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Tunisia: Energy Development Plan to Decarbonise the Economy

prepared for Power Shift Africa

By The University of Technology Sydney
Institute for Sustainable Futures

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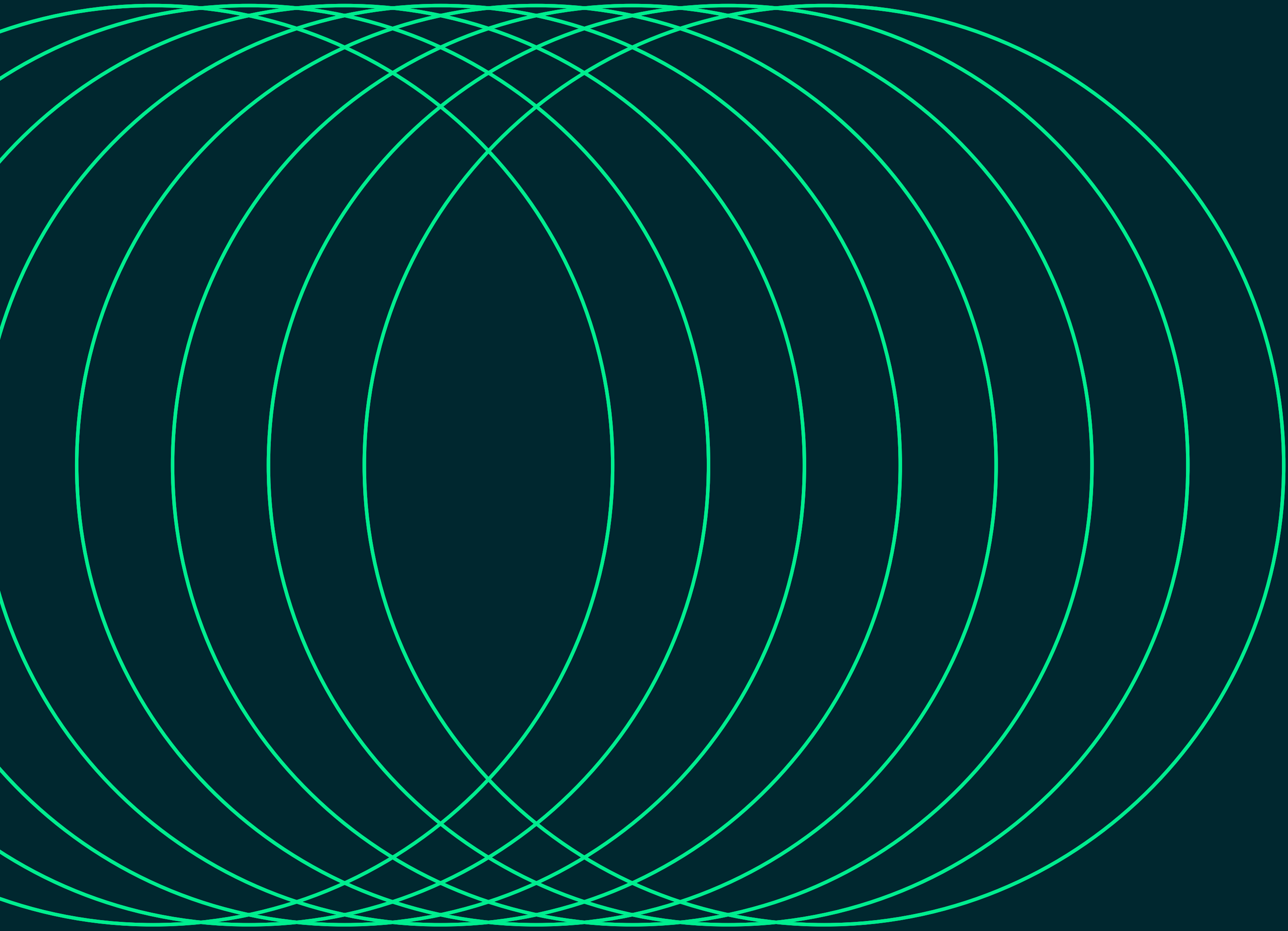

About the authors

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government, and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human well-being, and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

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The energy scenario software – the One Earth Climate Model – for the long-term projections and economic parameters is based on the development of the German Aerospace Centre (DLR), Institute for Technical Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart/ Germany, and has been applied to over 100 energy scenario simulations for global, regional, and national energy analysis.

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All conclusions and any errors that remain are the authors' own.

Disclaimer

The authors have used all due care and skill to ensure the material is accurate as at the date of this report. UTS and the authors do not accept any responsibility for any loss that may arise by anyone relying upon its contents.

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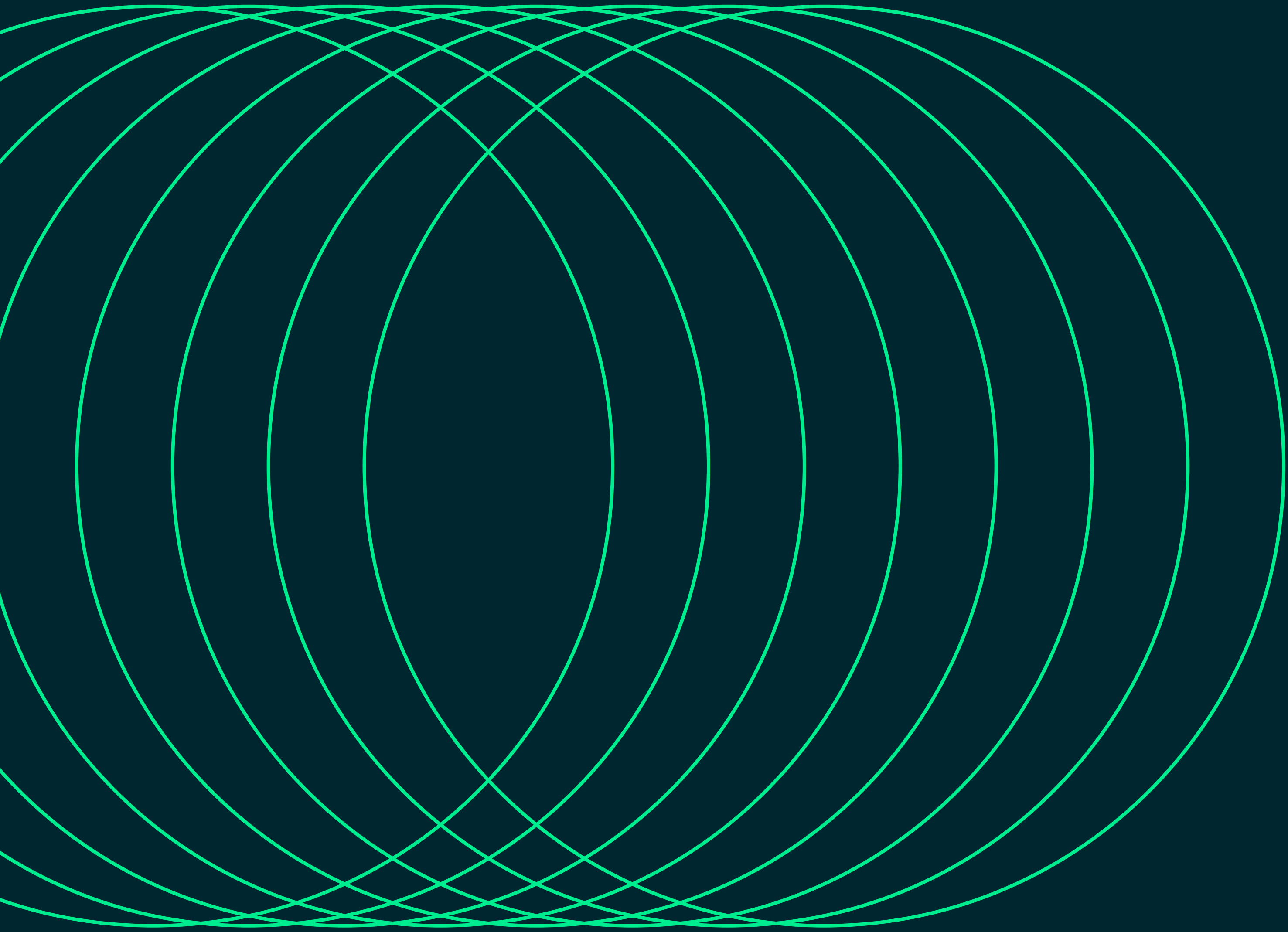
Executive Summary



Since the Revolution in 2011, Tunisia's government has made progress in the right direction regarding their obligations to submit nationally determined contributions (NDCs) and set a net zero emissions target consistent with the goals of the Paris Climate Agreement.

This progress includes the submission of the first NDC in 2015, followed by a strengthened revision of the NDC in 2021, with an accompanying long-term strategy and a net-zero target.[1] The updated NDCs outline a commitment to a 45% reduction in carbon intensity (27% unconditional) by 2030 relative to 2010 levels, and the long-term strategy entitled 'Strategy of Carbon Neutral and Resilient Development to Climate Change at the 2050 Horizon' sets a 2050 target for carbon neutrality.[2] The target established can be viewed as a strong pathway towards decarbonisation, and also the basis for a holistic approach to sustainable development.[3]

The challenges for Tunisia in terms of sustainable development goals and a decarbonisation trajectory aligned with the Paris Agreement is securing a sufficiently high level of political and economic stability across institutions and civil society to allow the NDCs and long-term strategy to be put into action. Despite these challenges, there is cause for hope, particularly given Tunisia's willingness to pursue a strategy of sustainable development. As stated by Alexandre Arrobbio, the World Bank's Country Manager for Tunisia, "there are significant opportunities for Tunisia to transform and strengthen its economy. With strategic investments, particularly in renewable energy, Tunisia could significantly enhance its economic resilience and sustainability."[4] This press release goes on to state that there are "large economic benefits of deepening this transition through an ambitious decarbonisation agenda one of the flagship projects on this agenda is the electricity interconnection between Tunisia and Italy. This project aims to improve the resilience of Tunisia's electricity system and transform it into a net exporter of electricity. This would significantly reduce the country's dependence on costly natural gas imports and improve its balance of payments."[5]

IEA Summary of Recent Energy Policies in Tunisia[6]

Policy Name	Year	Details
Fossil fuels and electricity subsidies	2023	The Tunisian Government ear-marked subsidies for fossil fuels and electricity in 2023. The support is distributed among state-owned energy companies ensuring price regulation.
Tunisian Investment Fund subsidies – Decree 2017-389, Article 3	2017	The Tunisian Investment Fund (FTI) announced subsidies for renewable energy projects. The subsidies aim to promote and attract renewable energy investments in Tunisia, and include a range of policies sub-divided by project costs. One offer is equity contribution by the FTI in enterprises with investment volume of less than 15 million dinar, including working capital and investment expansion.
Renewable Energy Law for Electricity Production (no. G74/2013)	2015	The law seeks to encourage investment in renewable energy and consequently increase the contribution of renewable-energy-derived electricity to 30% (equivalent to 3,800 MW) of the total electricity production by 2030.
A decree on connection and access of renewable electricity to the national grid	2011	The decree sets the conditions for the connection and access of renewable electricity producers to the national grid. It supersedes the previous conditions set in 2007.
Tax exemptions for the import of materials required for the manufacture of renewable-energy- and energy-efficiency-associated equipment	2010	Amendment of the list of the materials and products necessary to manufacture equipment to support energy efficiency or renewable energy supply, which are exempt from VAT or have reduced import duties. The previous list was established in 1995.

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[1] Climate Watch, Tunisia webpage, accessed September 2024: https://www.climatewatchdata.org/countries/TUN?end_year=2021&start_year=1990

[2] ibid.

[3] UNDP Climate Promise, Tunisia webpage, accessed September 2024: https://climatepromise.undp.org/what-we-do/where-we-work/tunisia

[4] ibid.

[5] ibid.

[6] IEA Policy Database, Tunisia webpage, accessed September 2024: https://www.iea.org/policies?country=Tunisia

Tunisia has experienced dynamic and evolving political and economic milieux over the last decade. This document does not evaluate the 2011 Revolution, its consequences, or the current political climate in Tunisia. The authors refer to the political and economic context of Tunisia where relevant, as it relates to the subject matter of the energy transition and the sustainable development ambitions of Tunisia and its people.

It is lamentable that in this time of political friction, Tunisian citizens are faced with a difficult economic outlook, with the decade of attempted democratisation accompanied by slowing economic growth. Gross domestic product (GDP) growth fell from 3.5% between 2000 and 2010 to 1.7% between 2011 and 2019. Moreover, recent negative economic events have challenged the Tunisian economy. COVID-19, higher food and fuel prices, a fall in European demand for Tunisian products, and rising global interest rates have sharply increased the magnitude of the deterioration in the GDP growth rate. This difficult context has affected many of Tunisia's fellow African nations, because the global disruptions caused by the COVID-19 pandemic have been felt across the continent and have only compounded the existing structural constraints in Africa, e.g., slow domestic job creation, high vulnerability to natural disasters, climate change, environmental degradation, and large infrastructural gaps. The pandemic has also recently triggered a surge in debt levels, which must be addressed.

Despite the political and economic challenges, there are still positive indicators of the maturity and level of development of Tunisia, with the nation ranking 14th of 54 African nations in terms of total GDP (US$54 billion). The standing of Tunisia only improves when GDP per capita is considered, because the Tunisian value is much stronger than its sub-Saharan counterparts and those of countries such as Morocco. Tunisia comes in around 10th place, with a GDP per capita of US$3,895 (higher than either Egypt or Morocco). Given this context and the potential of Tunisia's economy to strengthen alongside an agenda of sustainable development, strong economic growth is assumed for the development of the energy scenario.

Electricity consumption was 1,111 kWh/person in 2005, which had grown by 25% in 2020 (reaching 1,389 kWh/person). Although this electricity usage is substantially higher than that of Tunisia's sub-Saharan counterparts, it is still significantly lower than the global average consumption, which exceeds 3,000 kWh/person per annum. The primary energy supply is dominated by oil and gas (around 88% in 2020), which are used across the economy for a variety of end uses, including cooking and heating, as well as for the generation of electricity. Historically, Tunisia's electricity supply has been almost entirely from gas generation, and gas-generated electricity has regularly been > 95% of all electricity consumed between 2005 and 2020. (Of the 16 years in this range, 11 of them had > 95% gas generation).[7] Tunisia's primary energy consumption was 347 PJ/a in 2005 and grew to 440 PJ/a in 2020 (at an average growth rate of 1.19%). If the primary energy supply continues to grow according to the average historical rate, the primary energy demand will reach 628 PJ/a by 2050. However, our 1.5°C-compatible scenario assumes a net reduction of primary energy to around 395 PJ by 2050 – which will only be possible with fuel switching, electrification, and increased appliance efficiency. The following sections provides an overview of the key results of our energy scenarios.

Power Shift Africa and the University of Technology Sydney (UTS) have developed a comprehensive energy pathway for Tunisia that is aligned with the goals of the Paris Climate Agreement.

Development of the electricity demand

To develop a projection for the residential electricity demand in Tunisia over the coming 30 years, to achieve the Tunisia 1.5°C (T-1.5°C) scenario, a bottom-up electricity demand analysis was performed. The T-1.5°C scenario aims to increase the access to energy – especially electricity – for all by 2050, while increasing the electrification and comfort standards to the levels of OECD countries. The growing economy requires a reliable power supply for small and medium businesses, industry, and the transport sector. It is assumed that households will use modern energy-efficient applications, according to the highest efficiency standards, to slow the growth of the power demand and to allow the parallel expansion of the energy infrastructure and the construction of renewable power plants. Electrification will be organised from the 'bottom up' in a new and innovative approach developed by University of Technology Sydney-Institute for Sustainable Futures (UTS-ISF).

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[7] IEA World Energy Balances

It is assumed that households with an annual consumption indicated under the household type to be in 'phase 1' will increase their demand to 'phase 2' or 'phase 3' values over time. There are currently three household types, distinguished by their annual electricity demands: rural households, which have an average annual electricity demand of just under 1250 kWh; semi-rural households, which consume around 1200 kWh per year; and urban households, with an annual consumption of 1700 kWh. (Note: the values for urban households are higher than Tunisia's current average consumption.)

The electricity demand will gradually increase as the electrical applications for each of the three household types progress from households with very basic needs, such as light and mobile phone charging, to a household standard equivalent to that of industrialised countries. The different levels of electrification and the utilisation of appliances are described with the affixes 'phase 1', 'phase 2', and 'phase 3' for rural households. In contrast, semi-urban and urban households are assigned to two groups: one for the basic level of electrification and one for the more-advanced stage. These households will develop over time from the basic group towards the more advanced group.

The third phase of a rural households includes an electric oven, refrigerator, washing machine, air-conditioning, and entertainment technologies, and aims to provide the same level of comfort as households in urban areas in industrialised countries. Adjustments will be made to the levels of comfort in households in city and rural areas to discourage residents – especially young people – from leaving their home regions and moving to big cities. The phase-out of unsustainable biomass liquefied pressurised gas (LPG) and paraffin, for cooking is particularly important in decarbonising Tunisia's household energy supply. A staged transition towards electric cooking is assumed.

Energy for cooking

A 2021 report published by the World Bank Group indicated that 96% of Tunisians use gas as their energy source for primary cooking, whereas only 3% of citizens use electricity as their primary energy source for cooking.[8] The daily and annual energy demands for the three main fuel-based cooking technologies are shown in Table 9. Based on these estimates, a scenario for transitioning from fuel-based cooking to electricity-based cooking (e-cooking) was developed (Table 9).

Fuel-based cooking applications will be gradually phased-out and replaced with electric cooking appliances. The total phase-out of fuel-based systems will be for environmental and economic reasons. Fuel-based cooking requires fuel that generates emissions, and the fuel supply is, in most cases, not sustainable. Burning LPG causes CO_2 emissions, and its production is based on fossil gas, which must be phased-out by 2050 to remain within the global carbon budget to limit the global mean temperature rise to a maximum of +1.5°C. The remaining wood- and bio-energy-based cooking in 2050 will be with sustainable charcoal. Electric cooking can be supplied by renewable energy sources and will be emissions-free. There are some challenges to the introduction of electric cooking stoves:

- Tunisians are used to cooking with gas, given its history and prevalence across society. This can lead to bias in terms of the cooking fuel preferences and scepticism that the results of electric cooking are the same as those of gas cooking.
- Given that households are already connected to the gas network and own gas ovens and stoves, they will incur costs in transitioning from gas cooking to electric.
- Therefore, in relative terms, the initial investment and monthly costs will be high.
- The use of e-cooking is perceived to be expensive.
- There are quality concerns regarding the appliances.

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[8] World Bank Group (Energy Sector Management Assistance Program), 'Primary Household Energy for Cooking and Heating in 52 Developing Economies', 2021

Projection of the transport energy demand

Tunisia's transport sector is significantly dominated by passenger vehicles, with cars accounting for 70% of all registered vehicles. Light duty vehicles (defined as vehicles used for the carriage of goods, with a maximum mass of £3.5 tonnes, e.g., pick-up trucks, vans) account for a further 25% of the vehicle stock.

The total numbers of passenger- and freight-kilometres are the basis for the projection of the future transport demand. The contraction of the transport demand in 2020 due to COVID is expected to end. It is anticipated that the pre-COVID transport demand of 2019 will be reached by 2023 and will then increase with population growth and GDP. It is assumed that the annual passenger-kilometres (pkm) will increase by 3% annually until 2050, whereas the freight transport demand will increase by 2% annually. All assumptions and calculated energy demands are shown in Table 14. The energy intensities for all vehicles are assumed to decrease over time with the implementation of more-efficient engines, the phase-out of fossil-fuel-based drives, and their replacement with electric drives. To achieve the terms of the Paris Climate Agreement, all energy-related CO_2 emissions must be phased-out by 2050. Therefore, all fossil-fuel-based vehicles must be phased-out, and electric drives will dominate, supplemented with a limited number of biofuel-based vehicles.

On average – across all passenger vehicle types – the energy intensity will decrease from 1.88 MJ per pkm to 1.75 MJ in 2030 and to 1.6MJ in 2050. The energy required by freight vehicles to move 1 tonne for 1 kilometre will decrease from around 1.51 MJ to 1.14 MJ by 2030 and to 1.06 MJ by 2050. Both reductions will only be possible with high shares of electric drives. The electrification of large parts of these fleets is unavoidable if the transport sector is to be decarbonised. The supply of – sustainably produced – biofuels will be limited and will be directed to large commercial vehicles, buses, and the large trucks used in remote rural areas, where the required charging infrastructure for electric vehicles is unlikely to be developed in the next two decades.

Tunisia's 'Strategy for Carbon Neutral and Resilient Development to Climate Change' sets a 2050 target for carbon neutrality.[9] In section 4.1.4. Approaches and sectoral variations, the document highlights the need for transportation to be considered part of Tunisia's emission reduction strategy, both in terms of the use of public transport and electrification. "The Tunisian transport sector is energy-intensive and constitutes a significant source of carbon emissions. National carbon neutrality will be able to rely on an objective of decarbonisation of transport. Several solutions are possible, in particular the improvement of performance energy of light and heavy vehicles from here to 2030, then their systematic electrification… Concerning public transport, essential attention must be paid to the needs of travellers in order to give public transport a competitive advantage over individual modes."[10]

Projections of electricity supply: assessment of solar and wind energy potential

The average annual solar irradiation (DNI) level in Tunisia is 1,141–2,262 kWh/m^2/year, and the higher end of that range is in the southern part of the country, particularly the South Dessert region. Tunisia also has large potential onshore wind energy. The wind speeds in Tunisia range from 3 to 15.2 m/s at 100 m height, and high-wind-speed areas are predominantly located in the mid-northern region (Global Wind Atlas). In this analysis, we have included only areas with an average annual wind speed of ≥ 5 m/s. Tunisia's solar and wind potential has been mapped under two different scenarios:

- **Scenario 1:** Available land – excluding protected areas (PA), extreme topography (slope > 30% [mountainous areas], S30), and certain land-cover classes, including closed forests, wetlands, moss and lichen, snow and ice, and water (permanent water bodies) (LU).
- **Scenario 2:** See 1, with the additional restriction that excludes areas ≤ 10 km from existing transmission lines (PT10).

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[9] Tunisia's submission to UNFCCC, Stratégie de Développement Neutre en Carbone et Résilient aux Changements Climatiques à l'horizon 2050', 2022

[10] ibid.

Tunisia is blessed with huge solar and wind energy resources. Scenario 1 provides 139,748 km^2 of areas with solar potential and a total potential for utility-scale solar PV capacity of 3,494 GW. The solar potential under Scenario 2, when the land area is restricted by its proximity to power lines (£ 10 km), decrease to 30,032 km^2, which allows utility-scale solar farms of 751 GW in Tunisia. The available potential for onshore wind is like that of solar in terms of land area, and Scenario 1 provides 132,165 km^2 of area, whereas Scenario 2 provides 26,525 km^2 of potential area. The overall wind potential under all restrictions is 661 GW for Scenario 1 and 133 GW under Scenario 2.

Tunisia's total solar and onshore wind potential far exceeds the projected electricity demand in 2050 – with the full electrification of all households, industry, and the entire transport sector – by an order of magnitude. The potential is so substantial that Tunisia could be considered ideally placed to become an exporter of electricity to neighbouring countries and/or to the European continent via a connection to Italy.

Assumptions for energy scenario development

Tunisia must build up and expand its power generation system to increase the energy access rate to 100%. Building new power plants – no matter the technology – will require new infrastructure (including power grids), spatial planning, a stable policy framework, and access to finance. With lower solar PV and onshore wind prices, renewable power has become an economic alternative to building new hydro and gas power plants. Consequently, renewables achieved a global market share of over 80% of all newly built power plants in 2021. Tunisia has significant solar resources, but moderate to good wind potential. The costs of renewable energy generation are generally lower with stronger solar radiation and stronger wind speeds. However, constantly shifting policy frameworks often lead to high investment risks and higher project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building process for all scenarios includes assumptions about policy stability, the role of future energy utilities, centralised fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Tunisia will establish a secure and stable framework for deploying renewable power generation. Financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement that ensures a relatively stable price for a specific quantity of electricity is required to finance the project. However, daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any power plant with a technical lifetime of 20 years or longer.
- **Strengthened energy efficiency policies:** Existing policy settings – energy efficiency standards for electrical applications, buildings, and vehicles – must be strengthened to maximise the cost-efficient use of renewable energy and to achieve high energy productivity by 2030.
- **Role of future energy utilities:** With 'grid parity' of roof-top solar PV below most current retail tariffs, this modelling assumes that the energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** Projections of population and GDP are based on historical growth rates. Projections of population growth are taken from the World Bank Development Indicators.[11]
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in all calculated scenarios target the firm capacity. Firm capacity is the "proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed."[12] Firm capacity is important to ensure a reliable and secure energy system. Note that variable renewable energy systems still have a firm capacity rating, and the combination of technology options increases the firm capacity of the portfolio of options.

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[11] World Bank (2023) Reviewed on: https://data.worldbank.org/indicator/SP.POP.TOTL

[12] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf

Assumptions for the Tunisia 1.5°C scenario

The Tunisia 1.5°C (T-1.5°C) scenario is built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector. The main assumptions considered in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures taken to meet the CO_2 emissions reductions in the T-1.5°C scenario include strong improvements in energy efficiency, which will double energy productivity over the next 10–15 years, and the dynamic expansion of renewable energy across all sectors.
- **Growth of renewables industry:** The dynamic growth of new capacities for renewable heat and power generation is assumed based on current knowledge of the potential, costs, and recent trends in renewable energy deployment. Communities will play a significant role in the expanded use of renewables, particularly in terms of project development, the inclusion of the local population, and the operation of regional and/or community-owned renewable power projects.
- **Fossil-fuel phase-out:** The operational lifetime of gas power plants is approximately 30 years. Because Tunisia is dominated by gas infrastructure, gas will be phased-out in parallel with renewable development (renewable development is slower in the REFERENCE scenario). In the T-1.5°C scenario, gas plants may be phased-out before the end of their operational lifetime.
- **Future power supply:** Solar PV and onshore and offshore wind power are expected to be the main pillars of the future power supply, complemented by minor contributions from bioenergy. The figures for solar PV combine those for both roof-top and utility-scale PV plants. Because Tunisia has high-quality solar and wind resources, it is envisioned that – with sufficient diversity of resources spread across geographic locations and some offshore wind projects, which offer a more consistent wind resource – Tunisia will be able to transition towards a 100% renewable supply powered predominantly by variable power sources. The capacity for large hydro power remains relatively flat in Tunisia over the entire scenario period.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. Power generation from biomass and gas-fired backup capacities and storage are considered important for the security of supply in a future energy system, and are related to the output of firm capacity, discussed above. Storage technologies will increase after 2030, including battery electric systems, dispatchable hydro power, and hydro pump storage.
- **Electrification of transport:** Efficiency savings in the transport sector will result from fleet penetration by new, highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The scenarios assume the limited use of biofuels for transportation, given the limited supply of sustainable biofuels.
- **Hydrogen and synthetic fuels:** Hydrogen and synthetic fuels generated by electrolysis using renewable electricity will be introduced as a third renewable fuel in the transport sector, complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses. However, the limited potential of biofuels, and probably battery storage, for electric mobility, means it will be necessary to have a third renewable option in the transport sector. Alternatively, this renewable hydrogen could be converted into synthetic methane or liquid fuels, depending on the economic benefits (storage costs versus additional losses) and the technological and market development in the transport sector (combustion engines versus fuel cells). Because Tunisia's hydrogen generation potential is limited, it is assumed that hydrogen and synthetic fuels will be imported. Furthermore, hydrogen utilisation will be limited to the industry sector, and is not expected to contribute more than 5% of industry's energy supply by 2050.

Tunisia's 1.5°C scenario (T-1.5°C) takes an ambitious approach to transforming Tunisia's entire energy system to an accelerated new renewable energy supply. However, under the T-1.5°C scenario, a much faster introduction of new technologies will lead to the complete decarbonisation of energy for stationary energy (electricity), heating (including process heat for industry), and transportation. In the transport sector, there will be a strong role for storage technologies, such as batteries (road), synthetic fuels (aviation), and hydrogen (shipping).

Assumptions for the Tunisia reference scenario

The REFERENCE scenario for Tunisia has been developed based on the Tunisia T-1.5°C scenario, but assumes an implementation delay in the order of 10–15 years. The REFERENCE scenario can be interpreted as a business-as-usual (BAU) scenario, consistent with some of the existing policies and targets outlined in Tunisia's NDC submission from 2021. For example, in the REFERENCE scenario, the total renewable capacity will reach 3.3 GW rather than the target of 3.8 GW by 2050, reflecting a transition towards renewables while maintaining much of the existing gas supply.

