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Long-Term Energy System Modelling for a Clean Energy Transition in Egypt's Energy Sector

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Abstract: Egypt has the potential to generate a significant amount of energy from renewable technologies, in particular solar PV, concentrated solar power (CSP), and onshore and offshore wind. The energy sector is reliant on fossil fuels, particularly natural gas, for electricity production and is at risk of locking itself into a high carbon pathway. Globally, reducing greenhouse gas (GHG) emissions associated with national energy sectors is a target outlined in the UN's Paris Agreement. To reduce carbon dioxide (CO_2) emissions associated with a higher dependence on fossil fuels, Egypt must consider upscaling renewable energy technologies (RETs) to achieve a clean energy transition (CET). This research modelled six scenarios using clicSAND for OSeMOSYS to identify the technologies and policy target improvements that are needed to upscale RETs within Egypt's energy sector. The results showed that solar PV and onshore wind are key technologies to be upscaled to contribute towards Egypt's CET. The optimal renewable target is the International Renewable Energy Agency's (IRENA) target of 53% of electricity being sourced from RETs by 2030, which will cost USD 16.4 billion more up to 2035 than Egypt's current Integrated Sustainable Energy Strategy (ISES) target of 42% by 2035; it also saves 732.0 $MtCO_2$ over the entire modelling period to 2070. Socio-economic barriers to this transition are considered, such as recent discoveries of natural gas reserves combined with a history of energy insecurity, political instability impacting investor confidence, and a lack of international climate funding. The paper concludes with policy recommendations that would enable Egypt to progress towards achieving a CET.

Keywords: clean energy transition; renewable energy technologies; OSeMOSYS; Egypt; energy policy

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1. Introduction

Long-term energy system modelling can assist our understanding of how countries might transition towards clean energy systems. Egypt, a lower middle-income country, has one of the largest economies within the Middle East and North Africa (MENA) region [1]. According to the World Bank Group [2], Egypt's population is projected to grow to 122.6 million by 2030 from 109.3 million in 2021, placing pressure on the nation's economy [3].

Large fossil fuel subsidies in the early 2010s discouraged investment in the power sector [4]. These subsidies, a decline in production, and an increase in demand meant that the energy sector could no longer meet the demands of the growing population, resulting in severe power shortages and blackouts [4]. Previous political instability, such as the Arab Spring social unrest beginning in 2011, resulted in an unemployment rate of 13.1% in 2013, further exacerbating the economic situation [5]. Following this, the ensuing recession resulted in Egypt's transition from an energy exporter in 2009 to an energy importer by 2014 [4]. To tackle this, the government implemented ambitious reforms in 2016, designed to restore political and macroeconomic stability, which included raising taxes, reducing fossil fuel energy subsidies, and introducing feed-in tariffs to promote renewable energy production [3,6]. These efforts have resulted in a significant increase in investment, boosting electricity production [6].

Currently, Egypt is heavily dependent on fossil fuels for electricity production, primarily natural gas, which are supplemented by renewable resources such as hydropower, wind, and solar photovoltaics (PV). Due to Egypt's climate, the country is suitable for both wind (onshore and offshore) and solar PV and concentrated solar power (CSP). Egypt receives between 2900 and 3200 h of sunshine annually, with total radiation intensity varying between 2000 and 3200 kWh/m^2/year [7]. Egypt is also suitable for harnessing wind energy, with stable wind speeds between 8 and 10 m/s at 100 m in the Gulf of Suez area [7]. Progress has been made with the building of large renewable projects such as the Benban Solar PV Park, Kom Ombo Solar PV plant, and Zaafarana Wind Farm.

Egypt's current climate policies require substantial updates to be consistent with the Paris Agreement's 1.5 °C target, such as including a quantifiable emissions reduction target within its Nationally Determined Contribution (NDC). In 2016, Egypt set a target of 42% of electricity generation to be sourced from renewable technologies by 2035, as outlined in its Integrated Sustainable Energy Strategy (ISES) [7–9].

To investigate Egypt's potential pathway towards a clean energy transition (CET), three research objectives were set. They were as follows:

(1) To generate six scenarios that investigate the impact of upscaling RETs on Egypt's energy system using the long-term energy system model OSeMOSYS.
(2) To determine the technologies and policies that are required to ensure a CET.
(3) To identify the main economic and socio-political barriers that may prevent Egypt from achieving a CET.

This research paper covers Egypt's current energy policies and previous modelling work in the literature review, which leads on to the Experimental section describing the modelling methodology that was undertaken to generate the six scenarios. The Results and Discussion section includes the findings from the modelling and other socio-economic considerations, followed by the policy recommendations and conclusions. This research aims to highlight the influence that national policy making can have in aiding a clean energy transition and quantifies the associated carbon emission reduction and financial impact of these policies.

2. Literature Review

2.1. Current Egyptian Energy Policies

Despite the lack of a quantitative target for reducing CO_2 emissions, sectors within Egypt are working towards a CET guided by strategies such as the Integrated Sustainable Energy Strategy (ISES) for 2035, Vision 2030 [10], and the National Climate Change Strategy 2050 (NCCS) [11].

The ISES 2035 was initiated by the Egyptian Government in 2013 through a project funded by the European Union [8]. The strategy primarily aims to rapidly increase the use of renewable energy technologies (RETs) and to improve energy efficiency in the energy sector [7]. The most quantifiable renewable energy targets within this strategy are 20% of electricity generation to be sourced from RETs by 2022 and 42% by 2035; the latter is broken down into different technologies, as shown in Figure 1. It also includes plans to increase Egypt's electricity generation from coal to 16% by 2035, up from 0% currently [9].

The analysis of Egypt's renewable target by the International Renewable Energy Agency (IRENA) in 2018 classified the ISES 2035 target as unambitious. IRENA's scenario suggests that 53% of Egypt's electricity generation should be sourced from RETs by 2030 [7]. This target has been deemed economically feasible due to the financial mechanisms in place for renewable projects such as the Build Own Operate (BOO) schemes and bilateral foreign investment agreements into renewable projects [7].

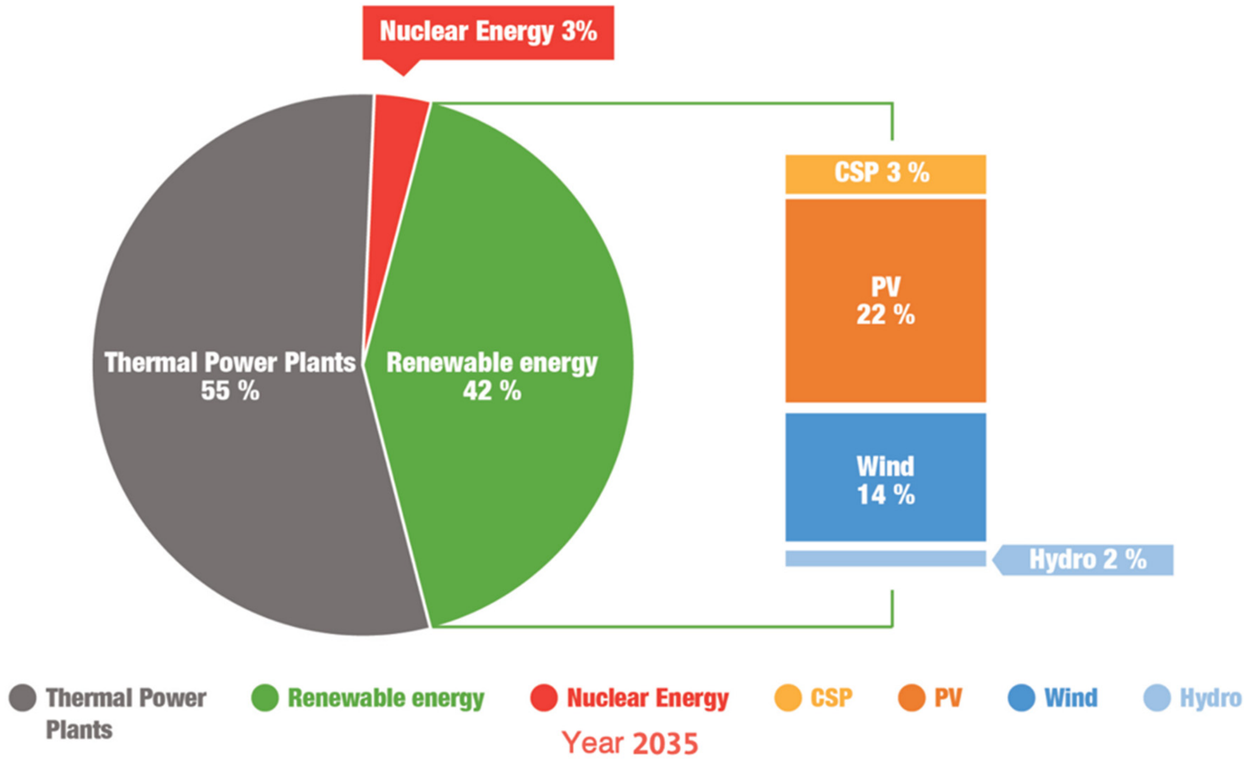

Figure 1. The breakdown of electricity-generation sources for 2035. Source: NREA, 2020.

