasts made in 2007) equivalent to a 20% reduction (RCM no. 20/2013), **After 2020:** The same conditions from 2020 are considered	**2020**: Emissions caps considering the objectives of the Effort-Sharing Decision for Portugal (+1% in 2020 compared to the emissions verified in 2005) and, in the case of the CELE, considering the current value of 5€/t for the emissions from the sectors involved, namely the power-producing sector. **After 2020:** The same conditions from 2020 are considered	The phase-out of coal-powered thermal power plants is considered in Sines and Pego, in line with Trajectory A of the Safety Monitoring Report on the Supply of the National Electricity System 2017-2040 (DGEG, 2017), i.e. an extension of the Sines Station is admitted to the end of 2025, but in the case of the Pego station, its decommissioning is considered on the date set in the CAE/MEC, 2021. Dedicated FER-E may only reach a maximum value of 60%
Mitigation - 60%	The policies of the conservative FER-E scenario are understood as base conditions	**2020:** Identical conditions to the conservative FER-E scenario **After 2020:** Linear reduction of total emissions from the energy sector and industry until reaching -60% in 2050, compared to 1990.	Identical conditions to the Conservative FER-E scenario, except for the maximum limit of FER-E, without considering any restriction to the percentage of FER-E

Mitigation - 75%	The policies of the conservative FER-E scenario are understood as base conditions	**2020:** Identical conditions to the conservative FER-E scenario **After 2020:** Linear reduction of total emissions from the energy sector and industry until reaching -60% in 2040, compared to 1990 and -75% in 2050/1990.	Identical conditions to the Conservative FER-E scenario, except for the maximum limit of FER-E, without considering any restriction to the percentage of FER-E

THE INEVITABLE ROLE OF RENEWABLE ELECTRICITY PRODUCTION

This section shows the results obtained for each of the scenarios previously described and simulated through the TIMES_PT model, structured in a way as to provide a response to the main question: what is the role and the value of the production of renewable electricity for the Portuguese energy system? A series of indicators is presented, as well as their respective key message, namely its impact on the global cost of the electricity system, their savings/GHG emission reduction, its impact on the commercial balance of energy products and the degree of energy dependency, among others.

A. Contribution of renewable electricity to the decarbonisation of the national energy system

The Figure 5 illustrates the trajectory of emissions in the national energy system (including emissions from industry processes) for the different scenarios under analysis. Without a specific target for CO_2 mitigation for a maximum cap of 60% renewable electricity, national emissions only reach a reduction of -21% compared to 1990, -26% compared to 2030 and 2050, respectively, which is well below the necessary expressive mitigation to reach the goals defined on the Paris Agreement.

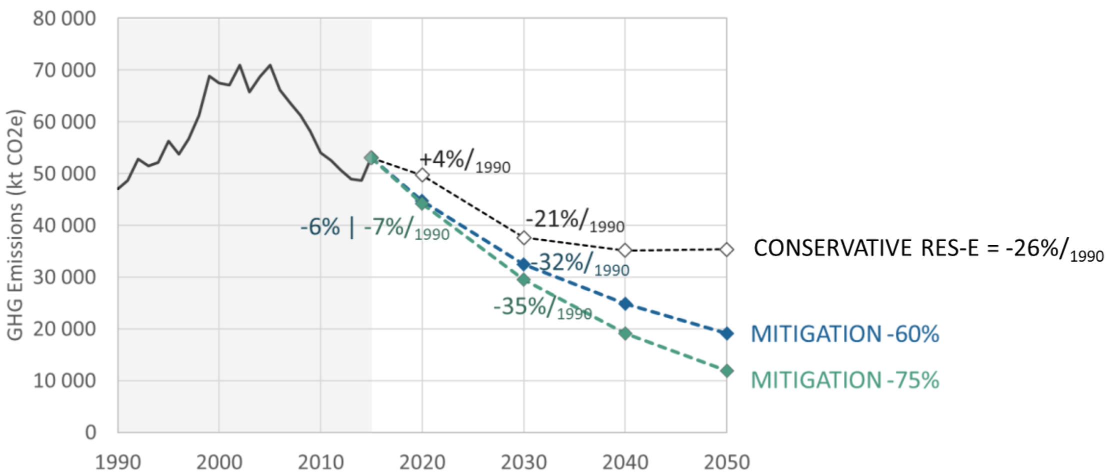

FIGURE 5 | TRAJECTORY OF GREENHOUSE GAS EMISSIONS IN THE NATIONAL ENERGY SYSTEM (INCLUDING EMISSIONS FROM INDUSTRY PROCESSES) IN THE 3 SCENARIOS UNDER ANALYSIS.

Looking at total emissions avoided in the mitigation scenarios, it is seen that the role of the power-producing sector will be considerable (Figure 6). In 2030, the power-producing sector will be responsible for 89% of emissions avoided in the Mitigation Scenario -60% facing the Conservative FER-E Scenario. In the Mitigation -75% Scenario, more demanding in terms of restricting the emissions, the value decreases to 68%. Even in the long run, the power-producing sector is responsible for more than 2 thirds of the emissions reduced in the mitigation scenarios compared to the conservative scenario, specifically 52% and 37% for the Mitigation -60% scenario and Mitigation -70% scenario, respectively.