The key differences between the REFERENCE and T-15 °C scenarios are:

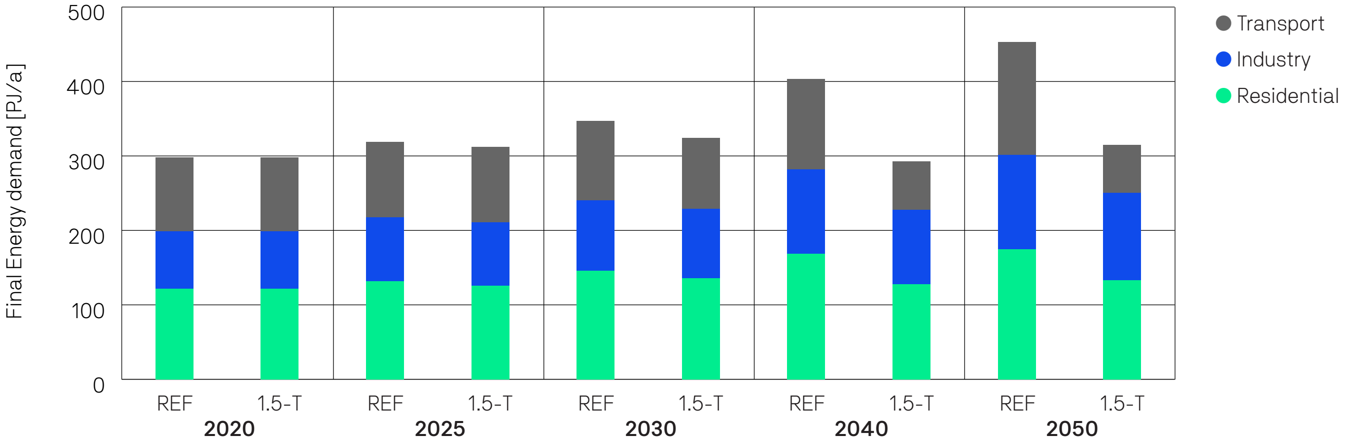
1. **Heating sector:** In the REFERENCE scenario, the phase-out of oil and gas is delayed by 15 years for the residential, service, and industry sectors. Accordingly, electric heat pumps and solar collector systems will remain niche technologies until 2040 but will grow thereafter and increase their shares by 2050.
2. **Transport sector:** In the REFERENCE scenario, electric mobility will experience significant delays, whereas transport demand will increase as projected in the T-1.5°C scenario. Vehicles with internal combustion engines (ICEs) will remain dominant until 2040. Market shares for electric vehicles will start to grow significantly from 2040 onwards, and biofuels will increase in the road transport sector.
3. **Power supply:** In the REFERENCE scenario, the delayed electrification of the heating and transport sectors will lead to slower growth of the power demand than under the T-1.5°C scenario. In addition to the slower growth in demand, it is assumed that renewable power generation will not increase at the same rate as under the T-1.5°C scenario. In the REFERENCE scenario, the total renewable capacity will reach (2050) 3.3 GW rather than the target of 3.8 GW, reflecting a transition towards renewables while maintaining much of the existing gas supply. Therefore, fossil-fuel-based power generation will be notably higher than under the T-1.5°C scenario.

Tunisia – final energy demand

The projections for population development, GDP growth, and energy intensity are combined to project the future development pathways for Tunisia's final energy demand. As a result of the projected continued annual GDP growth of 2.4% on average until 2025 and 2.8% thereafter until 2050, the overall energy demand is expected to grow under both scenarios. Although the residential sector will experience slower growth than the industry sector across both scenarios, the residential and other sectors will remain dominant in energy demand. The energy demand of the industry sector will increase continuously under both scenarios, by around 50% by 2050, making this sector the second highest consumer after transport under both scenarios. The energy demand of the transport sector will increase by 60% by 2050 under the REFERENCE scenario, whereas it will decrease to 68% of the 2020 value under the T-1.5°C scenario. The main reason for the significant difference in growth projections is the high rates of electrification in the T-1.5°C pathway.

The large efficiency gains achieved in the T-1.5°C scenario are attributable to the high electrification rates, mainly in the cooking and transport sectors, because combustion processes with high losses will be significantly reduced.

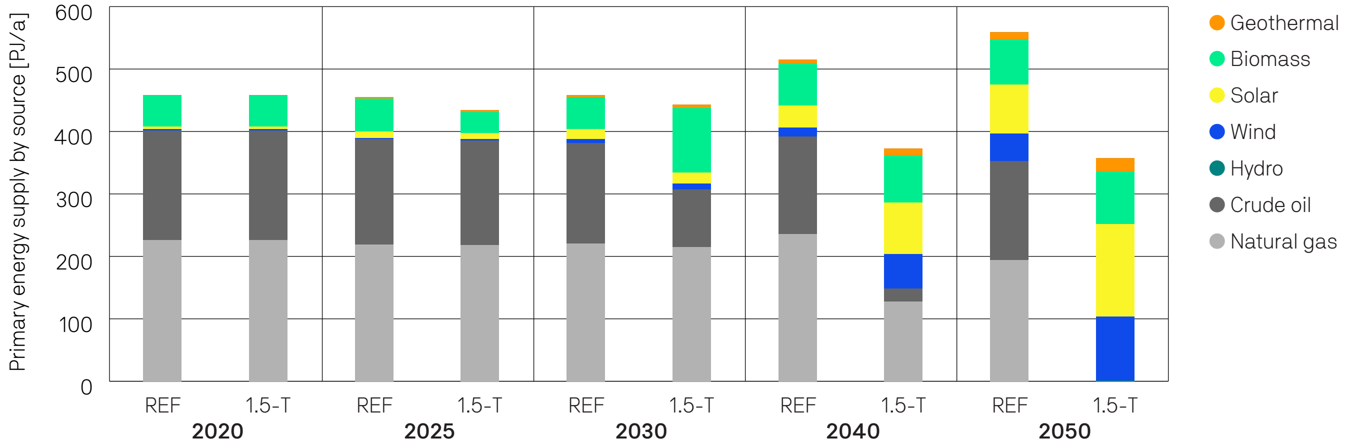
Figure E1. Projection of the total final energy demand by sector (excluding non-energy use and heat from combined heat and power [CHP]



Primary energy consumption

The T-1.5°C scenario will result in primary energy consumption of around 395 PJ in 2050. The T-1.5°C scenario aims to phase-out oil in the transport sector and oil for industrial use as fast as is technically and economically possible, through the expansion of renewable energies. The fast introduction of very efficient vehicle concepts in the road transport sector will replace oil-based combustion engines. Therefore, when non-energy consumption is excluded, the T-1.5°C scenario aims for a renewable primary energy share of 100% in 2050 (92% when non-energy consumption is included).

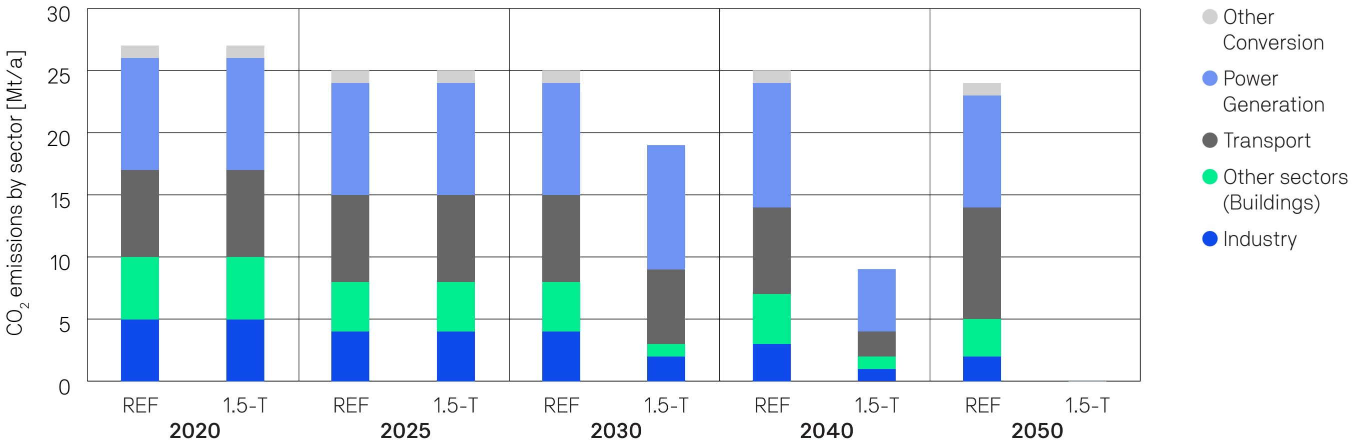
Figure E2. Projection of total primary energy demand by energy carrier (including electricity import balance)



CO_2 emissions trajectories

The T-1.5°C scenario will reverse the trend of increasing energy-related CO_2 emissions from 2025, leading to a reduction of 27% by 2030 relative to 2020 – which is the same of order of magnitude specified by the unconditional emission reduction target of 27% relative to the 2010 emissions levels. (The T-1.5°C scenario represents 22% emissions reduction relative to the 2010 baseline used). The target of the T-1.5°C scenario increases substantially, and by 2040, reaches an emissions reduction of 66% relative to 2020 (64% relative to 2010). In 2050, full decarbonisation of Tunisia's energy sector will be achieved under the T-1.5°C scenario.

Figure E3. Development of CO_2 emissions by sector



Cost analysis

Finally, the fuel costs for the power, heating, and transport sectors are presented. All three sectors will reduce their fuel costs over time because electricity generation will be based on renewables – with significant shares of solar and wind power.

However, increased electrification will lead to higher investment costs in power generation and higher overall electricity supply costs for Tunisia. The T-1.5°C scenario requires an investment of 110 billion Tunisian dinar (trillion TND US$36 billion) in power generation and 129 billion TND (US$42 billion) in heat generation. The total investment in power and heat generation capacities therefore adds up to 239 billion trillion TND (US$78 billion).

Additional power generation investments will be compensated by fuel cost savings in the decade in which they are made. Across the entire scenario period, fuel cost savings under the T-1.5°C scenario relative to the REFERENCE scenario will be 170 billion TND (US$56 billion) – about 4 times higher than the additional investment in power generation capacities until 2050. Although fuel cost predictions are subject to a great deal of uncertainty, this result makes the cost-effectiveness of electrification very clear.

Accumulated fuel costs for heat generation under the REFERENCE and T-1.5°C scenarios in billion US$ and trillion TND

		2020–2030		2031–2040		2041–2050		2020–2050		2020–2050 average per year	
REFERENCE		[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD
Power	Total	56.9	18.8	56.9	18.8	53.1	17.5	166.8	55.1	5.6	1.8
Heat	Total	55.9	18.5	56.8	18.8	47.6	15.7	160.4	52.9	5.3	1.8
Transport	Total	90.4	29.8	99.2	32.7	90.0	29.7	279.5	92.2	9.3	3.1
Summed Costs		**203.2**	**67.0**	**212.9**	**70.3**	**190.7**	**62.9**	**606.7**	**200.2**	**20.2**	**6.7**
		2020–2030		**2031–2040**		**2041–2050**		**2020–2050**		**2020–2050 average per year**	
T-1.5 °C		[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD
Power	Total	50.3	16.6	50.3	16.6	24.4	8.1	125.0	41.2	4.2	1.4
Heat	Total	54.4	17.9	46.5	15.4	28.3	9.4	129.3	42.7	4.3	1.4
Transport	Total	89.2	29.4	69.3	22.9	23.4	7.7	181.8	60.0	6.1	2.0
Summed Costs		**193.8**	**64.0**	**166.1**	**54.8**	**76.1**	**25.1**	**436.1**	**143.9**	**14.5**	**4.8**
Difference REFERENCE versus T-1.5°C		**9.3**	**3.1**	**46.8**	**15.4**	**114.5**	**37.8**	**170.6**	**56.3**	**5.7**	**1.9**

Power sector analysis

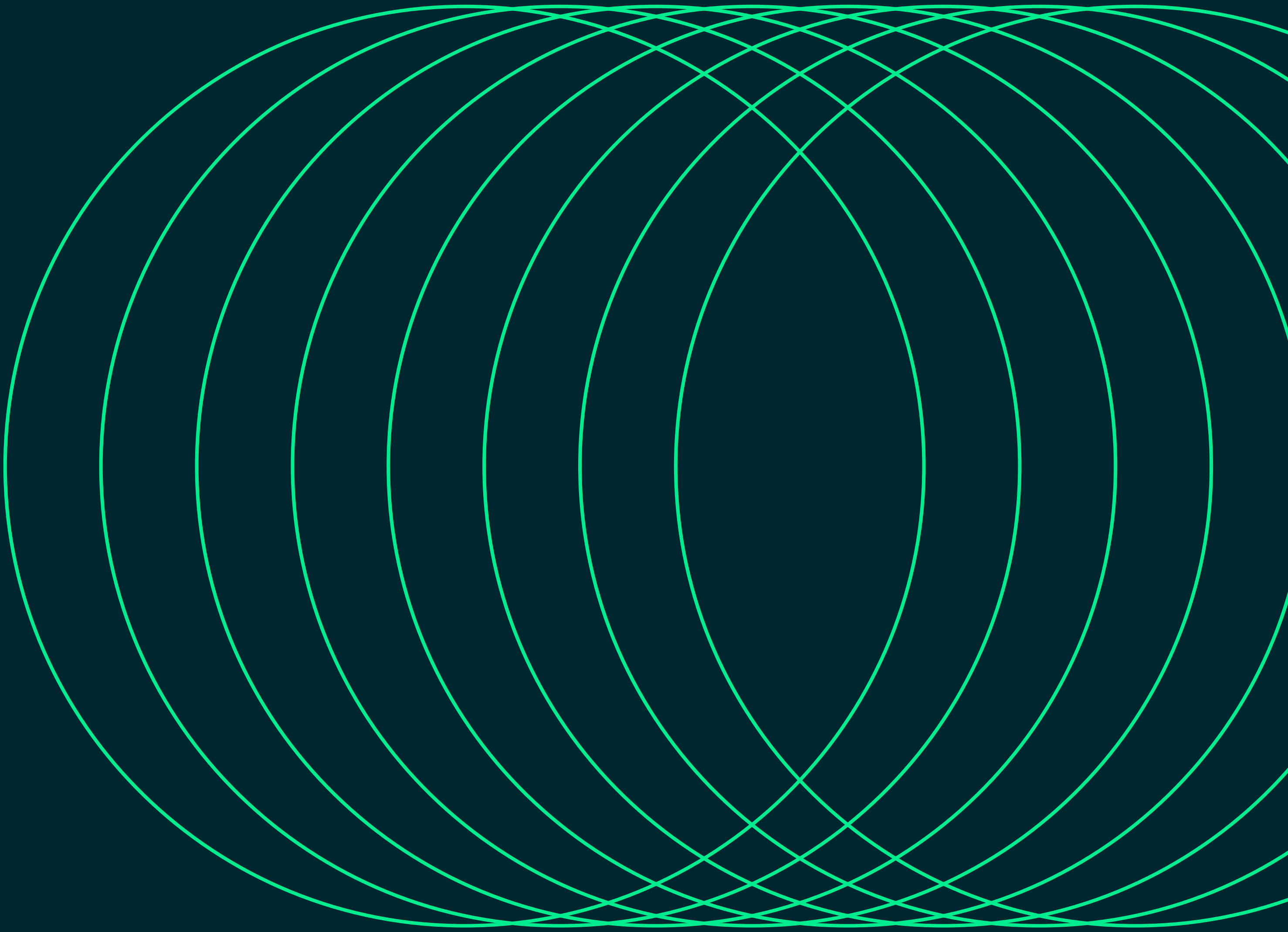
In a last step, after the assessment of the solar and wind potential and the projection of the future electricity demand for households, industry, and the transport sector, the power sector is analysed. The electricity demand projections and resulting load curves are calculated as important factors, especially for power supply concepts with high shares of variable renewable power generation. Furthermore, the calculation of the required dispatch and storage capacities is vital in developing energy electricity supply concepts that lead to high security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, allowed a detailed forecast of the demand. The energy sector analysis was conducted for Tunisia's projected electricity demand and supply for 2030 and 2050 under the T-1.5°C pathway.

Conclusion

We found that Tunisia can cost-effectively build a reliable electricity supply based on local power generation, with high proportions of solar and wind power. With an onshore wind potential greater than 30 times the projected 2050 demand and a solar potential greater than 100 times that demand, Tunisia has exceptional renewable energy potential. The power sector analysis undertaken in this study demonstrates that Tunisia can cover its future electricity needs, and allow renewable electricity to be exported to neighbouring countries. The excess generation may also be utilised for the generation of clean fuels and chemical feedstock. Ensuring that the load centre of Greater Tunis has sufficient interconnection to neighbouring regions will allow Tunisia a higher degree of self-sufficiency in using its renewable resources. In terms of exports, sufficient transmission to neighbouring countries (via existing interconnections to Algeria and Libya) and the establishment of new interconnections to Italy will provide a significant economic benefit to Tunisia through the sale of excess electricity generated during periods in which domestic demand is already covered by local renewable generation.

1

Introduction



This report focuses on the development of a 100% renewable energy pathway for Tunisia. Here, the 100% renewable energy scenarios is constructed to be robust and technically and financially feasible. Moreover, the 100% renewable energy pathways will be a clear demonstration of the security of supply for Tunisia's industry, transport, and residential sectors.

The scenarios for the energy pathways do not claim to predict the future, but provide useful tools with which to describe and compare potential development pathways from the broad range of possible 'futures.' The Tunisia 1.5°C (T-1.5°C) scenario is designed to calculate the efforts and actions required to achieve the ambitious objective of a 100% renewable energy system and to illustrate the options available to change Tunisia's energy supply system into a truly sustainable one. It may also be used as a reliable basis for further analysis of the possible ideas and actions required to implement pathways to achieve the desired results.

100% renewable energy scenarios for electricity generation, energy demand, energy supply, and transport are included. The investments required to achieve these scenarios and the policies that will enable them are described for the specific scenarios.

Finally, the report includes simulations of the national grid capacity required now and, in the future, and the necessary linkages between different parts of the country's power grid. The simulations support the assessment of the grid expansion requirements, the power-trade balance, and the investments required to strengthen the backbone of Tunisia's electricity infrastructure to ensure its reliability and resilience.

In this report, we aim to inform policymakers, researchers, and practitioners of the extent of the interventions required for Tunisia to reach its target of 100% renewable energy by 2050. The decade-by-decade scenarios can inform important milestones that will allow further sector-wise energy-related targets to be defined and tracked.

1.1 Research Scope

Since 2017, the University of Technology Sydney Institute for Sustainable Future (UTS-ISF) has undertaken detailed country-specific energy analyses (see reference list) ranging from the global south, including Tunisia, to industrialised countries, including all the G20 countries and Switzerland.

All UTS-ISF energy analyses include the following components:

- A renewable energy resource analysis based on spatial GIS data under constrained land availability conditions (excluding protected areas, areas with a steep slope, and certain land-cover classes, such as closed forests, wetlands, snow and ice, and permanent water).
- The development of future energy demands for 2025, 2030, 2035, 2040, 2045, and 2050, based on the latest available statistics – the base year for energy demand is 2019 – broken down into the main energy sectors (power, buildings, industry, and transport).
- The sectoral energy demands (see above) are broken down to the level of provinces.
- The development of the following scenarios:
  - 1.5°C scenario[13] – 100% renewable energy plan to decarbonise the energy sector by 2050 within the global carbon budget required to achieve a temperature rise of 1.5°C with 66% certainty (based on IPCC AR6 2021).
  - Compared with a REFERENCE scenario.
- These scenarios are combined with renewable energy scenarios with different shares of variable power generation (solar photovoltaic [PV], wind, bioenergy, and hydro power).
- Based on the different power demand-and-supply scenarios, a projection of the required loads from industry, and commercial and residential demands are compared with the available power generation capacity – to stress-test the security of supply.
- The power generation capacity is simulated at 1-hourly resolution for seven provinces with regional long-term average meteorological data for solar and onshore wind.
- The current and future required national grid capacities are simulated, together with the required linkages between different parts of the country's national power grid and import/export transactions with neighbouring countries.

This simulation is particularly important in terms of the role of 24/7 power generation and the power flows between regions and neighbouring countries. Included are the:

- Grid expansion and storage requirements;
- Visualisation of the hourly demand and supply curves;
- Carbon emissions (annual and cumulative);
- Investment required in additional power generation capacity – including fuel costs and fuel cost savings, and operation and maintenance costs for all power generation capacities;
- The power sector trade balance (electricity and fuel) with neighbouring countries;
- A cost comparison of all scenarios.

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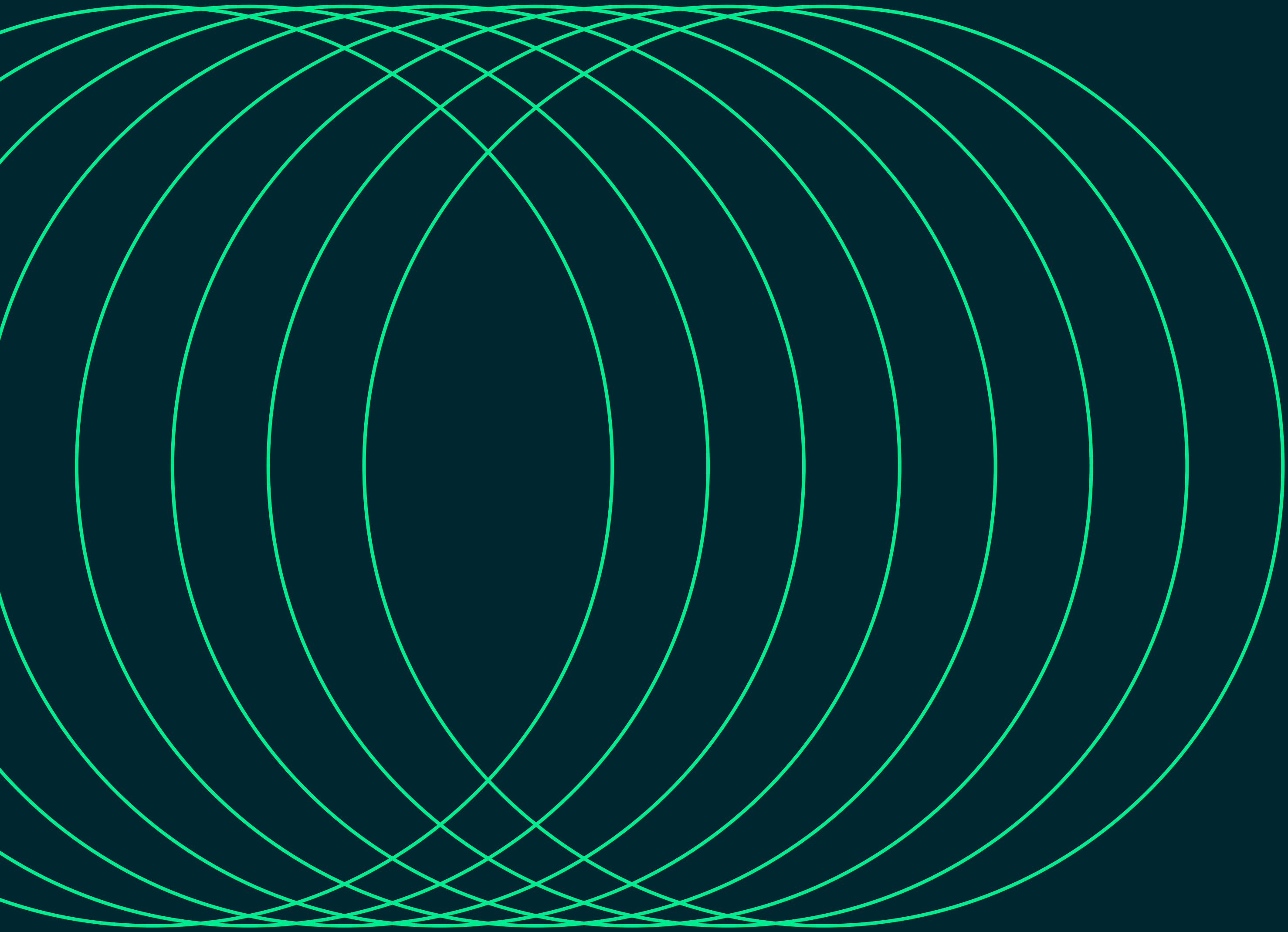
[13] 1.5°C scenario: Series of scenarios with total global carbon budget of 400 $GtCO_2$ to limit the global mean temperature rise to a maximum of 1.5°C with 67% likelihood, as defined in IPCC AR6.

2 Scenario Assumptions



2.1 Tunisia: Country overview

Tunisia is situated in Northern Africa, bordering the Mediterranean Sea, between Algeria and Libya. Tunisia's borders narrow in the southernmost section of the country as they reach further into the Sahara Desert due to the geographic boundaries of Algeria and Libya in the Saharan area. The official language is Arabic, and most citizens speak a Tunisian Arabic dialect, whereas modern standard Arabic is taught in schools. Although the Arabic language is used throughout the country in both conversational and commercial settings, French still plays a large role as a language spoken throughout the nation, particularly in the world of business, given the colonial history of France in Tunisian territory. Tunisia became a protectorate of France by treaty, from 1881 to 1956. It should also be noted that 1.4% of the Tunisian population are of Amazigh (Berber) ethnicity (mostly residing in the southern parts of the country), and that in these tribes, Tamazight languages are also spoken.[14] Although French is not an official language of Tunisia, it was estimated in 2007 that approximately 64% of the population spoke French.[15]

It is lamentable that in this time of political friction, Tunisian citizens are facing a difficult economic outlook, with the decade of attempted democratisation accompanied by slowing economic growth. "GDP growth fell from 3.5% between 2000 and 2010 to 1.7% between 2011 and 2019".[16] Moreover, there have been recent negative economic events that have challenged the Tunisian economy. "COVID-19, higher food and fuel prices, a fall in European demand for Tunisian products, and rising global interest rates sharply increased the magnitude of the deterioration" in the GDP growth rate.[17]

Despite these political and economic challenges, there are still positive indicators of Tunisia's maturity and level of development, and the nation ranks 14th of 54 African nations in terms of total GDP (US$54 billion).[18] The standing of Tunisia only improves when GDP per capita is considered, because the nation has a much stronger GDP than its sub-Saharan counterparts and countries such as Morocco. Tunisia comes in around 10th place, with a GDP per capita of US$3,895, higher than either Egypt or Morocco.[19]

The socio-economic assumptions, all data related to the energy demand and supply and GHG emissions, and statistical data that have been used for the development of the energy scenarios are from publicly available databases.

2.1.1 Climate and Energy Policy Context

Since the Revolution in 2011, Tunisia's government has made progress in the right direction in terms of their obligations to submit National Determined Contributions (NDCs) and set a net zero greenhouse gas (GHG) emissions target. This progress includes the submission of a first NDC in 2015, followed by a strengthened revision of the NDC in 2021, with an accompanying long-term strategy and a net-zero target.[20] The updated NDCs outline a commitment to a 45% reduction in carbon intensity (27% unconditional) by 2030 relative to 2010 levels, and the long-term strategy entitled 'Strategy of Carbon Neutral and Resilient Development to Climate Change at the 2050 Horizon' sets a 2050 target for carbon neutrality.[21] Given that "the revised NDC includes all sources of emissions and adopts a cross-sectoral approach for adaptation that covers the most vulnerable sectors for a more inclusive and sustainable development", the targets set out in the NDC submissions can be viewed not only as defining strong pathways toward decarbonisation, but as the basis for a holistic approach to sustainable development and adaptation.[22] Therefore, the challenge for Tunisia in meeting its sustainable development goals and a decarbonisation trajectory consistent with the Paris Agreement is securing a sufficiently high level of political and economic stability across institutions and civil society to allow the NDCs and long-term strategy to be put into action.

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[14] Encyclopedia Britannica, Tunisia Webpage, accessed September 2024: https://www.britannica.com/place/Tunisia

[15] Permanent Committee on Geographical Names, UK Government, Tunisia Toponymic Fact File, 2016

[16] Carnegie Endowment for International Peace, Why Tunisia Lost Faith in Democracy, accessed September 2024.

[17] Carnegie Endowment for International Peace, The Buildup to a Crisis: Current Tensions and Future Scenarios for Tunisia, accessed September 2024. https://carnegieendowment.org/research/2024/01/the-buildup-to-a-crisis-current-tensions-and-future-scenarios-for-tunisia?lang=en&center=middle-east

[18] Visual Capitalist, Breaking Down the $3 Trillion African Economy by Country, accessed September 2024: https://www.visualcapitalist.com/breaking-down-african-economy-by-country/

[19] World Bank group, GDP Per Capita (Current USD), accessed September 2024: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2023&locations=A9-TN-EG-MA

[20] Climate Watch, Tunisia webpage, accessed September 2024: https://www.climatewatchdata.org/countries/TUN?end_year=2021&start_year=1990

[21] ibid.

[22] UNDP Climate Promise, Tunisia webpage, accessed September 2024: https://climatepromise.undp.org/what-we-do/where-we-work/tunisia

Tunisia emits 0.08% of global emissions[23], but this does not mean climate change mitigation should not be prioritised across the nation. The World Bank Group identified a range of climate vulnerabilities facing Tunisia, which can be tackled with both adaptation and mitigation measures.

> *“The country’s location makes it one of the most exposed to climate change in the Mediterranean region, with temperature increases expected to be accompanied by reduced and more variable precipitation; a rising sea level with saltwater intrusion; an increase in forest fires; and escalating extreme weather in the form of floods and droughts. These climate-linked effects will deplete natural resources, exacerbate water scarcity, and drive losses of agriculture and coastal infrastructure. Some of these effects are already taking a toll. Four years of drought conditions culminated in a significant drop in Tunisia’s agricultural production in 2022/23.”*[24]

Given this context of vulnerability to climate change, both mitigation and adaptation strategies should be advanced for the benefit of Tunisia and its citizens. Tunisia’s NDC sets out a positive path for increased food security and the resilience of the water supply, and the decarbonisation efforts described in the NDCs offer important national benefits for citizens in terms of access to energy and electricity. Renewable energy technologies provide the currently most affordable sources of power, from both a household perspective and a project or capital cost perspective. Therefore, installing clean sources of energy will increase the reliability of the power supply, ensuring that affordable power is supplied to households with increasing access to electricity and the electrification of end uses (thus increasing demand). Installing wind and solar generation will also help Tunisia reduce its exposure to international price increases for imported fossil fuel, helping both the budgets of households and the government as a whole. It would alleviate Tunisia’s trade imbalance and borrowing, ultimately reducing its current account deficit.[25]

The IEA provides a summary of recent policy measures adopted by Tunisia that support the ambitions set out in the NDC and the long-term strategy.

Table 2: IEA Summary of Recent Energy Policies in Tunisia[26]

Policy Name	Year	Details
Fossil fuels and electricity subsidies	2023	The Tunisian government ear-marked subsidies for fossil fuels and electricity in 2023. The support is distributed to state-owned energy companies ensuring price regulation.
Tunisian Investment Fund subsidies – Decree 2017-389, Article 3	2017	Tunisian Investment fund (FTI) announced subsidies for renewable energy projects. The subsidies aim to promote and attract renewable energy investment in Tunisia, and include a range of policies subdivided by project costs. One offer is equity contribution by the FTI in enterprises with investment volumes of < 15 million dinar, including working capital and investment expansion.
Renewable Energy Law for Electricity Production (no. 74/2013)	2015	The law encourages investment in renewable energy, and consequently increasing the contribution of renewable energy electricity to 30% (equivalent to 3,800 MW) of total electricity production by 2030.
Decree on connection and access of renewable electricity to the national grid	2011	The decree sets the conditions for the connection and access of renewable electricity producers to the national grid. It supersedes the previous conditions set in 2007.
Tax exemptions for the import of renewable-energy-associated and energy-efficiency equipment	2010	Amendment of the list of the materials and products necessary for the manufacture of energy-efficient or renewable-energy-associated equipment that are exempt from VAT or have reduced import duties. The previous list was established in 1995.