Egypt's Vision 2030 aims to find a pathway to economic and social justice which will revive the role of Egypt in regional leadership [10]. At present, 30% of the total planned projects are underway, with plans for 50% by June 2025. Prominent green projects include the Benban Solar PV, wastewater treatment plants, and the desalination project at El Dabaa [12]. Most recently, a development cooperation portfolio of USD 26 billion has been set to fund 372 ongoing projects under Vision 2030 in various sectors that are aligned with the SDGs [13].

The recently published NCCS 2050 addresses climate change impacts, and it aims to (1) improve the quality of life for Egyptian citizens, (2) achieve sustainable development and economic growth, and (3) strengthen Egypt's leadership at the international level [11]. The NCCS 2050 emphasises integrated action between strategies and sectors, utilising financing opportunities under the Paris Agreement from international sources, such as the Green Climate Fund (GCF) and the World Bank, and strengthening international bilateral and multilateral cooperation [11].

At the international level, Egypt ratified the Paris Agreement in 2017, and its NDC action plan aims to develop policy targets that rely on five main pillars: the efficient use of energy, the increased use of renewable energy, the use of locally appropriate and more efficient fossil fuel technologies (including nuclear), the use of energy efficiency to decouple energy demand and economic growth, and the reform of energy subsidies [14]. Overall, the NDC stresses the importance of international financial assistance to develop policy targets and focuses on qualitative mitigation and adaptation measures, but it fails to mention a quantifiable CO_2 or GHG reduction target or a net zero target. An update to Egypt's NDC in June 2022 also did not provide any quantifiable targets [15].

2.2. Previous Modelling Work

Recent studies have highlighted the role of global energy system models such as the Open-Source Energy Modelling System (OSeMOSYS) in generating low-carbon scenarios to assist with the decarbonisation of national energy systems [16,17].

National-scale examples of previous OSeMOSYS modelling projects include the exploration of the possibility of a clean energy transition in Indonesia's electricity sector [18]. This research uses OSeMOSYS to conclude that large-scale renewable energy projects and the retirement of coal power stations are critical pathways to achieving a clean energy transition for Indonesia. OSeMOSYS was also used to explore a just energy transition in Indonesia whilst reducing the country's dependence on fossil fuels [19]. The paper also recommends that coal-fired power plants be retired more quickly and to impose a more aggressive carbon tax rate and prioritise investment into solar technologies to ensure a just transition. Other examples include the examination of Cyprus' natural gas outlook [20] and meeting Bolivia's Intended Nationally Determined Contribution (INDC) [21]. Larger-scale projects include The Electricity Model Base for Africa (TEMBA) study, which investigated the electricity supply systems of 47 countries and generated a 2040 scenario that showed how an enhanced grid network can alter Africa's generation mix and reduce electricity-generation costs [22]. OSeMOSYS analysis has been expanded to the global scale in a study that used the GENeSYS-MOD Global Energy System Model to assess the feasibility of global decarbonisation pathways and concluded that a reorientation of the energy system would be driven by decreasing costs of renewable energy sources, leading to the phase out of fossil fuels [23].

Previous modelling studies have been conducted for Egypt using both OSeMOSYS and other long-term energy system models. A key study by Mondal et al. [24] used the TIMES energy system model to examine Egypt's energy policy goals, as reflected in Egypt's Vision 2030. This study concluded that the current supply of energy needs to diversify from predominantly natural gas to a mix of technologies and that it may be wise to target the promotion of renewable energy for power generation and to develop a low-carbon society [24]. This study included a renewable energy development scenario based on Vision 2030. In comparison, the study described here is based on ISES 2035 targets and IRENA's proposed modifications. Rady et al.'s paper [25] used OSeMOSYS to model Egypt's power-generation sector and to provide policymakers with information to better plan for future investments in the power sector. It concluded that the lowest-cost electricity-generation mix always includes hydropower, natural gas-fired steam cycles, wind power, and solar PV rooftop technologies [25]. This study focused on the analysis of two different energy demand scenarios and did not investigate increasing renewable energy technologies for power generation in Egypt.

3. Experimental Section

OSeMOSYS was used to define a long-term decarbonisation strategy for Egypt's energy sector. OSeMOSYS is a dynamic, bottom-up, multi-year energy system model that applies linear optimisation techniques to determine an array of least-cost technologies to satisfy a defined energy demand. It uses energy system parameters sourced from international and national datasets, and these were constrained to generate six scenarios. The scenario outputs were analysed against the criteria of CO_2 emissions and cost to determine a pathway towards a CET for Egypt's energy sector.

The model is driven to satisfy an exogenously defined energy demand, which can be achieved through a combination of technologies and fuels [22]. A 'technology' in OSeMOSYS has a flexible definition and can be composed of any fuel use and conversion, from resource extraction and processing to generation, transmission, and distribution, as well as appliances [26]. A 'technology' is intended as a black-box with user-defined transfer functions and characteristics, alongside fuels that represent any energy vector, energy service, or proxy entering or exiting a technology, such as an input of natural gas and output of electricity for a natural gas power plant [27]. The technologies and fuels represented in this modelling are shown in Table 1.

Table 1. The power plant technologies and corresponding fuels (under commodities) used in this study. Source: OSeMOSYS Model Sets Tab.

Technologies		Commodities	
Code	**Description**	**Code**	**Description**
PWRBIO001	Biomass Power Plant	OIL	Crude Oil
PWRCOA001	Coal Power Plant	BIO	Biomass
PWRGEO	Geothermal Power Plant	COA	Coal
PWROHC001	Light Fuel Oil Power Plant	LFO	Light Fuel Oil
PWROHC002	Oil Fired Gas Turbine (Simple Cycle Gas Turbine (SCGT))	NGS	Natural Gas
PWRNGS001	Gas Power Plant (Combined Cycle Gas Turbine (CCGT))	HFO	Heavy Fuel Oil
PWRNGS002	Gas Power Plant (SCGT)	SOL	Solar
PWRSOL001	Solar PV (Utility)	HYD	Hydropower
PWRSOL002	Solar PV (Distributed with Storage)	WND	Wind
PWRCSP001	CSP without Storage	URN	Uranium
PWRCSP002	CSP with Storage	GEO	Geothermal
PWRHYD001	Large Hydropower Plant (Dam) (>100 MW)	ELC001	Electricity from Power Plants
PWRHYD002	Medium Hydropower Plant (10–100 MW)	ELC002	Electricity after Transmission
PWRHYD003	Small Hydropower Plant (<10 MW)	ELC003	Electricity after Distribution
PWRHYD004	Off-grid Hydropower		
PWRWND001	Onshore Wind		
PWRWND002	Offshore Wind		
PWRNUC	Nuclear Power Plant		
PWRSOL001S	Utility-scale PV with 2-h Storage		
PWRWND001S	Onshore Wind Power Plant with Storage		

In short, OSeMOSYS prioritises the least-cost pathway formed from technologies to determine a country or region's future energy mix [28]. An optimal least-cost approach is useful for the operational analysis of variable and fixed costs of both short-term upfront capital costs and long-term investment plans [29]. Due to the model's open-source nature, the input data are ideally free and publicly available. This overcomes a significant barrier when modelling the energy systems of countries with developing economies, as access to data has previously been proven to delay the decision-making process [30]. OSeMOSYS has a user-friendly Excel-based graphical user interface: the parameters are inputted via Climate Compatible Growth's (CCG) Simple and Nearly Done (clicSAND) interface to generate a *csv Excel output file. A combination of accessibility and transparency made OSeMOSYS an appropriate model to use in this research. A thorough description of the methodology on how to run the model and use the clicSAND interface and detailed technology parameters such as operational life, cost, efficiencies, and capacity factors can be found on Zenodo [31].

