Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – Achieving zero greenhouse gas emissions and overcoming the water crisis

Ghorbani Narges, Aghahosseini Arman, Breyer Christian

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Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – Achieving zero greenhouse gas emissions and overcoming the water crisis

Narges Ghorbani*, Arman Aghahosseini and Christian Breyer
Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland
* Corresponding author, E-mail address: narges.ghorbanikoltapeh@lut.fi

Abstract

Transition of Iran's power system from 2015 to 2050 through three scenarios was modelled. Two scenarios present a transition pathway towards a fully renewable run power system with different involved sectors (power only, power sector coupled with desalination and non-energetic gas sectors). The third scenario is based on the country's current policies. The energy model performs an hourly resolution to guarantee meeting energy demand for every hour of the whole year. It is found that renewable energy resources in Iran can satisfy 625 TWh of power sector demand in 2050. Further, it is technically and economically feasible that electricity demand for supplying 101 million m^3 desalinated water and 249 TWh_{LHV} synthetic natural gas for non-energetic industrial gas demand can be supplied via renewable resources. A 100% renewable power system with 54 €/MWh_{el} levelised cost of electricity (LCOE) is more cost-effective than the current power system in Iran with 88.3 €/MWh_{el} LCOE in 2015. LCOE of the system can decrease further and reach to 41.3 €/MWh_{el} in 2050 via sector coupling. On the other hand, the current policies of the country lead to an inefficient power system with a LCOE of 128 €/MWh_{el} and 188 Mt/a emitted CO_2 in 2050.

Keywords: energy transition, renewable energy, seawater desalination, storage technologies, regional power transmission interconnection, levelised cost of electricity (LCOE)

Nomenclature

AC	alternating current	LCOE	levelised cost of electricity
A-CAES	adiabatic compressed air energy storage	LCOG	Levelised cost of gas
BP	best policy	LCOS	Levelised cost of storage
BPS	best policy scenario	LCOT	Levelised cost of transmission
Capex	capital expenditures	LCOW	Levelised cost of water
CCGT	combined cycle gas turbine	MED	multiple-effect distillation
CCS	carbon capture and storage	MSF	multi-stage flash
COP21	The 21st Conference of Parties	OCGT	Open cycle gas turbine
CP	current policy	Opex	operational expenditures
CPS	current policy scenario	PHES	Pumped hydro energy storage
CSP	concentrating solar thermal power	PP	power plants
desal	desalination	PtG	power-to-gas
DAC	direct air capture	PtH	power-to-heat
FLH	full load hours	RE	renewable energy
GT	gas turbine	SNG	synthetic natural gas
HVAC	high-voltage direct current	ST	steam turbine
ICE	internal combustion engine	SWRO	Seawater reverse osmosis
IEA	International Energy Agency	TES	thermal energy storage
LCOC	levelised cost of curtailment	WACC	Weighted average cost of capital

1. Introduction

Currently the major source of the global energy system is fossil fuel, finite and territorial imbalanced energy which also is the main source of greenhouse gas (GHG) emissions. However, due to energy demand growth, energy security, climate crisis, and highly attractive economics, attention has been drawn to renewable energy (RE) as sustainable alternative energy resources.

RE is rapidly growing especially in the power sector due to ongoing cost decline of renewable technologies and dedicated policy initiatives. The average cost of solar photovoltaic (PV) modules and wind turbines fell by 80% and 33% respectively between 2009 and 2014 [1]. Consequently, in 2014, global power system experienced 127 GW renewable power installation which accounts for 49% of total installation [2], and in 2017, the share of newly RE installation reached to 70% of total addition to power capacity globally [3].

The ongoing growth of RE capacity is developing the idea of a RE-based energy system, particularly for the power sector. Many studies have examined and proved the feasibility and viability of a global pathway towards a 100% RE electricity supply. Hoffmann [4] discussed that only a quick transition of current fossil power plants to renewables is a practical solution for the future energy system and to limit global average temperature to below 2°C. It has been mentioned that other solutions like postponing the transition, nuclear energy and carbon capture and storage (CCS) are not possible alternatives due to monetary and safety reasons. Pleßmann et al. [5] showed that a global 100% renewable electricity supply is feasible at decent cost based on an energy model simulation for hourly electric demand of more than 160 countries. Breyer et al. [6] performed a global energy transition towards 100% RE for the power sector by 2050. The study, which is carried out in high spatial and temporal resolution, shows a 100% RE based power system not only is feasible but also is more cost-effective than the current system. The levelised cost of electricity (LCOE) for the proposed power system in 2050 is 52 €/MWh compared to 70 €/MWh of the existing system in 2015. Detailed results of this energy transition and its socio-economic benefits categorised into 9 major regions of the world are presented by Ram et al. [7]. Moreover, several publications have investigated a fully RE-based energy system for several countries and regions around the world and pointed out that a renewable powered system not only is feasible but also is cost comparative with the current system [8–12].

In Iran, the second largest country in the Middle East, the heart of the world's fossil fuel reserves, the share of solar and wind energy in the power sector is less than 1%, while fossil fuels account for 83% of the country's installed power capacity [13]. Although the share of RE in the country's energy mix is currently too marginal, the government has started some policies and support mechanisms like revising feed-in tariffs and subsidy reforms to push the development of RE [14]. The main motivation of the government to take effort to increase deployment of the RE resources and diversify the power supply can be summarised as follows:

- While fossil fuel resources are depleting, electricity demand in Iran as an emerging country by economic and population growth is growing rapidly. The installed capacity of power plants and total electricity generation of the country over past decades are presented in Fig. 1. Only over the last decade, the installed capacity of the power plants almost doubled and reached to 65 GW in 2015 from 37 GW in 2005 to keep up with growing electricity demand. During this period electricity generation increased by an average of 5% per year. It is projected that a 2.7% increase per year is needed to meet electricity demand by 2040 [15]. Therefore, taking into account alternative sources of energy is necessary to meet the growing demand and promote energy security in the country. Energy security addresses several dimensions [16], whereof the most important ones may be availability, diversity, cost, technology and efficiency, environment and policy.

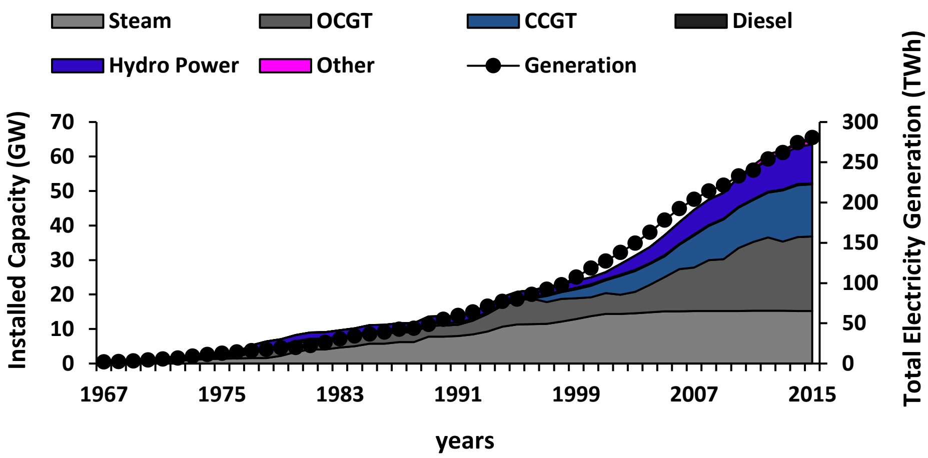


Fig. 1. The installed capacity of power plants and total electricity generation of the country [17]

- In Fig. 2, the country's power system energy flow is traced from primary energy to generated electricity. It can be seen that more than half (53%) of the primary energy is wasted due to inefficiencies .The unsustainable energy system in Iran has had a profound negative impact on environmental, economic, and social development [18]. Hence, restructure of the exiting energy system and considering RE as a main source of primary energy can highly increase the power sector efficiency and have positive impacts on the environment and economy.
- Iran is highly endowed with renewable resources in particular solar and wind, which have a rapid cost decrease globally. Iran is located in the world's Sun Belt area with an average solar irradiation of 1880 kWh/(m^2·a) and 280 sunny days on 90% of its land area [19]. Concerning wind energy, Iran has many sites with strong wind flows leading to a technical potential of 140 GW in the country [20]. Fig. 3 presents the potential of solar PV and wind energy in Iran. Using the high potential of RE to generate electricity is more reasonable and economical than consuming fossil fuels which impose extra expenses on society due to their environmental impacts and health effects. Jorli et al. [21] applied a detailed impact pathway approach to estimate the monetary value of health damage arising from emissions of fossil power plants in Iran. The health damage cost varies from 0.06 to 22.41 USD/MWh depending on the quality of fossil fuel burned in the power plants and population density around the power plants. However another comparable study ranged the environmental damage cost from 15.94 to 74.66 USD per MWh [22].
- Water crisis and rapidly declining water resources in Iran is a serious issue which would lead to an absolute water scarcity by 2025 [23]. A renewable energy powered

desalination system is a potential solution to meet the water demand of the country, considering Iran's high potential of RE resources and surrounding water bodies [24].

- The Paris Agreement (COP 21) clearly declared that holding the rise in global average temperatures to less than 2°C requires a global defossilisation by mid-21st century [25]. Since Iran is among countries that ratified the agreement, the country should act in line with the global approach and restructure its power system as a first step for achieving a zero emission energy system.

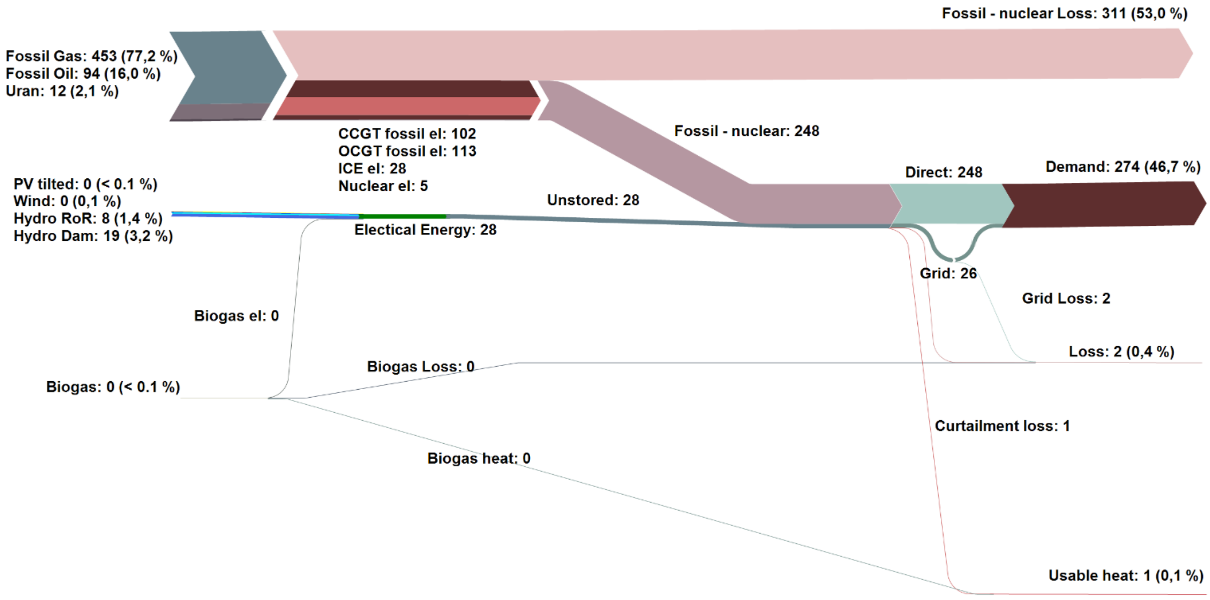


Fig. 2. Power system energy flow for Iran in 2015.

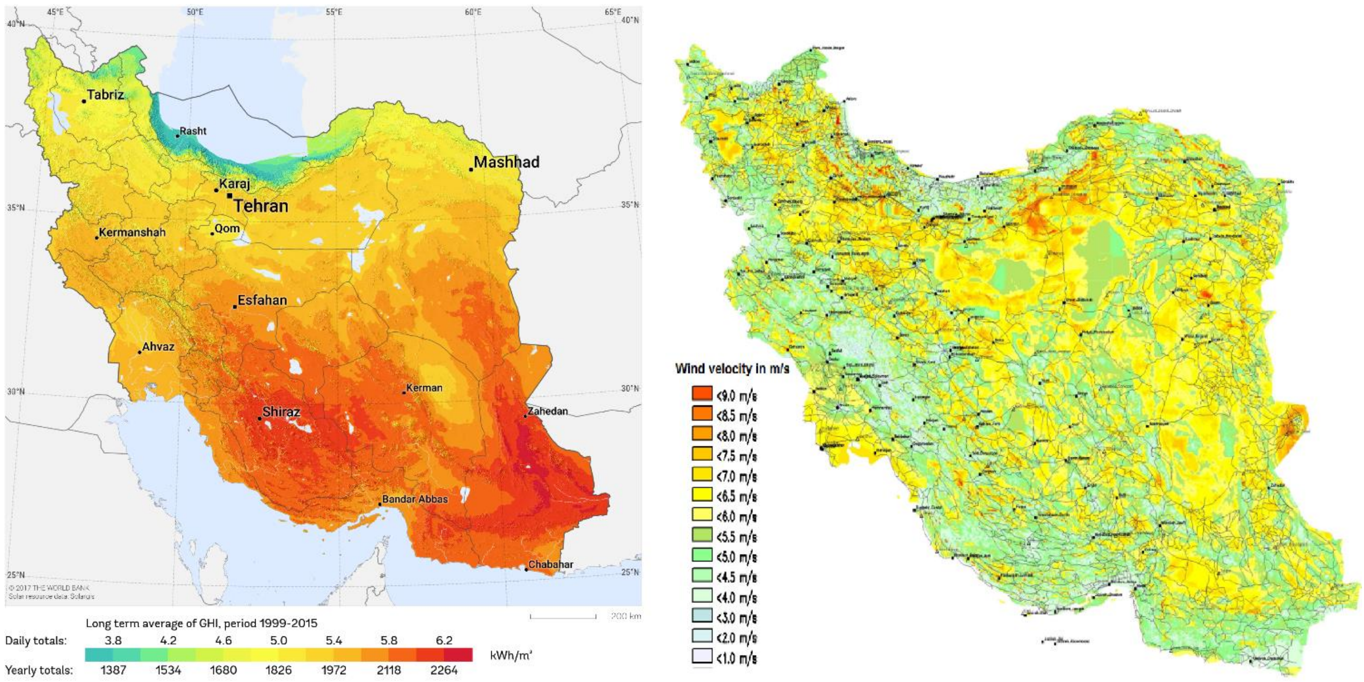


Fig. 3. Iran's global horizontal irradiation map (left) [26] and wind speed map [27] (right).