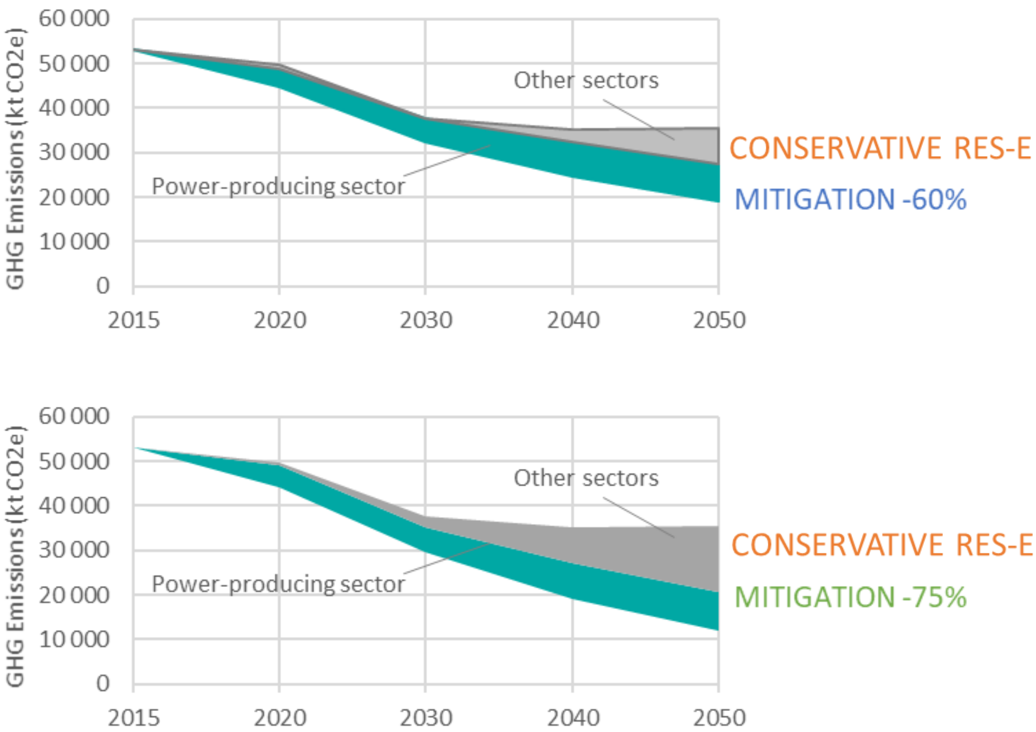

FIGURE 6 | TRAJECTORY OF GREENHOUSE GAS EMISSIONS IN THE NATIONAL ENERGY SYSTEM (THE GREEN AND GREY ZONES REPRESENT EMISSIONS AVOID BY THE POWER-PRODUCING SECTOR AND EMISSIONS AVOIDED BY OTHER SECTORS, RESPECTIVELY, COMPARED TO THE CONSERVATIVE FER-E SCENARIO).

The emissions avoided by the power-producing sector in the mitigation scenarios are associated to significant values of renewable electricity. The percentage of renewable electricity is approximately 80% in 2030 (between 79% and 87% depending on it being the total electricity in the scenario *Mitigation -60%* or only dedicated electricity in the *Mitigation -75%*) scenario and 90% in 2050 (between 89% and 94%) (Figure 7 and Figure 8). These figures illustrate the crucial role of renewable electricity to reach an accentuated decarbonisation in the national energy system, which is not verified in the *Conservative FER-E* scenario.

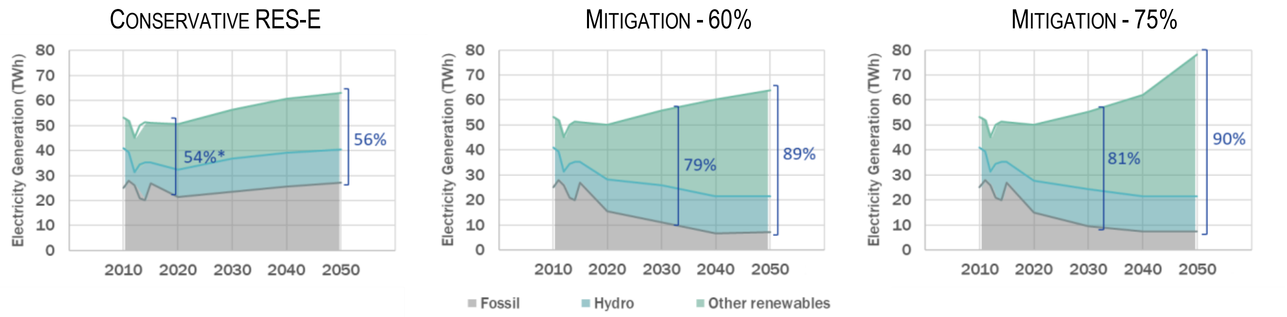

FIGURE 7 | EVOLUTION OF TOTAL ELECTRICITY GENERATION (INCL. COGENERATION) (TWh) PER TYPE OF RESOURCE IN THE 3 SCENARIOS UNDER ANALYSIS.

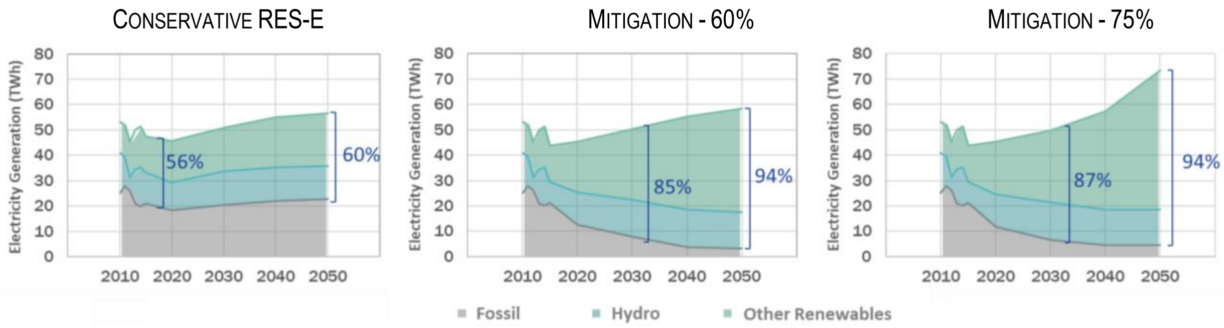

FIGURE 8 | EVOLUTION OF DEDICATED ELECTRICITY GENERATION (NOT INCL. COGENERATION) (TWh) PER TYPE OF RESOURCE IN THE 3 SCENARIOS UNDER ANALYSIS.