3.1. Constraints

Technical constraints, emission limits, or economic realities can be applied to the technologies within the model to generate scenarios or to reflect operational requirements, governmental policies, or socio-economic realities [22]. These constraints can include altering the relationship between different types of energy inputs and outputs, placing upper limits on GHG emissions, lower limits on renewable generation, or upper and lower limits on financial investment [27]. Several constraints were used to generate the six scenarios, explained in the following subsection.

3.2. Scenarios

To investigate the impact of upscaling RETs for Egypt's CET, six scenarios were modelled for Egypt's energy sector. The decision to base the scenarios on upscaling renewables was made in consultation with the Energy Transition Council (ETC). The ETC is a UK Government body formed ahead of COP26. It aimed to ensure that clean and sustainable power is the most reliable and affordable option for all [32]. A summary of the scenarios is shown in Table 2, and they are explained in more detail in this subsection.

Table 2. Summary of scenarios.

Scenario Code	Scenario Name	Description/Purpose
LC	Least Cost	Represents the least cost future for Egypt's energy system with no policy interventions.
FFF	Fossil Fuel Future	Quantifies the emissions generated and the cost of relying on fossil fuels.
NZ2050	Net Zero by 2050	Identifies the range of technologies needed to decrease CO_2 emissions to net zero by 2050.
ISES2035	Integrated Sustainable Energy Strategy 2035	Models Egypt's ISES 2035 target of reaching 42% of electricity generation from renewables by 2035.
IRENA2030	IRENA's REmap 2030 Analysis	Models IRENA's suggestion that the ISES 2035 renewables target should be upgraded to 53% by 2030.
60BY2035	60% Renewables by 2035	Models the scenario where 60% of Egypt's electricity generation comes from renewables by 2035.

The Least Cost (LC) scenario represents the reference scenario for Egypt's energy sector, where fossil fuel technologies and RETs generate electricity with limited constraints and without policy intervention to minimise cost. Reduced time slices (see the Temporal Structure subsection) were applied and technologies and commodities needed to meet transport demand were removed, as including these produced results with a much higher fossil fuel capacity demand than is possible within Egypt. The technology that represents transmission imports in the power sector (PWRTRNIMP) was also removed to investigate how Egypt will meet electricity demand domestically and increase their energy security in the future. In addition, the biomass power plant (PWRBIO001) technology was constrained to 1.4% of 2030 electricity demand based on IRENA's 2018 analysis to reduce its domination of Egypt's electricity generation. These four constraints were applied to all scenarios for consistency. Input data sources for the LC scenario (and therefore the base of all other scenarios) are explained in the Model Data Sources subsection.

To form the Fossil Fuel Future (FFF) scenario, a further constraint was added to the LC scenario by the removal of new capital investment into RETs. For the Net Zero by 2050 (NZ2050) scenario, historical emissions between 2015 and 2019 were averaged to calculate an assumed annual linear increase in CO_2 emissions, which was then extrapolated to peak in 2030. The peak in emissions was set to occur in 2030 as developing economies will not be able to immediately reduce their emissions. This peak value was then linearly decreased to 0 Mt by 2050. Achieving Net Zero by the year 2050 was chosen for Egypt by default due to the lack of an existing target.

The ISES2035 scenario models Egypt's ISES target to investigate whether the policy target is ambitious enough to achieve a CET in Egypt in the future. The ISES's 2035 target is broken down into 14% from wind, 22% from solar PV, 3% from CSP, and 2% from hydropower technologies [7]. To complete this scenario, the ISES 2035 target also includes a rapid increase in coal to 16% of Egypt's total electricity generation and 3.3% of electricity generation from nuclear.

The process of determining the breakdown of the ISES2035 target is shown in Equations (1) and (2).

$$Electricity\ Demand\ in\ 2035 = \sum (RESELC_{2035}\ COMELC_{2035}, INDELC_{2035}) \quad (1)$$

$RESELC\ 2035$ = *Residential Electricity demand in 2035*
$COMELC\ 2035$ = *Commercial Electricity demand in 2035*
$INDELC\ 2035$ = *Industrial Electricity demand in 2035*

$$ISES\ Target\ Breakdown\ in\ 2035 = \frac{Electricity\ Demand\ in\ 2035 \times (ISES\ defined\ \%\ generation\ for\ a\ technology)}{number\ of\ years} \quad (2)$$

Equation (1) calculates the sum of electricity demand for 2035, which is then multiplied by the ISES-defined percentage of a technology for 2035 in Equation (2), e.g., 22% for solar PV. This value was divided by the number of years to linearly increase the proportion of each technology to reach their respective 2035 targets. Additionally, this could be apportioned between multiple types of power plants, e.g., the 14% for wind generation was split into 60% from onshore and 40% from offshore (an assumption based on the space available in the desert and at sea). For hydropower technologies, the generation capacity input data causes the model to generate an accurate amount of electricity, as hydropower capacity is capped in Egypt at 2.8 GW due to the maximum number of dams already built on the River Nile.

These values were inserted into the model to produce the minimum percentage of electricity generation required from a certain technology by 2035.

A report by IRENA states that Egypt's ISES 2035 42% renewable target should be increased to 53% of Egypt's electricity generation to be supplied from RETs by 2030 [7]. IRENA's target is split into 4.0% hydropower, 18.4% wind, 1.4% biofuels, 21.3% solar PV, and 8.3% from CSP [7]. The methodology is similar to the ISES2035 scenario; however, the total electricity demand used to calculate the percentages for each technology is based on the lesser 2030 demand value rather than the 2035 value.

To model a more ambitious target, the 60% by 2035 (60BY2035) scenario was created to represent a still-higher proportion of electricity generation from RETs. The custom percentages of each technology are broken down as follows: 20% wind, 2% biofuels, 24% solar PV, and 9% CSP (and 5% hydropower). The methodology is similar to both SES2035 and IRENA2030.

A more detailed description of the analysis can be found online on Zenodo [31].

The constraints for the six scenarios are summarised in Table 3.

Table 3. The six scenarios created using OSeMOSYS, with their respective constraints.

Scenario Code	OSeMOSYS Constraints						
	Reduced Time Slices (96→8)	Transport Technologies Removed	PWRTRNIMP Removed	PWRBIO001 (Biomass) Constrained to x% of 2030 Demand	New Investment into RETs Removed	Annual Emissions Limited	Production Limited per Technology
LC	✓	✓	✓	1.4	N/A	N/A	N/A
FFF	✓	✓	✓	1.4	✓ (Geothermal, solar PV, CSP, hydro, and wind)	N/A	N/A
NZ2050	✓	✓	✓	1.4	N/A	✓	N/A
ISES2035	✓	✓	✓	1.4	N/A	N/A	✓ (Solar PV, CSP, wind, biomass, hydro, coal, nuclear)

Table 3. *Cont.*

Scenario Code	OSeMOSYS Constraints						
	Reduced Time Slices (96→8)	Transport Technologies Removed	PWRTRNIMP Removed	PWRBIO001 (Biomass) Constrained to x% of 2030 Demand	New Investment into RETs Removed	Annual Emissions Limited	Production Limited per Technology
IRENA2030	✓	✓	✓	1.4	N/A	N/A	✓ (Solar PV, CSP, wind, biomass, hydro)
60BY2035	✓	✓	✓	2.0	N/A	N/A	✓ (Solar PV, CSP, wind, biomass, hydro)

3.3. Temporal Structure

Within OSeMOSYS, the energy load curve is represented by time slices, which are defined as the time split of each modelled year. These time slices allow the separation of periods of high or low demand, and they can be grouped into seasons or night and day. For this study, each model year was represented by four seasons, each with two 12 h components representing night and day.

3.4. Reference Energy System

The interactions and flow of energy between the technologies and fuels are systematically represented in the form of a Reference Energy System (RES). The RES illustrates the structure of Egypt's energy sector (Figure 2) with the four tiers from left to right consisting of primary fuel supply, power generation technologies, transmission and distribution infrastructures, and the final demand sectors [25].