A renewable based energy system is an undeniable necessity for Iran to mitigate its economic, social and environmental issues [28] and the government has taken path breaking steps to promote the expansion of RE. However, the absence of a comprehensive pathway to redesign the current energy system is one of the major challenges in the country and requires a more aggressive policy. Changing the existing power system and infrastructure towards a system entirely based on RE requires a detailed study of RE resources, the current power structure, the current and future electricity demand. Furthermore, an analysis of economic and technical capabilities and opportunities for a radical transition is necessary.

For Iran, there is only research regarding technological aspects and the potential of RE resources in the country and the necessity of a full deployment of these resources for a sustainable development of the country. However, a study to determine a transition pathway towards a sustainable energy system for the country on a regional basis with a high share of RE deployment is lacking in literature. The present study through a detailed technical and economic analysis provides a transition pathway for Iran to achieve a power system based on 100% RE at an optimal cost. Aghahosseini et al. [29] have conducted a research with an overnight approach to study a 100% RE power system for Iran for the year 2030 and the country was modelled as a single node. Ghorbani et al. [30] presented a transition pathway for Iran's power system from 2015 to 2050, but the country was modelled as a single node and the transmission grid was not considered in the model. The aim of that research was to show a fully renewable run power system is feasible for Iran. However, in the current study, Iran's power system has been modelled by a multi-node approach and the country is structured into nine regions. This research is a big step towards a detailed and practical study for Iran's transition pathway to a zero GHG emission system. In this study, all input data such as load demand, lower and upper limits of installed power plant capacities, historical weather data for solar irradiation and wind speed are provided for each region and the regions are connected via high voltage alternating current (HVAC) power lines. Moreover, the integration of desalination and industrial non-energetic gas sectors are examined and finally the transition scenario is compared with the results obtained from a scenario which is modelled based on the current policies of the country.

2. Materials and methods

2.1. Model overview

The LUT Energy System Transition model is used to model the transition of Iran's power sector from 2015 to 2050. The model performs an hourly resolution which guarantees meeting energy demand for every hour of the whole year. The optimisation of the model is based on the linear method which due to the less required calculation time, enables modelling of more sophisticated and integrated energy systems. The aim of the optimisation is finding a least cost energy system while meeting a set of constraints such as electricity demand, installed capacity limits and techno-economic restrictions. Therefore, the proposed energy system has the minimum annual cost which consists of installation costs of different technologies, energy generation and energy ramping costs. The target function of the model for minimising the annual cost is presented in Eq. (1).

$$\min \left(\sum_{r=1}^{reg} \sum_{t=1}^{tech} \left(Capex_t \cdot crf_t + Opex_{fixed_t}\right) \cdot Installed\ Capacity_{t,r} + Opex_{Vaiable_t} \cdot E_{generated\ t,r} + Ramping\ Cost_t \cdot Total\ Ramping_{t,r} \right) \quad (1)$$

Where *reg* and *tech* are the numbers of total regions and technologies in the energy system.

Satisfying the electricity demand is the main constraint in the model which is indicated by Eq. (2) for every hour of the year.

$$\forall h \in [1{,}8760] \sum_{t}^{tech} E_{generation,t} + \sum_{r}^{reg} E_{import,r} + \sum_{t}^{stor} E_{storage\ discharge} = E_{demand} + \sum_{r}^{reg} E_{Export,r} + \sum_{t}^{stor} E_{storage\ charge} + E_{curtailment} \quad (2)$$

Where $stor$ represents storage technologies in the system.

The limit for minimum installed capacity for each technology is equal to its capacity in the previous time step and for 2015 the lower limit represents the existing capacity. For maximum installed capacity limits, the model follows different approaches for different technologies. For wind power plants, CSP, single-axis tracking and optimally tilted PV systems maximum limits are based on the capacity density and land use limitation [31]. For PHES and hydro power plants upper limits are set to 200% and 150% of the existing installed capacities in 2015. Upper limits for biomass, biogas and waste-to-energy resources are based on German Biomass Research Centre [32] and geothermal energy potential is calculated based on the methodology explained in [33]. For other technologies no maximum limit is assigned. A variety of technical restrictions including efficiency numbers and lifetimes for power generation, storage and transmission systems are considered in the model. In addition to all these constraints, a set of financial assumptions that were taken from different relevant literature are applied to the model which is discussed in section 3.5.

Key feature of the model is its flexibility and expandability, which allows modelling of energy systems on local, national, regional or global level and for a variety of scenarios. The LUT model has been described in detail by Bogdanov and Breyer [31] and Breyer et al. [6]. A flowchart of main input data, output data and operation sequence of the model is presented in Fig. 4.

2.2 Applied Technologies

The block diagram of the energy model is presented in Fig. 5. Main components of the model can be classified into four categories:

- Electricity generation technologies: solar photovoltaic (PV) rooftop, PV fixed-tilted, PV single-axis tracking, wind onshore, hydro power (dam and run of river), concentrating solar thermal power (CSP), geothermal, biomass and waste-to-energy power plants. In addition to RE technologies, fossil generation technologies and nuclear power plants are considered in the energy system. Gas turbines are used over the first steps of the transition in their conventional way, by consuming natural gas, but as the transition progresses, they are fed by RE-based synthetic natural gas and biomethane.
- Energy storage technologies: batteries, pumped hydro energy storage (PHES), thermal energy storage (TES), adiabatic compressed air energy storage [34], and power-to-gas (PtG) storage. PtG technology consists of water electrolysis, methanation and CO_2

direct air capture (DAC) [48]. The technical assumptions for storage technologies are provided in the Supplementary Material (Table S2-2).

- Electricity transmission technology: HVAC. The length of the transmission lines is calculated based on the existing high voltage grids (400 and 230 kV) in Iran.
- Energy sector bridging technologies: PtG, PtH and seawater reverse osmosis (SWRO) desalination. Bridging technologies by converting excess energy into valuable products provide more flexibility for the energy system, increase the efficiency and decrease the overall costs.

In addition, the energy system incudes PV prosumers which are developed in another hourly model enabling installation of residential, commercial and industrial rooftop PV systems and their corresponding batteries. The excess PV electricity from self-consumption sector is transferred into the grid.

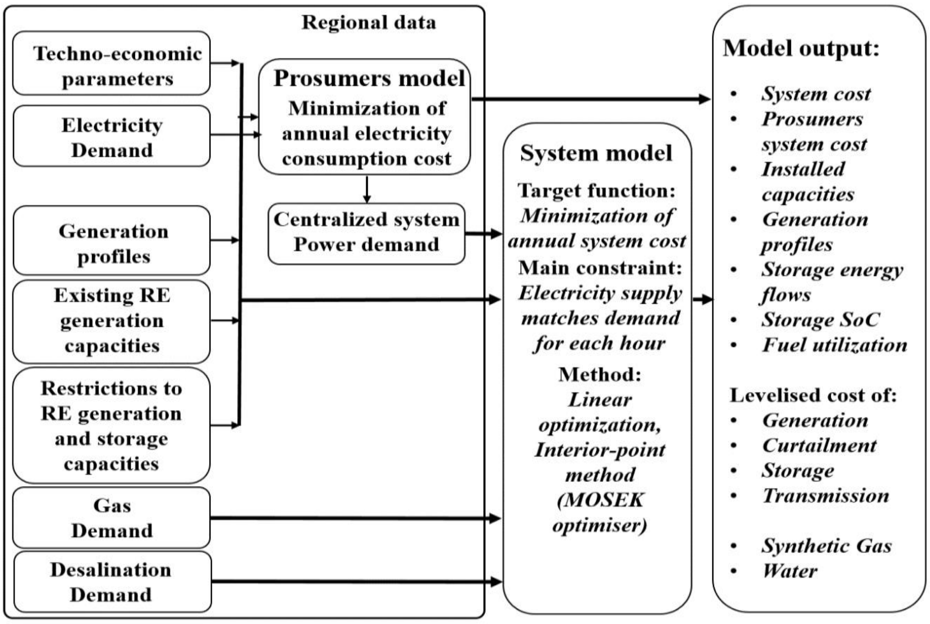


Fig. 4. Flowchart of the energy model [35].

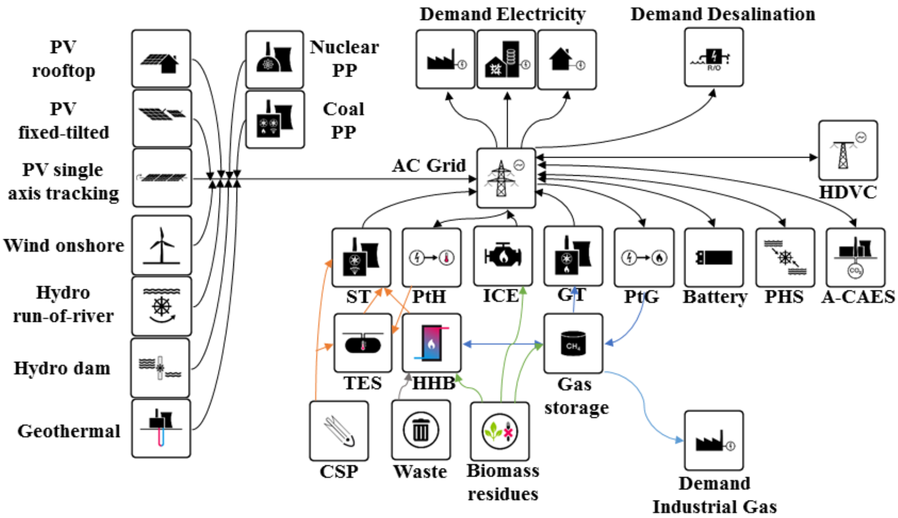


Fig. 5. Block diagram of the energy model components [35].

2.3. Methodology for cost calculation

LCOE is a standard metric for economic comparison of different electricity generation technologies [36]. In general, LCOE includes lifetime costs of construction and operation of a power generation plant. However, in this study the LCOE calculation is extended to assess the LCOE for the whole energy system including levelised cost of curtailment (LCOC), levelised cost of storage (LCOS) and levelised cost of transmission (LCOT). GHG emissions costs are added to the LCOE calculation. Total cost and LCOE in this study are characterised by Eq. (3).

$$Total\ Cost_{system} = \sum_{r}^{reg} LCOE_r \cdot E_{demand,r} \quad (3.1)$$

$$LCOE_r = LCOE_{primary,r} + LCOC_r + LCOS_r + LCOT_r \quad (3.2)$$

$$LCOE_{primary,r} = \frac{\sum_{t=1}^{tech}(Capex_t \cdot crf_t + Opex_{fixed,t}) \cdot Capacity_{t,r} + Opex_{variable,t} \cdot E_{generation,t,r}}{E_{demand,r} + E_{export,r} - E_{import,r}} \quad (3.3)$$

where $Capex$ is capital expenditures of the power generation technologies (€/MW_{el}) and $Opex_{fixed}$ is fixed operational expenditures (percentage of $Capex/year$) and $Opex_{variable}$ is variable operational expenditures (€/MWh_{el}).

$$LCOC_r = LCOE_{primary,r} \cdot \frac{E_{curtailment,r}}{E_{demand,r} + E_{export,r} - E_{import,r}} \quad (3.4)$$

$$LCOS_r = \frac{\sum_{t=1}^{Storagetech}(Capex_t \cdot crf_t + Opex_{fixed,t}) \cdot Capacity_{t,r} + Opex_{variable,t} \cdot E_{storage,discharge,t,r}}{E_{demand,r} + E_{export,r} - E_{import,r}} \quad (3.5)$$

where $Capex$ and $Opex$ are capital and operational expenditures of the storage technologies and $Capacity$ is installed capacity of storage technologies and is expressed in MW.

$$LCOT_r = \frac{TotalCost_{transmission} \cdot share_r}{E_{demand,r} + E_{export,r} - E_{import,r}} \quad (3.6)$$

$$TotalCost_{transmission} = \sum_{l=1}^{lines}(Capex_{TL} \cdot crf_{TL} + Opex_{fixed,TL}) \cdot Capacity_{TL,l} \cdot Length_{TL} + Opex_{variable,TL} \cdot E_{transmission,t,l} \quad (3.7)$$

$TotalCost_{transmission}$ is total annual cost of transmission grids and $Capex_{TL}$ and $Opex_{TL}$ are capital and operational expenditures of the transmission lines.

$$share_r = 0.5 \cdot \frac{E_{export,r}}{\sum_r^{reg} E_{export,r}} + 0.5 \cdot \frac{E_{import,r}}{\sum_r^{reg} E_{import,r}} \quad (3.8)$$

where $share_r$ represents the regions' share in grid utilisation.

$$crf_t = \frac{WACC \cdot (1+WACC)^{N_t}}{(1+WACC)^{N_t}-1} \quad (3.9)$$

crf_t is the capital recovery factor, which is a function of weighted average cost of capital (WACC) and lifetime of the technology (N_t).

Additional abbreviations in Eqs. (3) are: electricity, E, region, r, technology, t, and transmission line, TL.

3. Scenario assumptions

3.1. Subdivision of the country and grid structure

In this study, Iran is modelled in nine regions based on the country's grid structure, electricity consumption and RE potential of the provinces (political subdivision of Iran is in the form of provinces). Table **1** presents the corresponding provinces of the modelled regions. Fig. 6 shows the modelled regions and interconnection power lines between them and also the consumption centre of each region. The city with the highest electricity demand in each region is assumed as a consumption centre. The interconnection lines on the map are only schematic lines to show the connection between regions. The length of the power transmission lines between consumption centres used in the simulation are measured according to the existing power grid structure of the country [37]. The regions are named after provinces where the consumption centres are located.

Table 1. The nine modelled regions and the corresponding provinces.