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[23] Ibid.

[24] World Bank Group Tunisia – Country, Climate, And Development Report, 2023

[25] ibid.

[26] IEA Policy Database, Tunisia webpage, accessed September 2024: https://www.iea.org/policies?country=Tunisia

2.1.2 Population development

Table 3: Overview – eight modelling regions of Tunisia. Source: Tunisia National Statistical Institute[27]

Scenario Region	Modelling Region	Governorates	Population [2021]	Area [km^2]	Population Density [persons/km^2]
1	Greater Tunis	Ben Arous	715,490	720	993
		L'Ariana	667,354	500	1,334
		La Manouba	423,111	995	425
		Tunis	1,075,020	376	2,859
	Greater Tunis		**2,880,975**	**2,591**	**1,403** (av.)
2	North-eastern	Biserte	597,490	3,636	164
		Nabeul	866,838	2,820	307
		Zaghouan	190,127	2,890	66
	North-eastern		**1,654,455**	**9,346**	**179** (av.)
3	North-western	Béja	308,148	3,555	87
		Jendouba	404,738	3,037	133
		Le Kef	247,289	5,091	49
		Siliana	228,691	4,696	49
	North-western		**1,188,866**	**16,379**	**80** (av.)
4	Central Coastal	Mahdia	445,704	2,927	152
		Monastir	606,401	972	624
		Sfax	1,022,900	7,322	140
		Sousse	747,887	2,447	306
	Central Coastal		**2,822,892**	**13,668**	**306** (av.)
5	Central Western	Kairouan	599,560	6,849	88
		Kasserine	463,497	8,053	58
		Sidi Bouzid	457,537	7,354	62
	Central Western		**1,520,594**	**22,256**	**69** (av.)
6	South-western	Gafsa	354,169	7,472	47
		Tozeur	115,675	6,226	19
	South-western		**469,844**	**13,698**	**33** (av.)
7	South Coastal	Gabès	404,829	7,365	55
		Médenine	519,074	8,402	62
	South Coastal		**923,903**	**15,767**	**59** (av.)
8	South Dessert	Kébili	170,450	21,889	8
		Tataouine	151,750	39,443	4
	Southern Dessert		**322,200**	**61,332**	**6** (av.)

Source: Tunisia National Statistical Institute (Statistiques Tunisie) (2021)

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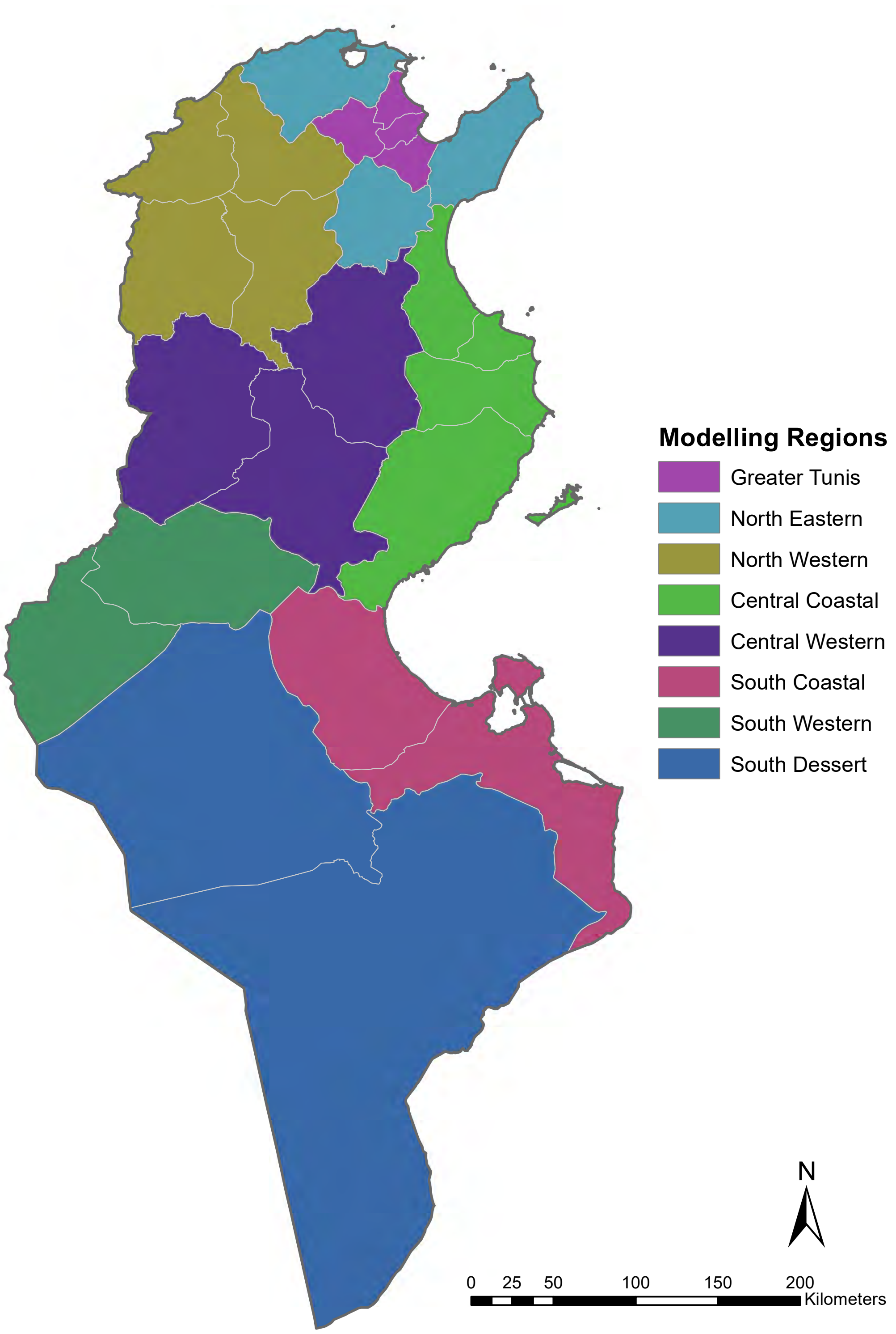
[27] Statistiques Tunisie: https://www.ins.tn/en/statistiques/111

Figure 1: Tunisia – Modelling Regions



Source: generated by ISF from World Administrative Divisions[28]

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[28] World Administrative Divisions, https://hub.arcgis.com/datasets/esri::world-administrative-divisions/explore

2.1.3 Economic Context

As discussed above in section 2.1, Tunisia experienced economic difficulties both before and after the Revolution in 2011. The post-revolution period was marked by the further exacerbation of the economic issues facing Tunisian citizens, with decade of attempted democratisation accompanied by slowing economic growth. GDP growth fell from 3.5% between 2000 and 2010 to 1.7% between 2011 and 2019.[29] Moreover, recent negative economic events have challenged the Tunisian economy. COVID-19, higher food and fuel prices, a fall in European demand for Tunisian products, and rising global interest rates sharply increased the magnitude of the deterioration in the GDP growth rate.[30]

Tunisia's rapid growth of public debt, increasing from 40.7% of GDP in 2010 to 79.8% in 2022.[31] In this context, a recent press release by the World Bank Group confirmed that "Tunisia's economic recovery slowed in 2023, due to a severe drought, tight financing conditions, and a modest pace of reform, leaving the country's growth below pre-COVID levels, and making it one of the slowest recoveries in the Middle East and North Africa region."[32]

Despite these challenging conditions, there is some cause for hope, particularly given Tunisia's willingness to advance a strategy of sustainable development.

Population and economic development projections until 2050

The population and GDP shown in Table 4are based on projections of the Tunisian Government, which have been used for the NDC and the long-term energy plan.

Table 4: Tunisia's population and GDP projections until 2050

Tunisia	Units	2019	2025	2030	2035	2040	2045	2050
Population	[Individuals]	11,694,721	12,665,802	13,100,768	13,449,717	13,769,345	14,072,180	14,315,779
Annual Population Growth	[%/a]	1.12%	1.36%	0.67%	0.52%	0.47%	0.43%	0.34%
GDP	[US$ billion – constant 2015]	49.20	50.28	56.44	64.80	75.12	87.09	99.74
Annual Economic Growth	[%/a]	1.40%	2.30%	2.50%	3.00%	3.00%	3.00%	2.75%
GDP/Person (calculated)	[US$/capita]	4,207	3,970	4,308	4,818	5,456	6,189	6,967

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[29] Carnegie Endowment for International Peace, "Why Tunisia Lost Faith in Democracy", accessed September 2024.

[30] Carnegie Endowment for International Peace, "The Buildup to a Crisis: Current Tensions and Future Scenarios for Tunisia", accessed September 2024. https://carnegieendowment.org/research/2024/01/the-buildup-to-a-crisis-current-tensions-and-future-scenarios-for-tunisia?lang=en&center=middle-east

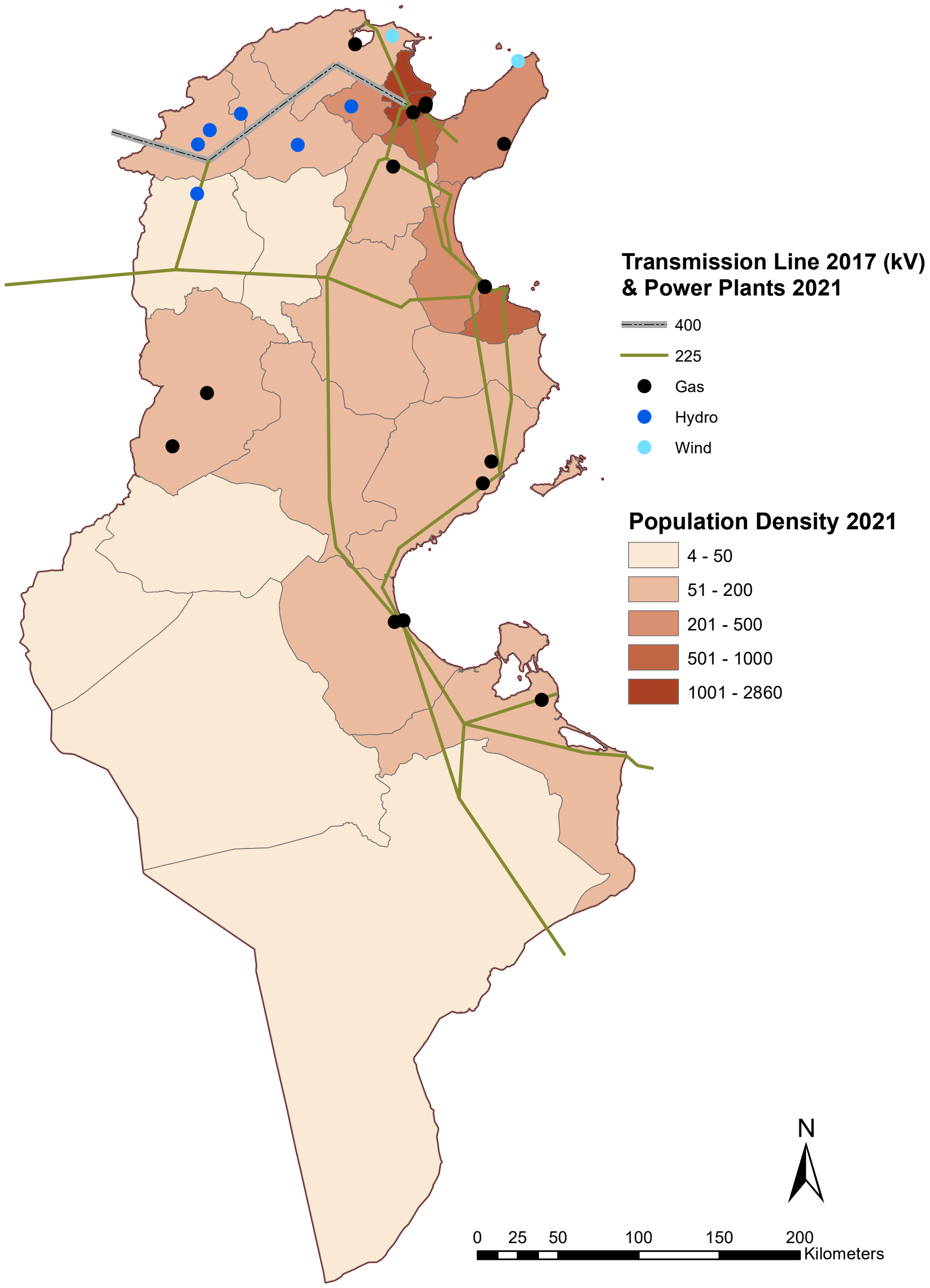
[31] ibid.

[32] World Bank Group, Press Release 'Tunisia's Sustained Recovery Requires Quick Action to Take Advantage of Opportunities', accessed September 2024: https://www.worldbank.org/en/news/press-release/2024/05/08/tunisia-s-sustained-recovery-requires-quick-action-to-take-advantage-of-opportunities

2.2 Electricity infrastructure and energy access

For this analysis, Tunisia's power sector is divided into eight regions. The regional distribution of the population and the availability of the energy infrastructure correlate with the socio-economic situation in all regions. The following map provides an overview of the locations of power lines and power plants, a regional breakdown of energy pathways, and the power sector analysis (Chapter 6).

Figure 2: Distribution of population and the existing electricity infrastructure in Tunisia



(Figure 2 references: transmission lines – Tunisia Electricity Transmission Network (2017)[33]; power stations – Global Power Plant Database (v1.3.0)[34]; the population density is based on Statistique Tunisia[35])

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[33] The World Bank: https://datacatalog.worldbank.org/search/dataset/0040234

[34] World Resources Institute, https://datasets.wri.org/dataset/globalpowerplantdatabase

[35] Statistiques Tunisie: https://www.ins.tn/en/statistiques/111

Figure 2 shows the population density for Tunisia. The highest population concentrations are shown in dark red and the lowest in white. The map clearly shows the high population densities in the metropolitan areas of Tunis, the northern regions, and the coastal regions. The existing constructed electricity infrastructure (power lines, power plants, and sub-stations), with their different types of grids, are shown as lines, and the differently coloured dots mark grid-connected power plants – each colour represents a specific technology, identified in the legend. The lines represent power transmission lines with different voltage levels, whereas the spatial data are only available for high-voltage transmission lines in Tunisia (225 kV and 400 kV). The figure visualises the distribution of the grid and the population density, but is not complete or up-to-date due to the reliance on historical data. The energy access rate of the local population in Tunisia is around 99.9%[36], although access to energy services does not necessarily mean that the supply is always available.

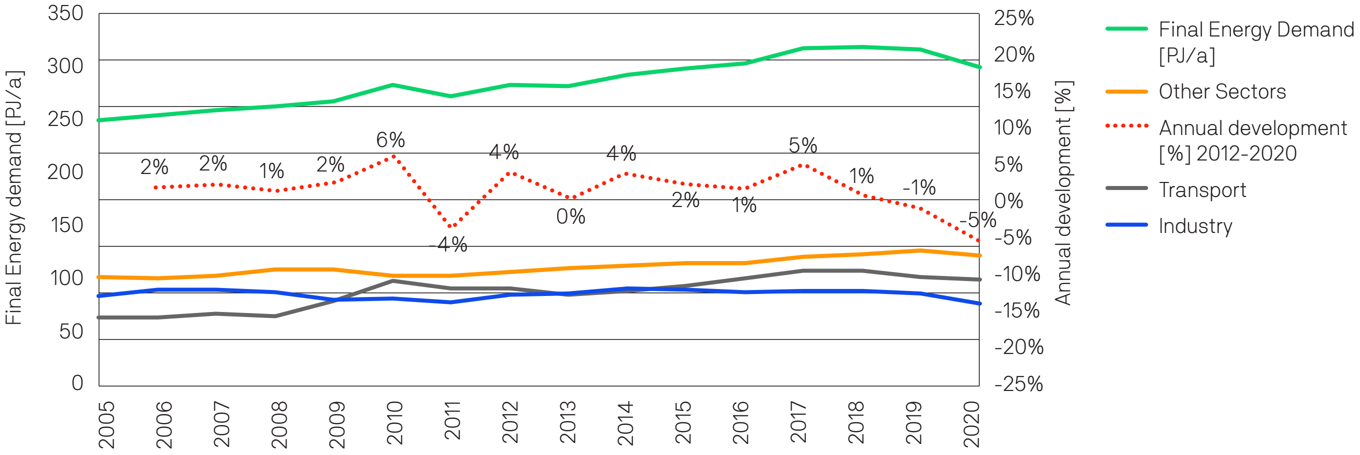
An updated map of Tunisia's electricity infrastructure was used as the basis for the power sector analysis described in Chapter 6. Detail provided by the Res4Africa Foundation allowed UTS-ISF to accurately include the interconnection limits between modelling regions in the 24-7 MATLAB model, which was based on conversion factors of line ratings to MW capacity constraints. The updated infrastructure map shows that Tunisia's electricity infrastructure has been significantly expanded relative to the 2017 data plotted in Figure 2, with a range of interconnection ratings spanning the country (90 kV, 150kV, 225kV, 400kV).[37]

2.3 Energy demand – development since 2005

It is necessary to analyse the development of the past energy demand to project that of the future. Therefore, we analysed the statistical data for Tunisia's energy demand between 2005 and 2019 (IEA 2022)[38].

Figure 3 shows Tunisia's final energy demand development between 2005 and 2020. The overall energy demand grew continuously, despite years of reduced demand due to reduced economic activity. The gross final energy demand has grown by about 20% since 2005 to around 300 petajoules per annum (PJ/a). The main energy demand is required in the residential sector (category "Other Sectors"), whereas only 26% of the energy is for industry use and 33% for the transport sector.

Figure 3: Final energy demand development in Tunisia from 2005 to 2019



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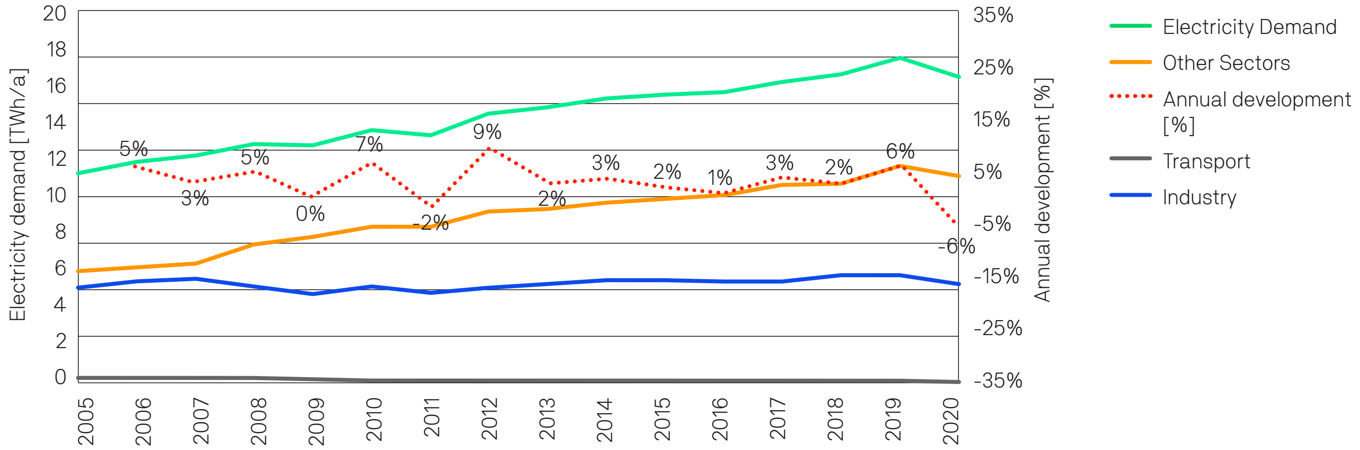
[36] The World Bank: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=TN

[37] Res4Africa, 'Deploying Battery Energy Storage Solutions in Tunisia', 2023

[38] IEA (2022) Advanced World Energy Balances, Tunisia

Tunisia's electricity demand has increased to a significant extent, by more than twice the growth in the final energy demand (46% compared with 20%). By 2019, the annual electricity demand was close to 16.4 billion kilowatt-hours (16.4 TWh/a), up from 11.2 TWh/a in 2005 (Figure 4), an approximately 1.5-fold increase. Again, the residential sector grew to the greatest extent, with "Other Sectors" almost doubling between 2005 and 2020. It is noteworthy that despite the aforementioned increases in both the final energy and electricity demand across the Tunisian economy, the electricity demand for industry showed negligible growth (4%). Furthermore, according to the IEA data used in this study, the electricity demand associated with transport declined markedly. In the T-1.5°C scenario, it is assumed that there will be increased electrification of vehicles, so this trend can be expected to reverse with the decarbonisation of the transport sector, with increases in either public or private electrified transport.

Figure 4: Electricity demand development in Tunisia from 2005 to 2020



An examination of Tunisia's residential electricity demand should clarify the above data. Electricity consumption per capita was 1,111 kWh/person in 2005, and this grew by 25% to 1,389 kWh/person by 2020. Although this electricity usage is substantially higher than that of Tunisia's sub-Saharan counterparts, it is still significantly lower than the global average consumption, which exceeds 3,000 kWh per capita per annum[39]. This is despite Tunisia's history of high electricity access rates, which according to the World Bank Group have exceeded 90% since 1995.[40] This implies that although the vast majority of Tunisians have access to electricity, the end uses available to households in developed countries are not widely available in Tunisia, or that there is a much greater reliance on fossil fuels and biomass for end uses such as cooking and heating (e.g., space, water) than in developed countries. This finding is supported by a 2021 report published by the World Bank Group that stated that 96% of Tunisians use gas as their primary energy source for cooking, and that only 3% of citizens use electricity.[41]

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39 World Bank Database 2019, https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?end=2019&name_desc=true&start=1960&view=chart

40 World Bank Group, Tunisia Webpage on Access to Electricity, accessed September 2024: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=TN

41 World Bank Group (Energy Sector Management Assistance Program), 'Primary Household Energy for Cooking and Heating in 52 Developing Economies', 2021

2.3.1 Energy supply

The primary energy supply is dominated by oil and gas (around 88% in 2020), which is used across the economy for a variety of end uses, including cooking and heating, as well as electricity generation. Historically, Tunisia's electricity supply has been derived almost entirely from gas generation, with percentages regularly above 95% between 2005 and 2020. (Of the 16 years in this range, > 95% of electricity was generated from gas in 11 of them).[42]

Table 5: Tunisia's primary energy supply between 2005 and 2019 (IEA World Energy Balances 2021)

Primary Supply–	**Units**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Annual development		-	4%	3%	4%	-2%	10%	-4%	5%	-8%	11%	3%	2%	2%	2%	-2%	-5%
Primary energy	[PJ/a]	347	361	372	387	379	418	400	420	386	430	443	452	463	471	461	440
Net Electricity Exports (–)/ Imports (+)	**[PJ/a]**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-1**	**-2**
Fossil fuels	[PJ/a]	294	311	324	333	324	369	352	371	375	378	389	397	407	414	407	388
Coal	[PJ/a]	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Lignite	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil	[PJ/a]	157	161	165	157	153	152	142	144	148	165	180	171	180	177	178	172
Gas	[PJ/a]	136	150	158	176	171	217	210	227	226	213	209	226	227	237	229	216
Nuclear	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Renewables	**[PJ/a]**	**41**	**43**	**44**	**45**	**48**	**40**	**40**	**41**	**3**	**43**	**43**	**43**	**43**	**44**	**44**	**45**
Hydro	[PJ/a]	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind	[PJ/a]	0	0	0	0	0	1	0	1	1	2	2	2	2	2	2	2
Solar	[PJ/a]	0	0	0	0	0	1	1	1	1	2	2	2	2	3	3	4
Biomass	[PJ/a]	41	42	44	45	47	39	39	39	0	39	39	39	39	39	39	39
Geothermal	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ocean energy	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Renewables Share:	**[%]**	**14%**	**14%**	**14%**	**14%**	**15%**	**11%**	**11%**	**11%**	**1%**	**11%**	**11%**	**11%**	**11%**	**11%**	**11%**	**12%**

Definition of renewable energy

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body assessing climate change. In its Special Report on Renewable Energy Sources and Climate Change Mitigation,[43] the IPCC defines the term 'renewable energy' as:

> *'RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydro power, tide and waves, ocean thermal energy and wind energy. However, it is possible to utilise biomass at a greater rate than it can grow or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilisation of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilisation.'*

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[42] IEA World Energy Balances

[43] Arvizu D, T. Bruckner, Chum H, Edenhofer O, Estefen S, Faaij A, Fischedick M, Hansen G, Hiriart G, Hohmeyer O, Hollands KGT, Huckerby J, Kadner, Killingtveit Å, Kumar A, Lewis A, Lucon O, Matschoss P, Maurice L, Mirza M, Mitchell C, Moomaw W, Moreira J, Nilsson LJ, Nyboer J, Pichs- Madruga R, Sathaye J, Sawin J, Schaeffer R, Schei T, Schlömer S, Seyboth K, Sims R, Sinden G, Sokona Y, von Stechow C, Steckel J, Verbruggen A, Wiser R, Yamba F, Zwickel T (2011) Technical Summary. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), Cambridge University Press, Cambridge, UK and New York, NY, USA.

2.4 Development of the Residential energy demand

To develop a projection for the residential electricity demand in Tunisia over the coming 30 years to achieve the Tunisia 1.5°C (T-1.5°C) scenario, a bottom-up electricity demand analysis was undertaken. The T-1.5°C scenario aims to increase the access and comfort standards related to energy – especially electricity – for all by 2050, while increasing electrification to the levels of OECD countries. As mentioned in section 2.3, although the official statistics indicate near-universal access to electricity, Tunisia still lags when it comes to electricity use per capita, which is associated with its reliance on gas for cooking and heating (e.g., space, water). The growing economy requires a reliable power supply for small and medium businesses, industry, and the transport sector. It is assumed that households will use modern energy-efficient applications, based on the highest efficiency standards, to slow the growth of the power demand and to allow the parallel expansion of the energy infrastructure and the construction of renewable power plants. Electrification will be organised from the 'bottom up' using the approach developed by UTS-ISF.

2.4.1 Household electricity demand

The current and future development of the electricity demand of Tunisia's households were analysed from the second half of 2021 onwards under the leadership of Power Shift Africa. The future development of the household demand was discussed in a multiple-stakeholder dialogue with representatives from Tunisia's academia, civil society, and government. Figure 5 shows the breakdown of Tunisia's households by size (UN-ES 2019)[44].

Figure 5: Households by size – Tunisia

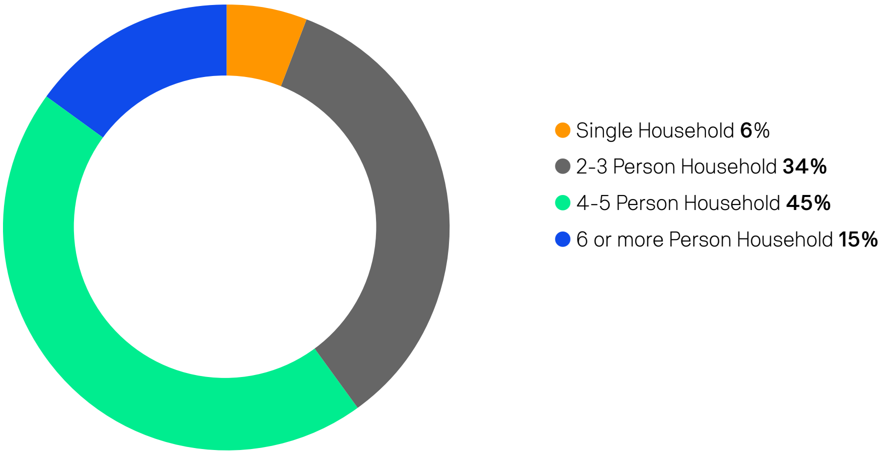

Table 6 shows the electricity demand and the electrical appliances used by households in Tunisia in 2020 and the projected '***phases***', with increased demand as electrification increases. It is assumed that households with an annual consumption indicated under the household type in 'phase 1' will increase their demand to 'phase 2' or 'phase 3' values over time. There are currently three household types, distinguished by their annual electricity demand: rural households, which have an average annual electricity demand of just under 1,250 kWh; semi-rural households, which consume around 1,200 kWh per year; and urban households, with an annual consumption of 1,700 kWh.

The electricity demand will gradually increase as the electrical applications for each of the three household types progress from households with very basic needs, such as light and mobile phone charging, to a household standard equivalent to that of industrialised countries. The different levels of electrification and the utilisation of appliances are described with the affixes 'phase 1', 'phase 2', and 'phase 3' for rural households. In contrast, semi-urban and urban households are assigned to two groups: one for the basic level of electrification and one for the more-advanced stage. The households will develop over time, from the basic group towards the more advanced group. The third phase of a rural household includes an electric oven, refrigerator, washing machine, air-conditioning, and entertainment technologies, and aims to provide the same level of comfort as households in urban areas in industrialised countries. Adjustments will be made to the levels of comfort in households in city and rural areas to discourage residents – especially young people – from leaving their home regions and moving to big cities.

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[44] UN-ES (2019) United Nations, Department of Economic and Social Affairs, Population Division (2019). Database of Household Size and Composition 2019, https://www.un.org/development/desa/pd/data/household-sise-and-composition

Table 6: Household types used in all scenarios and their assumed annual electricity demand levels in 2020.