Among the most cost-effective electricity generation in the decarbonisation scenarios, hydropower, onshore wind farms and solar PV stand out (Figure 9 and Figure 10). The first two can reach their maximum defined potential in the modelling (see Table 5), considered to be the potential with technical viability and expectation of economic feasibility compared to currently known data.

Onshore wind power could be responsible for approximately 38%/39% of generated electricity (not including cogeneration) by 2030, in the Mitigation -60% and Mitigation -75% scenarios, respectively. Solar PV, which currently represents only approximately 2% of the production of electricity, could produce approximately 12%/14% of electricity by 2030, gaining a significant relevance by 2050, with 30%/31%.

In the Mitigation -75% scenario, where there is a significant increase of the electricity generated, offshore wind power becomes even more cost-effective. Its lesser variability compared to other renewables justifies the competitiveness of the technology, for instance, being available in night periods and peak periods during Autumn and Winter, which does not happen with solar PV.

Additionally, on both decarbonisation scenarios, natural gas with carbon capture and sequestration becomes a cost-effective technological option. Although this technology shows a superior unitary cost compared to some renewable base technologies, it assures a secure supply and a stable network during situations of less renewable production, both at a seasonal and daily scale. It is worth noting that natural gas with CO_2 capture and sequestration acts as a backup technology, which could be replaced by batteries in case the technology had been integrated in the modelling.

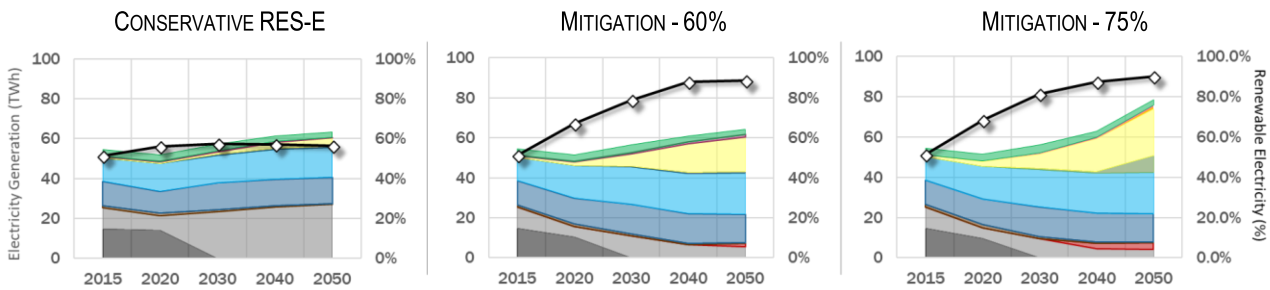

FIGURE 9 | EVOLUTION OF TOTAL ELECTRICITY GENERATION (INCL. COGENERATION) (TWh) PER TYPE OF RESOURCE IN THE 3 SCENARIOS UNDER ANALYSIS.

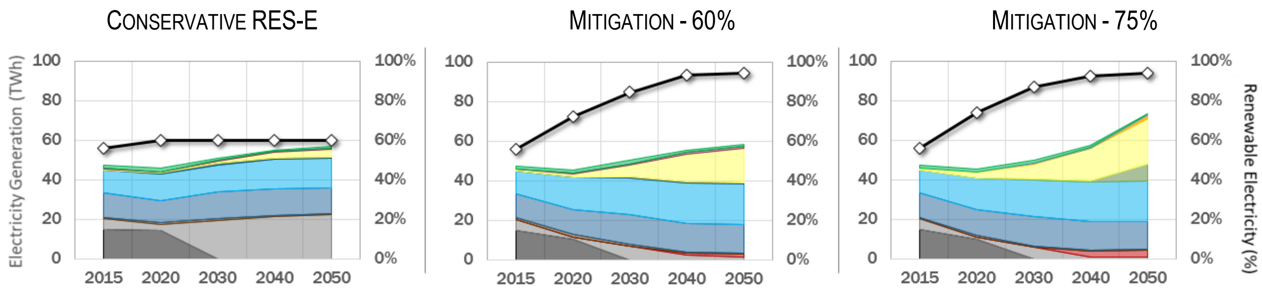

FIGURE 10 | EVOLUTION OF DEDICATED ELECTRICITY GENERATION (NOT INCL. COGENERATION) (TWh) PER TYPE OF RESOURCE IN THE 3 SCENARIOS UNDER ANALYSIS.

Besides the decarbonisation of the electric power sector, the electrification of the renewable-based economy becomes an essential strategy in a scenario of accentuated decarbonisation as is the case of the Mitigation -75% scenario. In this scenario, we see an annual growth of approximately 1.3% p.a. Between 2015 and 2050 in terms of electricity consumption, almost double the figure from the *Conservative FER-E* and *Mitigation -60%* scenarios *(*Figure 11*)*.

Even though the services and industry sectors are the ones with the higher absolute increase in electricity consumption, from the percentage point of view, the transportation sector will suffer the largest increase of electricity consumed. Currently, electricity represents less than 1% of energy consumption in the transportation sector, and it could grow to approximately 27% in the *Mitigation -75%* scenario. It is worth noting that electrical vehicles are significantly more efficient than internal combustion vehicles and 27% over the total consumption in the sector actually represents 87% of the stock of electricity-based private vehicles.