Region	Provinces
1-AZ	Azerbayejan East, Azerbayejan West, Ardabil, Zanjan, Qazvin
2-KO	Kordestan, Hamedan, Kermanshah, Markazi, Lorestan, Ilam
3-TE	Tehran, Alborz, Qom
4-MA	Mazandaran, Golestan, Gilan, Semnan
5-IS	Isfahan, Yazd
6-KHZ	Khozestan, Kohgiluyeh and Boyer-Ahmad, Chaharmahal and Bakhtiari
7-FA	Fars, Booshehr, Hormozgan
8-KHR	Khorasan North, Khorasan West, Khorasan Razavi
9-KE	Kerman, Sistan and Baluchestan

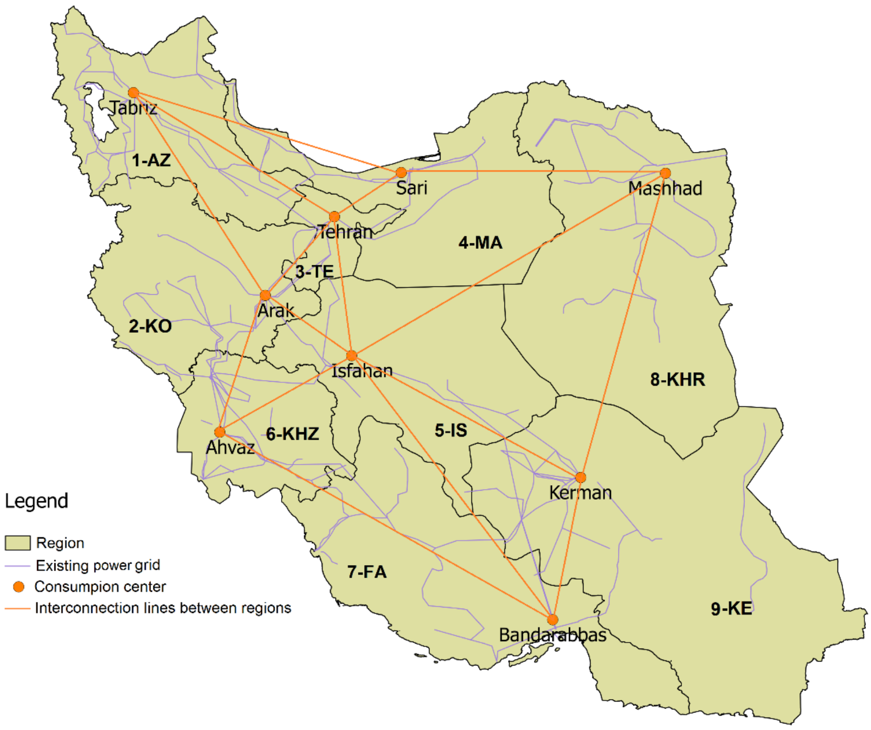


Fig. 6. Iran subdivision and transmission line structure.

3.2. Applied Scenarios

In this study, three scenarios for the transition of Iran's power system from 2015 to 2050 are studied:

1. Best Policy Scenario (BPS): A transition of Iran's power system from the current fossil fuel-based system to a fully RE-based system is modelled. Transition is applied from 2015 to 2050 in 5-year time steps. No new fossil or nuclear power plants are allowed to be installed and the existing ones are phased out according to their lifetimes. However, the installation of gas turbines is not restricted since they have higher efficiency and less CO_2 emission and in particular can utilise synthetic natural gas (SNG) and biomethane, both free of fossil sources, as fuel. This scenario only covers electricity demand of the power sector and presents an optimal mix for power plants in each time step over the transition.

2. Integrated scenario: This scenario is also a transition to a fully RE-based power system. For this scenario, the seawater desalination sector and non-energetic industrial gas sector demand are integrated with the power sector. Therefore, the power system not only supplies the electricity demand of the power sector but also the electricity needed for the seawater desalination sector to meet the water demand of the country as well as the electricity demand to produce SNG for non-energetic industrial gas demand.

3. Current Policy Scenario (CPS): In this scenario, the Iranian power system is modelled based on the country's current policies. The country's existing plans are taken into

account and it is assumed that all policies and plans concerning the power industry will be implemented. These policies are as follows:

- 5 GW wind and solar plants will be added by 2021 according to 6th Development Plan [38].
- 10 GW of total power capacity comes from wind and solar by 2025 according to 20-Year Vision [39].
- Installation of two nuclear power units, 1 GW by 2024 and another 1 GW by 2026.
- Turning gas turbine power plants into combined cycle gas turbine plants [40].

Since there is not any official plan for post-2026, we assumed that the installation of PV and wind plants would continue by the same rate according to the current policy. Therefore, the power system in Iran will experience installation of 5 GW PV and wind plants in every 5-year period until 2050.

3.3. Demand of the sectors

3.3.1 Power Sector

The country's hourly electricity consumption in 2015 is taken from [41] and is extrapolated for the next years according to the electricity demand growth rate estimated by the IEA [15]. An aggregated load profile for 2050 is presented in Fig. 7. Regions' load profiles are computed based on the country's hourly demand divided by the regions' electricity consumption multiplied to the sum of hourly profile. Annual projected electricity demand for the country and the modelled regions for all time steps over the energy transition are indicated in Table **2**.

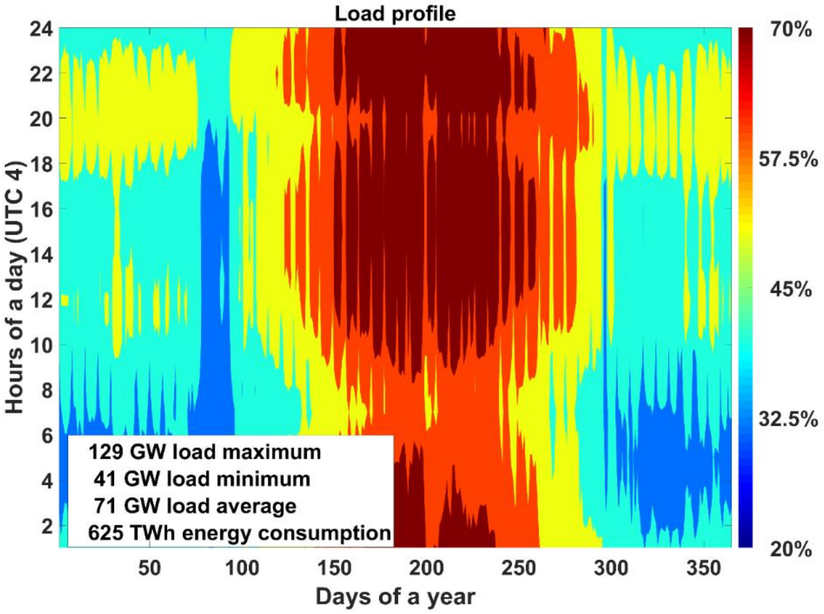


Fig. 7. Aggregated load profile for the year 2050.

Table 2. Projected electricity demand for Iran by regions [TWh_{el}].

Region	2015	2020	2025	2030	2035	2040	2045	2050
1-AZ	27	31	35	39	44	49	55	62
2-KO	24	28	31	35	39	44	50	56
3-TE	49	55	62	70	79	88	99	112
4-MA	22	24	28	31	35	39	44	50
5-IS	35	40	45	50	57	63	71	81
6-KHZ	35	40	45	50	57	63	72	82
7-FA	38	43	48	54	61	69	78	88
8-KHR	22	24	28	31	35	39	44	50
9-KE	19	21	24	27	31	34	39	44
Total	273	307	346	388	437	490	553	625
Electricity consumption per capita [kWh]*	3445	3683	3995	4386	4852	5377	6007	6782
Population [million]	79.1	83.4	86.5	88.5	90	91.2	92.1	92.2

* Rounding may lead to a difference between the calculated numbers for electricity consumption per capita and the total electricity demand and population.

3.3.2 Desalination Sector

In this study, a desalination sector powered by RE is applied to the energy model to investigate the capability of seawater desalination to meet the country's future water demand. For 2015, the capacity of the desalination sector is the sum of all active desalination capacities in the country, which is comprised of seawater reverse osmosis (SWRO), multiple-effect distillation (MED), and multi-stage flash (MSF) plants. For the next time steps, the capacity is calculated according to the water stress and water demand of Iran's regions. The model only installs seawater reverse osmosis (SWRO) technology due to its low costs, high efficiency [42] and projected attractive cost development [43]. The projected desalination demand for all regions is indicated in
Table **3**.

Table 3. Projected desalination demand in Iran [44].

Time step	2015	2020	2025	2030	2035	2040	2045	2050
Annual desalination demand [million m^3]	108	405	2981	23308	77494	90625	95990	101328
Annual electricity demand for SWRO desalination and pumping [TWh_{el}]	0.6	2.6	17.6	131.2	418.5	476.4	500.1	524.4

The levelised cost of water (LCOW) includes costs of desalination plant, electricity, water storage and transmission of desalinated water to the consumption centres. The LCOW is shown in Eq. (1) in which the components of $LCOW_{desal}$ are capital and operational expenditures (Capex and Opex) of desalination plant and for $LCOT_{desal}$ the main contributors are Capex and Opex of horizontal pumps, vertical pumps and pipelines needed to transfer desalinated water to the desalination demand site.

$$LCOW = LCOW_{desal} + LCOT_{desal} \tag{1}$$

Technical and financial assumptions for the desalination sector can be found in [42,45] Desalination water sources in this study are the Persian Gulf and Gulf of Oman that border Iran in the south. Caspian Sea situated in the north of Iran is not considered for water production using seawater desalination in this study. The reason is that since Caspian Sea is an enclosed water body, there are environmental concerns regarding the increasing of its salinity and reduction of its water level. However, currently a desalination plant is going to be installed after getting permission from Iran's Environment Protection Organization, despite considerable disagreement. The plan will have adverse effects on both marine environment due to discharging the high concentrate brine into the sea and land environment since there is a long transmission line crossing variety of natural features like mountain and forest [46].

3.3.3 Industrial Gas Sector

The non-energetic industrial gas consumption in 2015 is taken from [47]. The estimated demand of non-energetic industrial gas and the electricity needed to produce this amount of SNG by power-to-gas (PtG) technology are indicated in Table 4. An annual average growth rate of 2.1% is assumed for gas demand according to the projection of the IEA [15] for the natural gas demand for the Middle East. PtG technology is based on water electrolysis, methanation and CO_2 direct air capture (DAC) [48].

Table 4. Projected non-energetic industrial gas demand in Iran.

Time step	2015	2020	2025	2030	2035	2040	2045	2050
Annual non-energetic industrial gas demand [TWh_{th}]	120.4	133.6	148.2	164.4	182.4	202.4	224.6	249.1
Annual electricity demand for non-energetic industrial gas [TWh_{el}]	0	0	0	0	27.9	102.2	310.7	391

3.4. Feed-in for wind and solar energy

Feed-in full load hours (FLH) for optimally fixed-tilted solar PV, CSP and wind energy in Iran are calculated according to the approach described in [31] and for single-axis tracking PV according to [49]. The weather data is based on the NASA dataset for the year 2005 [50,51] and temporal and spatial resolutions of the dataset are hourly and 0.45°×0.45°, respectively. The average FLH for solar PV, CSP, and wind power plants in Iran are indicated in Table 5 and the regional breakdown is provided in the Supplementary Material (Table S1). The average aggregated feed-in profiles are presented in Fig. 8.

Table 5. Average full load hours for PV single-axis and fixed-tilted, CSP, and wind power plants.

Electricity generation system	PV single-axis tracking	PV fixed-tilted	CSP	wind
Full load hours	2064	1723	2253	2449

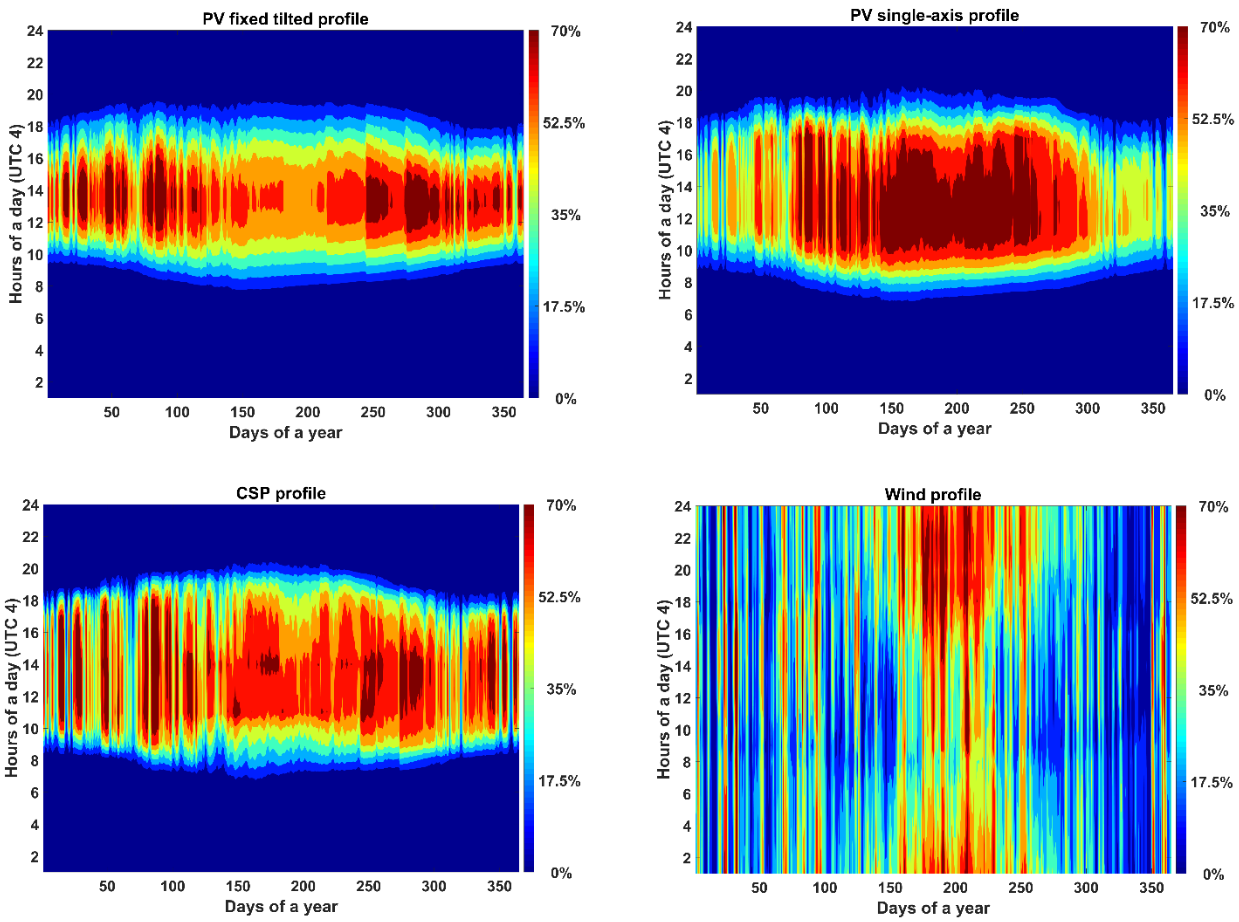


Fig. 8. Aggregated feed-in profiles for PV fixetitled-tilted (top left), for PV single-axis tracking (top right), for CSP solar field (bottom left) and for wind power plants (bottom right).