Tunisia – Annual Household Electricity Demands			
Household Type	**Group**		**Annual Electricity Demand [kWh/a]**
Rural	Phase 1	– Very-low-income rural household – Low-income rural household	1244
	Phase 2	– Lower-middle-income rural household	1609
	Phase 3	– Upper-middle-income rural household	2303
Semi-Urban	Basic	– Low-to-middle-income semi-urban household	1149
	Advanced	– Middle-income semi-urban household	1327
Urban – Apartment	Basic	– Low-to-middle-income urban household (apartment)	1692
	Advanced	– Middle-income urban household (apartment)	2766
Urban House	Basic	– Middle-income urban household (house)	2850
	Advanced	– Middle-to-high-income urban household (house)	3120

The typical household electricity demands are compared with an example of an OECD country. The authors have chosen Switzerland for its well-documented electricity demands and good exemplification of energy-efficient but highly electrified households among the OECD countries.

OECD household: Switzerland

Table 7 shows an example of the electricity demands of different household types in the OECD country Switzerland. Switzerland was chosen because of its well-documented electricity demands and its good exemplification of the energy-efficient and highly electrified households of the OECD countries. In predicting the future development of Tunisia's electricity demand, we assume that the levels of electrification and household appliances used will be like those in industrialised countries. Although the electricity demand of households in industrialised countries – excluding electric mobility – can be reduced through technical efficiency measures and more-efficient appliances as technical standards improve, the current demand provides an orientation for the future demands in developing countries.

Table 7: Standard household demand in an industrialised country (Switzerland)

Standard Household – OECD	Apartment			Separate House			
Category	**2 People [kWh/a]**	**Additional person [kWh/a]**	**4 People [kWh/a]**	**2 People [kWh/a]**	**Any additional person/s [kWh/a]**	**4 People [kWh/a]**	**Calculated Urban Family 2 [kWh/a]**
Cooking/baking including special equipment, e.g., coffee maker	300	80	460	300	80	460	0
Dishwasher	250	25	300	250	25	300	
Refrigerator with or without freezer compartment	275	40	355	325	60	445	340
Separate freezer	275	25	325	350	25	400	
Lighting	350	90	530	450	125	700	198
Consumer electronics (TV, video, hi-fi, various players, etc.)	250	60	370	275	80	435	110
Home office (PC, printer, modem, comfort phone, etc.)	200	60	320	200	80	360	
Div. Nursing and small appliances including humidifier	250	45	340	325	60	445	272
Washing machine	225	65	355	250	78	405	127
Laundry dryer (about 2/3 of the laundry, with a tumbler)	250	85	420	275	88	450	
General (building services)	400		400+	900	150	1200	
Total	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**1047**
Climatisation							1,013
Total, including climatisation	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**2060**

Source: Der typische Haushalt-Stromverbrauch Energieverbrauch von Haushalten in Ein- und Mehrfamilienhäusern/Schweis, https://www.energieschweiz.ch/stories/energieeffiziente-elektrogeraete/

The development of country-wide shares of the electricity demand in Tunisia according to the various household types is presented in Table 8. Electrification starts with basic household types, such as rural, semi-urban, and urban (apartments or houses) and moves to better-equipped households. Therefore, the proportion of fully equipped households will grow constantly, whereas the proportion of basic households will increase in the early years and decrease towards the end of the modelling period. By 2050, most households will have a medium-to-high level of comfort equipment. The authors of this report have deliberately chosen a high standard for Tunisia's households to close the gap between them and households in OECD countries.

Table 8: Household types – development of household shares of the electricity demand country-wide in Tunisia

	Country-wide electricity shares [%] (rounded)			
Household type	**2020**	**2030**	**2040**	**2050**
No access to electricity	20.00%	14.00%	8.00%	0.00%
Rural – Phase 1	11.00%	9.00%	7.00%	5.00%
Rural – Phase 2	11.00%	12.50%	14.00%	15.50%
Rural – Phase 3	11.00%	12.50%	14.00%	15.50%
Semi-Urban – basic	4.00%	6.00%	8.00%	10.00%
Semi-Urban – advanced	4.00%	3.00%	2.00%	1.00%
Urban Apartment – basic	4.00%	3.00%	2.00%	1.00%
Urban Apartment – advanced	10.00%	12.00%	14.00%	16.00%
Urban House – basic	15.00%	16.00%	17.00%	20.00%
Urban House – advanced	10.00%	12.00%	14.00%	16.00%
Total	**100%**	**100%**	**100%**	**100%**

Source: CDP, REB, DESCO, and UTS-ISF research

Since 1995, Tunisia has demonstrated a strong track record when it comes to their official statistics on access rates to electricity, and according to the World Bank Group, electricity access rates have exceeded 90%.[45] However, households may not have access to reliable and uninterrupted electricity. For those living in more remote areas or regions near the edge of the electrical infrastructure, mini-grids may be the most appropriate choice. Mini-grids have proven a successful technology option for bringing energy services to remote communities, helping villages develop local economies and providing alternative opportunities for young people to establish careers outside metropolitan areas.

2.4.2 Household Fuel demand – cooking

A 2021 report published by World Bank Group indicated that 96% of Tunisians use gas as their primary energy source for cooking, and only 3% of citizens use electricity.[46] The daily and annual energy demands for the three main fuel-based cooking technologies are shown in Table 9. Based on these estimates, a scenario for transitioning from fuel-based cooking to electricity-based cooking was developed (Table 9).

Fuel-based cooking applications will be gradually phased-out and replaced with electric cooking appliances. The total phase-out of fuel-based systems will be for environmental and economic reasons. Fuel-based cooking requires fuel that generates emissions, and the fuel supply is, in most cases, not sustainable. Burning LPG causes CO_2 emissions, and its production is based on fossil gas, which must be phased-out by 2050 to remain within the global carbon budget to limit the global mean temperature rise to a maximum of +1.5°C. The remaining wood- and bio-energy-based cooking in 2050 will be with sustainable charcoal.

Electric cooking can be supplied by renewable energy sources and will be emissions-free.

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[45] World Bank Group, Tunisia webpage on Access to Electricity, accessed September 2024: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=TN

[46] World Bank Group (Energy Sector Management Assistance Program), 'Primary Household Energy for Cooking and Heating in 52 Developing Economies', 2021

Table 9: Transition scenario from fuel-based to electricity-based cooking in Tunisia under the T-1.5°C pathway

Share of Households with Wood- and Bio-energy-Fuel-based Cooking			**Rural – Phase 1**	**Rural – Phase 2**	**Rural – Phase 3**	**Semi-Urban 1**	**Semi-Urban 2**	**Urban Apartment 1**	**Urban Apartment 2**	**Urban House 1**	**Urban House 2**
Average Energy Demand by Household (HH; based on World Future Council 2019)			8,796	8,796	8,796	22,870	7,623	8,796	8,796	8,796	8,796
2020	1%	[MJ/a HH]	88	88	88	229	76	88	88	88	88
2025	1%	[MJ/a HH]	88	88	88	229	76	88	88	88	88
2030	1%	[MJ/a HH]	88	88	88	229	76	88	88	88	88
2035	1%	[MJ/a HH]	88	88	88	229	76	88	88	88	88
2040	1%	[MJ/a HH]	88	88	88	229	76	88	88	88	88
2045	0%	[MJ/a HH]	0	0	0	0	0	0	0	0	0
2050	0%	[MJ/a HH]	0	0	0	0	0	0	0	0	0

Share of Household with Gas/ Liquefied natural-gas-based Cooking			**Rural – Phase 1**	**Rural – Phase 2**	**Rural – Phase 3**	**Semi-Urban 1**	**Semi-Urban 2**	**Urban Apartment 1**	**Urban Apartment 2**	**Urban House 1**	**Urban House 2**
Average Energy Demand by Household (HH; based on World Future Council 2019)			1,255	1,255	1,255	3,264	1,088	1,255	1,255	1,255	1,255
2020	96%	[MJ/a HH]	1,205	1,205	1,205	3,133	1,044	1,205	1,205	1,205	1,205
2025	96%	[MJ/a HH]	1,205	1,205	1,205	3,133	1,044	1,205	1,205	1,205	1,205
2030	96%	[MJ/a HH]	1,157	1,157	1,157	3,008	1,003	1,157	1,157	1,157	1,157
2035	89%	[MJ/a HH]	1,117	1,117	1,117	2,905	968	1,117	1,117	1,117	1,117
2040	79%	[MJ/a HH]	992	992	992	2,578	859	992	992	992	992
2045	60%	[MJ/a HH]	753	753	753	1,958	653	753	753	753	753
2050	5%	[MJ/a HH]	63	63	63	163	54	63	63	63	63
Phase-in of Electric Cooking 2020–2050											
Share of Households with Electric Cooking			**Rural – Phase 1**	**Rural – Phase 2**	**Rural – Phase 3**	**Semi-Urban 1**	**Semi-Urban 2**	**Urban Apartment 1**	**Urban Apartment 2**	**Urban House 1**	**Urban House 2**
Average Energy Demand by Household (HH; based on World Future Council 2019)			302	302	302	786	262	302	302	302	302
2020	3%	[kWhelectric/ a HH]	9	9	9	24	8	9	9	9	9
2025	3%	[kWhelectric/ a HH]	9	9	9	24	8	9	9	9	9
2030	3%	[kWhelectric/ a HH]	9	9	9	24	8	9	9	9	9
2035	10%	[kWhelectric/ a HH]	30	30	30	79	26	30	30	30	30
2040	20%	[kWhelectric/ a HH]	60	60	60	157	52	60	60	60	60
2045	40%	[kWhelectric/ a HH]	121	121	121	314	105	121	121	121	121
2050	95%	[kWhelectric/ a HH]	287	287	287	747	249	287	287	287	287

There are challenges in the Tunisian context that must be addressed if electric cooking stoves are to become widespread throughout society:

- Tunisians are used to cooking with gas, given its history and prevalence across society. This may lead to bias in terms of cooking fuel preferences and scepticism that electric cooking achieves the same results as gas cooking.
- Because households are connected to the gas network and own gas ovens and stoves, there will be costs when households transition from gas cooking to electric.
- Therefore, in relative terms, the initial investment and monthly costs will be high.
- The use of e-cooking is perceived to be expensive.
- There are quality concerns about the appliances.
- It is a new technology that requires learning to operate.
- The current business models of distribution are not well suited to low-income households. Most vendors use an upfront model of payment rather than other innovative models, such as pay as you go, which have proven beneficial for many other technologies.

There are already numerous electric cooking devices on Tunisia's market, including:

- Induction stoves
- Electric pressure cookers
- Electric ovens
- Hot plates
- Microwave ovens
- Electric and gas hobs
- Infrared stoves
- Rice cookers
- Slow cookers
- Electric frying pans
- Air fryers
- Electric kettles

- **Among these, the most viable energy-efficient appliances are:**
- Induction stoves
- Infrared stoves
- Rice cookers
- Electric pressure cookers

- **The supply-side barriers to e-cooking are:**
- Electric cooking stoves do not seem to be manufactured locally.
- After-sales service is poor (i.e., poor access to repairs and maintenance).
- Concerns exist around the quality and stability of the electricity supply.

Technical challenges posed by e-cooking for electric utilities and energy service companies

The increase in the peak load during mealtimes will require the electricity distribution grid to be upgraded in terms of load management and the ability of the power grid to supply higher loads. The introduction of electric vehicles to replace fossil-fuel-driven vehicles will further increase the electric load and require grid expansion and reinforcement to be implemented by electric grid operators.

Furthermore, current household electricity connections are often limited to 5-ampere meters, which significantly limits the load for each household, and the parallel operation of multiple appliances is not possible when electric stoves are used. The technical standard of household wiring is also low; cables are often not properly installed, or a lack of protective earthing compromises electrical safety.

2.5 Industry and business demands

The analysis of Tunisia's economic development is based on a breakdown of the fiscal year 2020. It assumes that the overall structure of the economy will not change, and that all sectors will grow at a rate equal to that of GDP over the entire modelling period. Figure 6 shows that in the fiscal year 2020/21, machinery, manufacturing, chemicals, as well as food the textile industry and food beverage, contributed all shares between 5% and 10% documenting a diversified economy.

Figure 7 presents the annual GDP growth rate from 2005 to 2020.

Figure 6: Contributions of sub-sectors to GDP growth

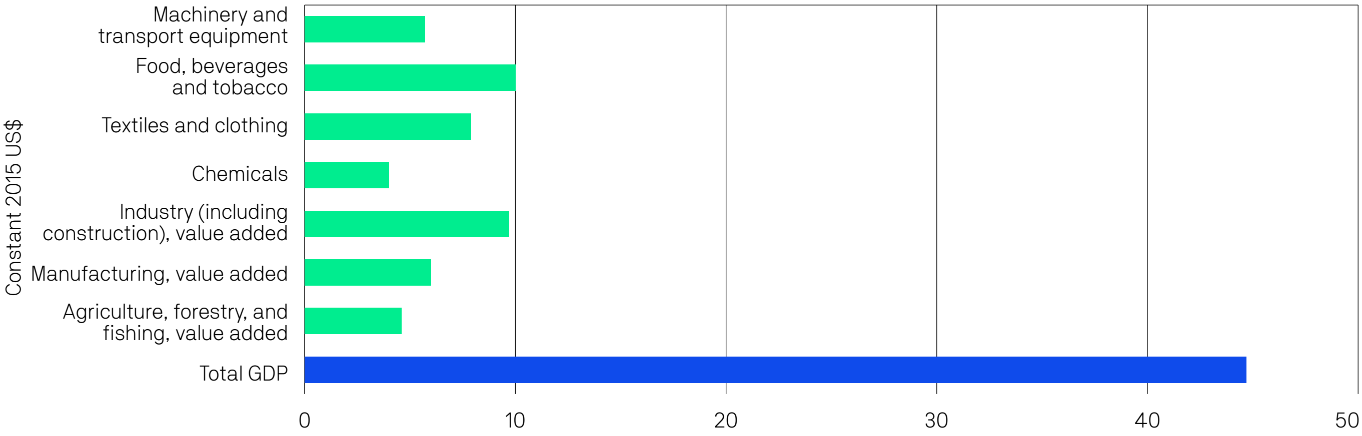
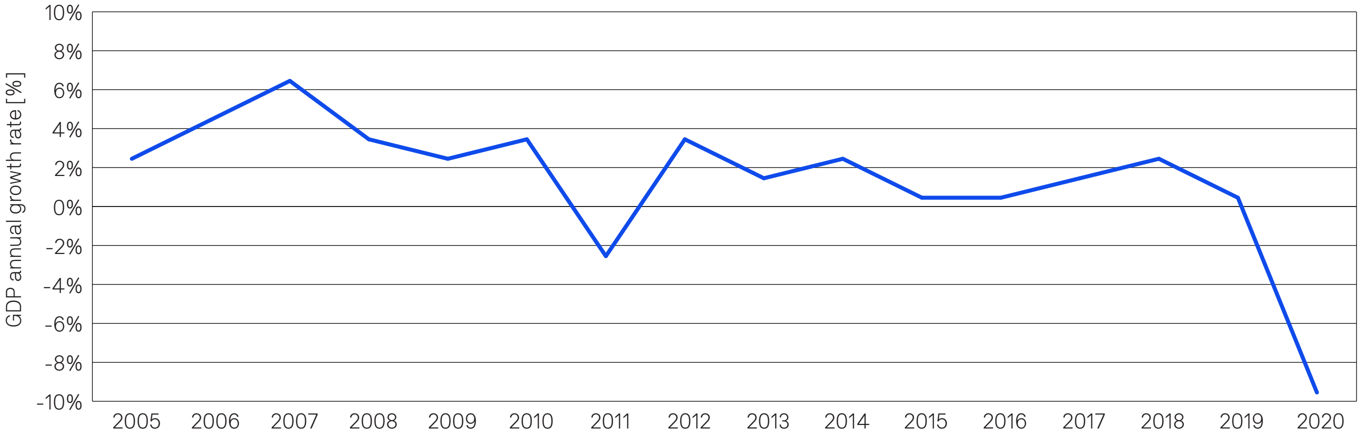


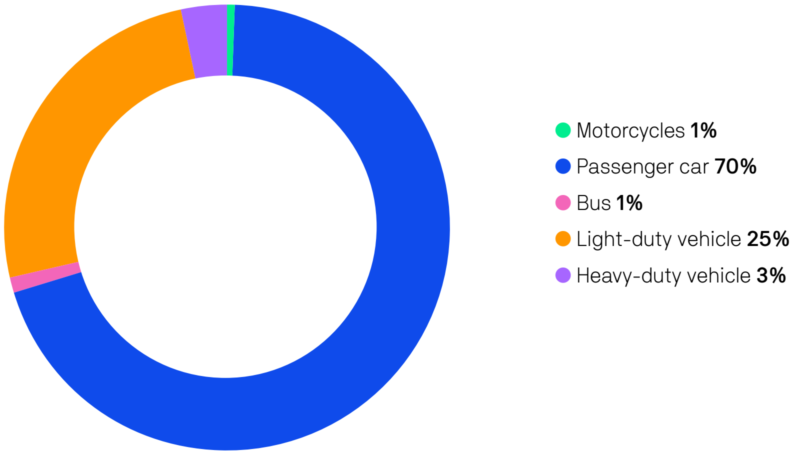
Figure 7: Growth rate of gross domestic product (GDP)



2.6 Transport Demand

Tunisia's transport sector is significantly dominated by passenger vehicles, with cars accounting for 70% of all registered vehicles. Light duty vehicles account for a further 25% of the vehicle stock (defined as vehicles used for the carriage of goods, with a maximum mass not exceeding 3.5 tonnes, e.g. pick-up trucks, vans).

Figure 8: Categories of registered vehicles, with the percentages of the total number of registered vehicles (financial year 2019/2020).



Source: [47]

To develop a future transport scenario, the technical parameters of all vehicle options are required to project the future energy demands. The following section provides an overview of the vehicular energy intensities for passenger and freight transport. Based on these, the actual utilisation – in terms of annual kilometres per vehicle – is estimated to calculate the energy demand over time until 2050.

The energy intensities for different vehicle types and each available drive train play an important role in calibrating the transport modes and projections. Each transport mode has different vehicular options. Each of the vehicles has different drive-train and efficiency options. The technical variety of passenger vehicles, for example, is extremely large. The engine sizes for five-seater cars range between around 20 kW to > 200 kW.

Furthermore, drive trains can use a range of fuels, from gasoline, diesel, and bio-diesel to hydrogen and electricity. Each vehicle has a different energy intensity in megajoules per passenger-kilometre (MJ/pkm). Therefore, the energy intensities provided in the following tables are average values.

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[47] Tan N, et al. (2019) Historical socio-transport data for Tunisia Zenodo. https://zenodo.org/api/records/10409803/files-archive

2.6.1 Technical Parameters – Passenger Transport

Passenger transport by road is the commonest and most important form of travel (TUMI 2021)[48]. There are numerous technical options to 'move people with vehicles': bicycles, motorcycles, tricycles, city cars, and four-wheel-drive SUVs. Each vehicle has a very different energy intensity per km. Although this research project aims for high technological resolution, simplifications are required. Table 10 shows the energy intensities for the main vehicle types (electric and with internal combustion engines [ICEs]) and forms the basis for the energy scenario calculations.

Table 10: Energy intensities for passenger transport – road transport

			Passengers		Vehicle Demand	Consumption per Passenger	Energy Demand
Passenger Transport			**Average Passengers per Vehicle**	**Assumed Occupation Rate**	**Average**	**Average**	**Assumption for Scenario Calculation**
Scooters & motorbikes		**Fuels**			**Litre/100 km**	**Litre/100 pkm**	**[MJ/pkm]**
	2-wheeler	Gasoline	1	1	3.0	3.0	1.21
E-bikes Scooters Motorbikes Rickshaw		**Electricity**			**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	2-wheeler	Battery	1	1	1.0	1.0	0.04
	2-wheeler	Battery	1	1	1.8	1.9	0.06
	2-wheeler	Battery	1	1	4.8	4.8	0.17
	3-wheels	Battery	3	2	8.0	4.0	0.14
Cars		**Fuels**	**0**	**0**	**Litre/100 km**	**Litre/100 pkm**	**[MJ/pkm]**
	Small	ICE-oil	2	1.8	5.0	2.8	1.12
	Medium	ICE-oil	4	2	7.5	3.8	1.51
	Large	ICE-oil	5	2	10.5	5.3	2.11
	Small	ICE-gas	2	1.8	4.5	2.5	0.63
	Medium	ICE-gas	4	2	7.0	3.5	1.41
	Large	ICE-gas	5	2	10.0	5.0	1.25
	Small	ICE-bio	2	1.8	5.0	2.8	0.91
	Medium	ICE-bio	4	2	7.5	3.8	1.51
	Large	ICE-bio	5	2	10.5	5.3	1.72
	Small	Hybrid-oil	2	1.8	4.0	2.2	0.89
	Medium	Hybrid-oil	4	2.5	6.0	2.4	0.96
	Large	Hybrid-oil	5	2.5	8.5	3.4	1.37
		Electricity			**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	Small	Battery	2	1.8	16.0	8.9	0.32
	Medium	Battery	4	2	25.0	12.5	0.45
	Large	Battery	5	2	32.5	16.3	0.59
	Large	Fuel Cell	4	2	37.5	18.8	1.36

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[48] TUMI (2021), Teske S, Niklas S, Langdon R., (2021), TUMI Transport Outlook 1.5°C – A global scenario to decarbonise transport; Report prepared by the University of Technology Sydney for the Detsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; Published by TUMI Management, Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH, Friedrich-Ebert-Allee 36 + 40, 53113 Bonn, Germany; https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf

2.6.2 Technical Parameters – Public transport

There is a huge variety of public transport vehicles – from rickshaws to taxis and mini-buses to long-distance trains. The occupation rates for those vehicles are key factors in calculating energy intensity per passenger per kilometre. For example, a diesel-powered city bus transporting 75 passengers uses, on average, about 27.5 litres per 100 kilometres. If the bus operates at full capacity during peak hour, the energy demand per passenger is as low as 400 mL per kilometre, lower than almost all fossil-fuel-based road transport vehicles. However, if the occupancy drops to 10% – e.g. for a night bus – the energy intensity increases to 3.7 litres, equal to that of a small energy-efficient car. Occupation rates vary significantly and depend upon the time of day, day of the week, and season.

There are also significant regional differences, even within a province. Again, the parameters shown in Table 11 are simplified averages and are further condensed for the scenario calculations. Although high technical resolution is possible for the scenario model, it would pretend an accuracy that does not exist because the statistical data required for this resolution are not available at the regional level.

Table 11: Energy intensities for public transport – road and rail transport

			Passengers		**Vehicle Demand**	**Consumption per Passenger**	**Energy Demand**
Public Transport			**Average Passengers per Vehicle**	**Assumed Occupation Rate**	**Average**	**Average**	**Assumption for Scenario Calculation**
Buses		**Fuels**			**Litre/100 km**	**Litre/100 pkm**	**[MJ/pkm]**
	Small	Diesel	12	40%	8.8	1.8	0.73
	Small	Bio	12	40%	8.8	1.8	0.60
	12 m	Diesel	75	40%	27.5	0.9	0.37
	12 m	Bio	75	40%	27.5	0.9	0.30
	Large	Diesel	135	40%	57.5	1.1	0.43
		Electricity	**0**	**0**	**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	Small	Battery	12	40%	31	6.4	0.23
	Small	Fuel Cell	12	40%	77	15.9	0.57
	12 m	Battery	75	40%	143	4.8	0.17
	12 m	Fuel Cell	75	40%	358	11.9	0.43
	Large	Overhead lines	135	40%	263	4.9	0.18
Trains		**Fuels**	**0**	**0**	**Litre/100 km**	**Litre/100 pkm**	**[MJ/pkm]**
	Metros	Diesel	400	40%	150	0.9	0.38
	Metros	Bio	400	40%	150	0.9	0.31
	Commuter Trains	Diesel	600	40%	300	1.3	0.50
	Commuter Trains	Bio	600	40%	300	1.3	0.41
		Electricity	**0**	**0**	**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	Trams	Electric	300	40%	495	4.1	0.14
	Metros	Electric	300	40%	1,200	10.0	0.14
	Commuter Trains	Electric	600	40%	1,950	8.1	0.17

2.6.3 Technical Parameters – Freight transport

The energy intensity data for freight transport are not as diverse as those for passenger transport because the transport vehicle types are standard and the fuel demands are well known. However, the utilisation rates of the load capacities vary significantly, and consistent data are not available for the calculated regional and global levels. Therefore, the assumed utilisation rate greatly influences the calculated energy intensity per tonne–kilometre (tkm). The average energy intensities per tkm used in the scenario are shown in Table 12 and are largely consistent with those from other sources in the scientific literature (EEA 2021)[49]. The assumed energy intensities for electric and fuel cell/hydrogen freight vehicles are only estimates because this technology is still in the demonstration phase. Therefore, none of the scenarios factor in large shares of electric freight transport vehicles before 2035.

Table 12: Energy intensities for freight transport – road and rail transport

Freight Transport			**Maximum Load Capacity (tonnes)**	**Assumed Utilisation Rate**	**Vehicle Demand**	**Consumption per Tonne**	**Energy Demand**
					Average	**Average**	**Assumption for Scenario Calculation**
Trucks		**Fuels**			**Litre/100 km**	**Litre/tkm**	**[MJ/tkm]**
	3.5 tonne	Diesel	3.5	40%	11	7.9	3.16
	3.5 tonne	Bio	3.5	40%	11	7.9	2.57
	7.5 tonne	Diesel	7.5	40%	20	6.5	2.61
	7.5 tonne	Bio	7.5	40%	20	6.5	2.13
	12.5 tonne	Diesel	12.5	40%	25	5.0	2.01
	12.5 tonne	Bio	12.5	40%	25	5.0	1.64
		Electricity			**kWhel/100 km**	**kWhel/tkm**	**[MJ/tkm]**
	3.5 tonne	Battery	3.5	40%	19	13.6	1.34
	3.5 tonne	Fuel Cell	3.5	40%	46	33.2	1.33
	7.5 tonne	Battery	7.5	40%	41	13.6	0.49
	7.5 tonne	Fuel Cell	7.5	40%	100	33.2	1.19
	12.5 tonne	Battery	12.5	40%	68	13.6	0.49
	12.5 tonne	Fuel Cell	12.5	40%	166	33.2	1.19
Trains		**Fuels**			**Litre/100 km**	**Litre/tkm**	**[MJ/tkm]**
	Freight – 740 m	Diesel	1,000	40%	300	0.8	0.30
	Freight – 740 m	Bio	1,000	40%	300	0.8	0.25
		Electricity			**kWhel/100 km**	**kWhel/tkm**	**[MJ/tkm]**
	Freight – 740 m	Electric	1,000	40%	5,840	14.6	0.53

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[49] European Environment Agency, https://www.eea.europa.eu/publications/ENVISSUENo12/page027.html

2.6.4 Utilisation of vehicles

In the second step, the utilisation of vehicles must be analysed to develop a projection into the future. No up-to-date surveys are available. The annual pkm for passenger transport and tkm for freight transport are calculated based on the current energy demand and the energy intensities of the vehicles in use. The average energy intensity across all passenger vehicles is assumed to have been around 1.8 MJ per kilometre in 2020 – which reflects the current vehicle fleet of cars (average energy demand of 1.5 MJ/pkm) and SUVs and pick-up trucks (2–6 MJ/pkm). The assumed average energy intensity for freight vehicles is calculated accordingly, assuming vans and mini-vans are the main transport vehicles. It is also assumed that ICEs and not electric drives are in use.

Table 13: Tunisia – projected passenger and freight transport demand under the T-1.5°C scenario

		2019	2020	2025	2030	2035	2040	2045	2050
Road: Passenger Transport Demand	[PJ/a]	97	93	100	93	67	64	59	63
Annual passenger-kilometres	[Million pkm]	36,175	34,678	40,201	46,604	54,026	62,631	72,607	84,171
Average energy intensity – passenger vehicles	[MJ/pkm]	1.88	1.88	1.88	1.75	1.71	1.66	1.63	1.60
Annual demand variation:	[%/a]			3.00%	3.00%	3.00%	3.00%	3.00%	3.00%
Kilometres per person per day	[km/person day]	3093	2934	3174	3557	4017	4549	5160	5880
Road: Freight Transport Demand	[PJ/a]	29	28	28	26	22	22	22	23
Annual freight kilometres	[Million tkm]	19,367	18,565	23,469	25,912	28,609	31,586	34,874	38,504
Average energy intensity – freight vehicles	[MJ/tkm]	1.51	1.51	1.20	1.14	1.11	1.08	1.07	1.06
Annual demand variation	[%/a]			2.00%	2.00%	2.00%	2.00%	2.00%	2.00%

The total numbers of passenger and freight kilometres are the basis for the projection of the future transport demand. The contraction of the transport demand in 2020 due to COVID is expected to end. It is anticipated that the pre-COVID transport demand of 2019 will be reached by 2023, and that the transport demand will increase with population growth and GDP. It is assumed that the annual pkm will increase by 3% annually until 2050, whereas the freight transport demand will increase by 2% annually. All assumptions and calculated energy demands are shown in Table 13. The energy intensities for all vehicles are assumed to decrease over time with the implementation of more-efficient engines, the phase-out of fossil-fuel-based drives, and their replacement with electric drives. To achieve the terms of the Paris Climate Agreement, all energy-related CO_2 emissions must be phased-out by 2050. Therefore, all fossil-fuel-based vehicles must be phased-out, and electric drives will dominate, supplemented with a limited number of biofuel-based vehicles.

The energy required by freight vehicles to move 1 tonne for 1 kilometre will decrease from around 1.5 MJ to 1.11 MJ by 2030 and to 1.06 MJ by 2050. Both reductions will only be possible with high shares of electric drives. Figure 9 and Figure 10 show the development of drive trains for passenger and freight transport vehicles, respectively, over time. The electrification of large parts of these fleets is unavoidable if the transport sector is to be decarbonised. The supply of – sustainably produced – biofuels will be limited and will be directed to large commercial vehicles, buses, and the large trucks used in remote rural areas, where the required charging infrastructure for electric vehicles is unlikely to be developed in the next two decades.