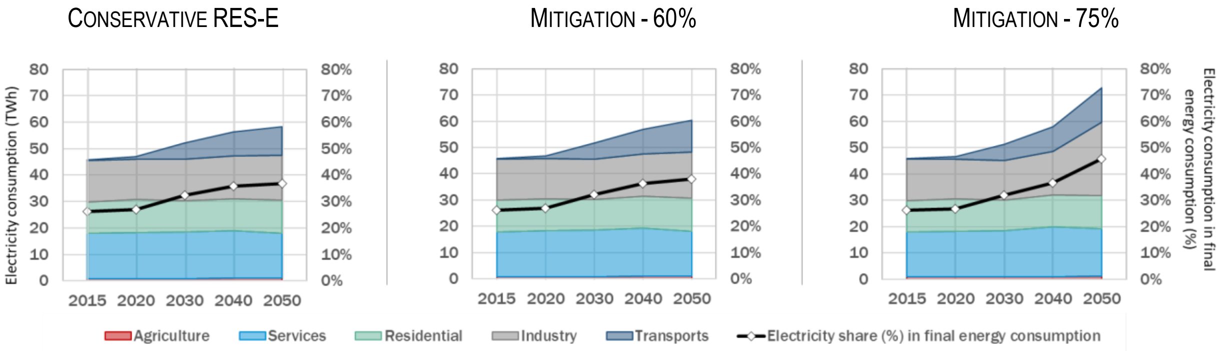

FIGURE 11 | EVOLUTION OF ELECTRICITY CONSUMPTION (TWh) PER TYPE OF RESOURCE IN THE 3 SCENARIOS UNDER ANALYSIS.

B. Value of renewables from the national energy and electricity system

Besides the inevitable role of the FER-E in the decarbonisation of the national energy system, its increase carries other positive impacts, such as the decrease in energy dependency, the reduction of costs with emission permits, among others. Next, we show a series of indicators that reflect the value of renewable sources for the national energy system and mainly, the electricity sector.

> **Consumption of primary energy and energy dependency**

In the Conservative FER-E scenario, due to the emergency of more efficient technologies, there is a high potential of energy efficiency with an impact on the reduction of primary energy. Therefore, even in the absence of specific mitigation targets, a 30% reduction in primary energy compared to 2015 is expected, mainly focused on fossil energy. In its turn, the decarbonisation scenarios include an additional reduction of primary energy and the contribution of imported fossil energy is significantly inferior, particularly in 2050.

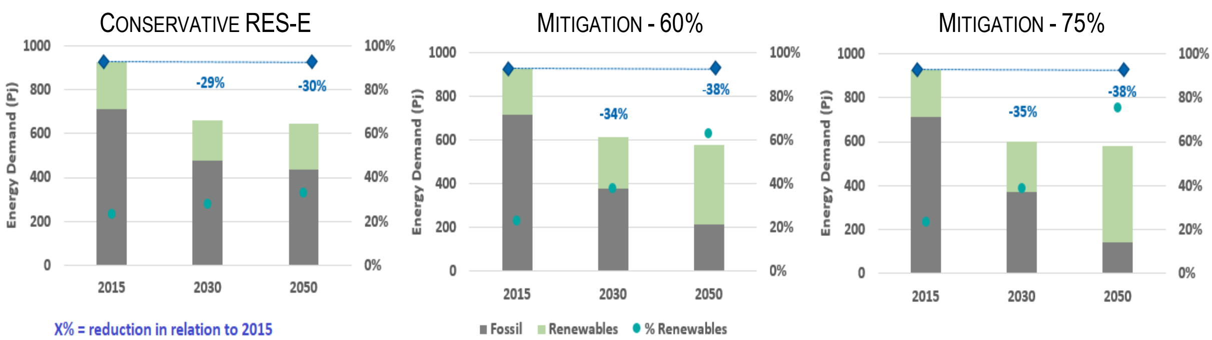

FIGURE 12 | EVOLUTION OF THE CONSUMPTION OF PRIMARY ENERGY AND PERCENTAGE OF CONSUMPTION OF RENEWABLE ENERGY (SCALE ON THE RIGHT) IN THE 3 SCENARIOS UNDER ANALYSIS.

This evolution in the consumption and configuration of primary energy has an impact on energy dependency. In a Conservative FER-E scenario, there is a reduction in the national energy dependency, which may decrease from the current 77% to 69% in 2050 (Figure 13). However, in scenarios with an accentuated decarbonisation, with the presence of a high percentage of renewable electricity, this value may suffer a considerable decrease reaching approximately 46% and 33% in the *Mitigation -60%* and *Mitigation -75%* scenarios, respectively. The reduction in energy dependency associated to the electricity producing sector will be even more significant, since endogenous renewable sources will gain a fundamental role in the generation of electricity, as previously observed. Therefore, the energy dependency in the power-producing sector, which already counts on values of approximately 56% in the long run, a Conservative FER-E scenario, will be of approximately 10% in the mitigation scenarios (Figure 14).