3.5 Financial assumptions

The main target of the model is to define a least cost system configuration under applied constraints and assumptions**.** The financial assumptions for all energy system components, which are based on the technologies' learning curves and various scientific literature, are tabulated in the Supplementary Material (Table S2). The power transmission and distribution losses are considered in the simulation according to Sadovskaia et al. [52] and the corresponding efficiencies are indicated in Supplementary Material (Table S2-5).Assumptions are made for 5-year time periods from 2015 to 2050. The Capex and Opex generally refer to a kW of electrical power. For the case of water electrolysis to a kW of hydrogen thermal combustion energy, and for CO_2 DAC, methanation and gas storage to a kW of methane thermal combustion energy. For weighted average cost of capital (WACC) an average value of 7% is assumed for all technologies and all time steps, but for residential solar PV prosumers, due to lower financial return requirements, WACC is set to 4%. A WACC of 7% might be argued to be low for Iran , taking into account the market specifics of the country and a research estimated Iran's total equity risk premium (ERP) to be 11.2% [53]. However, in the present study a WACC of 7% is assumed for all time steps from 2015 to 2050 and it is assumed that by increasing the share of renewables the risk of investment will decrease and a 7% WACC is possible by 2050 in Iran.

4. Results

4.1. Power sector projection in BPS and CPS

In this section, the transition of the power sector in the BPS and CPS is investigated and the results of the integrated scenario are discussed in section 4.2.

Fig. 9 presents the shares of different power plants to supply the country's growing electricity demand during the transition for both scenarios. The absolute numbers of installed capacities are tabulated in the Supplementary Material (Table S3). It can be seen in the BPS (Fig. 9 (left)) that the power system experiences a transition from a fossil fuel based energy system in 2015 to a fully renewables powered energy system in 2050. Solar PV appears in the power technology mix in 2020 and its penetration increases steadily to dominate the power system from 2040 onwards. In 2050, 77% (546 TWh) of total generated electricity is produced by solar PV technologies, of which 44%, 36% and 20% are delivered from PV fixed tilted, PV single-axis tracking and PV prosumers, respectively. For wind electricity generation, there is a rapid increase from 0.3 TWh in 2015 to 172 TWh in 2030. However, for the following years, the contribution of wind energy to the total electricity generation remains constant. In 2050, the contribution of wind decreases due to phasing out of capacities reached their lifetimes, and there are no wind power re-investments due to the lower cost of solar PV and battery systems.

In the CPS (Fig. 9 (right)), the power capacity mix is completely different from the BPS. Gas turbine power plant based natural gas is the main technology to supply the country's electricity demand in 2015. After 2015, only combined cycle gas turbine (CCGT) plants are installed in the system due to its higher efficiency. Although, electricity produced by wind and solar PV increases, their contribution in total electricity generation is marginal. Moreover, there is an increase in the share of nuclear energy according to the country's policy, in spite of its expensive cost.

The required capacities of different power plants from 2015 to 2050 for both scenarios are shown in Fig. 10. Total installed capacity in the BPS is higher than for the CPS for all years. This is not only due to the lower full load hours of PV and wind plants in general in comparison to conventional fossil fuel power plants, but also due to the extremely high FLH (6680 hours [54]) of gas power plants in Iran. Although the power system in the BPS has a larger capacity, its LCOE is lower in comparison to the CPS. Contributions of power system components to the LCOE for both scenarios are presented in Fig. 11. As can be seen, electricity cost in the BPS is less than that in the CPS for all time steps over the transition except 2020 when the CPS experiences a fall in electricity cost due to the elimination of large amount of internal combustion engines capacity from the system and consequently having less fuel and GHG emission costs. As demonstrated in Fig. 11 (right), fuel cost accounts for the major contribution in LCOE in 2015. Although for the BPS fuel and GHG emission costs are being eliminated over the transition due to the replacement of fossil fuels by renewables, for the CPS, fuel cost and GHG emission cost remain the largest contributors to the system's LCOE. Capex, fixed Opex and variable Opex for the new generation capacities for both BPS and CPS are provided in the Supplementary Material (Fig. S3-S5).

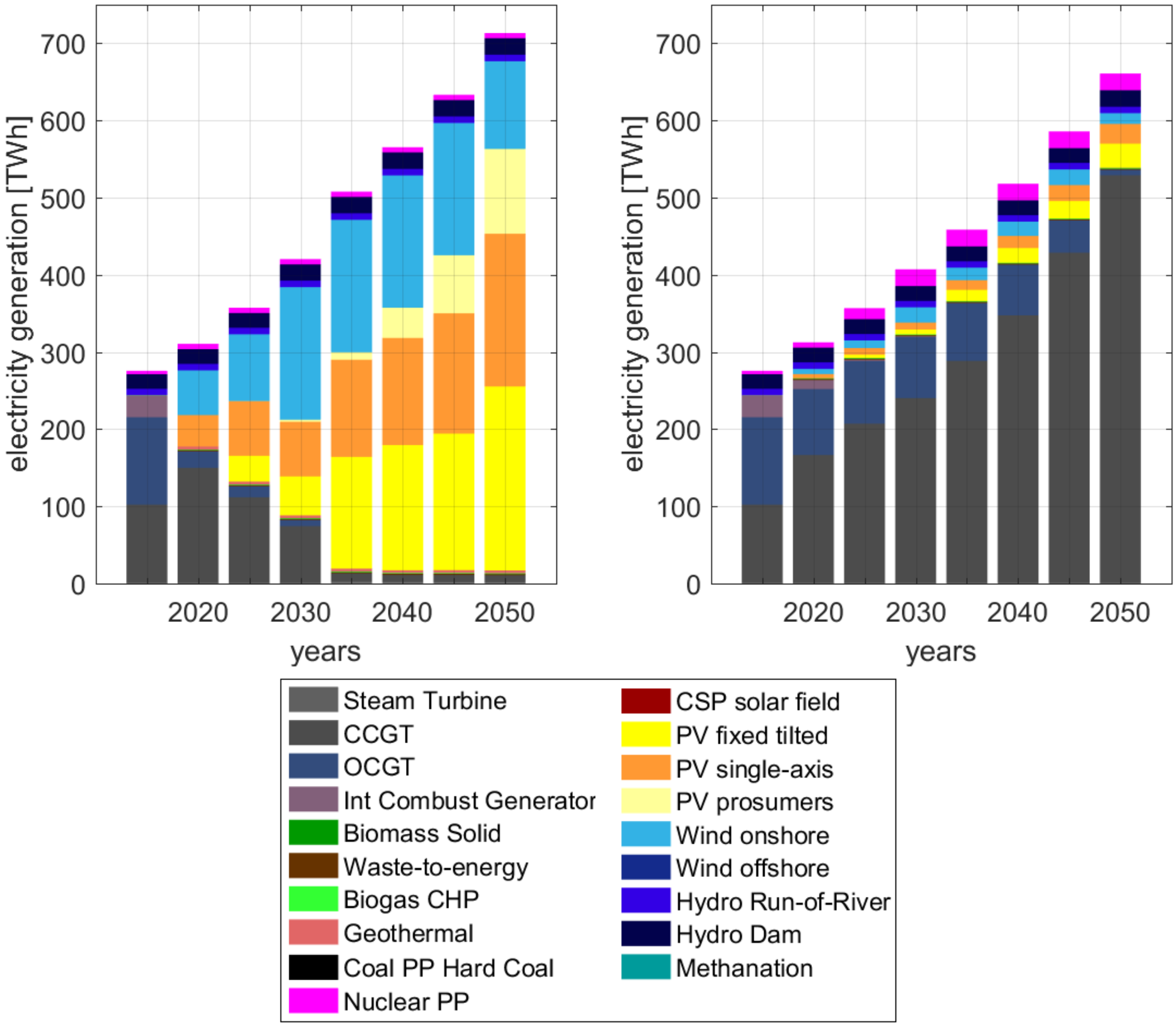
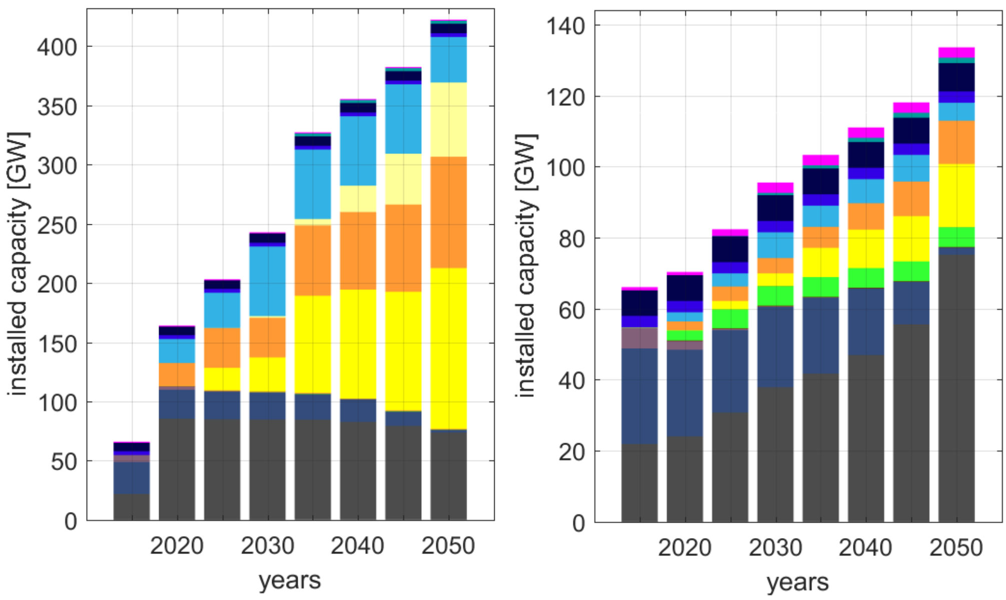


Fig. 9. Electricity generation by technology for the BPS (left) and CPS (right) from 2015 to 2050.



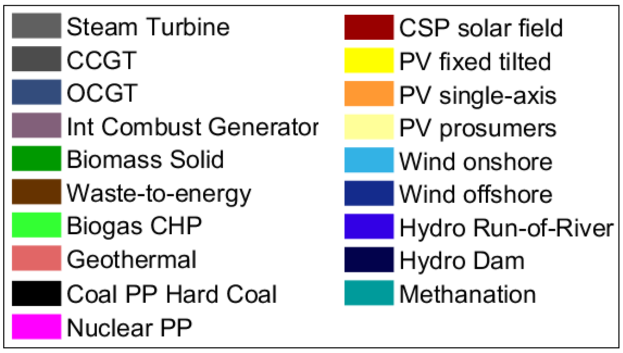


Fig. 10. Power plants mix for the BPS (left) and CPS (right) from 2015 to 2050

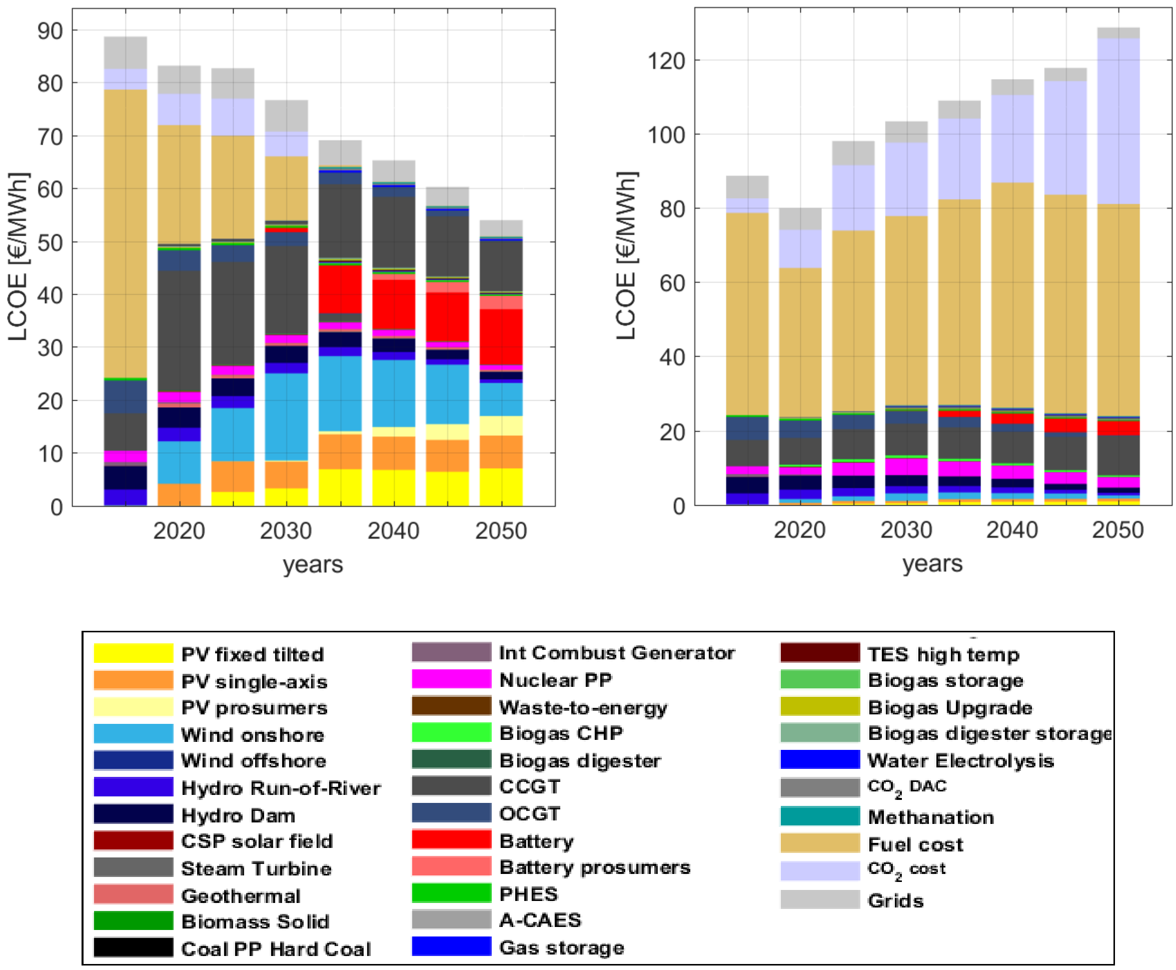


Fig. 11. LCOE by technology for the BPS (left) and CPS (right) from 2015 to 2050.

Fig. 12 (top) presents the required storage capacity from 2015 to 2050 for corresponding power systems in the BPS and CPS and Fig. 12 (bottom) presents the electricity output of storage technologies for each time step. For both scenarios, a larger and more diverse storage system is required over time. However, the BPS with a substantially higher share of RE requires more storage capacity compared to the CPS. Moreover, the storage technology mix of the scenarios is different. For the BPS, storage technologies come into effect after 2030 when the RE exceeds 98% of the total electricity generation, as shown in Fig. 9. Although gas storage has a large capacity in the BPS, its electricity output is insignificant compared to the battery storage output as can be seen in Fig. 12. Gas storage operates as a seasonal storage, whereas battery storage works as a daily energy storage to complement solar PV. For the CPS, storage systems only supply 5% of the total electricity demand of the power system compared to 34% in the BPS in 2050. In addition, as shown in Fig. 12 (top right), gas storage is added to the CPS system earlier to decrease curtailment of PV excess electricity in the inefficient CPS power system. Energy storage capacity and storage output in all regions for BPS and CPS are presented in the Supplementary Material (Fig. S7).