Figure 9: Passenger transport – drive trains by fuel

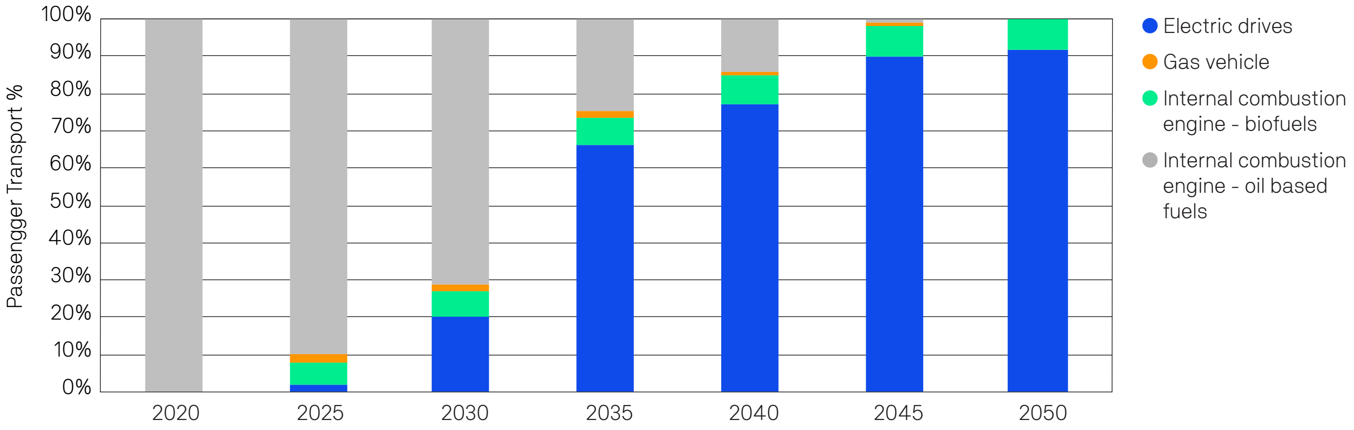
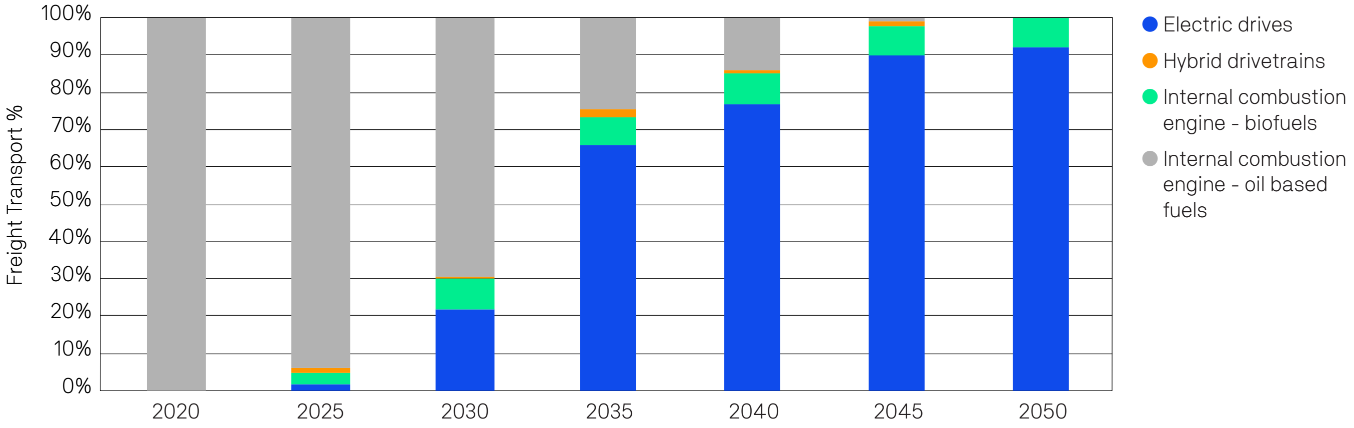


Figure 10: Freight transport – drive trains by fuel



Tunisia's 'Strategy of Carbon Neutral and Resilient Development to Climate Change' sets a 2050 target for carbon neutrality.[50] In section 4.1.4 Approaches and sectoral variations, the document highlights the need for transportation to be considered part of Tunisia's emission reduction strategy, both in terms of the use of public transport and electrification: "The Tunisian transport sector is energy-intensive and constitutes a significant source of carbon emissions. National carbon neutrality will be able to rely on an objective of decarbonisation of transport. Several solutions are possible, in particular the improvement of performance energy of light and heavy vehicles from here to 2030, then their systematic electrification … Concerning public transport, essential attention must be paid to the needs of travellers in order to give public transport a competitive advantage over individual modes."[51]

Supply-side barriers to e-vehicles

Currently, most e-vehicles are imported. The infrastructure required for electric mobility, in terms of maintenance and service centres and charging stations across urban and rural areas, is lagging. The resilience and reliability of the electricity supply – especially in rural areas – is still under development and faces challenges. Therefore, a rapid expansion of the charging infrastructure, which will increase the load even further, will depend on the progress of electricity services. However, the decarbonisation of Tunisia's energy sector will require increased electrification of the transport sector, and the expansion of a resilient power supply based on sustainable power generation technologies is essential.

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[50] Tunisia's submission to UNFCCC, Stratégie de Développement Neutre en Carbone et Résilient aux Changements Climatiques à l'horizon 2050', 2022

[51] ibid.

2.7 Technology and fuel cost projections

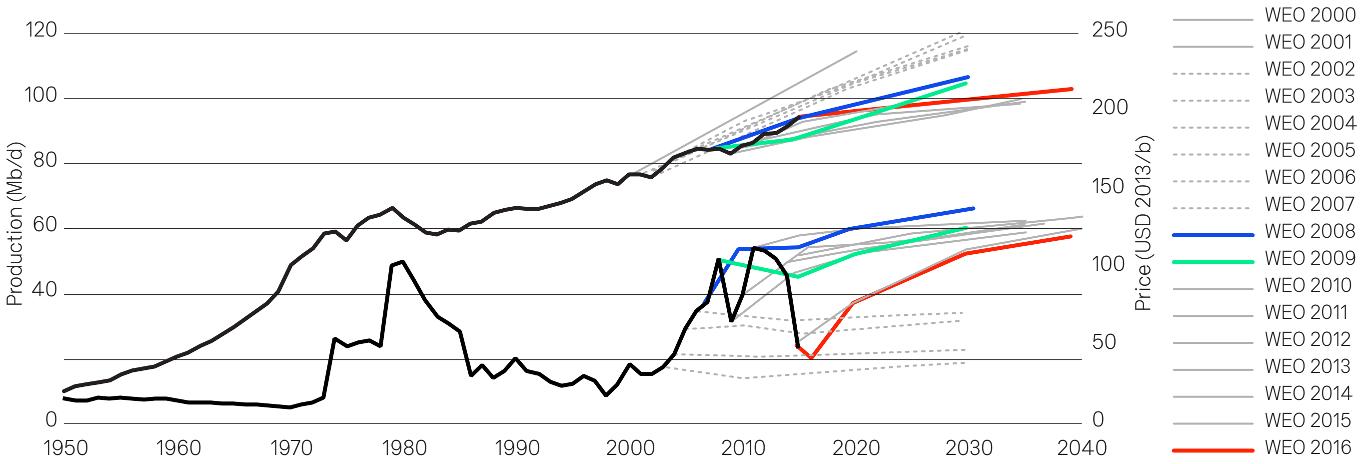
All cost projections in this analysis are based on a recent publication by Teske et al. (2019)[52]. Section 5.2 is based on Chapter 5 of that book, written by Dr. Thomas Pregger, Dr. Sonja Simon, and Dr. Tobias Naegler of the German Aerospace Center/DLR. The parameterisation of the models requires many assumptions about the development of the characteristic technologies, such as specific investments and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

The speed of an energy system transition also depends on overcoming economic barriers. These largely involve the relationships between the cost of renewable technologies and of their fossil and nuclear counterparts. For our scenarios, the projection of these costs is vital to ensure a valid comparison of energy systems. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs.

Moreover, efficiency measures generate costs that are usually difficult to determine, and depend on technical, structural, and economic boundary conditions. Therefore, in the context of this study, we have assumed uniform average costs of 3 cents per kWh of electricity consumption avoided in our cost accounting.

During the last decade, fossil fuel prices have seen huge fluctuations. Figure 11 shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar fluctuations (IEA 2017)[53]. Therefore, fossil fuel price projections have also seen considerable variations (IEA 201760; IEA 2013[54]) and this has influenced the scenario results.

Figure 11: Historical development and projections of oil prices (bottom lines) and historical world oil production and projections (top lines) by the World Energy Outlook (WEO), published by the International Energy Agency (IEA), according to Wachtmeister et al. (2018)



Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the IEA leading the way in 2018 (Roland Berger 2018)[55]. An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[56] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections showed errors of 40%–60%, even when made only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from US$70 to US$140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation,

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[52] Teske S (2019), Achieving the Paris Climate Agreement Goals – Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2.0 °C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019.

[53] IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

[54] IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

[55] Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. https://www.rolandberger.com/en/Insights/Publications/2018-oil-price-forecast-who-predicts-best.html. Accessed 10.9.2018 2018

[56] Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138–153. doi: https://doi.org/10.1016/j.apenergy.2018.03.013

the IEA provides a comprehensive set of price projections. Therefore, we have based our scenario assumptions on these projections, as described below.

However, because most renewable energy technologies provide energy without fuel costs, the projections of investment costs become more important than fuel cost projections, and this limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. These costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials to comparatively expensive energy crops. Because bioenergy has a significant market share in all sectors in many regions, a detailed assessment of future price projections is provided below.

Investment cost projections also pose challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most commonly used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[57]; Rubin et al. 2015[58]). Therefore, the reliability of cost projections largely depends on the uncertainty of future markets and the availability of historical data.

Fossil fuel technologies provide a large cost dataset featuring well-established markets and large annual installations. They are also mature technologies, so many cost-reduction potentials have already been exploited.

For conventional renewable technologies, the picture is more mixed. For example, like fossil fuels, hydro power is well established and provides reliable data on investment costs. Other technologies, such as solar PV and wind, are experiencing tremendous installation and cost-reduction developments. However, although solar PV and wind are the focus of cost monitoring and big data are already available on existing projects, their future markets are not readily predictable, as seen in the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA 2007, IEA 2014, and IEA 2017). Small differences in cost assumptions for PV and wind lead to large deviations in the overall costs, so cost assumptions must be made with particular care.

Furthermore, many technologies have only relatively small markets, such as geothermal, modern bio-energy applications, and concentrated solar power (CSP), for which costs are still high and for which future markets are insecure. The cost reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technology options in the long term after 2040, but their cost reduction potential cannot be assessed with any certainty today.

Therefore, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not internally calculated, we assume the same progressive cost developments for all scenarios. In the next sections, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment, fuel costs, and potential CO_2 costs in the scenarios.

2.7.1 Power technologies

The focus of cost calculations in our scenario modelling is the power sector. We compared the specific investment costs estimated in previous studies (Teske et al. 2015)[59], which were based on a variety of studies, including the European Commission-funded NEEDS project (NEEDS 2009), projections of the European Renewable Energy Council (Zervos et al. 2010)[60], investment cost projections by the IEA (IEA 2014), and current cost assumptions by IRENA and IEA (IEA 2016c). We found that investment costs generally converged, except those for PV. Therefore, for consistency, the power sector's investment and operation and maintenance costs are based primarily on the investment costs within WEO 2016 (IEA 2016c) up to 2040, including their regional disaggregation. We extended the projections until 2050 based on the trends in the preceding decade.

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[57] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255–261. doi: https://doi.org/10.1016/S0301-4215(00)00122-1

[58] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198–218. doi: https://doi.org/10.1016/j.enpol.2015.06.011

[59] Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T, Schmid S, Özdemir ED, Pagenkopf J, Kleiner F, Rutovitz J, Dominish E, Downes J, Ackermann T, Brown T, Boxer S, Baitelo R, Rodrigues LA (2015) Energy [R]evolution– A sustainable world energy outlook 2015. Greenpeace International.

[60] Zervos A, Lins C, Muth J (2010) RE-thinking 2050: a 100% renewable energy vision for the European Union. European Renewable Energy Council (EREC).

For renewable power production, we used investment costs from the 450-ppm scenario from IEA 2016c. For technologies not distinguished in the IEA report (such as geothermal combined heat and power [CHP]), we used cost assumptions based on our research (Teske et al. 2015). Because the cost assumptions for PV systems made by the IEA do not reflect recent cost reductions, we based our assumptions on a more recent analysis by Steurer et al. (2018)[61], which projects lower investment costs for PV in 2050 than does the IEA.

The costs for onshore wind were adapted from the same source (Steurer et al. 2018) to reflect more recent data. Table 14 summarises the cost trends for power technologies derived from the assumptions discussed above for Tunisia. It is important to note that the cost reductions are not a function of time but of cumulative capacity (production of units), so dynamic market development is required to achieve a significant reduction in specific investment costs. Therefore, overall, we might underestimate the costs of renewables in the REFERENCE scenario compared with those in the ***With the Existing Measures*** (WEM) scenario and the T-1.5°C pathway (see below).

However, our approach is conservative when we compare the REFERENCE scenario with the more ambitious renewable energy scenarios under identical cost assumptions. Fossil-fuel power plants have limited potential for cost reductions because they are at advanced stages of the technology and market development. The products of gas and oil plants are relatively cheap, at around US$670/kW and US$822/kW, respectively.

In contrast, several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are deployed extensively. Hydro power and biomass have remained stable in terms of costs. Tremendous cost reductions are still expected for solar energy and wind power, even though they have experienced significant reductions already. Whereas CSP might deliver dispatchable power at half its current cost in 2050, variable PV costs could drop to 35% of today's costs.

Table 14: Investment cost assumptions for power generation plants in US dollars (US$) and the local currency (trillion TND) by kW until 2050

Assumed Investment Costs for Power Generation Plants										
	2020		**2025**		**2030**		**2040**		**2050**	
Technology	[US$/ kW]	[TND/ kW]	[US$/ kW]	[TND/ kW]	[US$/ kW]	[TNDK/ kW]	[US$/ kW]	[TND/ kW]	[US$/ kW]	[TND/ kW]
Coal power plants	2,018	6,114	2,018	6,114	2,018	6,113	2,018	6,114	2,018	6,114
Diesel generators	908	2,751	908	2,751	908	2,751	908	2,751	908	2,751
Gas power plants	504	1,528	504	1,528	504	1,528	590	1,788	676	2,048
Oil power plants	938	2,843	918	2,782	898	2,721	847	2,568	827	2,507
Conventional renewables										
Hydro power plants*	2,674	8,101	2,674	8,101	2,674	8,101	2,674	8,101	2,674	8,101
New renewables										
PV power plants	878	2,659	744	2,255	736	2,232	520	1,574	474	1,437
Onshore wind	1,594	4,830	1,559	4,723	1,523	4,616	1,438	4,356	1,412	4,280
Offshore wind	3,723	11,280	3,097	9,385	2,472	7,489	2,207	6,687	2,119	6,420
Biomass power plants	2,371	7,184	2,346	7,107	2,320	7,031	2,174	6,588	2,129	6,450

*Values apply to both run-of-the-river and reservoir hydro power

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[61] Steurer M, Brand H, Blesl M, Borggrefe F, Fahl U, Fuchs A-L, Gils HC, Hufendiek K, Münkel A, Rosenberg M, Scheben H, Scheel O, Scheele R, Schick C, Schmidt M, Wetzel M, Wiesmeth M (2018) Energiesystemanalyse Baden-Württemberg: Datenanhang zu techoökonomischen Kenndaten. Ministerium für Umwelt Klima und Energiewirtschaft Baden-Württemberg, STrise: Universität Stuttgart, Deutsches Zentrum für Luft- und Raumfahrt, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Stuttgart.

2.7.2 Heating technologies

Assessing the costs in the heating sector is even more challenging than for the power sector. Costs for new installations differ significantly between regions and are interlinked with construction costs and industrial processes, which are not addressed in this study. Moreover, no data are available to allow the comprehensive calculation of the costs for existing heating appliances in all regions. Therefore, we have concentrated on the additional costs of new renewable applications in the heating sector.

Our cost assumptions are based on a previous survey of renewable heating technologies in Europe, which focused on solar collectors, geothermal energy, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies that can provide higher shares of heat demand from renewable sources are still under development and rather expensive. Market barriers will slow the further implementation of and cost reductions for renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in all scenarios.

Table 15 presents the investment cost assumptions for heating technologies, disaggregated by sector. Geothermal heating shows the same high costs in all sectors. In Europe, deep geothermal applications are being developed for heating purposes at investment costs ranging from €500/kWthermal (shallow) to €3000/kWthermal (deep), with the costs strongly dependent on the drilling depth. The cost reduction potential is assumed to be around 30% by 2050. No data are available for the specific situation in Tunisia. However, geothermal power and heating plants are not assumed to be built under any scenario.

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently cover a large bandwidth and are expected to decrease by only 20% to US$1450/kW by 2050.

We assume the appropriate differences between the sectors for biomass and solar collectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single-room stoves to heating or CHP plants on a megawatt scale. Investment costs show similar variations: simple log-wood stoves can be run for US$100/kW, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive to run. The running costs of log-wood or pellet boilers range from US$500 to US$1300/kW, and large biomass heating systems are assumed to reach their cheapest cost in 2050 at around US$480/kW for industry. For all sectors, we assume a cost reduction of 20% by 2050.

In contrast, solar collectors for households are comparatively simple and will become cheap to run, at US$680/kW, by 2050. The costs of simple solar collectors for service water heating might have been optimised already, whereas their integration into large systems is neither technologically nor economically mature. For larger applications, especially in heat-grid systems, the collectors are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be a cost reduction potential until 2050.

Table 15: Specific investment cost assumptions (in US$2015) for heating technologies in the scenarios until 2050

Investment Costs for Heat Generation Plants									
		2020		**2030**		**2040**		**2050**	
		[US$/ kW]	**[TND/ kW]**	**[US$/ kW]**	**[TND/ kW]**	**[US$/ kW]**	**[TND/ kW]**	**[US$/ kW]**	**[TND/ kW]**
Solar collectors	Industry	820	2,485	730	2,212	650	1,970	550	1,667
	In heat grids	970	2,939	970	2,939	970	2,939	970	2,939
	Residential	1,010	3,060	910	2,757	800	2,424	680	2,060
Geothermal		2,270	6,878	2,030	6,151	1,800	5,454	1,590	4,818
Heat pumps		1,740	5,272	1,640	4,969	1,540	4,666	1,450	4,394
Biomass heat plants		580	1,757	550	1,667	510	1,545	480	1,454
Commercial biomass heating systems	Commercial scale	810	2,454	760	2,303	720	2,182	680	2,060
Residential biomass heating stoves	Small scale/Rural	110	333	110	333	110	333	110	333

2.7.3 Renewable Energy costs in Tunisia In 2021

The following tables provide an overview of the assumed renewable energy costs in Tunisia. This information is based on research by the authors and energy scenario developments for various countries of the global south. The costs may also vary from region to region.

Table 16: Solar Home Systems – estimated costs

Solar Home Systems	**[TND]**	**[US$]**	**[US$/kWpeak]**
10 W	139	46	4,572
20 W	261	86	4,322
50 W	482	159	3,186
55 W	524	173	3,152
60 W	558	184	3,059
80 W	636	210	2,629
100 W	758	250	2,495
Institutional Solar Power Systems	**[TND]**	**[US$]**	**[US$/kWpeak]**
1000 W	6,899	2,277	2,277
2000 W	11,562	3,816	1,908

Table 17: Solar dryers – estimated costs

Solar Dryers [1 sqft = 0.0929 m²]	**[TND]**	**[US$]**	**[US$/m²]**
3–6 sqft (household) [	782	258	617
10–15 sqft (household)	1,776	586	505
> 21 sqft (institutional)	2,745	906	464

Table 18: Solar cookers – estimated costs

Solar Cookers	**[TND]**	**[US$]**
Parabolic – household	594	196
Parabolic – institutional	3,636	1,200

Table 19: Biomass stoves – estimated costs

Biomass Stoves	**[TND]**	**[US$]**
Institutional improved stove – type 1	1,179	389
Institutional improved stove – type 2	1,236	408
Institutional improved stove – type 3	1,470	485
Natural draft stove	106	35
Forced draft stove	215	71
Improved metallic stove	294	97

Source of Tables 16 – 19: UTS-ISF own research, March 2023

2.7.4 Fuel cost projections

Fossil Fuels

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions up to 2040 on ***World Energy Outlook 2023*** (IEA 2023). Beyond 2040, we extrapolated the price developments between 2035 and 2040 and present them in Table 20. Although these price projections are highly speculative, they provide prices consistent with our investment assumptions.

Table 20: Development projections for fossil fuel prices in US$2015 based on World Energy Outlook 2023 (STEPS) (IEA 2023)

Development Projections for Fossil Fuel Prices										
	2019		2025		2030		2040		2050	
All Scenarios	[US$/GJ]	[TND/GJ]	[US$/GJ]	[TND/GJ]	[US$/GJ]	[TND/GJ]	[US$/GJ]	[TND/GJ]	[US$/GJ]	[TND/GJ]
Oil	8.5	26	12	36	11	33	10	30	10.5	32
Gas	9.8	30	20	61	10	30	11	33	12	36
Coal	3.2	10	3.5	11	4	12	3.8	12	3.5	11

2.7.5 Biomass prices

Biomass prices depend on the quality of the biomass (residues or energy crops) and the regional supply and demand. The global variability is large. Lamers et al. (2015)[62] reported a price range of €4–€4.8/GJ for forest residues in Europe in 2020, whereas agricultural products might cost €8.5–€12/GJ. Lamers et al.69 modelled a range for wood pellets from €6/GJ in Malaysia to €8.8/GJ in Brazil. IRENA modelled a cost supply curve on a global level for 2030, ranging from US$3/GJ for a potential of 35 EJ/yr up to US$8–10/GJ for a potential of up to 90–100 EJ/yr (IRENA 2014) (and up to US$17/GJ for a potential extending to 147 EJ).

Bioenergy prices in Tunisia in 2021

Table 21: Biogas prices – small quantities – in Tunisia by region

	2 m³		4 m³		6 m³		8 m³	
Biogas	[TND]	[US$]	[TND]	[US$]	[TND]	[IS$]	[TND]	US$]
Household – low cost assumption	1,245	411	1,779	587	2,048	676	2,291	756
Household – average cost assumption	1,457	481	1,960	647	2,268	749	2,474	817
Household – high cost assumption	1,670	551	2,142	707	2,488	821	2,657	877

Source: UTS-ISF own research, March 2023

Table 22: Biogas prices – medium quantities – in Tunisia by region

	12.5 m³		40 m³		60 m³		100 m³	
Biogas	[TND]	[US$]	[TND]	[US$]	[TND]	[US$]	[TND]	[US$]
Household – low cost assumption	6,578	2,171	18,953	6,255	25,161	8,304	36,699	12,112
Household – average cost assumption	7,201	2,377	20,122	6,641	28,952	9,555	42,182	13,922
Household – high cost assumption	7,823	2,582	21,292	7,027	32,742	10,806	47,665	15,731

Source: UTS-ISF own research, March 2023

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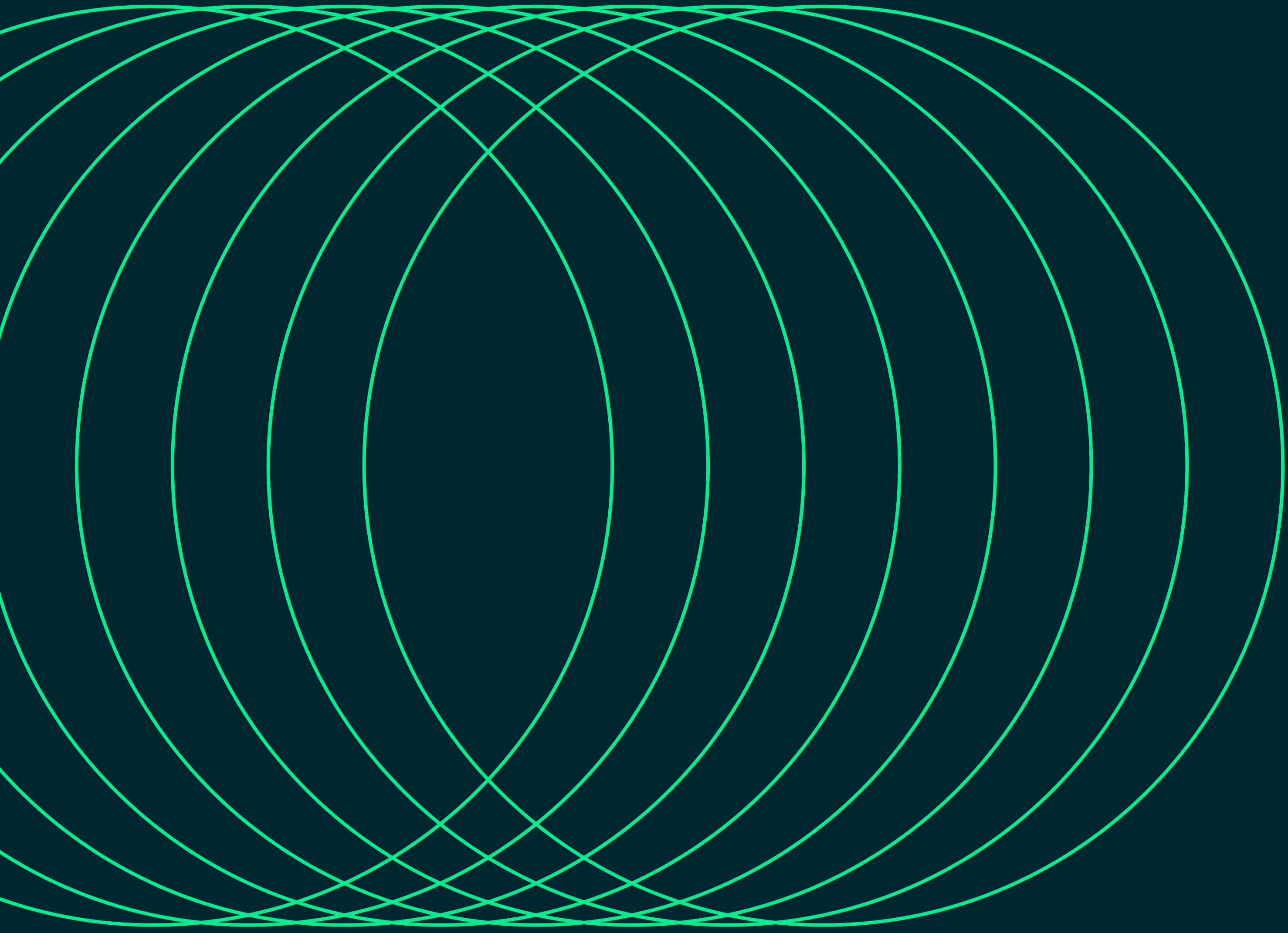
[62] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A (2015) Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. GCB Bioenergy 7 (4):618–634. doi: https://doi.org/10.1111/gcbb.12162

3

Tunisia: Renewable Energy Potential



Tunisia's solar and wind potential was assessed as an input for energy scenario development. In this section, we examine the technical potential under space-constrained conditions.

3.1 The [R]E SPACE Methodology

The [R]E Space methodology is part of the One Earth Climate Model (OECM) methodology. GIS mapping was used to ascertain Tunisia's renewable energy resources (solar and wind). It was also used in the regional analysis of geographic and demographic parameters and the available infrastructure that could be leveraged in developing the scenarios. Mapping was performed with the software ESRI ArcGIS10.6.1, which allows spatial analysis and maps the results. It was used to allocate solar and wind resources and for the demand projections for the eight modelling regions. Population density, access to electricity infrastructure, and economic development projections are key input parameters in the region-specific analysis of Tunisia's future energy situation, to clarify the requirements for additional power grid capacities and/or micro-grids.

The [R]E Space methodology is part of the OECM methodology, used to map solar energy potential and onshore energy potential[63]. Open-source data and maps from various sources were collected and processed to visualise the country, its regions, and districts. Further demographic data related to the population and poverty were plotted on the maps, together with transmission networks and power plants. The main data sources and assumptions made for this mapping are summarised in Table 23.

Table 23: Tunisia – [R]E 24/7 – GIS-mapping – data sources

Data	Assumptions	Source
Land cover	Land cover classes suitable for solar energy and wind energy production were identified from Copernicus Global Land Cover 2019.	Copernicus Global Land Cover– 2019[64]
Digital Elevation Model (DEM)	For both wind and solar analyses, any land with a slope of > 30% was excluded from all scenarios.	SRTM Digital Elevation Data Version 4[65]
Population and Population Density	A population census was conducted in 2021 by the National Statistics Institute.	National Statistics Institute (Statistiques Tunisie)
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Database on Protected Areas[66]
Power Plants, Transmission Lines, and Network	Solar and wind potential of areas ≤ 10 km from transmission lines was considered (Scenario 2).	Global Power Plant Database (v1.3.0)[67] The World Bank, Tunisia – Electricity Transmission Network (2017)[68]
Solar Irradiance (Direct normal irradiation, DNI)	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m2 per year (2.7–13.6 kWh/m2 per day).	Global Solar Atlas[69]
Wind Speeds	Wind speeds ≥ 5 m/s were considered at a height of 100 m.	Global Wind Atlas[70]

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[63] Miyake S, Teske S, Rispler J, and Feenstra M (2024) Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20). Renewable and Sustainable Energy Reviews 202: 114622. https://doi.org/10.1016/j.rser.2024.114622

[64] Copernicus Global Land Cover–2019: https://land.copernicus.eu/global/products/lc

[65] SRTM Digital Elevation Data Version 4: https://srtm.csi.cgiar.org/

[66] World Database on Protected Areas: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA

[67] Global Power Plant Database (v1.3.0): https://datasets.wri.org/dataset/globalpowerplantdatabase

[68] Tunisia– Electricity Transmission Network: https://datacatalog.worldbank.org/search/dataset/0040234 For Tunisia, only high-voltage transmission lines (400 kV and 225 kV) were available.