3.5. Model Data Sources

If specific input data could not be sourced at the national level, parameters, such as the capacity factors for power plants, were assumed to be similar to other Northern African countries and sourced from international organisations such as the International Energy Agency (IEA) and IRENA. The current energy system data, fuel costs, and transmission and distribution data were sourced from Climate Compatible Growth's (CCG) Starter Data Kit (SDK) [30]. CCG is a UK Aid-funded research programme that assists developing countries in achieving low-carbon development [33]. Included in the SDK were the estimated installed capacities for the power generation technologies, sourced from Brinkerink and Deane [34], Brinkerink et al. [35], Byers et al. [36], and IRENA [37] for the 2018 values. Values for Egypt's electricity transmission and distribution were sourced from Pappis et al. [38]. Fuel price projections to 2050 were sourced from the Energy Information Administration [39] and IRENA [40]. Egypt's full country dataset, including capital fixed costs for power plants, was sourced from the SDK and is openly accessible on Zenodo [41]. Renewable constraints in the scenarios were based on policies from the New and Renewable Energy Authority (NREA) [9] and IRENA [40].

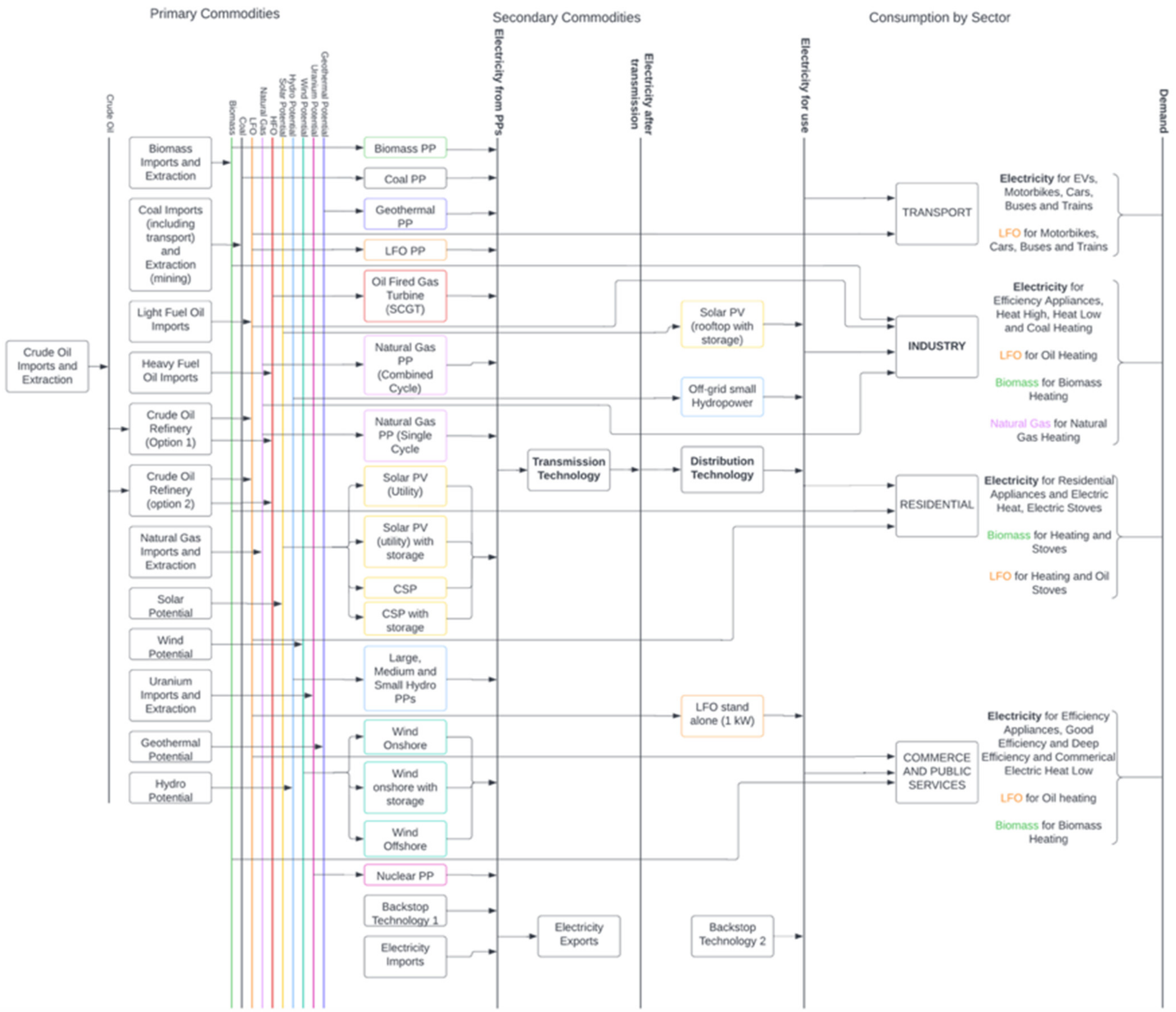

Figure 2. Egypt's Reference Energy System. The coloured lines within the Primary Commodities section represent fuel types. PP = power plant, LFO = Light Fuel Oil. Created with Lucid Chart based on the Starter Data Kit RES in Allington et al. [30].

3.6. Limitations

It should be borne in mind that a model represents a simplification of reality and cannot entirely include all considerations that impact an energy system. A significant limitation of OSeMOSYS is that variations in the climate system due to global warming are not represented in the constraints or input data. For example, an increase in temperature will negatively impact the efficiency of conventional power plants. There will also be a change to rainfall rates and distribution, impacting the electricity generation from hydropower plants [14]. In principle, OSeMOSYS can be combined with the Climate, Land, Energy and Water systems (CLEWs) model to overcome this limitation.

This study was limited to Egypt's energy sector without transport demand or electricity transmission imports. The scenario outputs have been restricted in two additional ways: (1) for the ISES2035, IRENA2030, and 60BY2035 scenarios, all solar technologies and wind technologies with storage (PWRSOL002, PWRSOL001S, PWRWND001S, and PWRCSP002) have been removed as the targets outlined in ISES and IRENA's 2018 report do not include storage technologies; and (2) energy-efficiency technologies that use less fuel resources but produce the same amount of electricity have not been included due to inaccurate cost projections associated with the model's output files.

4. Results and Discussion

4.1. Electricity Production

A summary of the electricity production for the six scenarios, measured in PJ, required from each technology each year is depicted in Figure 3.