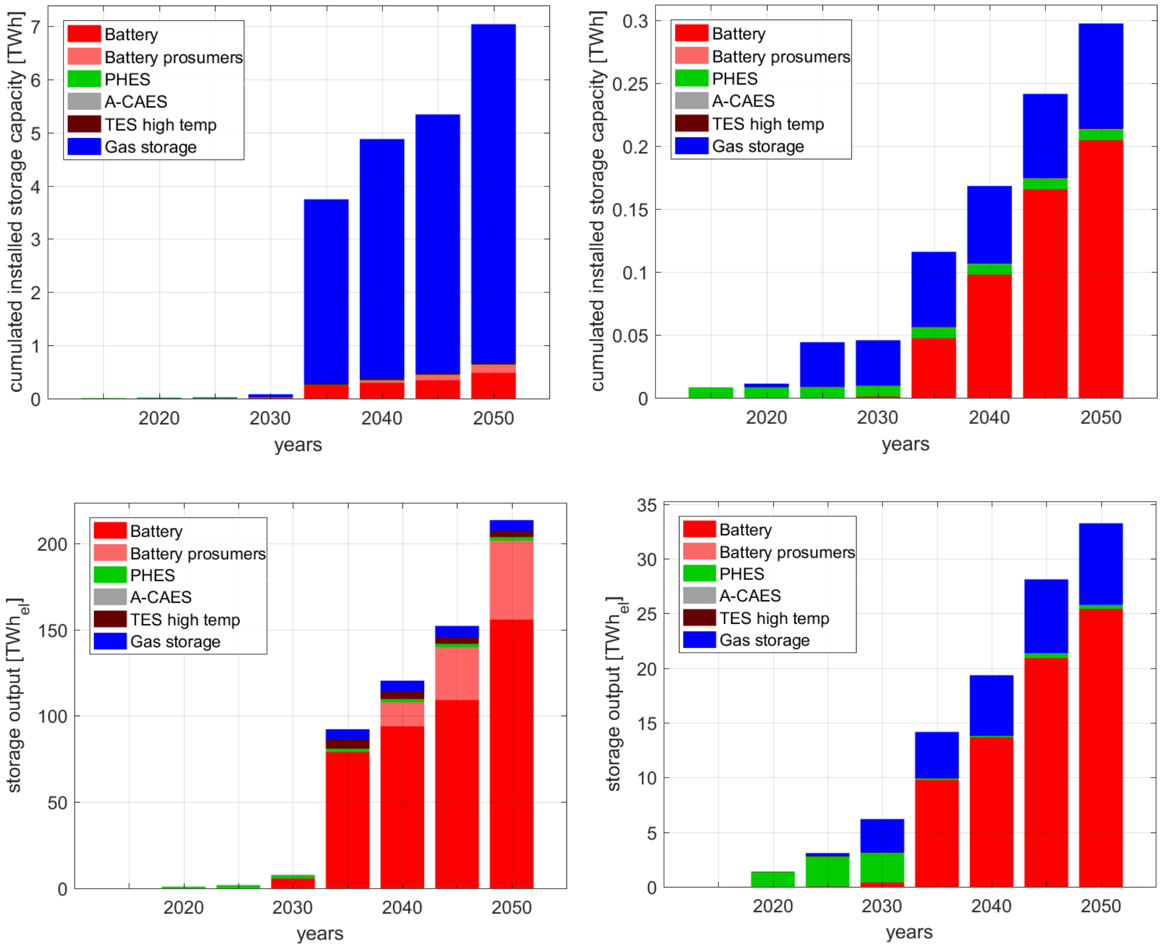


Fig. 12. Energy storage capacity for the BPS (top left) and CPS (top right) and storage output for the BPS (bottom left) and CPS (bottom right) from 2015 to 2050.

Fig. 13 illustrates GHG emissions for both scenarios over the transition. For the BPS, there is a drastic reduction of emitted GHG from 119 Mton/a in 2015 to zero by 2050. As seen in Fig. 13, there are two noticeable reductions for GHG emissions in the BPS. The first decrease is in 2020 due to a high penetration of the RE share in the power mix and the second one occurs in 2035 when natural gas is replaced by SNG. By contrast, in the CPS scenario, GHG emissions increase during the transition and reach to 188 Mton/a in 2050.

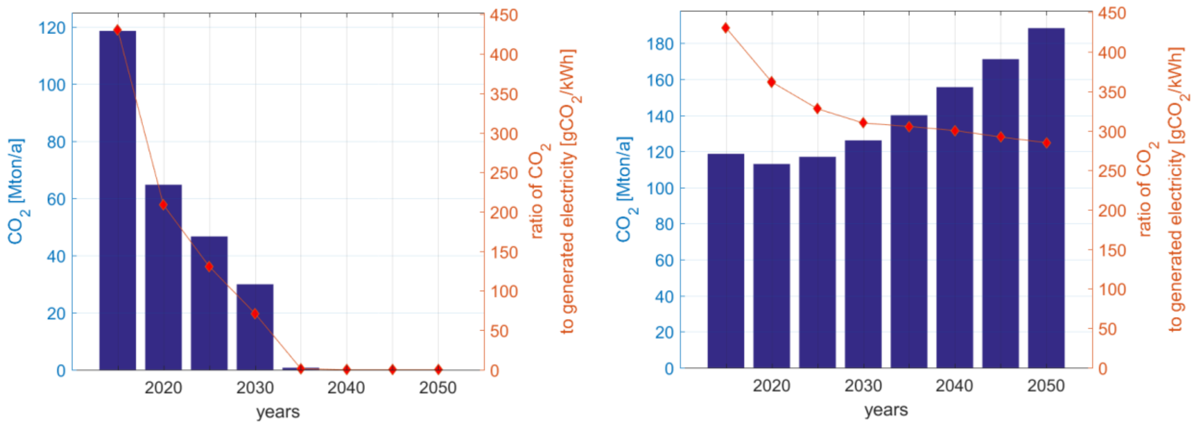


Fig. 13. Change in annual GHG emissions during the energy transition from 2015 to 2050 for the BPS (left) and CPS (right).

4.2. Integrated System

The results of transition for the power system integrated with desalination and non-energetic gas sectors are discussed in this section.

The result of LCOE for the integrated scenario is presented in Fig. 14. The cost structure is similar to the result for the BPS. In 2015, the power system, which is comprised of 83% fossil power plants, has the highest LCOE at 88 €/MWh$_{el}$ due to high fuel cost and GHG emissions cost. However, over the transition as the share of renewables increases and fossil power plants decommission, the LCOE decreases continuously and reaches to 41 €/MWh$_{el}$ in 2050. The LCOE in the integrated scenario is lower compared to the BPS for all time steps due to a fast ramp-up of low cost RE capacities and the positive impact of sector coupling by increasing the flexibility of the system that leads to a lower cost for curtailment, storage and transmission. This fact can be observed in Fig. 15, which shows the contribution of levelised costs of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost, and GHG emissions cost to the total LCOE for both scenarios.

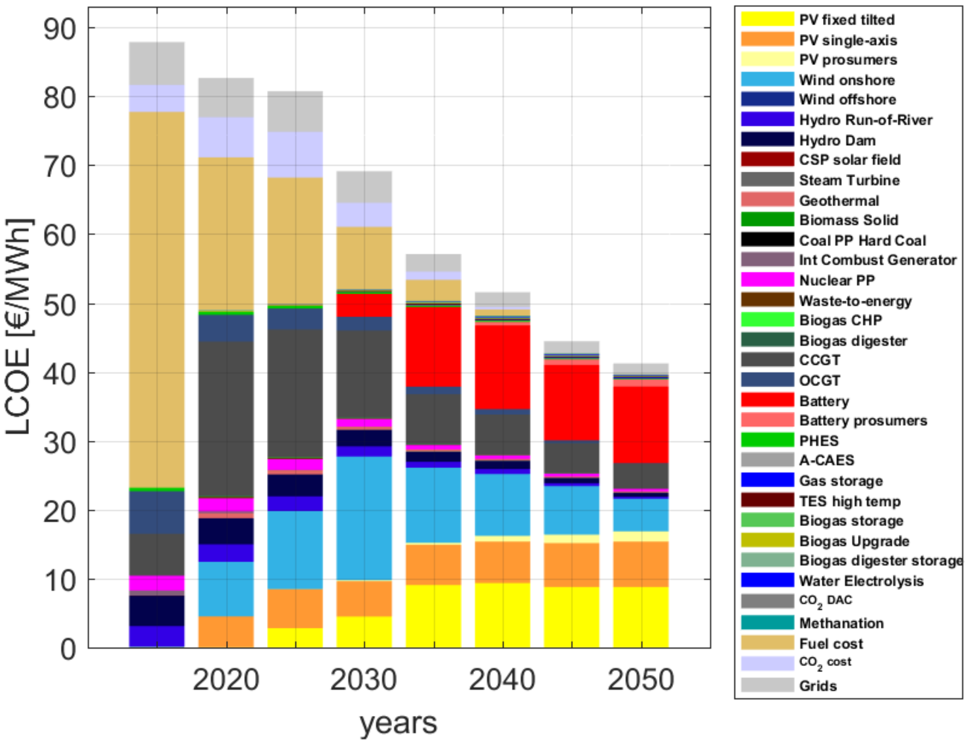


Fig. 14. LCOE by technology for the integrated scenario from 2015 to 2050.

Fig. 16 represents the cost optimal mix of installed power plants for the integrated scenario. The power plants installation follows a similar trend as for the BPS. In 2015, the installed capacity is dominated by fossil power plants by 83% but during the transition renewables, particularly solar PV, are installed and dominate the system to first reduce the FLH of fossil plants and second to replace the phased out fossil plants and meet the increasing electricity demand. In 2050, solar PV with 70% contribution to the total installed capacity is the dominant electricity generation technology due to its high cost competitiveness compared to all other electricity generation technologies. The significant difference between the installed capacities in the BPS (Fig. 10) and integrated scenario is due to additional electricity demand of desalination and non-energetic gas sectors in the integrated scenario. There is 159% additional solar PV installed capacity and consequently 119% more batteries in the integrated system. Fig. 17 (left) shows the required storage capacity for the integrated scenario. It can be observed that the increase in the gas storage requirement is much more than battery capacity since the additional capacity of gas storage in the integrated system is utilised more for producing SNG than meeting the electricity demand. This fact is more obvious in Fig. 17 (right) which presents the electricity output of storage technologies in the system. The share of gas storage output in total storage output decreased by 83% compared to the BPS (see Fig. 12 bottom left), clearly indicating the benefit of sector coupling. The capacities of installed power plants and storage technologies are indicated in the Supplementary Material (Tables S3 and S4).

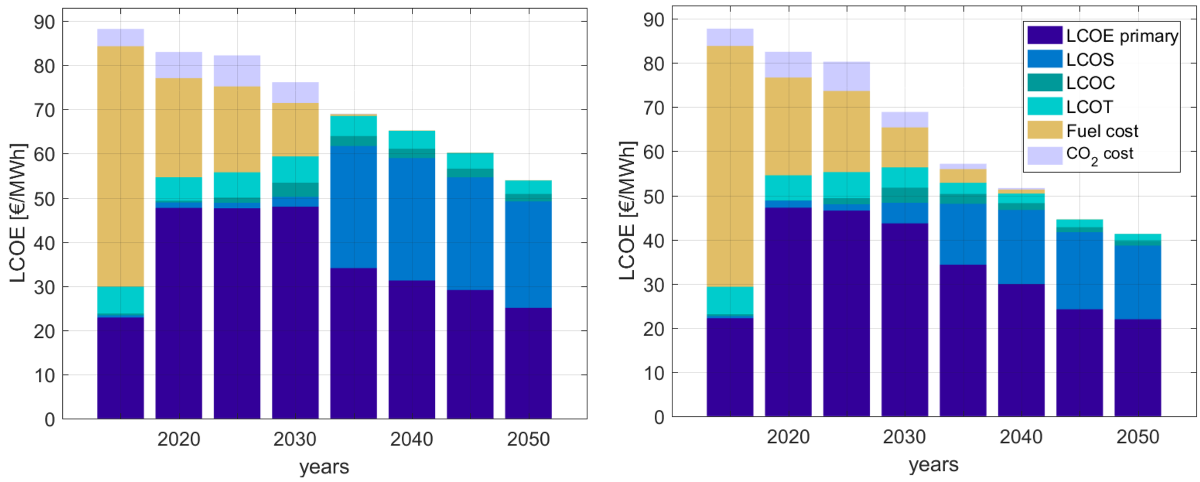


Fig. 15. Contribution of LCOE primary, LCOS, LCOC, fuel cost and GHG emissions cost to total LCOE for the BPS (left) and for the integrated scenario (right) from 2015 to 2050.

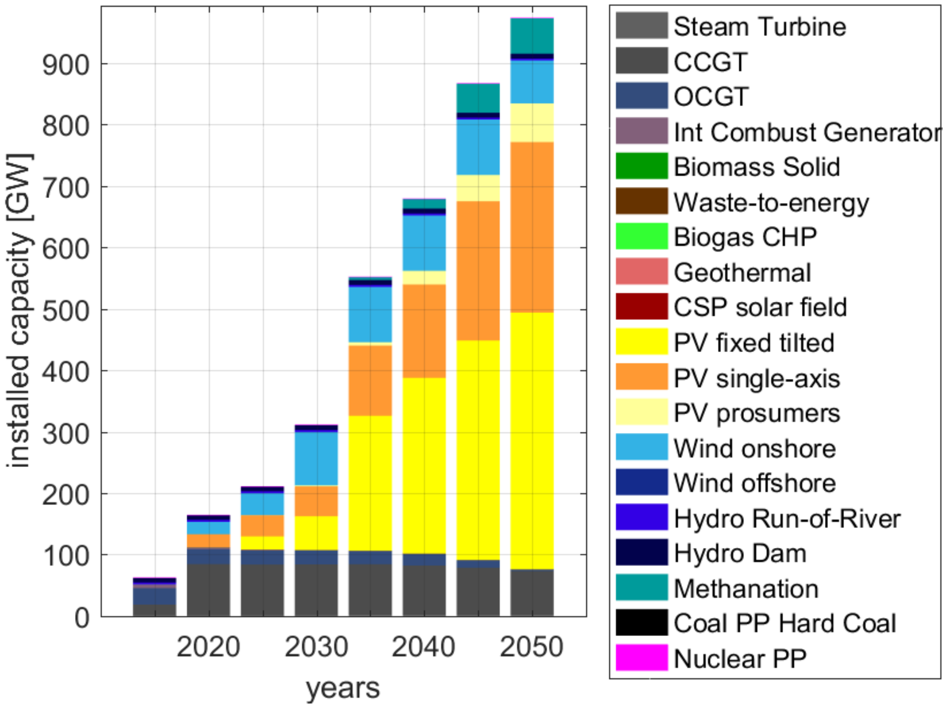


Fig. 16. Power plants capacity mix for the integrated scenario from 2015 to 2050.