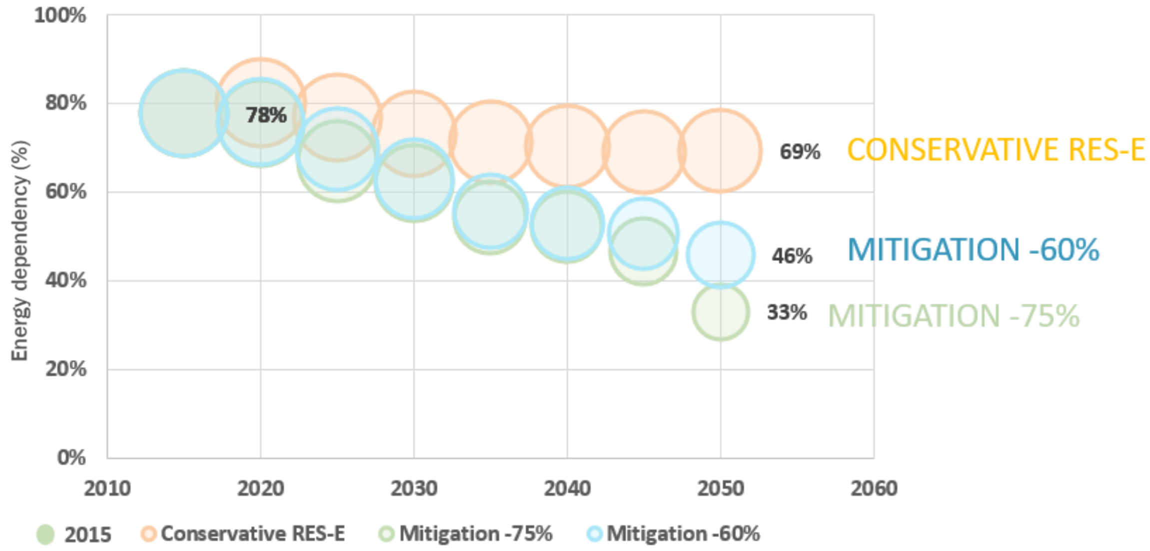

FIGURE 13 | EVOLUTION OF ENERGY DEPENDENCY (%) OF THE NATIONAL ENERGY SYSTEM IN THE 3 SCENARIOS UNDER ANALYSIS.

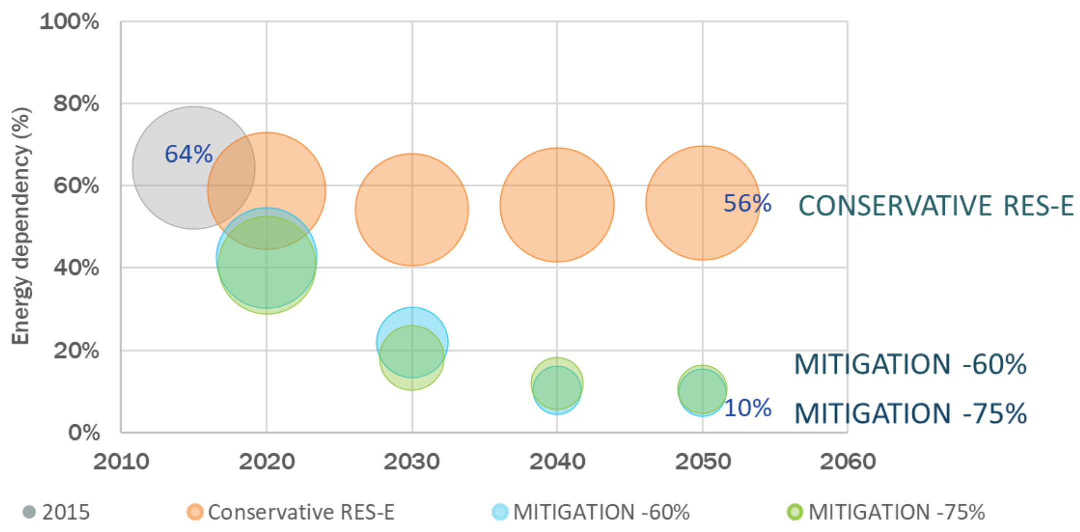

FIGURE 14 | EVOLUTION OF ENERGY DEPENDENCY (%) OF THE NATIONAL ELECTRICITY SYSTEM IN THE 3 SCENARIOS UNDER ANALYSIS.

> **Cost of the electricity system**

Contrary to the general idea that renewable energy increments the costs involved in power generation, the values obtained show that, in general, the total costs of the electricity system (electricity production sector + distribution and transportation network) with a smaller percentage of renewable electricity are superior to the mitigation scenarios (Figure 15). This fact occurs mainly due to the accentuated weight of fuel costs, more specifically natural gas, which represents nearly 30% of the total cost in 2050. In this sense, even with higher investment costs, the Mitigation -60% scenario presents total costs below those of the Conservative FER-E scenario, namely -14% in 2030 and -24% in 2050. Only in the Mitigation -75% scenario and in 2050, will the costs of the electricity system be slightly above (+2%) the cost in the Conservative FER-E scenario. This is mainly due to the very high investment value, which represents approximately 50% of the total costs on that year. However, the high costs of investment verified in the Mitigation -75% scenario are associated to the significant volume of electricity generated. Therefore, focusing the analysis on the unitary cost of production, it is verified that, regardless of the scenario or year, a production profile with a significant weighing of fossil energy always shows superior values, above 10% in 2030 and 20% in 2050, compared to the mitigation scenarios (Figure 16).

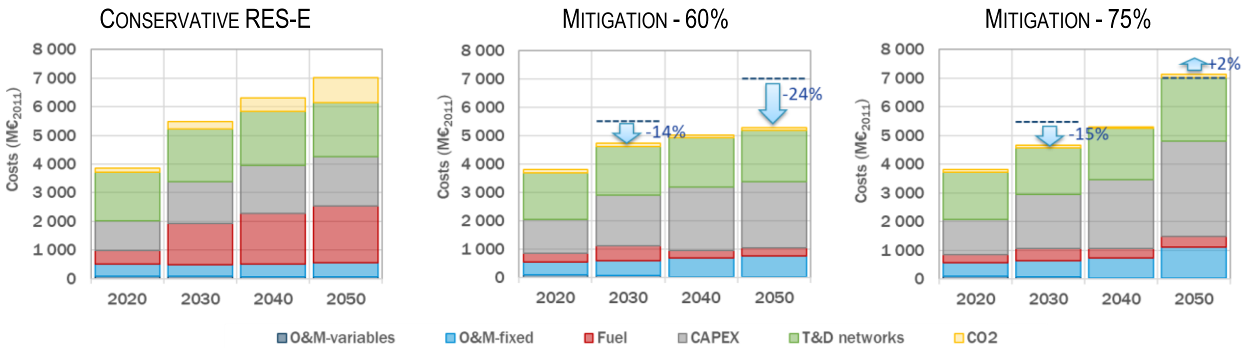

FIGURE 15 | EVOLUTION OF THE TOTAL COSTS OF THE ELECTRICITY SECTOR (€2011) PER COMPONENT IN THE 3 SCENARIOS UNDER ANALYSIS.