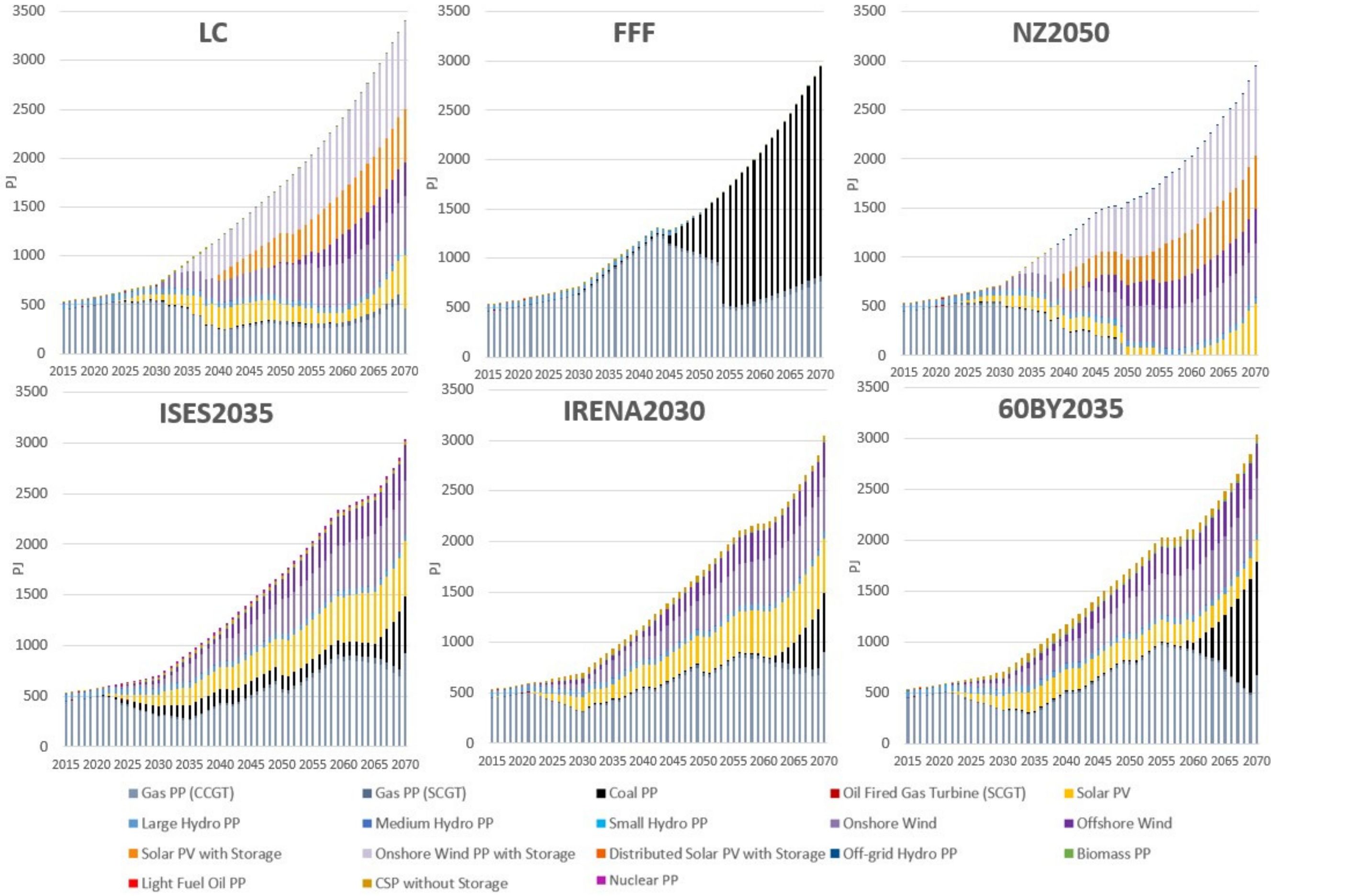

Figure 3. Electricity production (PJ) for all six scenarios.

In the LC scenario, examination of the raw data underlying the graph revealed that 26.8% of electricity production would be sourced from natural gas (CCGT and SCGT) technologies over the entire modelling period. The three wind technologies (onshore, offshore, and onshore with storage) dominate the LC pathway with a contribution of 46.5%. In the FFF scenario, the electricity production is dominated by natural gas technologies and coal, with coal power plants generating 42.6% of the required electricity over the modelling period. The Net Zero by 2050 scenario is dominated by wind and solar technologies, with 61.3% and 36.5%, respectively, of electricity generated by these sources in the year 2070.

The technologies required to meet Egypt's current target of 42% electricity generation to be sourced from RETs by 2035 are also depicted in Figure 3. Over the modelling period, coal power plants generate 9.4% of Egypt's electricity, considerably less than in the FFF scenario.

For the IRENA2030 scenario over the entire modelling period, 17.5% and 3.1% of electricity generation is from solar PV plants and CSP plants, respectively. Onshore wind projects produce 17.0% of electricity production across all modelled years, and offshore wind represents 10.4%.

The 60BY2035 scenario, despite relying on higher levels of RETs until 2035, shows a larger proportion of coal production (9.1%) than the IRENA2030 scenario (5.0%) over the entire modelling period. Overall, fossil fuel technologies still produce 52.5% of Egypt's electricity across all modelled years.

4.2. Installed Capacity

Figure 4 shows the total annual capacity in GW for the six scenarios. Overall, the amount of installed annual capacity in the FFF scenario is much lower in comparison to the LC scenario, with the system peaking at just 148 GW in the year 2070. The NZ2050 installed capacity is higher than in both the FFF and LC scenarios due to the severe reduction in fossil fuel technologies, and it is dominated by the three wind technologies. For the ISES2035 scenario, solar PV represents 2482.8 GW of the scenario's installed capacity over the model period. This is followed by onshore wind with an installed capacity of 1945.2 GW over the model period. The installed capacity for the 60BY2035 scenario is smaller than the ISES2035 and IRENA2030 scenarios due to the larger amount of capacity from natural gas and coal technologies.

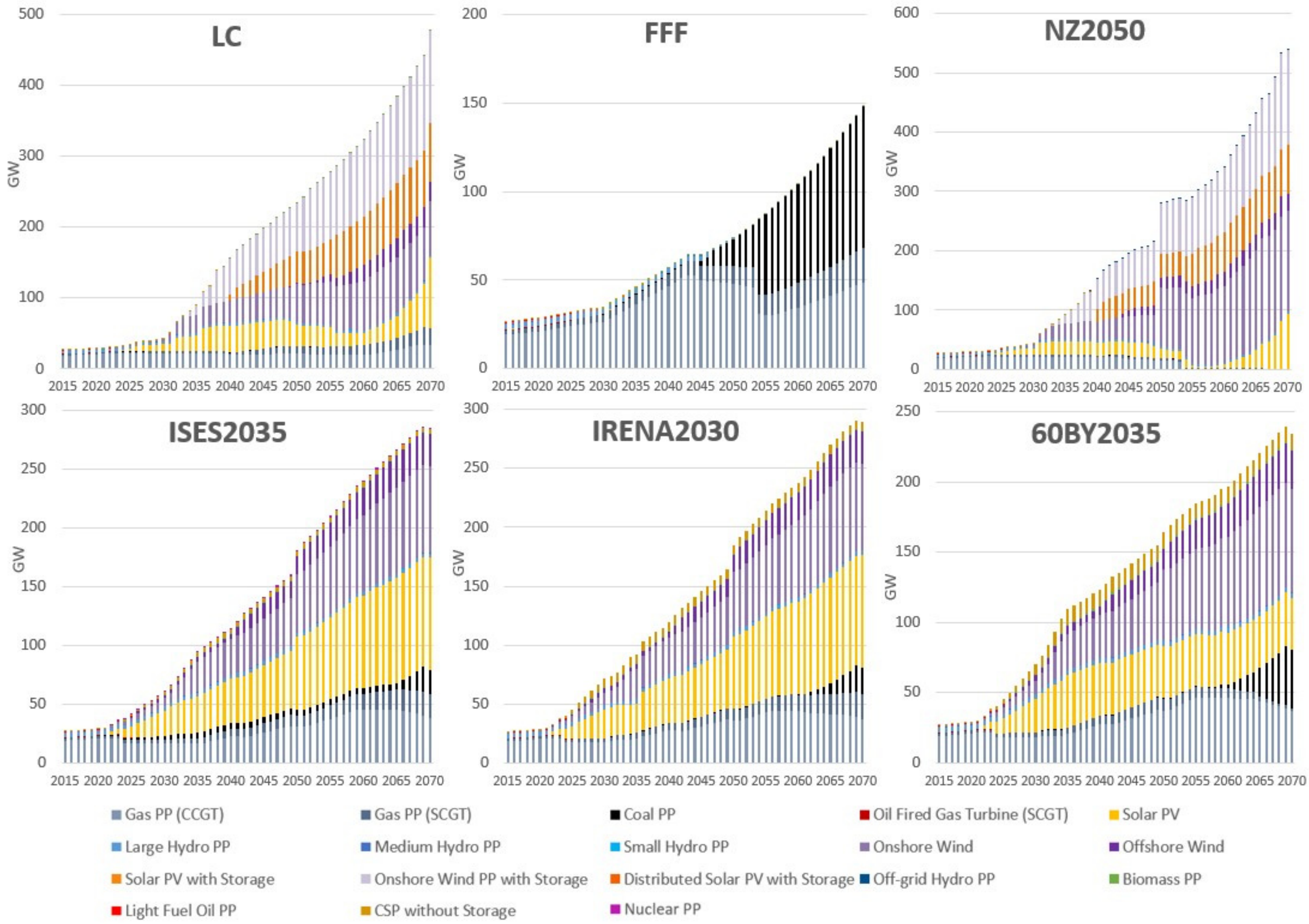

Figure 4. Total annual capacity (GW) for all six scenarios.