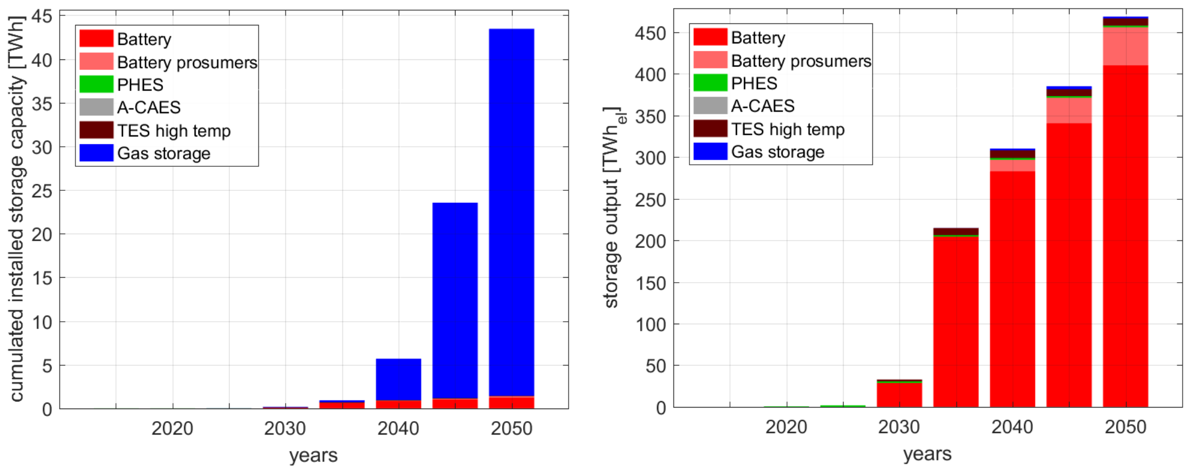


Fig. 17. Energy storage capacities (left) and storage output (right) for the integrated scenario from 2015 to 2050.

The desalination sector provides more than 50% of the country's water demand after 2030. The difference between water demand and desalination capacity is covered by renewable and non-renewable water sources. Among three different types of desalination plants (SWRO, MED and MSF) which are applied to the energy model, only SWRO technology is installed by the model due to its high efficiency, low costs and low electricity consumption. Fig. 18 shows Iran's water demand and the required desalination capacity to meet the demand from 2015 to 2050. In 2050 the country's water demand is 339 million m^3/day and the installed desalination plants cover 82% of the demand.

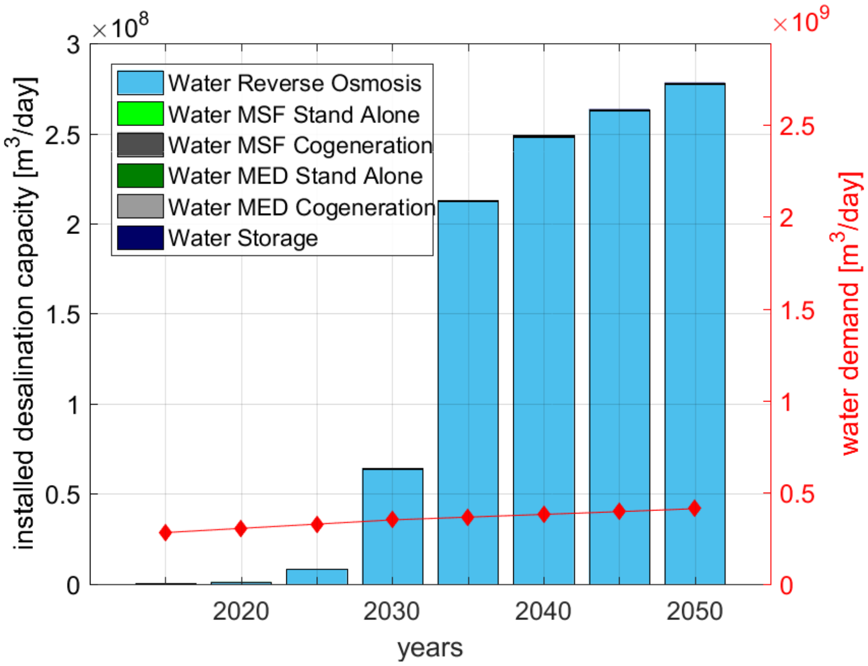


Fig. 18. Water desalination capacity to meet Iran's total water demand.

The levelised cost of water (LCOW) breakdown in cost categories is presented in Fig. 19. As can be observed, LCOW decreases continuously over the transition from 2.3 €/m^3 in 2015 to 1.5 €/m^3 by 2050. For the first 5-year time step, the reason for the decline in LCOW is due to removing the gas cost from the system by decommissioning the fossil fuel powered desalination plants. For 2020 onwards, the desalination sector enjoys an ongoing decrease in LCOE as discussed before due to decommissioning of fossil power plants and in addition to an increase in SWRO efficiency from 4.1 kWh/m^3 in 2015 to 2.6 kWh/m^3 in 2050. Since LCOW is dependent on SWRO efficiency and LCOE, there is a progressive decline in LCOW [42,45].

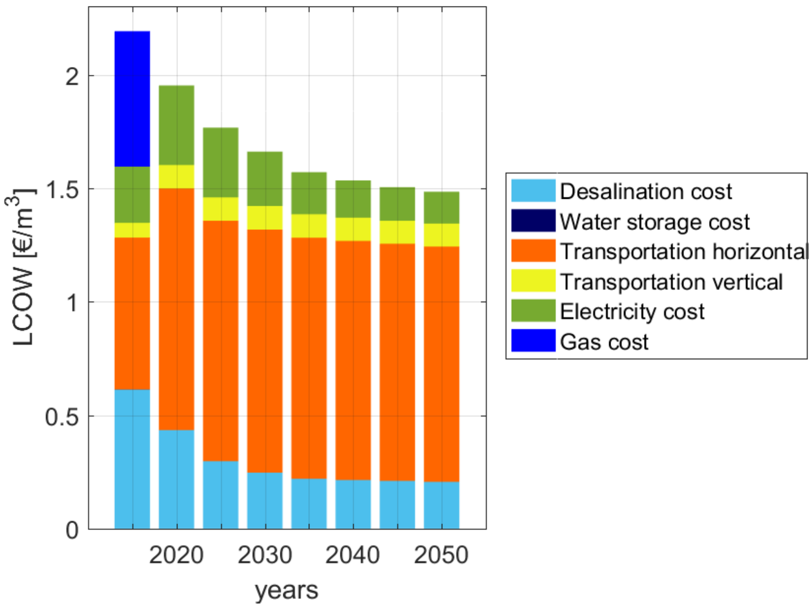


Fig. 19. LCOW breakdown in cost categories from 2015 to 2050.

The gas sector, similar to the desalination sector, increases the flexibility of the integrated system with providing better utilisation of the produced electricity by variable RE. Fig. 20 shows Iran's total gas demand from 2015 to 2050. The left figure is a breakdown of gas demand in fossil gas, biomethane and SNG, and the right one shows the share of gas demand utilised for electricity generation and non-energetic industrial gas demand. Total gas demand in Iran decreases from 576.1 TWh_{th} in 2015 to 255.8 TWh_{th} in 2050. Shifting from fossil gas to SNG is found to be cost competitive. In 2015, the total gas demand is supplied by fossil gas. A large amount of fossil gas (79%) is used for electricity generation. In 2020, biomethane appears with 4.9 TWh_{th} capacity, which remains constant over the transition while SNG is produced in the system from 2035 onwards with an increasing capacity over the transition.

The levelised cost of gas (LCOG) from 2015 to 2050 is presented in Fig. 21. In 2015, LCOG is 23.7 €/MWh_{th}, which increases to 83.4 €/MWh_{th} by 2045. There is a reduction in LCOG to 79.3 €/MWh_{th} in 2050 due to elimination of GHG emissions cost and no remaining fossil gas in the energy system.

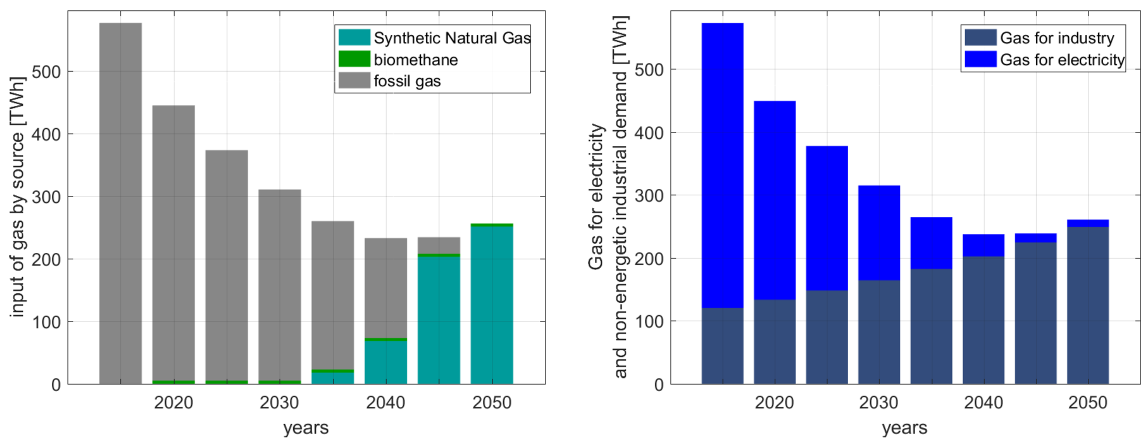


Fig. 20. Iran's total gas demand breakdown into fossil gas, biomethane and SNG (left) and share of gas demand for electricity generation and non-energetic industrial gas (right) from 2015 to 2050.

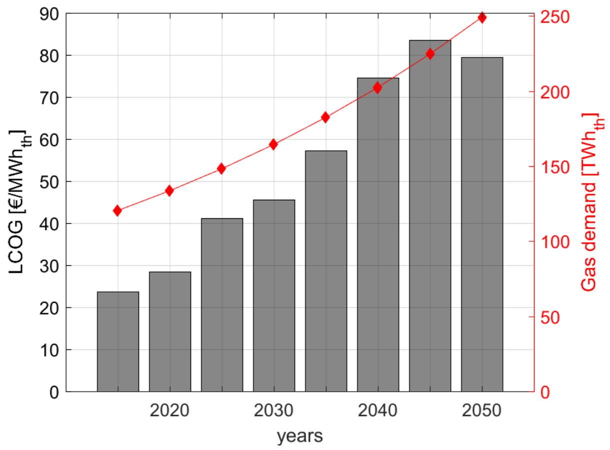


Fig. 21. LCOG in the integrated scenario from 2015 to 2050 and gas demand for non-energetic industrial gas sector.

Fig. 22 illustrates the hourly profiles for production and storage of SNG in 2050. FLH of the PtG plants are 4375 and major production occurs from March to November during the daytime. Moreover, when there is excess electricity from wind power plants, PtG plants produce SNG to avoid curtailment of the excess electricity in the system. Fig. 22 indicates that gas storage operates as a seasonal storage. The maximum charging occurs in November and gas storage is fully charged by the beginning of the last month of autumn. State-of-charge profiles for other storage technologies are presented in the Supplementary Material (Fig. S1). An energy flow diagram for the integrated scenario is presented in Fig. 23. The figure represents all generation and storage technologies and the HVAC transmission grid. The energy flow is started from primary RE resources to final electricity demand of the power system, desalination and non-energetic industrial gas sectors. The difference between primary energy and final demand is comprised of potentially useable heat and total losses in the system.

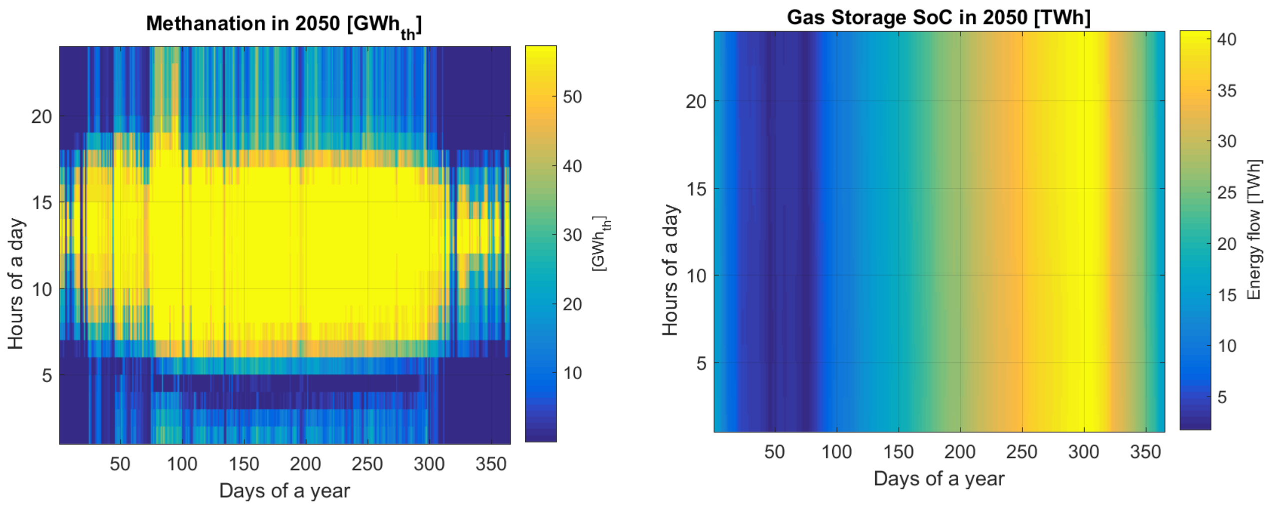


Fig. 22. Hourly profile of methanation (left) and state of charge profile for gas storage in the year 2050 (right).

4.3.Regional analysis

As described in section 3, in the present study Iran is structured into nine regions in the model to provide more detailed information on a regional basis. The model builds the optimised power system configurations which are characterised by optimised capacitates for a mix of electricity generation technologies, storage technologies and transmission power lines for each region. This section provides details of the integrated scenario over the nine defined regions in Iran and the transmitted power between the regions for the BPS.