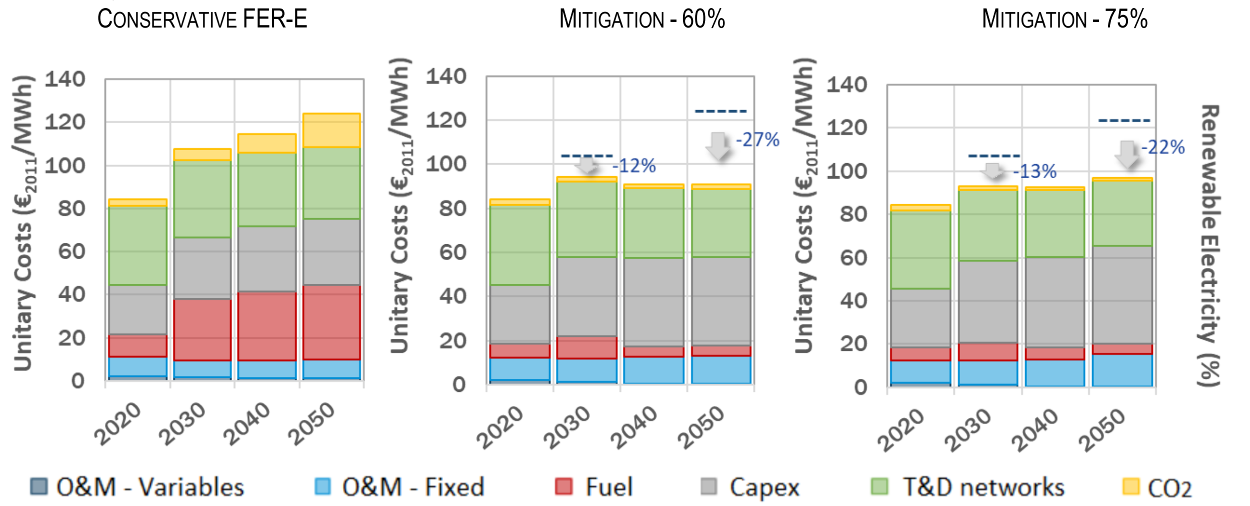

FIGURE 16 | EVOLUTION OF UNITARY COSTS IN THE POWER SECTOR (€2011/MWh) PER COMPONENT IN THE 3 SCENARIOS UNDER ANALYSIS.

> **Savings with the purchase of emission permits**

One of the relevant indicators in the decarbonisation of the power production sector is the savings associated with the purchase of emission permits in the sector. As observed in Figure 17, savings could reach, on average, and between 2020 and 2050, in excess of 280 M€, reaching a maximum absolute value of over 750 M€ in 2050. The savings with the emission permits may be even more relevant when considering a conservative price for emission permits from the Reference Scenario 2016 (UE, 2016) as shown in Figure 18. This study defines a modest reduction of emissions in the European Union of only 26% compared to 1990. However, in the future, and considering all the international context of climate policy, the reduction of GHG emissions should be more significant, above 80%, consequently leveraging the price of emission permits.

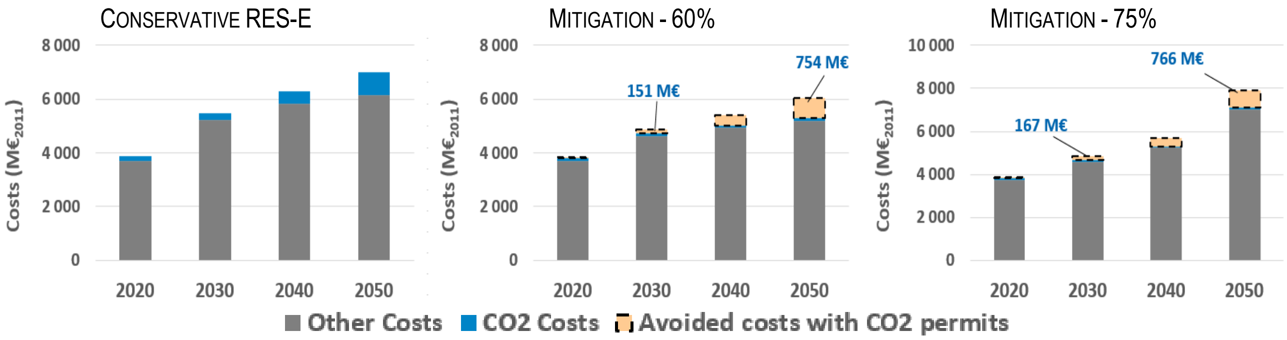

FIGURE 17 | EVOLUTION OF SAVINGS WITH EMISSION PERMITS (€2011) OVER THE 3 SCENARIOS UNDER ANALYSIS.

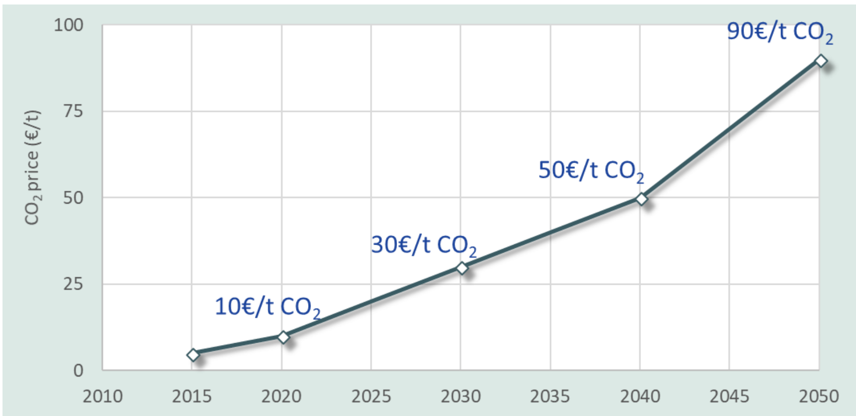

FIGURE 18 | EVOLUTION OF THE PRICE OF EMISSION PERMITS CONSIDERED IN THE PRESENT STUDY (SOURCE: EU, 2016)

> **Energy bill of the power-producing sector**

Focusing on the costs with fossil fuels, we can see that the savings in the energy bill of the power-producing sector can reach rising annual figures above 1 billion euros in the mitigation scenarios compared to the Conservative FER-E scenario (Figure 19). This figure is equivalent to approximately 28% of the national energy import balance currently verified (2015), representing a very positive impact for the Portuguese commercial balance.