4.3. Further Findings from the FFF, LC, and NZ2050 Scenario Data

The FFF scenario defines the technologies that would dominate a future without capital investment into RETs. The total cost of this scenario is USD 2.17 trillion, which is more expensive than the renewable scenarios (ISES2035, IRENA2030, and 60BY2035) due to the high operation and maintenance (O&M) costs of input fossil fuels (Figure 5).

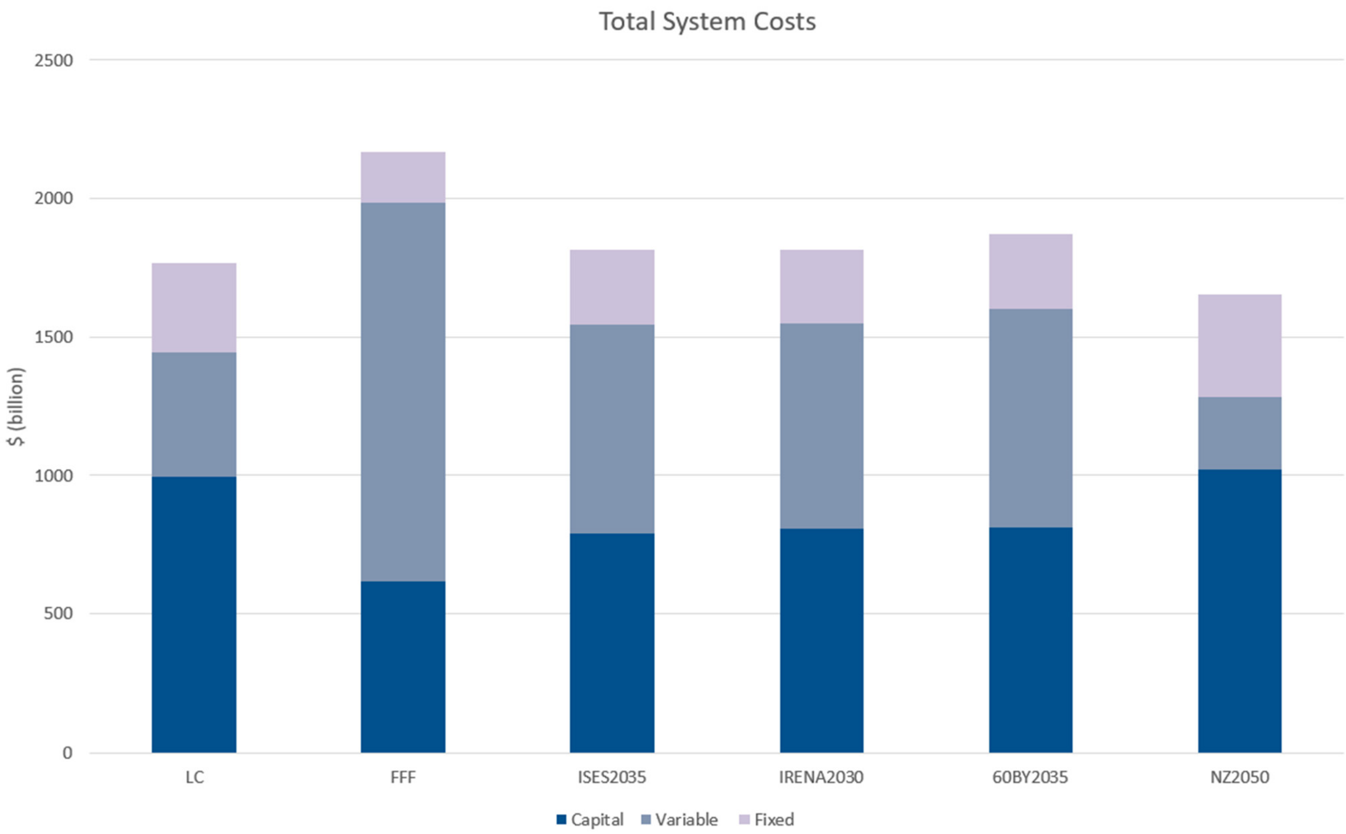

Figure 5. Total system costs (USD) for all six scenarios.

The NZ2050 scenario defines the technologies that are required to decrease CO_2 emissions to zero by 2050 and includes the phase out of natural gas. Despite the scenario's apparently less expensive total system cost (Figure 5), in reality, it would be much more expensive due to the need for energy-efficient technologies, the cost of which is not included in these results. From the NZ2050 and LC scenarios, it can be deduced that solar PV and onshore wind need to dominate Egypt's future renewables landscape and are needed to phase out natural gas (see LC and NZ2050 charts in Figure 3).

4.4. Further Findings from the ISES2035 Scenario Data

The ISES2035 scenario models the government's target of 42% of electricity generation to be sourced from RETs by 2035. The data behind Figure 5 revealed that this will cost USD 121.1 billion by 2035 and will save 7308.8 Mt of CO_2 emissions by 2070 compared to the FFF scenario (Figure A1). In this scenario, solar PV will need to produce the largest amount of electricity compared to other RETs.

The Egyptian government's decision to include coal production (16%) within the ISES2035 target was based on the need to import coal to supply Egypt's cement plants after the political instability of 2011 [42]. The current government, under President El-Sisi, continues to embrace coal imports for use in industrial production, although the COP26 mandate of 'unabated coal power phasedown' may encourage the Egyptian government to revise this target. If the Egyptian government agreed to prevent coal production in the future in line with United Nations Framework Convention on Climate Change (UNFCCC) requirements, this could create certainty for private investment into renewable alternatives [43] and provide environmental and health benefits [42].

4.5. Further Findings from the IRENA2030 and 60BY2035 Scenario Data

An important component of ensuring a clean energy transition is increasing the proportion of electricity generation from RETs. This process is represented in the IRENA2030 and 60BY2035 scenarios. The CO_2 emissions trajectory until 2035 for the six scenarios can be found in Figure 6. Data behind Figures 5 and 6 reveal that the total system costs of the IRENA2030 scenario between 2015 and 2030 is USD 16.4 billion more expensive than the equivalent period for the ISES2035 scenario but saves 110.0 Mt of CO_2 from being emitted over the same time period.