4.3.1 Installed capacities and LCOE

Fig. 24 presents electricity generation in each region. Solar PV is the dominant technology in all regions while wind energy with smaller shares contributes to power generation of all regions except region 3 (TE) and region 7 (FA). The contribution of hydro power is only noticeable in region 6 (KHZ) that currently has the largest hydro power capacity in the country with 9 GW. Fig. 25 shows how LCOE varies over the country in different regions. Region 7 with 380 TWh is the largest electricity producer in the country and has the lowest LCOE (31.3 €/MWh), while region 2 (KO) with the lowest electricity generation (82 TWh) has the highest LCOE (59.7 €/MWh) in the country. The levelised detailed results of power system cost for the nine regions are presented in Fig. 25. The next largest electricity producer regions after region 7 (FA) are region 5 (IS) and region 6 (KHZ) with 252 TWh and 229 TWh, respectively. However, LCOE in region 5 (IS) is slightly higher than that in region 6 (KHZ). The lower LCOE for region 6 can be explained by the highest installed capacity of hydro power among all regions, which provides flexibility in the system and reduces the need for energy storage (see Fig. 25c). Region 3 (TE) with 252 TWh has the second highest LCOE in the country. The reason is that there is no wind installation in the optimised power mix of this region; therefore, the region requires more storage to balance the demand during absence of solar radiation that leads to a higher LCOS compared to other regions. Hourly demand, generation and storage over a representative two-week period for 3 different regions are shown in the Supplementary Material (Fig. S8-S10).

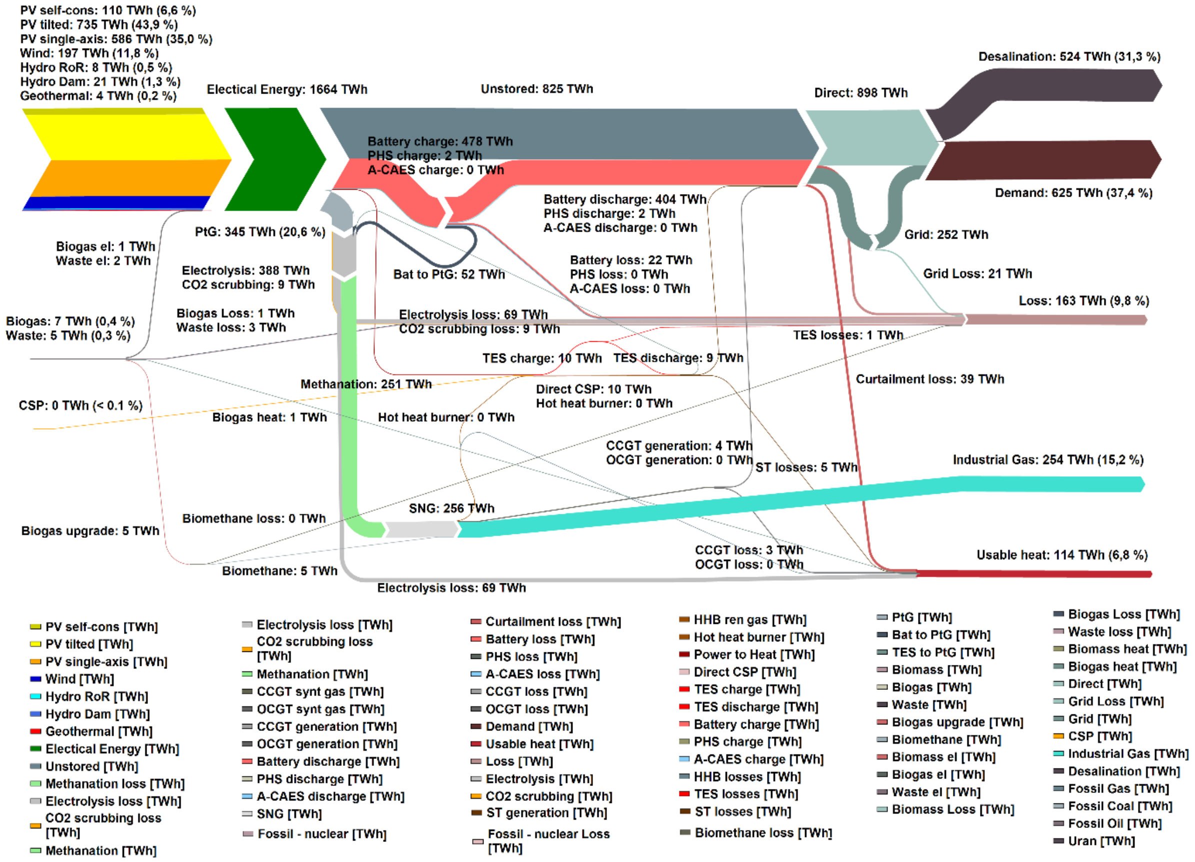


Fig. 23. Energy flow of the integrated system for the year 2050.

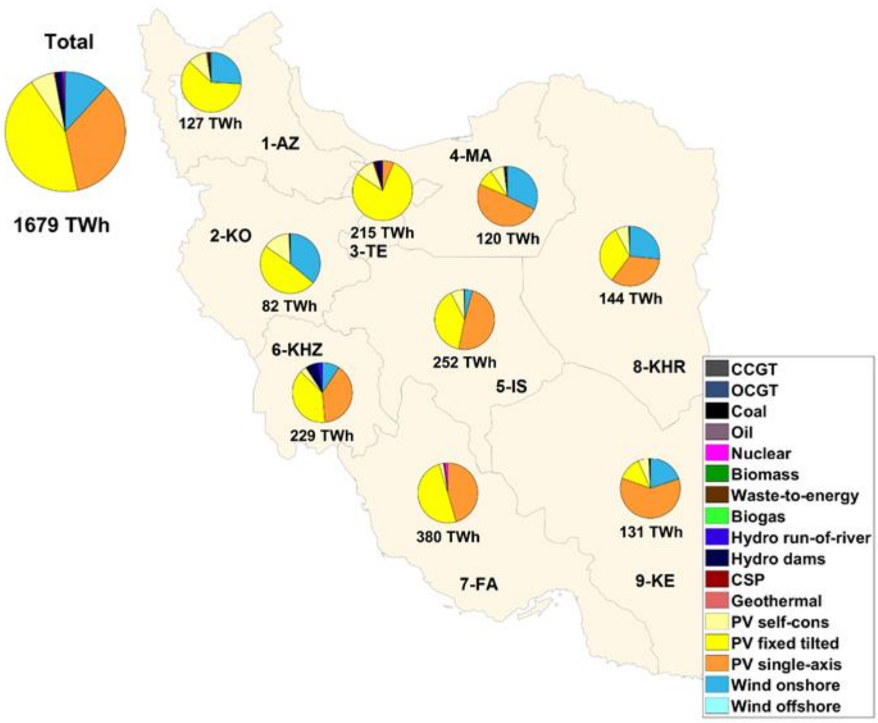


Fig. 24. Regional electricity generation for the integrated scenario in the year 2050.

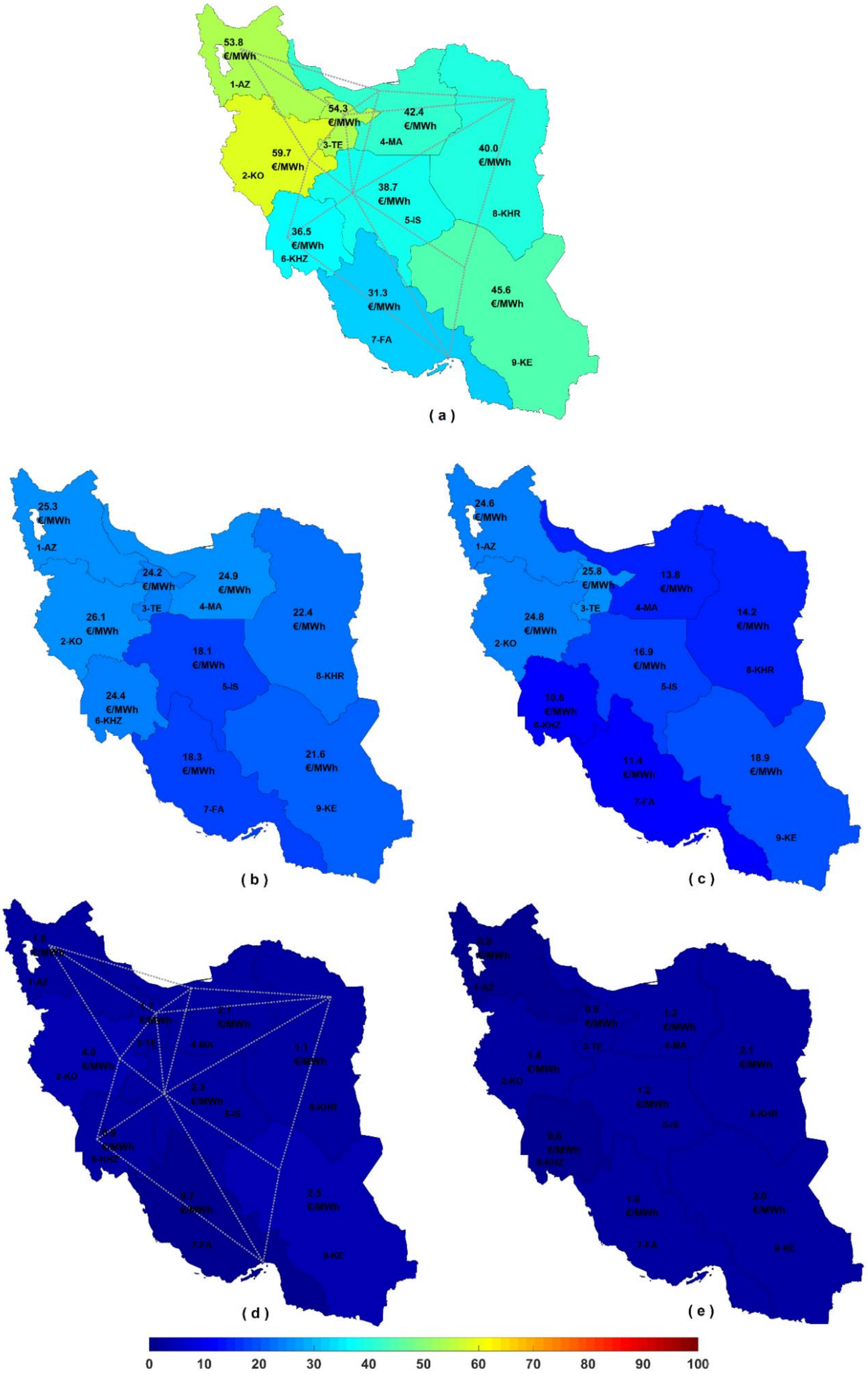


Fig. 25. Regional LCOE (a), LCOE for primary generation (b), LCOS (c), LCOT (d), LCOC (e) for the integrated scenario in the year 2050.

4.4 Electricity exchange

Electricity exchange among the nine modelled regions in Iran is enabled by HVAC power lines. Interconnection of the regions form a larger network with a higher reliability and a lower electricity cost. The cost of electricity transmission (LCOT) makes up only 4% of total LCOE but adds a valuable flexibility to the system and lowers the electricity cost by reducing the required storage capacity in the system. In 2050, the electricity grid transmits 22% of total electricity generated within the country. Annual electricity import and export between the regions for 2050 is presented in Fig. 26. The exporting flow from a region is shown with the same colour as the exporting region's arc. For example, the arc of KE region is green and also all connected flows have the same colour that indicates all of them are exporting flows from KE and this region is a net exporter. The KE region has a high FLH for PV systems. In addition, the KE region has the highest upper limit for installations of solar PV and wind power plants compared to the other regions due to its large area. Therefore, the KE region generates substantial electricity that makes this region a major net exporter with 64 TWh electricity export, which contributes to 47% of the total transmitted power in the country. On the other hand, the TE region with the smallest area and the highest electricity demand is a net importer that makes up 32% of total imported electricity in the county. The TE region imports electricity from all its neighbouring regions except the AZ region which is a net importer region due to limited resources and having the lowest PV FLH across the country. Upper limits for installable capacity for all technologies in all regions are provided in the Supplementary Material (Table S5) and the grid profile is presented in the Supplementary Material (Fig. S2).

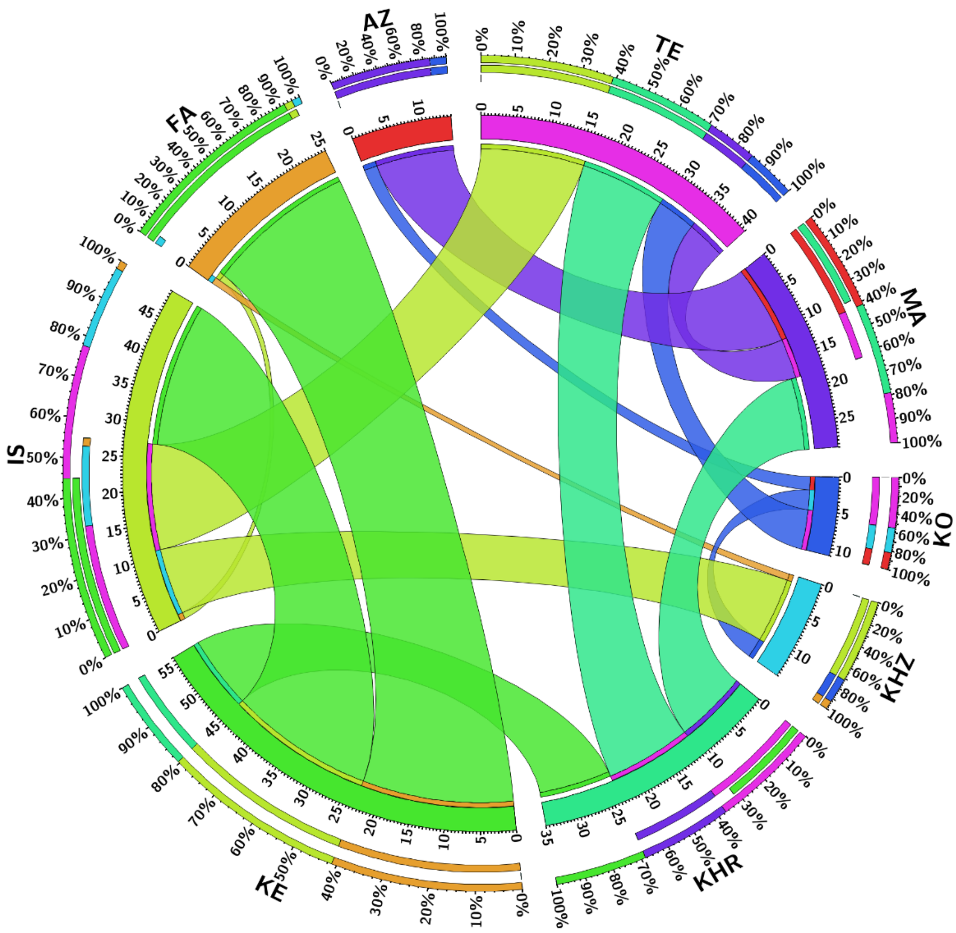


Fig. 26. Annual electricity exchange between regions for the BPS in the year 2050.