[69] Global Solar Atlas: https://globalsolaratlas.info/map

[70] Global Wind Atlas: https://globalwindatlas.info/en

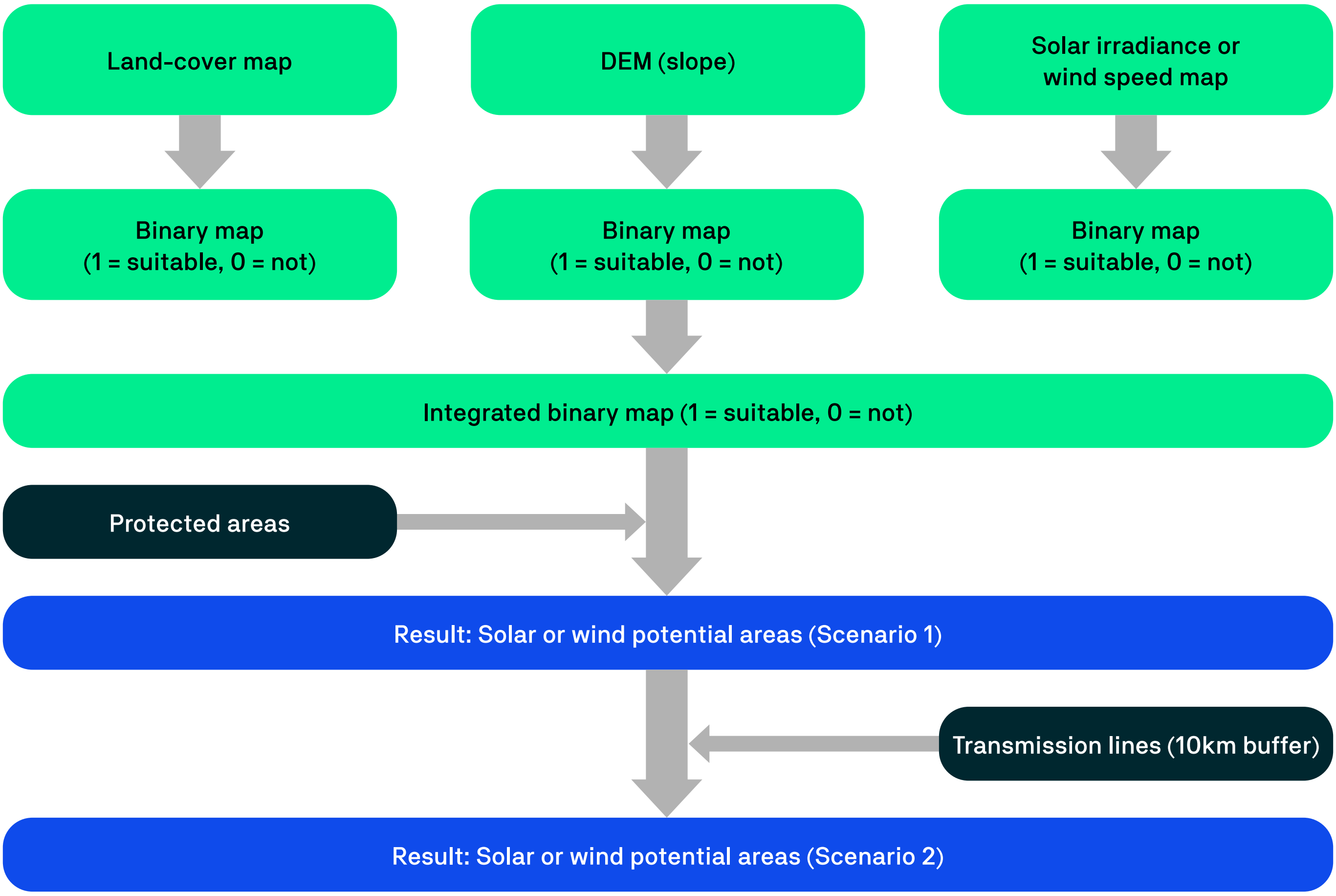
The [R]E Space mapping procedure is summarised in Figure 12. The land areas available for potential solar and wind power generation were calculated and visualised at the national and provincial levels with ArcGIS. The land-cover map, elevation (digital elevation model, DEM), World Database of Protected Areas, solar irradiation (direct normal irradiation, DNI) and wind speed data were obtained from the websites cited above as raster data, and were all converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) based on all the assumptions in Table 23. They were then combined into one binary map by overlaying all the raster data. This map integrates all the criteria cited above in one map with a value of 1 (land included in the potential area) or a value of 0 (land not included in the potential area).

Data on transmission lines and protected areas exist as vector data. For Tunisia, spatial data for high-voltage transmission lines (400 kV and 225 kV) were only available for the GIS mapping process. As mentioned in section 2.2, ISF was able to use the details provided in the Res4Africa Foundation report to accurately implement interconnection limits between modelling regions in the 24-7 MATLAB model. However, this map could not be included in the GIS mapping process because the data type of the image and GIS files was incompatible and the data quality poor. The updated infrastructure map used only for electricity system modelling constraints included a range of interconnection ratings spanning across the country (90 kV, 150kV, 225kV, 400kV). All protected areas were excluded from the above value-1 areas in the integrated raster data using a mask layer generated from the 'erase' function.

For Scenario 2 (see Figure 12), buffer layers were generated from data on high-voltage transmission lines (10 km), and then the raster data outside the protected areas were clipped by these buffer layers to generate potential area maps under Scenario 2. This input was fed into the calculations for the [R]E 24/7 model, as described below.

Disclaimer: The environmental criteria used to identify suitable areas for utility scale solar and wind projects do not reflect the current legislation in Tunisia, and the potential provided is a conservative estimate and may ultimately be larger.

Figure 12: [R]E Space Methodology – solar potential analysis and wind potential analysis



3.2 Mapping methodology for offshore wind

Offshore wind energy potential in Tunisia is also mapped for two scenarios. Open-source data and maps from various sources were collected and processed to visualise the offshore potentials.

Table 24: Tunisia – Offshore wind – GIS-mapping – data sources

Data	Assumptions	Source
Gridded Bathymetry Data – Water depth	For offshore wind map, two scenarios are generated: areas with water depth > 50 m or areas with water depth > 500 m were excluded from all scenarios.	GEBCO_2023 Grid [71]
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Database on Protected Areas
Ports	100 km radii from ports are marked on the map.	World Port Index 2019[72]
Maritime boundaries		Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM) (version: 11)[73]
Wind Speeds	Wind speeds ≥ 6 m/s at a height of 100 m were considered.	Global Wind Atlas

The mapping procedure for offshore wind potential involved gridded bathymetry data or water depth, for marine and coastal protected areas in the World Database of Protected Areas, and wind speed data (≥ 6 m/s). Similar to the [R]E Space methodology, all data were converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) based on all the assumptions in Table 24, and then combined into one binary map by overlaying all the raster data. Data from the World Port Index 2019 was used to map the locations of ports and their 100 km radii.

3.3 Mapping Tunisia

Despite having great solar and wind resources, Tunisia's electricity supply has almost entirely been supplied by gas generation, with percentages regularly > 95% between 2005 and 2020. (Of the 16 years in that range, gas generation accounted for > 95% of electricity supply in 11 of them).[74] The following sections outline exactly how much wind and solar potential Tunisia has, including the mapping outputs from the [R]E Space methodology.

3.3.1 Solar Potential

The average annual solar irradiation (DNI) in Tunisia is 1,141–2,262 kWh/m^2/year, and the higher end of that range is in the southern parts of the country, particularly the South Dessert region.

Tunisia's solar potential has been mapped under two different scenarios.

- **Scenario 1:** Available land – excluding protected areas (PA), extreme topography (slope > 30% [mountainous areas], S30), and certain land-cover classes, including closed forests, wetlands, moss and lichen, snow and ice, and water (permanent water bodies) (LU).
- **Scenario 2:** See 1, with the additional restriction that excludes areas ≤ 10 km from existing high voltage transmission lines (PT10).

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[71] GEBCO_2023 Grid: https://www.gebco.net/data_and_products/gridded_bathymetry_data/

[72] World Port Index 2019: https://msi.nga.mil/Publications/WPI

[73] Maritime Boundaries Geodatabase: http://comlmaps.org/how-to/layers-and-resources/boundaries/maritime-boundaries-geodatabase/

[74] IEA World Energy Balances

Table 25: Tunisia's potential for solar photovoltaic

Scenarios	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Regions	Solar Potential Area (km²)	Solar Potential (GW)	Solar Potential Area (km²)	Solar Potential (GW)
1. Greater Tunis	2,413	60	1,724	43
2. North-eastern	8,563	214	3,843	96
3. North-western	14,801	370	5,244	131
4. Central Coastal	12,905	323	6,762	169
5. Central Western	21,336	533	4,379	109
6. South-western	11,234	281	56	1
7. South Coastal	15,289	382	5,233	131
8. South Dessert	53,208	1,330	2,792	70
TOTAL	**139,748**	**3,494**	**30,032**	**751**

Figure 13 shows the results of the spatial analysis of the solar potential areas under Scenario 1 (LU + PA + S30). The scenario provides 139,745 km^2 of areas with solar potential and a total potential for a utility-scale solar PV capacity of 3,494 GW. Scenario 1 excludes all protected areas and areas with slopes > 30% because installing solar panels in steep mountainous areas is unrealistic. Open forests, shrubs, herbaceous vegetation, bare/spare vegetation, agricultural land, and urban/built-up land-cover classes in the Copernicus Global Land Cover 2019 dataset are included. However, certain land-cover classes (e.g., closed forests, wetlands, water bodies) are excluded from the scenarios selected for the consideration of solar energy potential.

Figure 14 shows the solar potential areas for Scenario 2 (LU + PA + S30 + PT10). When the land area is restricted by its proximity to high voltage transmission lines (£10 km) relative to the 2017 data used in the GIS mapping, the potential solar areas decrease to 30,032 km^2. This is because most electricity and road infrastructure are predominantly developed in the highly populated areas around Tunis, the northern regions, and the coastal areas. Under Scenario 2, utility-scale solar farms in Tunisia can potentially harvest 751 GW of solar PV. This analysis only considers the areas in close proximity to the high-voltage lines because the data availability is limited. The areas of solar potential would increase significantly if areas close to high-voltage lines were included, as referenced in the RES4Africa report.

Main challenges for utility-scale solar PV are financing and political and economic stability, which would favour international co-operation

As discussed in section 2.1.3, Tunisia faces difficult and unstable economic and political situations. However, despite these challenging conditions, there is some cause for hope, particularly given Tunisia's willingness to implement a strategy of sustainable development. As stated by Alexandre Arrobbio, the World Bank's Country Manager for Tunisia, "there are significant opportunities for Tunisia to transform and strengthen its economy. With strategic investments, particularly in renewable energy, Tunisia could significantly enhance its economic resilience and sustainability."[75]

Given this context, securing project finance for large-scale projects remains a barrier for Tunisia to realise its significant amount of solar potential. Although small- and medium-scale projects are key to Tunisian citizens participation in the energy transition and the realisation of the economic benefits of low-cost solar, it must also realise large-scale projects in less-populated areas. For example, the areas of Kébili and Tataouine in the south have great renewable potential for both solar and wind, but have limited connections to Tunisia's grid. Therefore, large-scale investment is required to build such projects and connect them to the grid. International collaboration with other nations and companies will be necessary to ensure that these projects can be developed, financed, and built, given Tunisia's economic situation and the need to leverage the technical expertise and project experience of engineering firms. International collaboration will also help Tunisia access the economic benefits of exporting renewable energy to Europe.

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[75] ibid.

Figure 13: Tunisia – Areas of Solar Potential (Scenario 1: LU + PA + S30)

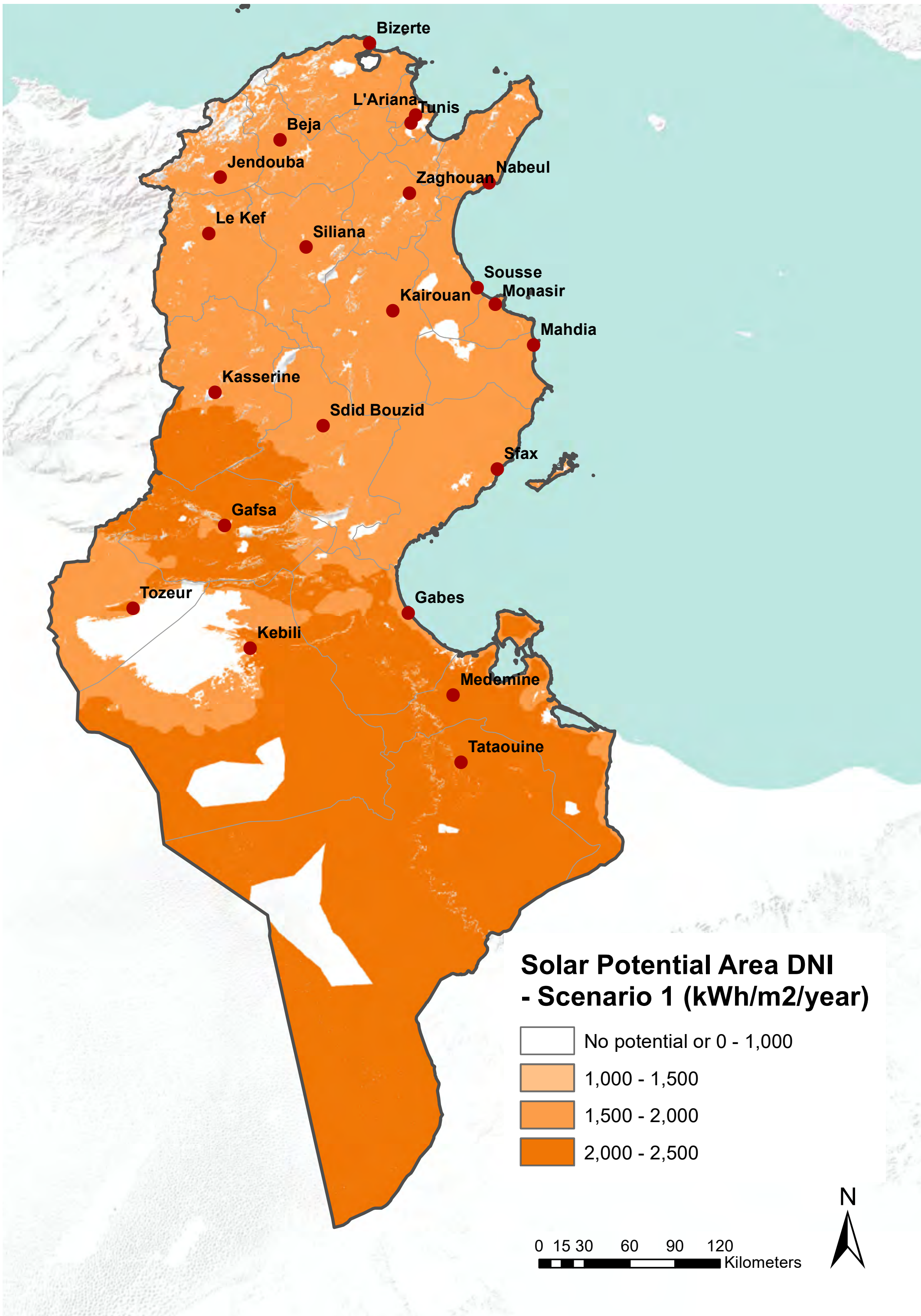
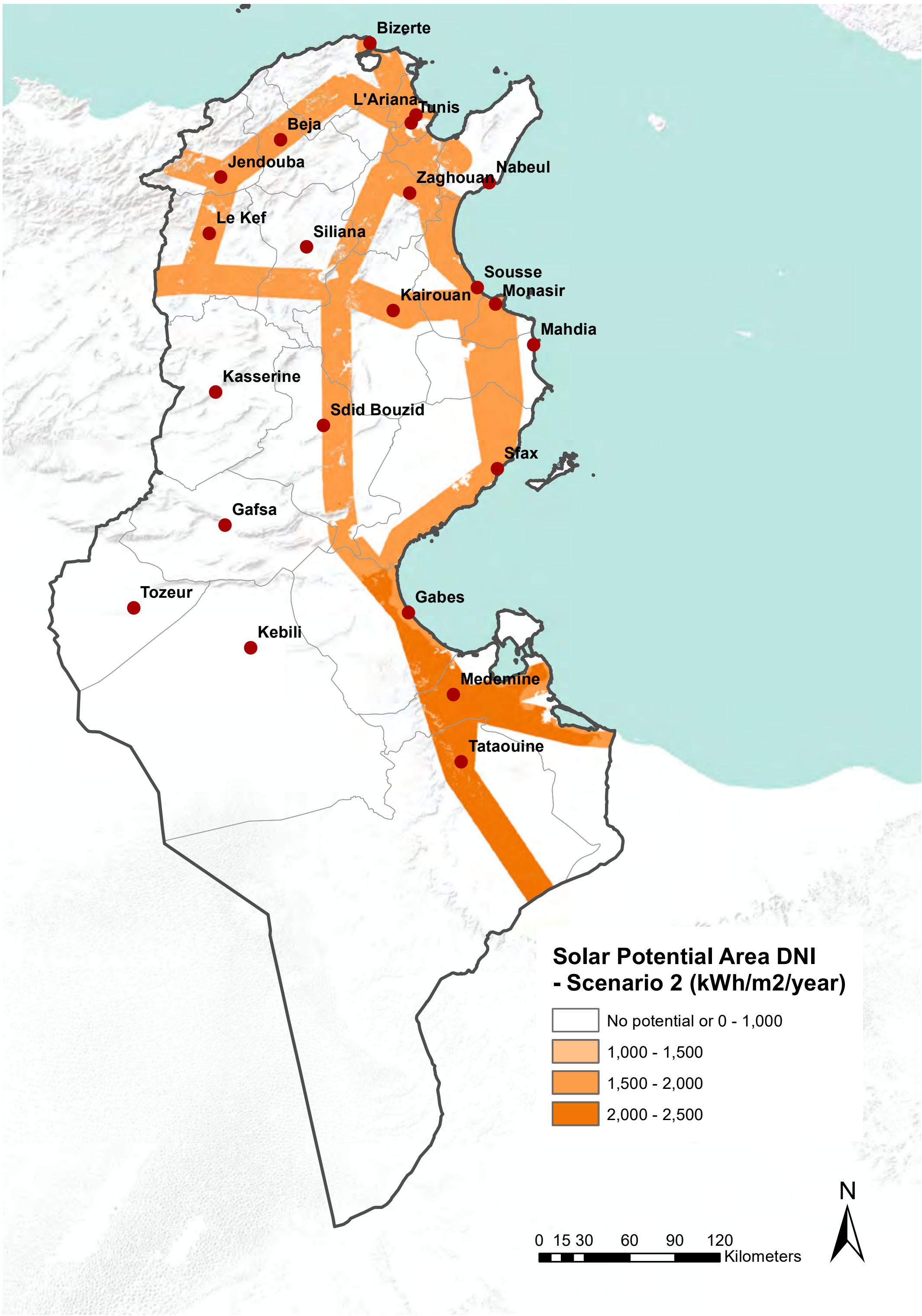


Figure 14: Tunisia – Areas of Solar Potential (Scenario 2: LU + PA + S30 + PT10)



3.3.2 Onshore Wind Potential

Tunisia also has large onshore wind energy potential. The wind speeds in Tunisia range from 3 m/s to 15.2 m/s at 100 m height, and high-wind-speed areas are predominantly located in the mid-northern region (Global Wind Atlas). In this analysis, we have included only areas with an average annual wind speed of ≥ 5 m/s. Tunisia's wind potential has been mapped under two different scenarios.

- **Scenario 1:** Available land – excluding protected areas (PA), topography (slope > 30% [mountain areas], S30), and existing land use, including forests and urban areas (LU).
- **Scenario 2:** See 1, with the additional restriction excluding areas ≤ 10 km from existing transmission lines (PT10).

Open forest, shrubs, herbaceous vegetation, bare/sparse vegetation, and agricultural land were included in the available land (LU) for the two wind scenarios, whereas the land-cover classes closed forests, wetland, moss and lichen, urban/built up areas, snow and ice, and permanent water bodies were excluded from this analysis of wind potential.

Table 26 shows that the overall wind potential under all restrictions is 661 GW for Scenario 1 (132,165 km^2). Overall, the spatial analysis identified slightly limited wind potential in Tunisia, especially under Scenario 2 (133 GW from 26,525 km^2) because there are few areas with an annual wind speed of ≥ 5 m/s and most of these areas are not located within close proximity to high-voltage transmission lines (≤ 10 km). The onshore wind potential area would increase significantly if areas closes to high-voltage lines were included, as referenced in the RES4Africa report.

Table 26: Tunisia's potential for utility-scale onshore wind power

Scenarios	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Regions	Onshore Wind Area (km^2)	Onshore Wind Potential (GW)	Onshore Wind Area (km^2)	Onshore Wind Potential (GW)
1. Greater Tunis	2,016	10	1,380	7
2. North-eastern	8,219	41	3,703	19
3. North-western	11,330	57	3,502	18
4. Central Coastal	12,099	60	6,152	31
5. Central Western	19,805	99	3,963	20
6. South-western	55,414	55	55	0
7. South Coastal	73,985	74	5,022	25
8. South Dessert	264,084	264	2,747	14
Total	**132,165**	**661**	**26,525**	**133**

Figure 15: Tunisia – Areas of Onshore Wind Potential (Scenario 1: LU + PA + S30)

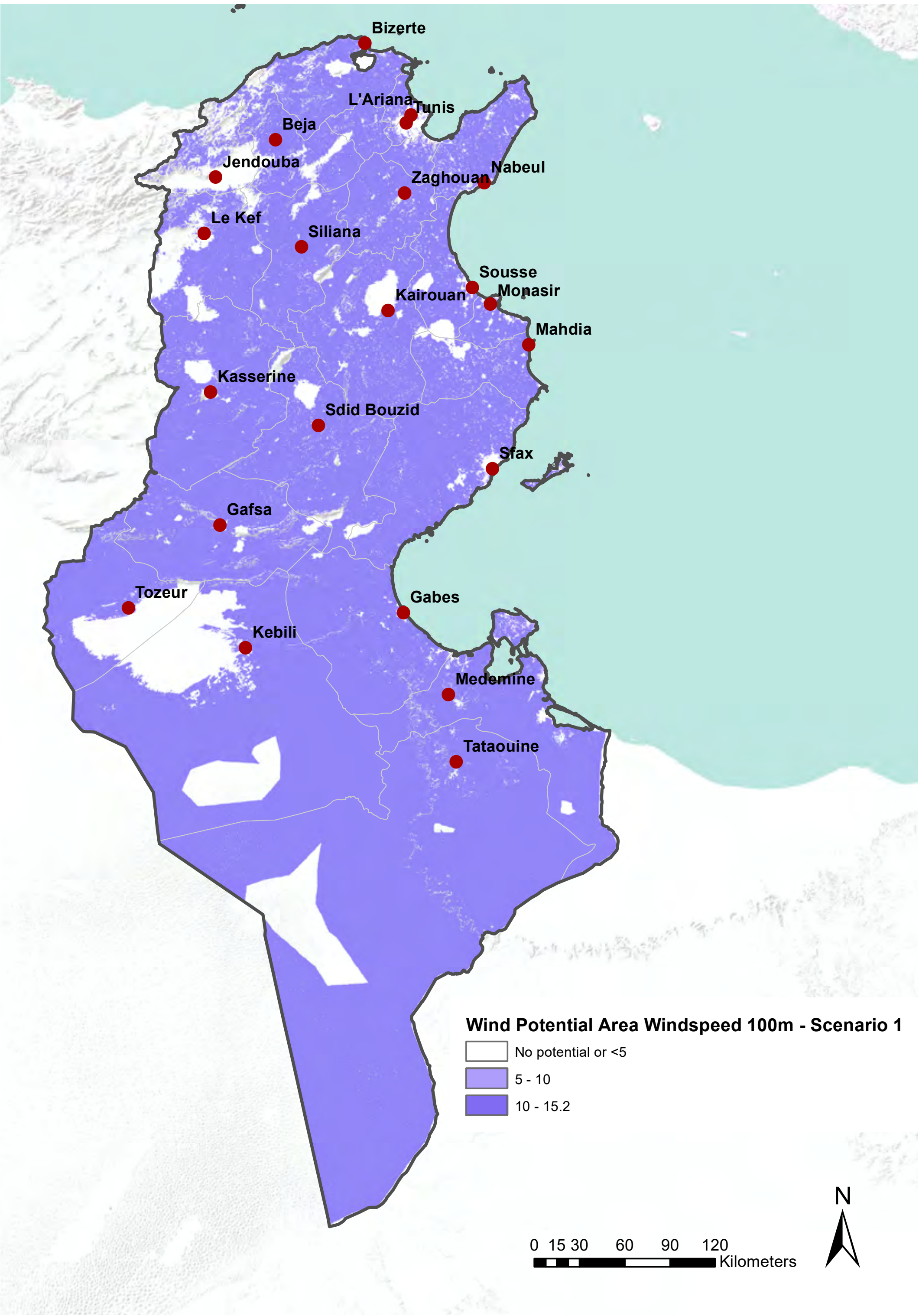
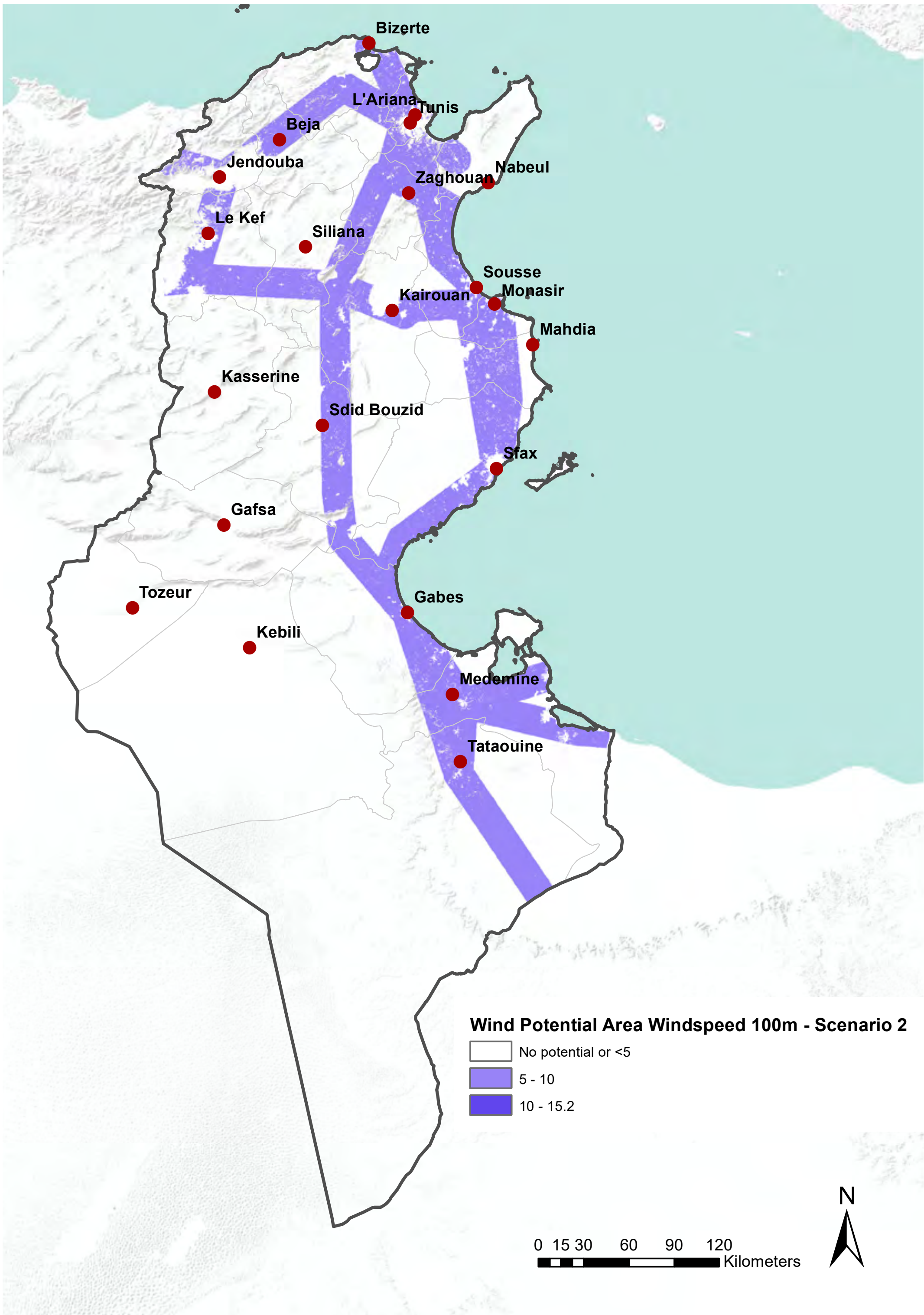


Figure 16: Tunisia – Areas of Onshore Wind Potential (Scenario 2: LU + PA + S30 + PT10)



3.3.3 Offshore Wind Potential

Tunisia has a long coastline of shallow waters on the Mediterranean Sea, offering great offshore wind potential. The wind speeds in the offshore areas of Tunisia range from 5.0 m/s to 9.7 m/s at 100 m height. For the offshore wind analysis, we included areas with an average annual wind speed of ≥ 6 m/s because offshore wind projects usually require higher wind speeds for economic viability than onshore projects. Tunisia's wind potential was mapped under two different scenarios.

- **Scenario 1:** Available offshore areas – excluding protected areas (PA), and water depths of ≤ 50 m (WD50) (PA + WD50).
- **Scenario 2:** Available offshore areas – excluding protected areas (PA), and water depths of ≤ 500 m (WD500) (PA + WD500).

Tunisia can expect large potential offshore wind energy because it has a long coastline. The total offshore wind potential is 156,680 MW (157 GW) for Scenario 1 and 443,991 MW (444 GW) for Scenario 2. Figures 17 and 18 show the offshore wind potential areas for Scenario 1 and Scenario 2, respectively.