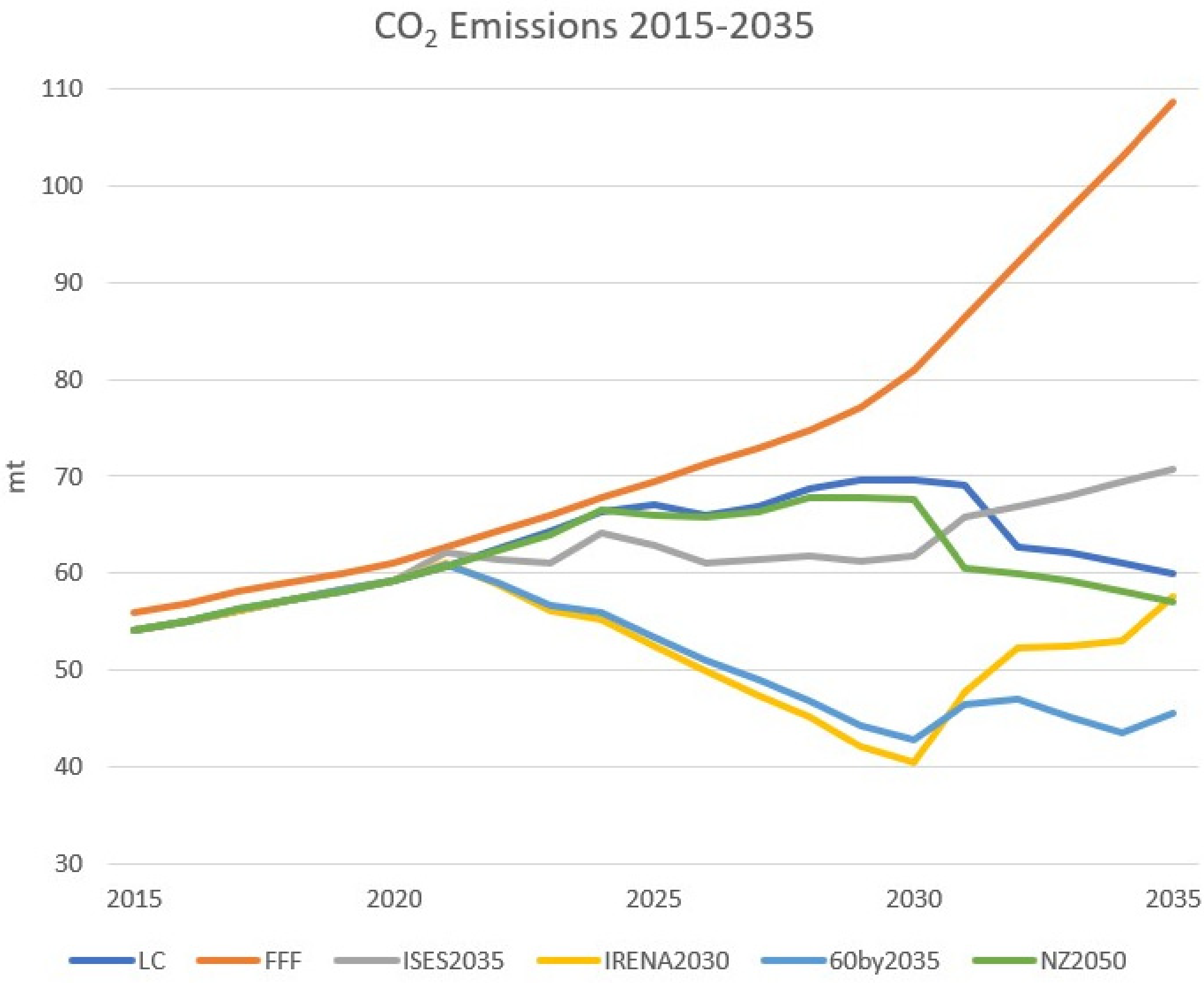

Figure 6. CO_2 emission (Mt) trajectory for the six scenarios between 2015 and 2035.

Although there is a large proportion of electricity production from RETs, the results of the IRENA2030 scenario highlight the importance of continuing to extend renewable energy targets into the second half of the 21st century. Until 2030, natural gas production (CCGT and SCGT) decreases to meet the 53% target; however, it increases between 2030 and 2059, and is then replaced by coal production (Figure 3).

The 60BY2035 scenario represents an increase in IRENA's analysis from 53% to 60% of electricity generation originating from RETs. By 2035, the 60BY2035 scenario will prevent 211.5 Mt of CO_2 emissions compared to the ISES2035 scenario. Overall, the 60BY2035 scenario will cost USD 55.3 billion more than ISES2035 (Figure 5). Despite the CO_2 emission reduction by 2035, between 2015 and 2070, the 60BY2035 scenario produces 180.5 Mt more than ISES2035 and 912.6 Mt more than IRENA2030 (Figure A1). This is due to significant coal production towards the end of the modelling period.

A large component of achieving a CET is reaching net zero CO_2 emissions by a certain year. When reviewing all three renewable scenarios, ISES2035, IRENA2030, and 60BY2035, Egypt's energy system CO_2 emissions in 2050 are 107.3 Mt, 89.8 Mt, and 104.2 Mt, respectively, compared to the NZ2050 scenario reaching 0 Mt by 2050 (Figure A2).

Although the upscaling efforts of RETs for electricity production are apparent, the presence of natural gas prevents the CO_2 emissions from decreasing more significantly. This highlights the importance of phasing out fossil fuel technologies alongside upscaling RETs to successfully achieve a CET.

4.6. Upscaling Renewable Energy Technologies: Private Investment and Bilateral Investment Treaties

Given Egypt's rapid population growth and subsequent increase in energy demand, private-sector investment into new renewable energy projects is critical, along with transforming existing power sector structures and processes [44,45]. The upfront cost of upscaling RETs will rely on private investment as public funding is unlikely to supply more than 15% of the investment needed [46]. The capital upfront costs for the ISES2035 and IRENA2030 scenarios are USD 791.7 billion and USD 806.7 billion, respectively (Figure 5), and these will rely on financing mechanisms within the private sector.

In addition to private-sector investment, RET upscaling could be supported by increasing the number of bilateral investment treaties to guarantee the free transfer of investments [44]. This depends on reliable governance, which is a fundamental necessity to secure both the bilateral and multilateral funding needed to develop large infrastructure projects [47]. The large-scale deployment of renewable energy capacity in Egypt would ensure that more natural gas is available for export (which is more profitable compared to domestic use), enabling domestic demand to be met by a larger percentage of RETs [44].

4.7. Barriers to a Clean Energy Transition in Egypt

Three major barriers may prevent Egypt from achieving a CET: (1) the recent discovery of natural gas reserves in the Mediterranean, (2) political instability that acts to decrease investor confidence, and (3) the need for sufficient climate finance from the international community.

According to the results of this research, natural gas is and will be a reliable source of electricity generation for Egypt. This is unlikely to change in the future due to the commissioning of the Zohr gas field in 2017, which was followed by the larger discovery of the Noor area close to the Cypriot gas fields [48]. These discoveries have helped Egypt to fill the growing domestic supply gap due to a decline in other Mediterranean fields and growing demand [49]. Based on Egypt's recent history of energy supply shortages, these discoveries represent future energy security and economic prosperity, and it is therefore likely Egypt will take advantage of this domestic fossil fuel production.

The second barrier to achieving a CET in Egypt is political instability that impacts investor confidence. Political instability refers to both social–political unrest, such as the 2011 revolution, but also the potential for government regimes to collapse [50]. There is a strong correlation between political instability and negative economic growth, as the uncertainty associated with instability harms macroeconomic variables such as private investment [51]. President El-Sisi has brought relative stability to Egypt, but recent developments such as armed clashes in the Sinai Peninsula and border tensions with Libya and Sudan may derail this stability in the future [51].

The final barrier preventing Egypt from achieving a CET is a lack of sufficient climate finance from the international community under the Paris Agreement, which is emphasised within Egypt's NDC. In 2019, the international community mobilised only USD 79.6 billion of the promised USD 100 billion per year, with the USA, Australia, and Canada not contributing their full share [52]. The funding is broken down into four funds, with the Green Climate Fund (GCF) financing two projects in Egypt: the adaptation programme and the GCF-EBRD Egypt Renewable Energy Financing Framework with total project values of USD 105.2 million and USD 1 billion, respectively [53]. The former aims to protect the vulnerable communities and coastline in the Nile delta, which is among the top three most vulnerable regions in the world to the impacts of climate change [53]. The latter aims to scale up investments to support the development and construction of renewable energy projects and will generate around 1400 GWh electricity annually and avoid 800,000 tCO_2e annually [53]. For more such projects to occur in Egypt, the UNFCCC climate financing process needs to reach its maximum annual capacity.

4.8. Policy Recommendations

The following policy recommendations are based on the scenario results and related discussion:

Short-term:

1. Integrate RETs, particularly onshore wind and solar PV, into the energy system via technical, financial, and regulatory recommendations.
2. To reduce CO_2 emissions sooner, update Egypt's national renewable energy target from 42% by 2035 to 53% by 2030, as recommended by IRENA.
3. To eliminate coal as a future option for Egypt, adopt the COP26 mandate of phasing out coal by introducing an energy-sector ban.

Long-term:

1. Based on environmental and financial analyses, extend national renewable energy targets into the second half of the 21st century to prevent an increase in fossil fuel production.
2. As the quantity of renewable projects increases, expand the grid as required through international bilateral projects or financial assistance from the government.
3. Alongside the extension of renewable targets, identify financial and regulatory mechanisms to phase out natural gas production.

5. Conclusions

This research investigated the impact on Egypt's energy sector of upscaling renewable energy technologies to determine whether a clean energy transition will be possible in the future. Overall, the upfront cost of upscaling RETs in Egypt will be high, but CO_2 emission reduction is needed to contribute to the prevention of global temperatures increasing above 2 °C, and it will be less costly than locking the country into a fossil fuel-dependent pathway. The results showed that solar PV and onshore wind are key technologies to be upscaled to contribute towards Egypt's CET. Furthermore, the results indicate that IRENA's suggestion to expand Egypt's current ISES 2035 renewables target from 42% to 53% by 2030 will cost USD 16.4 billion more between 2015 and 2030, saving 110.0 $MtCO_2$ over the same period. The overall capital investment into RETs (PV, CSP, onshore and offshore wind, and hydro) for the IRENA2030 scenario is USD 23.6 billion more than for ISES2035. The 60% RETs by 2035 scenario would cost USD 56.0 billion more than IRENA's 2030 analysis and emit more CO_2 over the entire modelling period due to the presence of coal production. Therefore, it can be concluded that IRENA's 2030 target of 53% is the optimal renewable generation target for Egypt, based on the scenarios modelled. The success of a CET in Egypt is dependent on reducing domestic natural gas production and preventing coal production in the future. This transition will be difficult due to recent natural gas discoveries in the Mediterranean and the challenge of achieving energy security in a rapidly changing country. This research aimed to highlight the accessibility of long-term energy system modelling using publicly sourced datasets and provided an overview of the carbon emissions and financial impact of introducing more ambitious national policy targets.