5. Discussion

The intention of this research was to provide a least cost transition pathway towards a zero GHG emission power system by 2050 for Iran, which fulfils the targets of the Paris Agreement and promotes energy security in Iran. The results of the BPS power system transition were compared with outcomes of a power system based on the country's current policies. The results indicate that Iran can build an affordable power system totally based on renewables, which is more cost-effective than the current power system. The LCOE of the proposed system by the BPS at the end of the transition in 2050 is 54 €/MWh, which is 39% lower than the country's power system cost in 2015. The electricity cost decreases further by sector coupling through the integrated scenario and reaches to 41 €/MWh in 2050. However, a power system constructed according to the existing policies of the country leads to a substantially higher LCOE of 128 €/MWh by 2050. The major contributors to this high LCOE are fuel cost and GHG emission cost by 45% and 35%, respectively. Although Iran is a fossil fuel exporter, if the growing energy demand in the country continues to be satisfied by fossil fuel, the country would be an importer of fossil fuels in the next decade that will have a significant adverse impact on the country's economy due to loss of oil revenues and enormous energy cost [28,55].

Concerning the cost structure of the BPS, solar PV and battery which enable the system to cover 70% of the total demand, make up 55.4% of the LCOE in 2050. In the integrated scenario, also solar PV and battery have the highest share in LCOE. However, due to the flexibility provided by sector coupling and enabling the system to utilise variable RE electricity in a more effective way, LCOT, LCOC and LCOS dropped by 93%, 56% and 45%, respectively, compared to the corresponding costs in the BPS. LCOE of the fully renewable power system for both, the BPS and integrated scenario, in this study are comparable to the results of other countries studies. For instance, LCOE of the power system for Saudi Arabia [45], Turkey [56], Pakistan [57] and India [58] are found to be 41 €/MWh, 65 €/MWh, 46 €/MWh and 52 €/MWh, respectively. The LCOE for the power sector in Iran is in line with these countries: 32%, 17% and 4% more than Saudi Arabia, Pakistan and India respectively and 17% less than Turkey. Another research carried out by the authors of the present study for Iran shows slightly lower LCOE for the BPS with 50 €/MWh and a higher one for the integrated scenario with 47 €/MWh, compared to the results of the current research [30]. In the previous study, Iran was modelled as a single node, therefore, only national electricity generation and consumption were taken into consideration. However, the current study analyses a 9-node power system with electricity transmission between the regions that represent a system closer to the real power system structure in Iran. The power scenario of a single node system presents a lower LCOE since all the available RE resources in the country are used to supply the demand in a copper plate approach, which utilises more of the best possible resources. Nevertheless, in the 9-node power system, every region is supposed to generate electricity for its own use and the excess generation can be transferred through the transmission network to neighbouring regions. The role of interconnected grids to balance the 9-node energy system is more noticeable when other energy sectors are coupled to the power system. Transmission grids help to decrease the additional capacity of energy storage and electricity curtailment in the system. Therefore, LCOE in the integrated scenario of 9-node system is less than the integrated system of a single node. It is noteworthy that, curtailment has technical and economic benefits in the energy transition and a system with optimum amount of curtailment costs less than a system with no curtailment. The simultaneous increase of curtailment, storage capacity and penetration of RE is part of the least cost solution in a 100% RE transition. The relation of three linked parameters (curtailment, storage and penetration) in the energy transition is studied in [59]. Curtailment electricity for both BPS and CPS are provided in the Supplementary Material (Fig. S6).

The power transmission system leads to exchanges of 22% of total generated electricity between the 9 modelled regions in the BPS scenario. The KE region is the major net exporter due to its excellent solar potential and land availability that leads to the highest potential for solar PV installations compared to all other regions. On the other hand, the TE region that includes the capital city of Tehran, as one of the largest consumers of electricity in the country, has the highest demand but the smallest area that makes the region a net importer. The TE region meets its demand by 36% import from its neighbouring regions. The total electricity exchange of 22% is in an order also found in other more detailed country studies, such as 18% for Turkey [56], 11% for India [58], 59% for Nigeria [61] and 12% for Europe [60].

Solar PV in both, the BP and integrated scenarios, covers the majority of electricity demand in all regions due to its high potential all over the county. Many studies indicate that solar PV will dominate an energy system based on 100% RE resources by 2050 all around the world due to its ongoing and rapid cost reduction [6–8,57,58,61,62]. Jacobson et al. [8] find a 55% share of solar PV in Iran's energy system by 2050. However, a study [63] which describes a zero CO_2 emissions energy system for Middle East by 2100 reports a very low share of solar energy in the energy mix. Besides the fact that that timeframe is far away from the Paris Agreement's target, the study considers very large capacities for nuclear energy and fossil CCS, despite their expensive costs and safety risks. The nuclear share in the energy mix is reported to be 30% while the contribution of solar energy is only 25% in 2100. This is while Middle East countries are well placed to utilise solar energy and they have ambitious plan for investing in solar PV [64], since it is now the least cost source of electricity. The results of the present study for the BPS show that Iran can achieve an affordable zero GHG emissions power system in 2050 with contribution of 68% solar PV to its total 429 GW installed power capacity. The share of PV fixed-tilted, PV single-axis and PV prosumer in total PV capacity are 46.4%, 32.1% and 21.4%, respectively. The lower share of PV prosumer is due to low cost electricity provided under current policies. However, PV prosumer can play an important role in dissemination of RE in Iran as it enables participation of private sector's investment in Iran's power system which is currently a state-owned system. Moreover, the distributed approach of self-generation could have several advantages for the country such as reducing cost of electricity transmission and distribution and the corresponding losses, electrification of isolated areas and shaving peak demand. Wind energy plays an important role in replacing the share of fossil fuels by renewable electricity in the system especially in the beginning of the transition period. In 2030, the capacity of installed wind plants reaches to 58.7 GW and with supplying 40.9% of total demand is the major electricity resource in the country. However, after 2030, there are no new installations for wind plants and also no re-investments for wind plants at the end of their technical lifetime, thus and solar PV dominates the power system due to its high cost competiveness. Hydropower and gas turbines (powered by SNG) by 30 TWh and 9 TWh make up 4.2% and 0.4% of total generated electricity, respectively, in 2050. Hydropower and gas turbines contribute to satisfying the demand when solar and wind generation is low, especially in winter. SNG appears in system in 2035 when its generation starts to become cost competitive and the share of RE exceeds 82% of total installed power capacity. Therefore, the power system requires to cover its seasonal storage to meet the demand during winter when there is relatively lower generation from RE especially solar PV. Storage technologies have a crucial role in the transition to a fully RE-based energy system. Gas storage installation starts in 2035 and with 6.4 TWh capacity contributes to 91% of total installed storage capacity in 2050. Due to gas storage operation as a seasonal storage, its share in total storage output is only 7%, since the full charge cycles are only 2.5 per year. By contrast, 90% of storage output is delivered by batteries, which achieve 330 full charge cycles per year. Batteries play a more critical role in the system and come into effect earlier in 2030 to store the solar PV excess generation during the daytime that can be utilised in the evening and night hours. Moreover, during night hours when the demand is lower, the stored electricity in batteries is transferred to PtG plants to enable storing energy for a longer term. This battery-to-PtG effect is more visible for Iran during the first month of the spring when there is the lowest demand in the year (see Fig. 7 and Fig. S11) and in total 4 TWh_{el} are transferred from batteries to electrolysers being equivalent to 0.63% of total electricity generation in 2050. This effect has been reported and described in more detail for India [58] and Nigeria [61]. The fast cost reduction of batteries [65–67] and the perfect match to solar PV [68,69] leads to high utilisation of batteries as vital part of storage system over the transition to enabling a very high solar PV share and in combination a very low-cost power system.

The structure of the power system in the CPS is quite different from the two other scenarios since the installations of solar PV and wind plants are restricted to the capacities defined in the country's plan. Although the capacity of solar PV and wind power plants in total increases from 0.18 GW in 2015 to 35 GW in 2050, this capacity is not able to keep up with the growing electricity demand and 80.9% of demand is met by gas turbine powered by fossil natural gas. Gas turbines contribute to more than 36 b€ fuel cost, 188 Mton emitted CO_2 and consequently 28.3 b€ GHG emissions cost in 2050. However, the CO_2 emissions might be higher than what is calculated in this study since the assumed thermal efficiencies for both OCGT and CCGT in this study are 12% higher than what are reported for Iran's GT plants [13]. The OCGT and CCGT efficiencies in the present study are assumed to be 43% and 58%, respectively (see the Supplementary Material (Table S2-1)), while according to the Iran's Ministry of Energy they are 31% and 46%. Moreover, according to Iran's report for the United Nations Framework Convention on Climate Change [70], the CO_2 emissions from upstream flaring in gas and oil activities which is called fugitive emissions is a considerable number for Iran and 40.9 Mton CO_{2eq} is reported for 2010 and also it is argued that extensive work is required to develop local emission factors. Therefore, the 119 Mton CO_2 emissions for 2015 in this study which is calculated based on the higher efficiencies for power plants and not considering fugitive emission is 55 Mton less than the number, which is reported in a document by Iran's Ministry of Energy [71]. On the other hand, the IPCC approach for calculating of CO_2 emissions [72] based on consumed fuels in the country's power plants which is reported by Iran's Ministry of Energy [13] leads to 117 Mton CO_2 which is close to the number of the present study.

In addition to the fuel emissions in the CPS, the sustainability of the power system would further be threatened by the installation of 2 GW planned nuclear power plant capacity. Nuclear energy has a LCOE of higher than 100 €/MWh [73–75] and its safety concerns and lack of sustainability cannot be neglected [12,76]. It is noteworthy to mention that the CPS that is supposed to represent the current policy of the country is more ambitious than the real situation of the power system. This is mainly because the outlined plans are not implemented according the schedule and they get postponed. Moreover, there is no plan for post-2026, but it was assumed that a 5 GW installation in each 5-year time step for solar PV and wind plants would continue till 2050. However, even the CPS modelled in this study leads to an inefficient and expensive power system that is far from the Paris Agreement targets and would strongly violate a 1.5ºC economy [77]. The CPS will have negative impacts on the economy and environment in the country, which have already been highly affected by the current inefficient power system. Although Iran has taken its first steps towards a promotion of RE such as a subsidy reform, revising feed-in tariffs and a 20-year power purchase agreement, the country has a long way to go to restructure its energy system based on RE. The lack of a rigorous plan and progressive policy framework for provision of energy for a sustainable development is a challenging barrier to the development of RE in the country. Other barriers are technical and economic challenges, weakness in higher education and respective capacity building and lack of social acceptance and awareness [28,78]. Moreover, the relationship of Iran with Western word countries and international sanctions on Iran result in more economic challenges and loss of foreign investors. For example, an agreement for the construction of a 600 MW solar PV power plant (that would be the world's sixth largest solar PV plant at the time of announcement) in Iran by a British company was suspended due to the sanctions imposed in 2018 [79]. The RE potential in Iran is extensive. Wind energy can be harvested in many regions and solar energy is feasible almost everywhere across the country. A research by Aghahosseini et al. [64] indicates that in a transition roadmap for the MENA region towards 100% RE Iran can play an important role as a net electricity exporter country due to its abundant solar energy resource and high land availability. RE in Iran is able to make the country's domestic market independent from fossil fuel and frees its fossil resources up for export before 2050 [80]. Although fossil resources, the country's primary revenue source, are limited and will be depleted. Fasihi et al. [81] show Iran can use its excellent RE resources and existing infrastructure for fossil fuel transportation to export synthetic fuels based on RE electricity. The study finds that RE-based fuels can reach fuel-parity in Iran in next decades depending on different factors including crude oil price and climate change mitigation mechanisms like GHG emissions cost. Moreover, RE deployment in Iran results in economic growth in short-term and long-term by microeconomic productivity, providing employment and other economic benefits [82].

On the other hand, the transition of the power sector through the integrated scenario, which presents the results of adding the desalination and non-energetic industrial gas sectors to the BPS, leads to a more efficient power system, which supplies electricity at a lower cost compared to the BPS due to more low-cost RE-based electricity generation and flexibility provided by sector coupling. Moreover, the integrated scenario enables Iran to address its serious water crisis and to meet the water demand by SWRO desalination plants powered by least cost electricity provided mainly by solar PV and batteries. In 2050, LCOW ranges from 0.5 €/m^3 in the KHZ region to 1.8 €/m^3 in the TE region and an average of 1.5 €/m^3 for whole country. The results are in agreement with the results reported by a research conducted by Caldera et al. [24] that analysed meeting the water demand of Iran in 2030 by desalination plants powered by a 100% RE-based power system. The LCOW found by Caldera et al. [24] ranges from 0.50 €/m^3 to 2 €/m^3 in the country. In addition to the water demand, Iran can supply its non-energetic industrial gas demand through the integrated scenario. SNG produced by PtG plants is becoming cost competitive after 2030 and it is a big step towards defossilating all energy sectors and reaching to an energy system totally based on RE.

6. Conclusion

The current policy of Iran concerning the power system will lead to an expensive and inefficient power system with a LCOE of 128 €/MWh (83.5 €/MWh if the GHG emission cost would be neglected) and 188 Mton emitted CO_2 in 2050 that supplies 80.9% of its total demand by GT powered by fossil gas. Iran can benefit from its excellent solar and wind energy potential and the globally decreasing costs of these technologies to achieve a zero GHG emission cost-effective power system with LCOE of 54 €/MWh. Solar PV with support of batteries will be the dominant generation technology, covering 77% of total demand. For a 100% RE-based power system in Iran solar PV complemented by wind energy and some hydro power are the backbone of the system while storage technologies play a crucial role in providing a resilient and reliable power system. Batteries with 632 GWh capacity deliver 90% of total storage output to cover diurnal storage demand and gas storage with a large capacity of 6367 GWh but a small share of 7% of total storage output provides seasonal storage. Moreover, power transmission grids provide more flexibility by balancing the demand through exchanging electricity between the regions that leads to a lower electricity cost due to lower capacities required for energy storage. The modelled KE region located in southeast of the country would be the major electricity exporter due to its large area and excellent solar energy and very good wind energy resources. By aid of sector coupling Iran's power system can make a more promising transition that results to a 24% lower electricity cost and addresses the serious water scarcity in the country by a growing desalination sector. Moreover, the integration of non-energetic gas demand in the integrated scenario indicates the capability of renewables to substitute fossil fuel by renewable electricity based fuels.

The current study focused on the defossilisation of power, desalination and non-energetic gas sectors in Iran. The next research shall include the sectors transport, heating/cooling and industrial feedstock to show comprehensive pathways for the transition to a zero GHG emission energy system.

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Appendix A. Supplementary Material

Supplementary data associated with this article can be found in the online version, at

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