Figure 17: Tunisia – Areas of Offshore Wind Potential (Scenario 1)

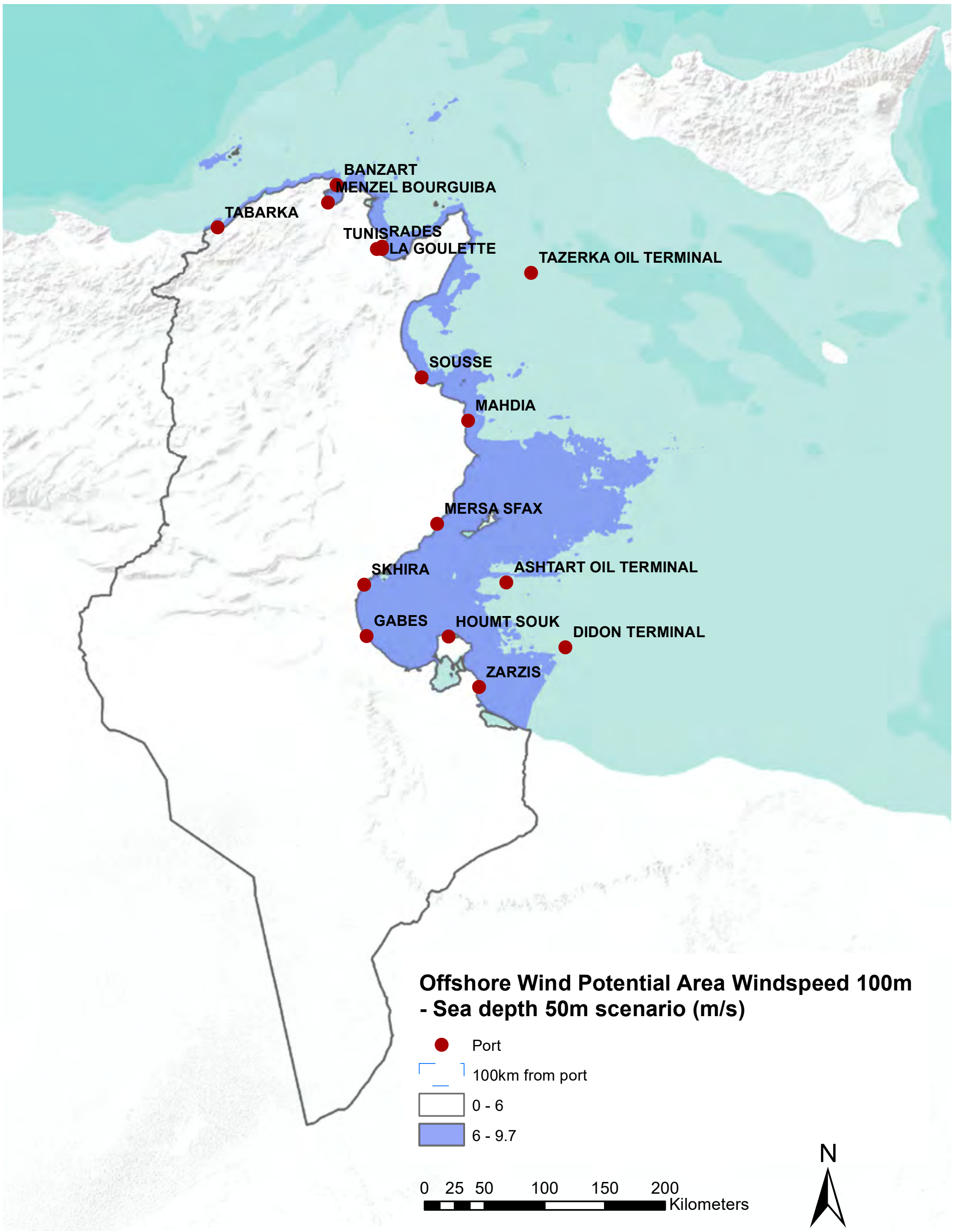
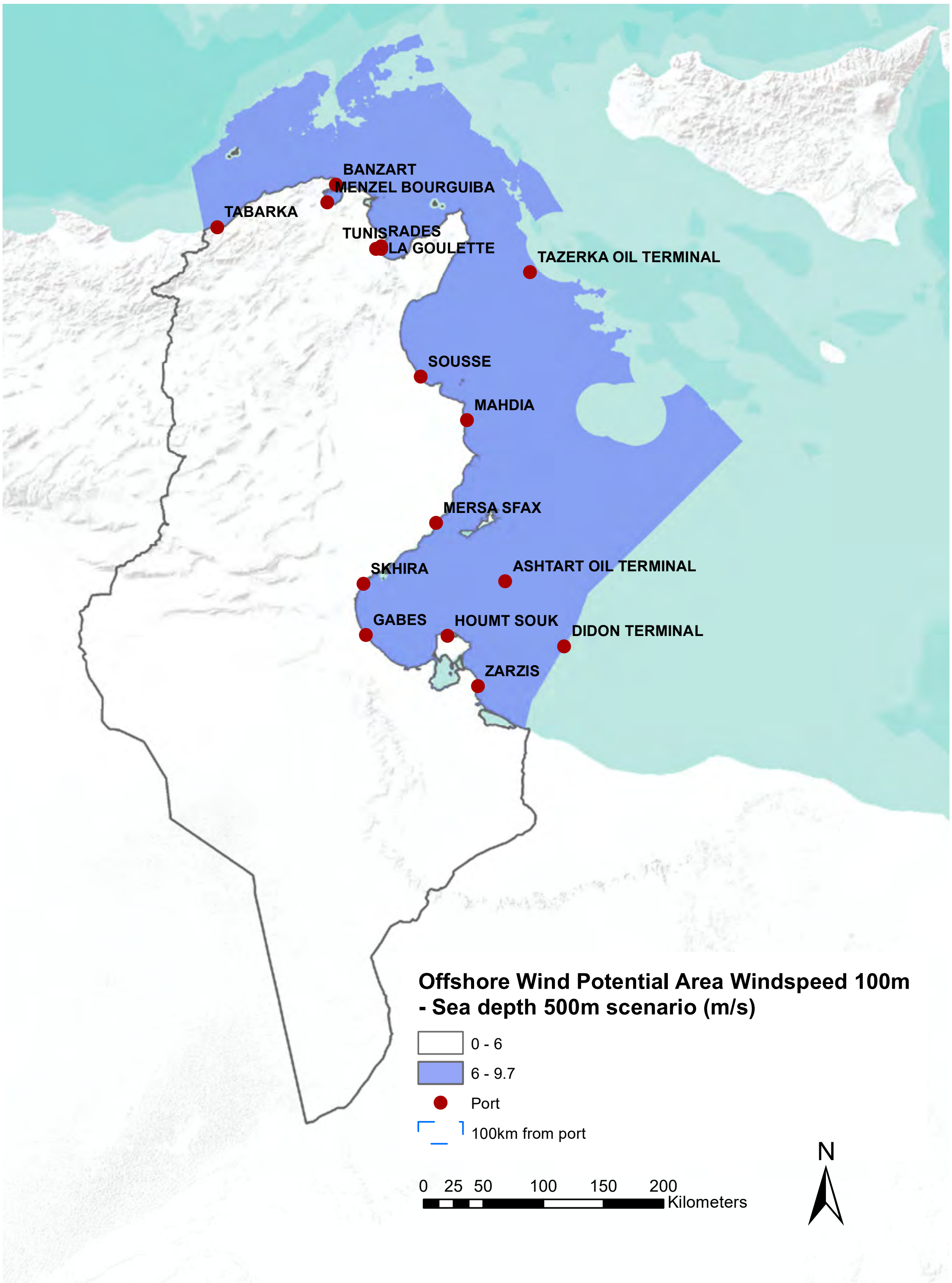


Figure 18: Tunisia – Areas of Offshore Wind Potential (Scenario 2)



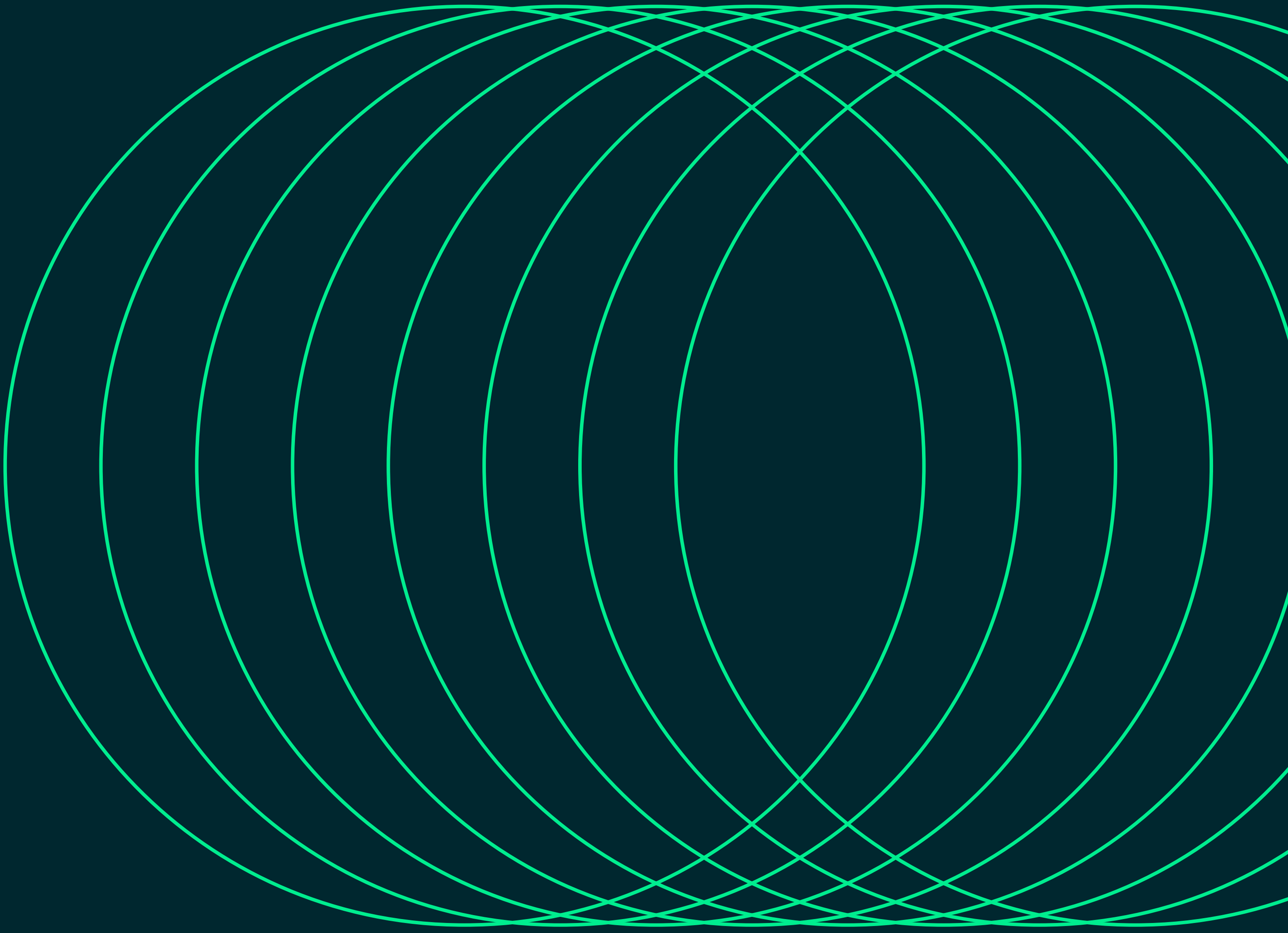
3.3.4 Assumptions for hydrogen and synfuel production

Under the Tunisia 1.5°C (T-1.5°C) scenario, hydrogen and sustainable synthetic fuels will be introduced as a substitute for natural gas. Unsustainable biomass will only play a minor role and will be used almost exclusively by industry after 2030. Hydrogen is assumed to be produced by electrolysis, generating an additional electricity demand that will be supplied by the extra renewable power production capacity, predominantly solar PV and hydro power. Renewable hydrogen and synthetic fuels will be essential for a variety of sectors.

- In the industry sector, hydrogen will be an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes whenever the direct use of renewable electricity is not applicable.
- The transport sector will also rely increasingly on hydrogen as a renewable fuel, where battery-supported electric vehicles reach their limits and where limited biomass potential restricts the extension of biofuel use. However, future hydrogen applications may be insufficient to replace the whole fossil-fuel demand, especially in aviation, heavy-duty vehicles, and navigation. The T-1.5°C scenario introduces synthetic hydrocarbons from renewable hydrogen, electricity, and biogenic/atmospheric CO_2. These synthetic fuels will be introduced after 2030 and provide the remaining fossil-fuel demand that cannot be met with biofuels because their potential is limited.

4

Areas of Forest Loss in Tunisia



The Food and Agriculture Organisation of the United Nations (FAO) is a specialised agency that leads international efforts to abolish hunger and improve nutrition and food security. The FAO has published extensive food production data and other data related to agriculture and forestry.

According to the FAO[76], the forest area in Tunisia in 2020 was 7,027 km^2 (including 4,883 km^2 of naturally regenerated forest). There was an increase in forested areas of 9.1% from 1990 and of 5.2% from 2000 with an increase in plantation forests (Table 27). However, naturally regenerated forest areas decreased by 0.6% in Tunisia between 2000 and 2020.

Table 27: Extent of forest areas and net emissions from forested land in Tunisia (FAO)

Extent of Forest		
Year	**Areas (km^2)**	**Change from 1990**
1990	6,440	-
2000	6,679	+4.8%
2010	6,874	+9.0%
2020	7,027	+13.3%

Source: Extent of Forest (FAO Global Forest Resources Assessment Country Reports (2020)

Global Forest Watch reported that between 2001 to 2023, Tunisia lost 365 km^2 of tree cover (equivalent to a 16% reduction in tree cover since 2000), which generated 8.9 Mt of CO_2 equivalent (CO_2e) emissions. From 2013 to 2023, 84% of the tree cover loss in Tunisia occurred within natural forests[77]. The loss of forested areas in Tunisia also visualised with ArcGIS. The spatial dataset by Hansen et al. (2013) was used to highlight the forest loss in 2000–2023 (Figure 19). Areas of forest loss are predominantly found in northern regions (e.g., Biserte, Jendouba, Béja, Siliana, Le Kef). Table 28 shows the areas of forest loss (km^2), which were also estimated from Hansen et al.,[78] together with the estimated CO_2e emissions since 2000 (the baseline year of this dataset).

Table 28: Tunisia – areas of forest loss (km^2) and estimated CO_2e emissions from that forest loss

Years	Area (km^2)	CO_2e emissions (kilotonnes)
2001–2005	30	853
2006–2010	33	906
2011–2015	92	2,165
2016–2020	125	2,904
2021–2023	85	2,080
Total areas of forest loss (2001–2023)	**365**	**8,908**

Source: Global Forest Watch

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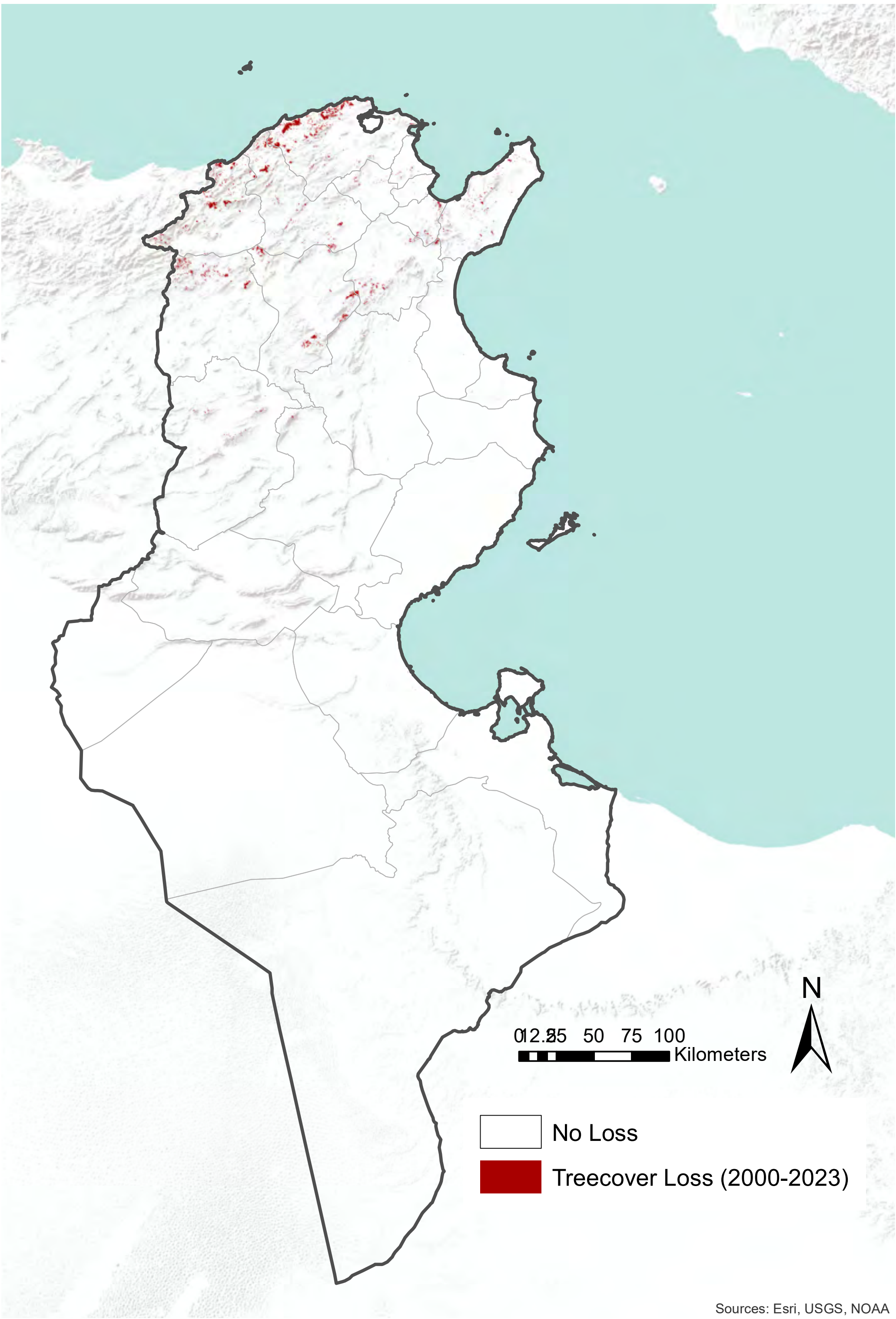
[76] FAO Global Forest Resources Assessment 2020 (Tunisia): https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/

[77] Global Forest Watch (Tunisia): https://www.globalforestwatch.org/dashboards/country/TUN/?location=WyJjb3VudHJ5IiwiVFVOIl0%3D&map=eyJjYW5Cb3VuZCI6dHJ1ZX0%3D

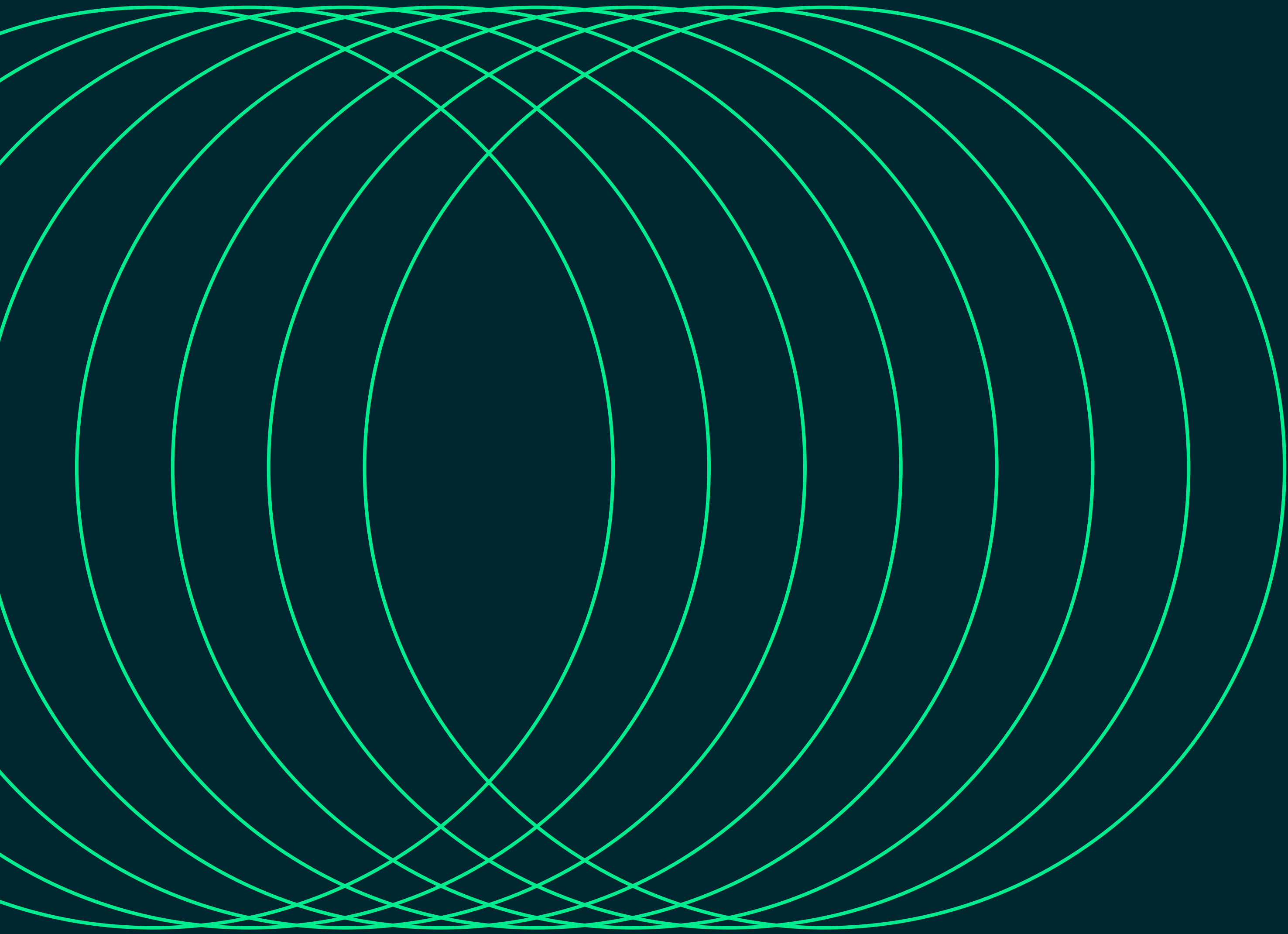
[78] Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov E, Chini L, Justice CO, Townshend JRG (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342 (15 November):850–853. Data available on-line at: https://glad.earthengine.app/view/global-forest-change.

Figure 19: Areas of forest loss in Tunisia in 2001–2023



Source: generated by ISF using data from Hansen et al. (2013)

5 Key Results – Long-term Scenario



Tunisia must build up and expand its power generation system to increase the energy access rate to 100%. Building new power plants – no matter the technology – will require new infrastructure (including power grids), spatial planning, a stable policy framework, and access to finance.

With lower solar PV and onshore wind prices, renewables have become an economic alternative to building new hydro and gas power plants. Consequently, renewables achieved a global market share of over 80% of all newly built power plants in 2021[79]. Tunisia has high-quality and substantial solar and wind resources, with either solar or wind potential alone able to cover projected electrical demand by 2050 many times over, based on GIS mapping results (projected demand in 2050: 57 TWh; solar potential of 6,100 TWh and wind potential of 1,900 TWh). The costs of renewable energy generation are generally lower with stronger solar radiation and stronger wind speeds. Improved political, economic, and policy s should allow Tunisia to circumvent higher investment risks and reduce project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building process for all scenarios includes assumptions about policy stability, the role of future energy utilities, centralised fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Tunisia will establish a secure and stable framework for deploying renewable power generation. Financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement that ensures a relatively stable price for a specific quantity of electricity is required to finance the project. However, daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any power plant with a technical lifetime of 20 years or longer.
- **Strengthened energy efficiency policies:** Existing policy settings – energy efficiency standards for electrical applications, buildings, and vehicles – must be strengthened to maximise the cost-efficient use of renewable energy and to achieve high energy productivity by 2030.
- **Role of future energy utilities:** With the 'grid parity' of roof-top solar PV below most current retail tariffs, this modelling assumes that the energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** Projections of population and GDP are based on historical growth rates. Projections of population growth are taken from the ***World Bank Development Indicators***[80].
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in the two scenarios target the firm capacity. Firm capacity is the "proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed."[81] Firm capacity is important to ensure a reliable and secure energy system. Note that variable renewable energy systems still have a firm capacity rating, and the combination of technology options increases the firm capacity of the portfolio of options.
- **Cost assumptions:** The cost assumptions are documented in Chapter 2.

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[79] REN21-Global Status report 2021.

[80] World Bank (2023) Reviewed on: https://data.worldbank.org/indicator/SP.POP.TOTL

[81] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf

5.1 The Reference Scenario

The One Earth Climate Model (OECM) builds on existing information. Table 31 provides an overview of the published energy scenarios and/or energy plans, including the National Determined Contribution (NDC). To compare the OECM for Tunisia, a new REFERENCE scenario has been developed because direct comparison with published energy plans is not possible because the sectoral breakdowns and technical resolutions differ.

Table 29: Tunisia – energy scenarios and parameters published in literature reviews

Tunisia – Parameter				
No.	**Key graphs drawn from our own modelling results:**	**One Earth Climate Model**	**Tunisia: National Determined Contribution (NDC)**	**Strategy of Carbon Neutral and Resilient Development to Climate Change at the 2050 Horizon**
1.	Final energy demand until 2050, according to sector (transport, industry, residential)	Yes		Reduction in primary energy intensity of 3.6%/year in 2020–2030, and a total reduction of 46% intensity by 2050
2.	Development of electricity demand until 2050 (TWh/a) (transport, industry, residential)	Yes		No
3.	Heat demand final energy [PJ/a] until 2050 (industry, residential)	Yes		No
4.	Development of road transport final energy [PJ/a] until 2050 (road passenger, road freight)	Yes		No
5.	Breakdown of electricity generation capacity [GW] until 2050 (according to source: PV, wind, biomass, hydrogen, fossil fuels)	Yes		No specific breakdown of renewable generation; target of 4 GW of renewable capacity by 2030 and 18 GW by 2050
6.	Energy supply for cooking heat [PJ/a] until 2050 (according to source: solar collectors, heat pumps, electric direct heating etc.)	Yes		No
7.	Installed capacity of renewable heat generation [GW] until 2050 (split by source)	Yes		No
8.	Transport energy supply by energy source [PJ/a] until 2050 (electricity, hydrogen, natural gas, synfuels, biofuels, fossil)	Yes		No
9.	Total primary energy demand by energy source [PJ/a] until 2050 (wind, solar, etc.)	Yes		No
10.	CO_2 emissions per sector [Mt/a] until 2050 (industry, buildings, transport, power generation, other)	Yes	45% reduction in carbon emissions by 2030 relative to 2010 levels (27% unconditional)	No
11.	Investment costs (billion $/a) until 2050	Yes	US$3.3 billion for unconditional goals, US$11.1 billion more for conditional goals	No
12.	Shares of cumulative investment in power generation 2020–2050	Yes		No
13.	Cumulative investment heating technologies 2020–2050	Yes		No
14.	Installed PV capacities up to 2050	Yes		No

5.1.1 Assumptions for the Tunisia 1.5°C scenario

The Tunisia 1.5°C (T-1.5°C) scenario is built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector. The main assumptions considered in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures taken to meet the CO_2 emissions reductions in the T-1.5°C scenario include strong improvements in energy efficiency, which will double energy productivity over the next 10–15 years, and the dynamic expansion of renewable energy across all sectors.
- **Growth of renewables industry:** Dynamic growth in new capacities for renewable heat and power generation is assumed based on current knowledge of the potential, costs, and recent trends in renewable energy deployment. Communities will play a significant role in the expanded use of renewables, particularly in terms of project development, the inclusion of the local population, and the operation of regional and/or community-owned renewable power projects.
- **Fossil-fuel phase-out:** The operational lifetime of gas power plants is approximately 30 years. Because Tunisia is dominated by gas infrastructure, gas will phased-out in parallel with renewable development (renewable development will be slower under the REFERENCE scenario). It may be the case that under the T-1.5°C scenario, gas plants will be phased-out before the end of their operational lifetimes.
- **Future power supply:** Solar PV and wind power are expected to be the main pillars of the future power supply, complemented by minor contributions of bioenergy and wind energy. The figures for solar PV combine those of both roof-top and utility-scale PV plants. Because Tunisia has high-quality solar and wind resources, it is envisioned that with sufficient diversity of resources spread across geographic locations, in conjunction with some offshore wind projects (which offer a more consistent wind resource than onshore projects), Tunisia will be able to transition towards a 100% renewable supply powered predominantly by variable power sources. The capacity of large hydro power remains relatively flat in Tunisia over the entire scenario period, whereas the quantities of bioenergy will increase slightly within the potential for sustainable biomass.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. Power generation from biomass and gas-fired backup capacities and storage are considered important for the security of supply in a future energy system and are related to the output of firm capacity discussed above. Storage technologies will increase after 2030, including battery electric systems, dispatchable hydro power, and hydro pump storage.
- **Electrification of transport:** Efficiency savings in the transport sector will result from fleet penetration by new, highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The scenario assumes the limited use of biofuels for transportation, given the limited supply of sustainable biofuels.
- **Hydrogen and synthetic fuels:** Hydrogen and synthetic fuels generated by electrolysis using renewable electricity will be introduced as a third renewable fuel in the transport sector, complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses; but the limited potential of biofuels, and probably battery storage, for electric mobility means it will be necessary to have a third renewable option in the transport sector. Alternatively, this renewable hydrogen could be converted into synthetic methane or liquid fuels, depending on the economic benefits (storage costs versus additional losses) and the technological and market development in the transport sector (combustion engines versus fuel cells). Because Tunisia's hydrogen generation potential is limited, it is assumed that hydrogen and synthetic fuels will be imported. Furthermore, hydrogen utilisation will be limited to the industry sector and is not expected to contribute more than 5% of industry's energy supply by 2050.