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Data Availability Statement: This work follows the U4RIA guidelines which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios, and results (Ubuntu/Community). The authors ensure that all data, source code, and results can be easily found, accessed, downloaded and viewed (retrievability), and licensed for reuse (reusability) and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability); ensuring the transfer of data, assumptions, and results to other projects, analyses, and models (interoperability); and facilitating peer-review through transparency (auditability).

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Appendix A

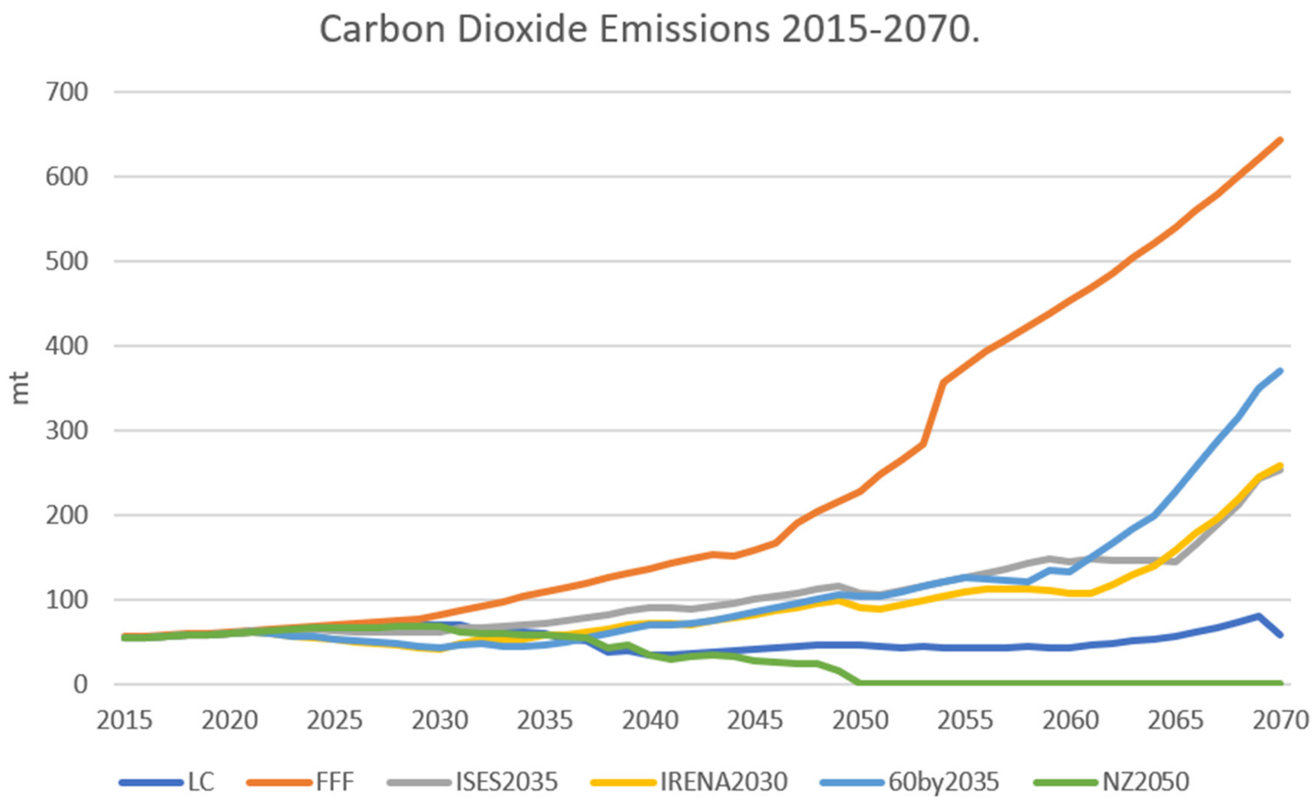

Figure A1. CO_2 emission (Mt) trajectory for the six scenarios between 2015 and 2070.

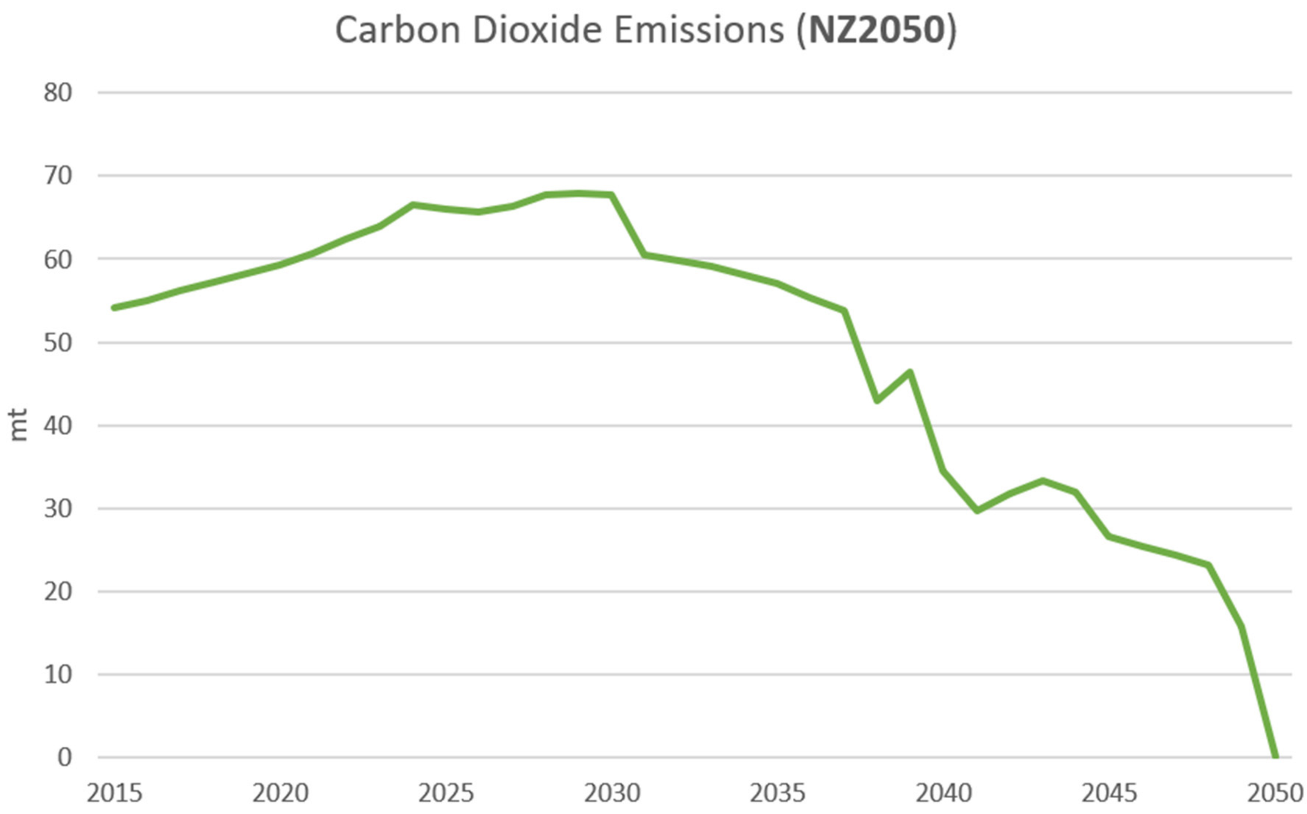

Figure A2. CO_2 emission (Mt) trajectory for the Net Zero by 2050 scenario (2015 to 2050).

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