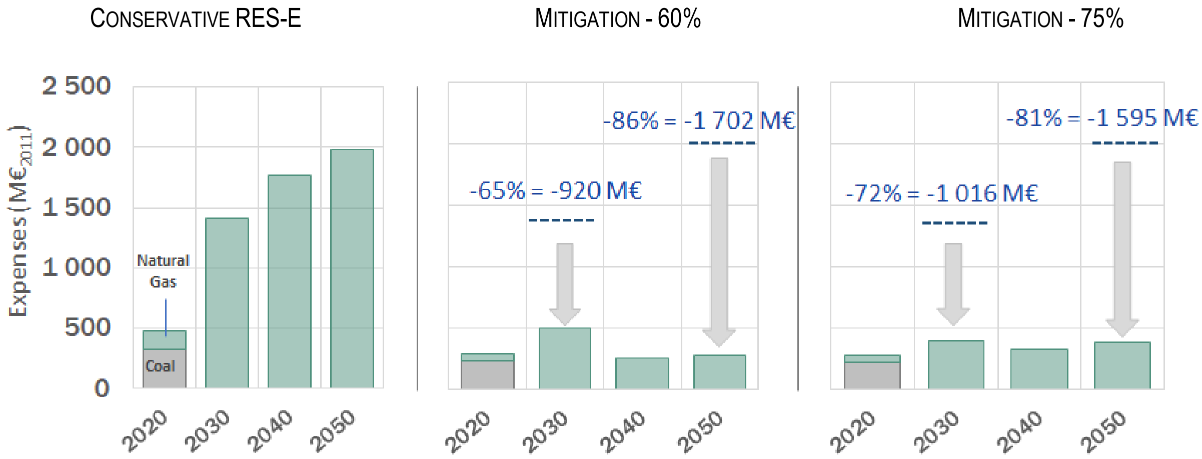

FIGURE 19 | EVOLUTION OF THE ENERGY BILL (€2011) IN THE POWER PRODUCTION SECTOR IN THE 3 SCENARIOS UNDER ANALYSIS.

> **Direct net jobs created**

One of the indicators analysed for each of the modelled scenarios is national jobs associated to the power-producing sector. To this end, we have considered indicators of direct jobs, i.e. Jobs directly associated to construction companies, installation, operation and maintenance of all the electricity generation technologies (including fossil thermal power plants) from the study *Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US?* (Wei et al., 2010).

The results obtained show that the scenarios with the highest generation of renewable electricity will be the ones with the higher number of jobs, and may reach on some years, more than double the figure from the Conservative RES-E scenario.

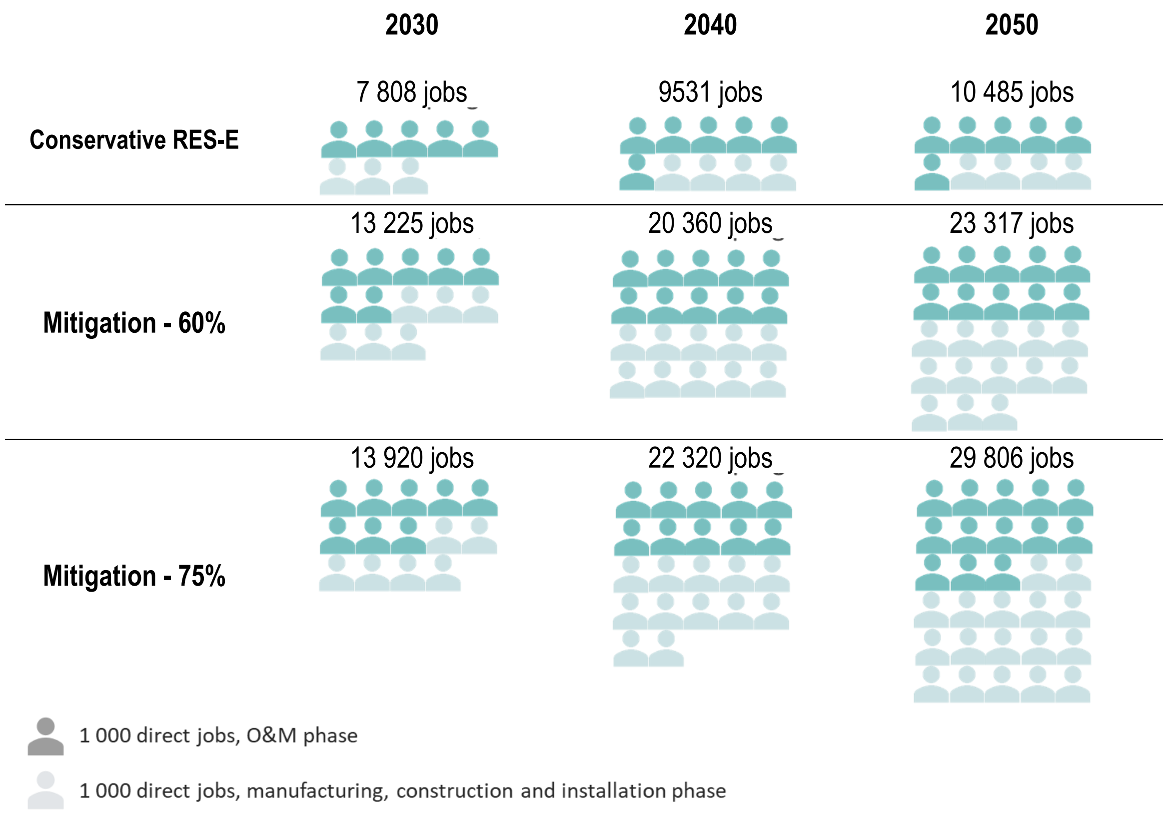

FIGURE 20 | ASSESSMENT OF THE NUMBER OF JOBS IN THE O&M STAGE AND CONSTRUCTION AND SETUP OF POWER GENERATION TECHNOLOGIES IN THE 3 SCENARIOS UNDER ANALYSIS

CONCLUSIONS

From the analysis undertaken throughout this project, it is possible to conclude that renewable electricity will have a crucial role, not only in the decarbonisation of the energy system, but also in bringing added value to the national economy. In this sense, the key messages extracted from the present analysis, are:

> Renewables in electricity production (RES-E) are a vector of decarbonisation that is cost-effective in the Portuguese economy in the medium and long-term;

> Renewables assume a dominant role in the generation of electricity (above 85% in 2030 and 90% in 2050), especially hydropower, onshore wind and solar PV. Offshore wind energy comes up as cost-effective in 2050 in more significative mitigation scenarios;

> Aggressive decarbonisation targets favour electrification in the final consumption, sustained by RES-E;

> Mitigation scenarios with a higher percentage of RES-E are beneficial versus a conservative RES-E scenario, both from the economic standpoint, translated in a smaller unit cost of power generation, and from the environmental standpoint, with significant GHG reductions both from the social point of view, expressed in a higher number of direct net jobs.

Table 8 presents a summary of the various indicators analysed throughout the present project, illustrating the value of renewables for the Portugal electricity system.

TABLE 8 | SUMMARY OF IMPACT INDICATORS IN THE POWER SECTOR

Indicators [Aggregated Values 2015 to 2050]	Conservative RES-E		Mitigation -60%	Mitigation -75%
			∆/RES-E Conservative	
Primary energy import for the production of power	PJ	5,357	-57%	-58%
GHG emissions from the power producer sector (CO_2e)	kt CO_2e	414,986	-46%	-52%
Global cost of the power system (including cost of CO_2)	M€$_{2011}$	190,651	-14%	-11%
Energy dependency of the power sector 2050	%	56	10%* (-46%)	10%* (-46%)
Employment (net)	x 1,000	297	74%	92%

* Real value of energy dependency of the power sector.

Although these results provide a response to the main questions made with this project, the results should also be analysed with caution due to restrictions brought by the model used. The TMES_PT model is an optimisation model which considers a perfect knowledge of the future (i.e., the model knows the cost curve of the technologies beforehand). The model does not assume budget restrictions, nor does it consider elasticities in demand-price. Throughout this project, it was also possible to identify some gaps that may and should be subject to improvement in a later update, namely the introduction of new technologies with an electrical base, i.e. Trucks and the inclusion of electrical energy storage technologies (e.g. Batteries, CSP with storage, hydrogen as a vector of energy storage). These technologies will be essential in a low or neutral carbon future, empowering the role of renewables.

REFERENCES

AIE (2016). World Energy Outlook 2016, International Energy Agency, Paris.

ENTSO-E (2011). ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2010. May 2011. ENTSO-E. 40 pp. Available on: https://www.entsoe.eu/publications/market-reports/Documents/TariffSynthesis_2010_updated_FINAL.PDF

Fortes, P., Alvarenga, A., Seixas, J. and Rodrigues, S. (2015). Long term energy scenarios: Bridging the gap between socio-economic storylines and energy Modelling. Technological Forecasting & Social Change. 91:161-178

International Monetary Fund (2016). 2016 World Economic Outlook. Available on: http://www.imf.org/external/pubs/ft/weo/2016/02/weodata/index.aspx

Loulou, R., U. Remme, A. Kanudia, A. Lehtila, G. Goldstein (2005a). Documentation for the TIMES model - PART I. www.etsap.org/tools.htm.

Loulou, R., U. Remme, A. Kanudia, A. Lehtila, G. Goldstein (2005b). Documentation for the TIMES model - PART II. www.etsap.org/tools.htm

United Nations (2015). 2015 Revision of World Population Prospects. United Nations. Available on: https://esa.un.org/unpd/wpp/

Seixas, J., Fortes, P., Dias, L., Dinis, R., Alves, B., Gouveia, J., Simões, S. (2012). Roteiro Nacional de Baixo Carbono: Portugal 2050 - Modelação de gases com efeito estufa, Energia e Resíduos. Lisboa. Available on: http://www.apambiente.pt/_zdata/RNCB/EnergiaResiduos_10_07.pdf

Seixas, J., P. Fortes, L. Dias, J. Carneiro, P. Mesquita, D. Boavida, R. Aguiar, F. Marques, Vitor Fernandes, J. Helseth, J. Ciesielska, K. Whiriskey (2015). CO2 Capture and Storage in Portugal -A bridge to a Low Carbon Economy, Faculdade de Ciências e Tecnologia- Universidade Nova de Lisboa. Caparica, Portugal. Available on: http://hub.globalccsinstitute.com/sites/default/files/publications/189763/co2-capture-storage-portugal-bridge-low-carbon-economy.pdf.

EU – European Union (2016). EU Reference Scenario 2016: Energy, Transport and GHG Emissions Trends to 2050. European Commission: Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport. Luxembourg: Publications Office of the European Union. Available on: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

Ueckerdt, F., Hirth, L., Luderer, G., Edenhofer, O (2013). System LCOE: What are the costs of variable renewables?, Energy, 63, pp. 61-75

Wei Max, Patadia Shana, M.Kammen Daniel (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? Energy Policy 38(2), 919-931