Tunisia's 1.5°C scenario (T-1.5°C) takes an ambitious approach to transforming Tunisia's entire energy system to an accelerated new renewable energy supply. However, under the T-1.5°C scenario, a much faster introduction of new technologies will lead to the complete decarbonisation of energy for stationary energy (electricity), heating (including process heat for industry), and transportation. In the transport sector, there will be a strong role for storage technologies, such as batteries, synthetic fuels, and hydrogen.

Under the T-1.5°C scenario, the share of electric vehicles will increase. This scenario also relies on a greater production of synthetic fuels from renewable electricity, for use in the transport and industry sectors. Renewable hydrogen will be converted into synthetic hydrocarbons, which will replace the remaining fossil fuels, particularly in heavy-duty vehicles and air transportation – albeit with the low overall efficiency typical of the synthetic fuel systems. Because renewable synthetic fuels require a (gas) pipeline infrastructure, this technology is not widely used in Tunisia's energy plan because the costs in the early development stages are relatively high. It is assumed that synthetic fuels and hydrogen will not enter Tunisia's energy system before 2040. Compensating for the high energy losses associated with producing synthetic fuels will require fundamental infrastructure changes, which seem too costly for a developing country. Electricity and hydrogen will play larger roles in the heating sector (mainly heat for industry), replacing fossil fuels. In the power sector, natural gas will also be replaced by hydrogen. Therefore, electricity generation will increase significantly under this scenario, assuming that power from renewable energy sources will be the main 'primary energy' in the future.

The T-1.5°C scenario also models a shift in the heating sector towards the increased direct use of electricity because of the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high-temperature process heat in industry. Increased implementation of a district heating infrastructure (interconnections of buildings in central business districts), bio-energy-based heat generation, and solar collectors and heat pumps for office buildings and shopping centres in larger cities is assumed, leading to an increase in electricity demand that partly offsets the efficiency savings in these sectors. A rapid expansion of solar and geothermal heating systems is also assumed.

The increasing shares of variable renewable power generation, principally from solar PV, will require the implementation of smart-grids and the fast interconnection of micro- and mini-grids with regional distribution networks, storage technologies such as batteries and pumped hydro, and other load-balancing capacities. Other infrastructure requirements will include an increasing role for the on-site generation of renewable process heat for industries and mining, and the generation and distribution of synthetic fuels.

5.1.2 Assumptions for the Tunisia Reference Scenario

The REFERENCE scenario for Tunisia has been developed based on the T-1.5°C scenario but assumes an implementation delay of 10–15 years. The REFERENCE scenario can be interpreted as a business-as-usual scenario aligned with some of the existing policies and targets outlined in Tunisia's National Determined Contribution (NDC) submission from 2021. For example, in the REFERENCE scenario, the total renewable capacity will reach 3.3 GW rather than the target of 3.8 GW, reflecting a transition towards renewables while maintaining some of the existing gas supply.

The key differences between scenarios are:

1. **Heating a sector:** In the REFERENCE scenario, the phase-out of oil and gas is delayed by 15 years for the residential, service, and industry sectors. Accordingly, electric heat pumps and solar collector systems will remain niche technologies until 2040, but will grow thereafter and increase their shares by 2050.
2. **Transport sector:** In the REFERENCE scenario, electric mobility will experience significant delays, whereas transport demand will increase as projected in the T-1.5°C scenario. Vehicles with ICEs will remain dominant until 2040. Market shares for electric vehicles will start to increase significantly from 2040 onwards. Biofuels will also increase in the road transport sector.
3. **Power supply:** In the REFERENCE scenario, the delayed electrification of the heating and transport sectors will lead to slower growth in the power demand than in the T-1.5°C scenario. It is also assumed that renewable power generation will not meet the increased electricity demand that arises when its implementation is delayed, and fossil-fuel-based power generation will therefore increase.

5.2 Tunisia – energy pathway until 2050

The following section provides an overview of the key results of the two different energy scenarios for Tunisia. The energy scenarios by no means claim to predict the future. Instead, they provide useful tools with which to describe and compare potential development pathways from the broad range of possible 'futures'. The T-1.5°C scenario was designed to demonstrate the efforts and actions required to achieve the ambitious objective of a 100% renewable energy system and to illustrate the options available to change our energy supply system into one that is truly sustainable. The scenarios may be used as a reliable basis for the further analysis of possible concepts and actions required to implement technical pathways to achieve measurable results.

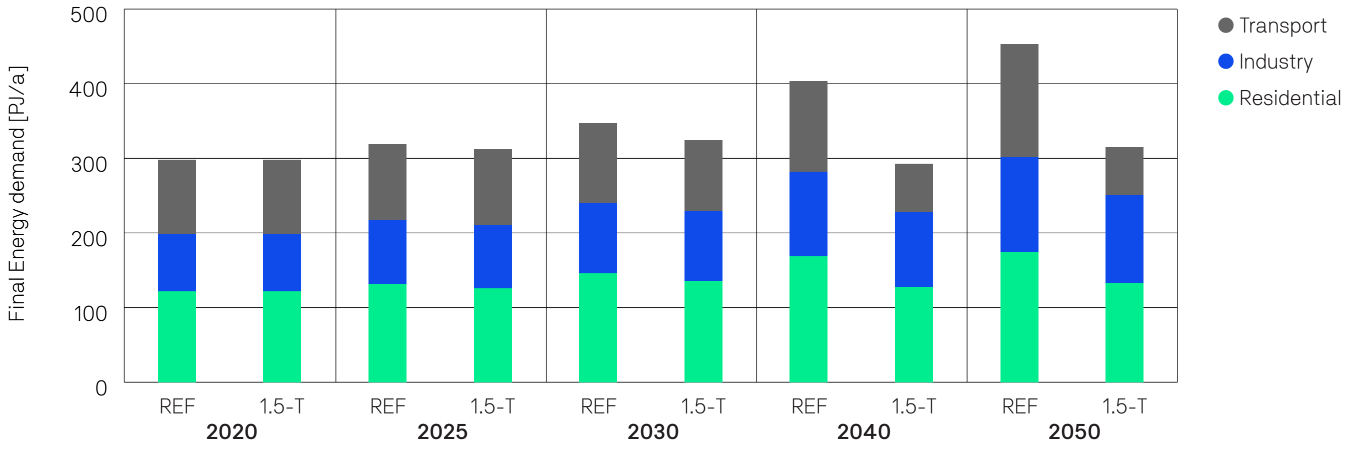
5.2.1 Tunisia – Final Energy Demand

The projections of population development, GDP growth, and energy intensity are combined to project the future development pathways for Tunisia's final energy demand. These are shown in Figure 20 for the REFERENCE and T-1.5°C scenarios. In the REFERENCE scenario, the total final energy demand will increase by 51% from 299 PJ/a to 453 PJ/a between 2020 and 2050. In comparison, in the T-1.5°C scenario, the total final energy demand will increase by 5% from 299 PJ/a to 315 PJ/a in the same period. The T-1.5°C scenario will reduce any additional costs by introducing a higher proportion of electric cars.

As a result of the projected continued annual GDP growth until 2050, the overall energy demand is expected to grow continuously under the REFERENCE scenario (Figure 20). However, due to the efficiency gains and electrification assumed in the transport and residential/building sectors, the T-1.5°C scenario will have a negligible final energy demand, largely thanks to the fact that electrical end uses will be much more efficient than their fossil-fuel counterparts (Figure 20). The residential and building sectors will remain somewhat dominant in Tunisia's energy demand under both scenarios, but under the REFERENCE scenario, the growth in fossil fuel use across transportation and industry will mean that these sectors grow as a proportion of the total demand. The energy demand of the transport sector will increase by 60% by 2050 under the REFERENCE scenario, whereas it will only be 68% of the 2020 value under the T-1.5°C scenario. The main reason for this significant difference in growth projections is the high rates of electrification in the T-1.5°C pathway.

The large efficiency gains achieved under the T-1.5°C pathway are attributable to the high electrification rates, mainly in the transport sector and in residential end uses, because combustion processes with high losses will be significantly reduced.

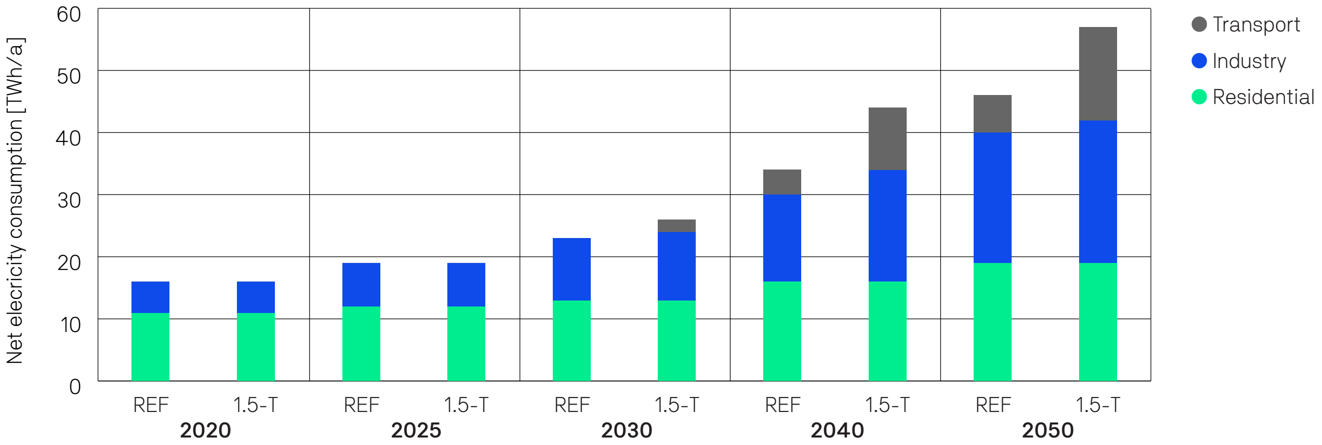
Figure 20: Projection of the total final energy demand by sector (excluding non-energy use and heat from combined heat and power [CHP])



The increased projected electrification of the heating, cooking, and transport sectors, especially under the T-1.5°C scenario, will lead to a significantly increased electricity demand (see Figure 21).

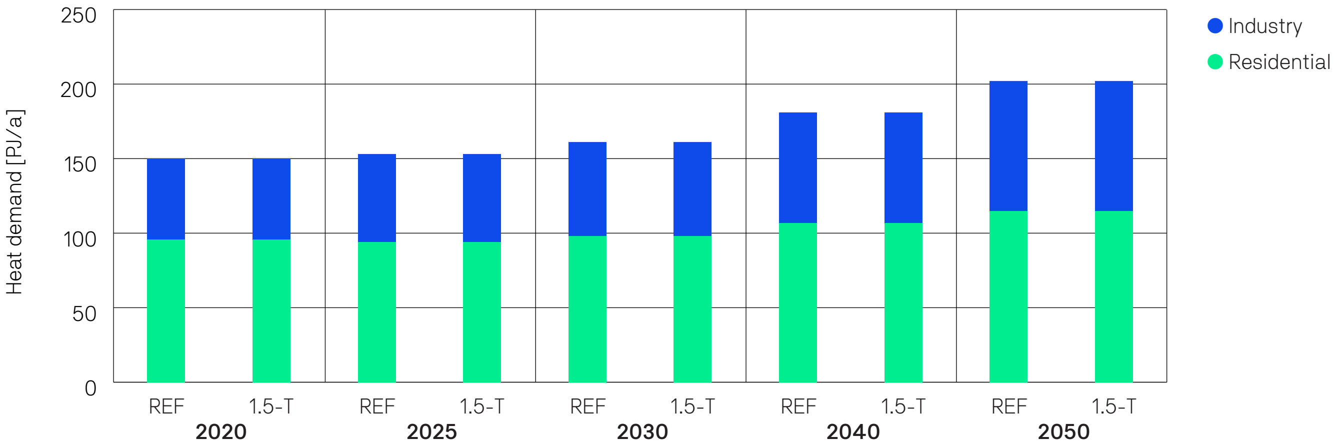
The T-1.5°C pathway will accelerate the electrification of the heating, cooking, and transport sectors more than other pathways, and aims to replace more fossil and biofuels with electricity. By 2050, Tunisia's electricity demand will increase to 57 TWh per year. Electricity will become the major renewable 'primary' energy, not only for direct use for various purposes, but also for the generation of a limited amount of synthetic fuels to substitute for fossil fuel in providing industrial process heat. Under the T-1.5°C, around 15 TWh will be used for electric vehicles and rail transport in 2050.

Figure 21: Development of electricity demand by sector



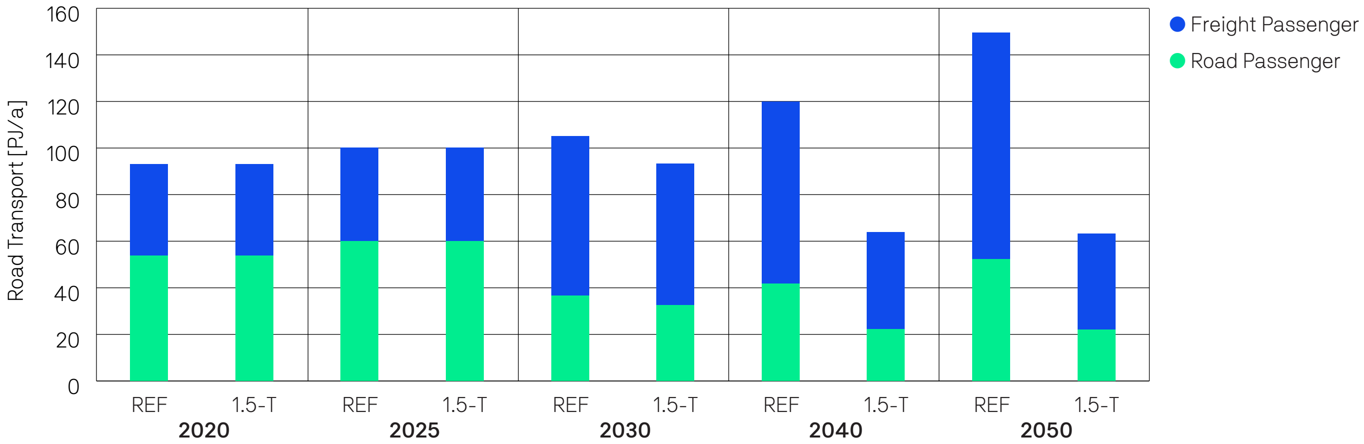
The energy demand for process heat, the space heating of residential and commercial buildings, and cooking will continues to grow under the T-1.5°C pathway. The main driver will be a combination of population growth and the increased role of the industry sector in Tunisia's GDP. The T-1.5°C pathway increases the role of electrification in the heating supply (with heat pumps) and with the introduction of electric cooking.

Figure 22: Development of the final energy demand for heat by sector



As a result, the T-1.5°C pathway will lead to an annual heat demand of around 115 PJ/a. The projected development of the road transport sector (see Figure 23) differs substantially across the two scenarios, although they share the same pkm and tkm growth trajectories. The difference between the two scenarios is the result of the high level of electrification achieved by 2050 under the T-1.5°C scenario. More details of the assumptions made for the transport sector projections, broken down into freight and passenger transport, are documented in section 2.6.

Figure 23: Development of the road transport energy demand for passengers and freight



5.2.2 Electricity generation

Electricity generation, capacity, and breakdown by technology

The development of the electricity supply sector is characterised by a dynamically growing renewable energy market and an increasing share of new renewable electricity, from both solar PV and wind energy. The additional electricity demand caused by the accelerated electrification of residential and commercial end uses and the introduction of electric vehicles under the T-1.5°C scenario will mean there will be a significant requirement for new renewable generation to supply the demand in an affordable and low-emissions manner.

By 2030, the share of new renewable electricity production should reach at least 31% and increase to 100% by 2050 under the T-1.5°C scenario. The installed capacity of new renewables will reach 3.9 GW by 2030 and 34.6 GW by 2050, under the T-1.5°C scenario. Table 30 shows the comparative evolution of Tunisia's power generation technologies over time. Solar PV and onshore wind will become the main power source under our net zero scenario. Supply security will be achieved with a share of variable power generation and demand-side management, together with the management of electric vehicle charging and other storage capacities, such as stationary batteries and pumped hydro power. The development of smart-grid management will be required from 2030 onwards to increase the power system's flexibility for grid integration, load balancing, and a secure supply of electricity.

Figure 24: Breakdown of electricity generation by technology

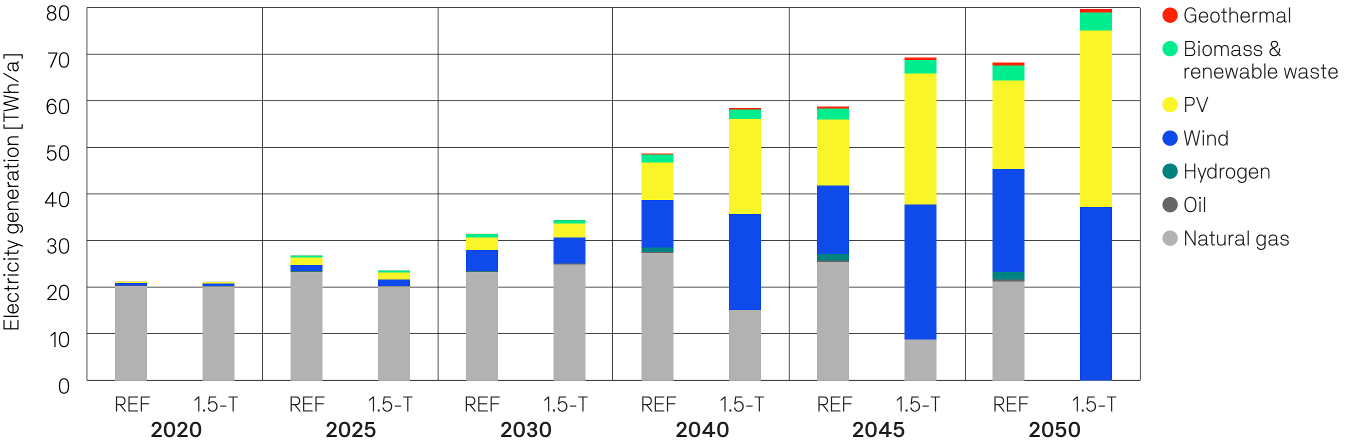


Table 30: Projection of renewable electricity generation capacities

Generation Capacity [GW]			2020	2030	2040	2050
Hydro	REFERENCE	GW	0	0	0	0
	T-1.5°C	GW	0	0	0	0
Biomass	REFERENCE	GW	0	0.1	0.4	0.7
	T-1.5°C	GW	0	0.2	0.5	0.9
Wind	REFERENCE	GW	0.2	1.6	3.3	7.0
	T-1.5°C	GW	0.2	1.9	6.9	11.9
PV	REFERENCE	GW	0.2	1.6	4.6	10.9
	T-1.5°C	GW	0.2	1.8	11.7	21.6
Total	**REFERENCE**	**GW**	**0.4**	**3.3**	**8.3**	**18.6**
	T-1.5°C	**GW**	**0.4**	**3.9**	**19.1**	**34.4**

5.2.3 Energy supply for cooking and Industrial Process heat

Today, gas meets around 96% of Tunisia's energy demand for fuel-based cooking and heating. Dedicated support instruments are required to ensure dynamic development, particularly of electric cooking stoves, renewable heating technologies for buildings, and renewable process heat production. Under the T-1.5°C scenario, gas-based cooking will be gradually replaced by electric cooking options. The increased electricity used for e-cooking will increase the electricity demand but will replace a significant amount of gas (lowering the associated emissions and primary energy needs). Under T-1.5°C, the use of heat pumps as one of the leading new heating supply technologies will accelerate, and direct electric heating, such as radiators, will be introduced, but only as an interim measure between 2025 and 2030. These will be exchanged for heat pumps at the end of their lifetimes.

- Energy efficiency measures will help to reduce the currently growing energy demand for heating, specially building standards.
- In the industry sector, solar collectors, geothermal energy (including heat pumps), and electricity and hydrogen from renewable sources will increasingly substitute for fossil-fuel systems.

Figure 25: Projection of heat supply by energy carrier (REFERENCE and T-1.5°C scenarios)

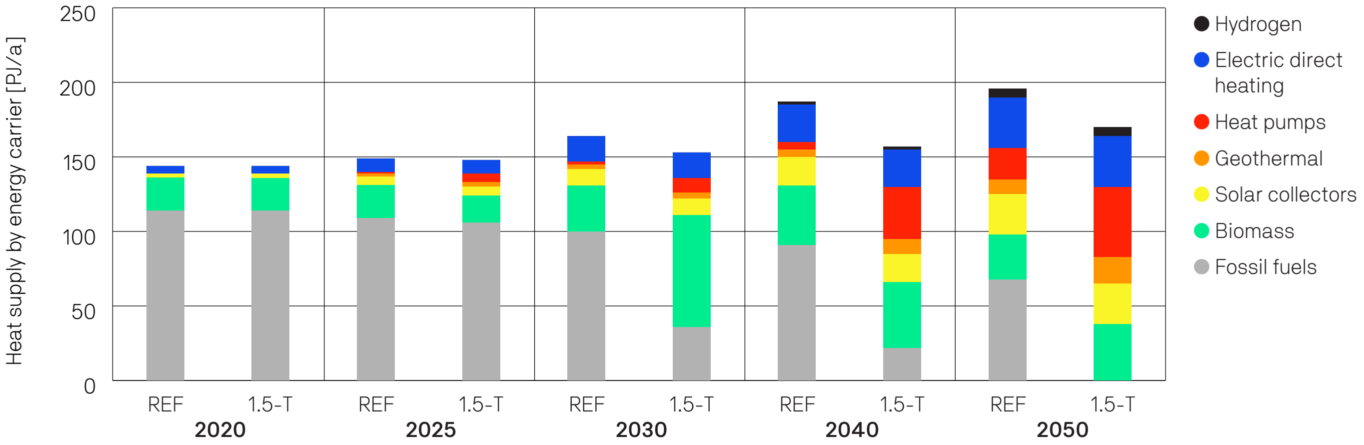


Table 31: Projection of renewable heat supply (cooking and process heat) in [PJ/a].

Supply (in PJ/a)		2020	2025	2030	2040	2050
Biomass	REFERENCE	22	22	31	40	30
	T-1.5°C	22	18	75	44	38
Solar Collectors	REFERENCE	3	6	11	19	27
	T-1.5°C	3	6	11	19	27
Heat Pumps (electric & geothermal)	REFERENCE	0	1	2	5	21
	T-1.5°C	0	6	10	35	47
Geothermal	REFERENCE	0	2	3	5	10
	T-1.5°C	0	3	4	10	18
Direct Electric Heating	REFERENCE	5	9	17	25	34
	T-1.5°C	5	9	17	25	34
Total	**REFERENCE**	**144**	**149**	**164**	**186**	**197**
	T-1.5°C	**144**	**148**	**154**	**156**	**171**

Table 31 shows the development of different renewable technologies for heating in Tunisia over time. After 2030, an increase in solar collectors and growing proportions of geothermal and environmental heat, as well as electrical heat and some limited renewable hydrogen for industrial process heat, will compensate for the phase-out of fossil fuels. The T-1.5°C scenario includes many efficient heat pumps, which can also be used for demand-side management and load flexibility (see also section 6.7.2).

Table 32: Installed capacities for renewable heat generation

Capacities (in GW)		2020	2025	2030	2040	2050
Biomass	REFERENCE	4	4	6	7	5
	T-1.5°C	4	3	11	7	6
Geothermal	REFERENCE	0	0	0	1	1
	T-1.5°C	2	0	1	1	3
Solar Heating	REFERENCE	1	2	4	6	8
	T-1.5°C	1	2	4	6	8
Heat Pumps (electric and geothermal)	REFERENCE	0	0	1	2	7
	T-1.5°C	0	2	4	11	16
Total	**REFERENCE**	**23**	**24**	**26**	**29**	**33**
	T-1.5°C	**23**	**24**	**25**	**29**	**33**

5.2.4 Transport

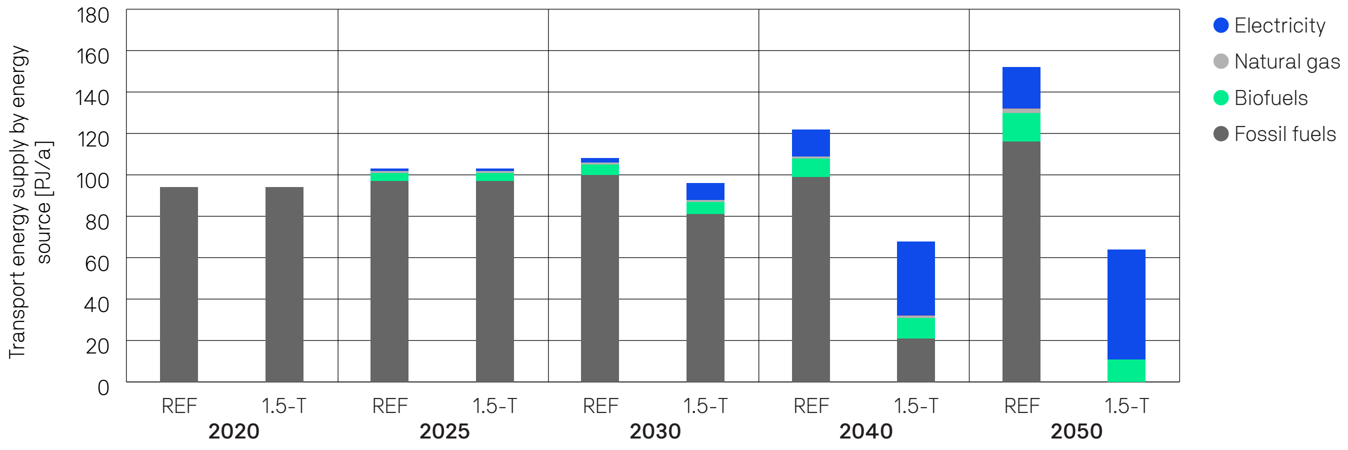
A key target in Tunisia is to introduce incentives for people to support the transition towards electric mobility, especially in urban and semi-urban regions. It is also vital that transport use shifts to efficient public transport modes, such as rail, light rail, and buses, especially in the large expanding metropolitan areas.

Highly efficient propulsion technology, with plug-in hybrid and battery-electric power trains, will bring large efficiency gains. By 2040, electricity will service 20% of the transport energy demand under the T-1.5°C scenario. The T-1.5°C scenario will achieve the total decarbonisation of the transport sector in Tunisia by 2050. More details about the assumptions made to calculate the transport demand and supply development are documented in Chapter 2.

Table 33: Projection of transport energy demands by mode

Transport Mode		Units	2020	2025	2030	2040	2050
Rail	REFERENCE	[PJ/a]	1	1	1	1	1
	T-1.5°C	[PJ/a]	1	1	1	1	1
Road	REFERENCE	[PJ/a]	93	100	105	120	150
	T-1.5°C	[PJ/a]	93	100	93	64	63
Domestic Aviation	REFERENCE	[PJ/a]	0	0	0	0	0
	T-1.5°C	[PJ/a]	0	0	0	0	0
Total	**REFERENCE**	**[PJ/a]**	**99**	**101**	**106**	**121**	**151**
	T-1.5°C	**[PJ/a]**	**99**	**101**	**95**	**65**	**64**

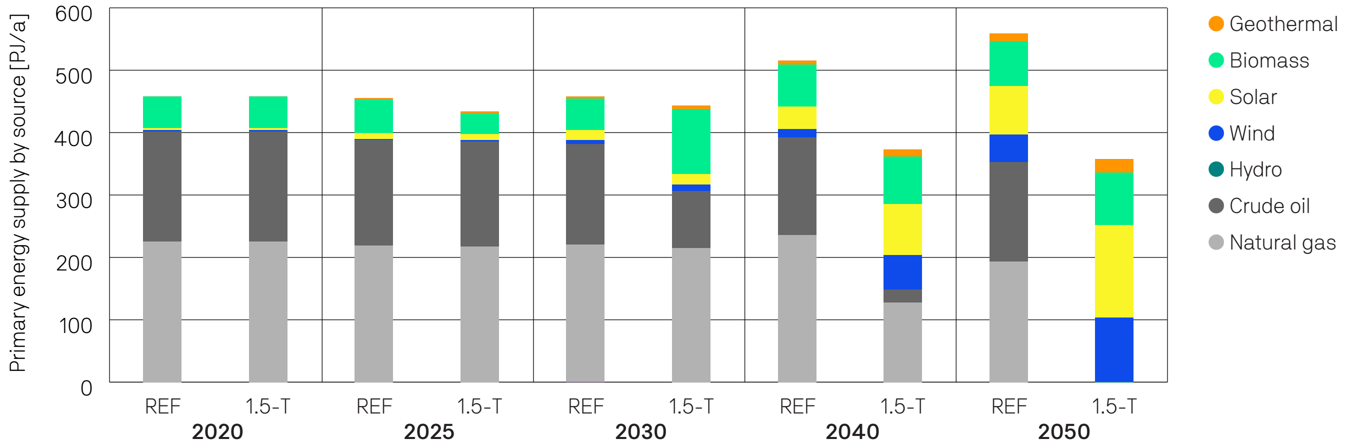
Figure 26: Final energy consumption by transport under the two scenarios



5.2.5 Primary energy consumption

Based on the assumptions discussed above, the resulting primary energy consumption under the T-1.5°C scenario is shown in Figure 27. The T-1.5°C scenario will result in primary energy consumption of around 395 PJ in 2050. It aims to phase-out oil in the transport sector and oil for industrial use as fast as is technically and economically possible, through the expansion of renewable energies. The fast introduction of very efficient vehicle concepts in the road transport sector will replace oil-based combustion engines. Therefore, when non-energy consumption is excluded, the T-1.5°C scenario aims for a renewable primary energy share of 100% in 2050 (92% when non-energy consumption is included).

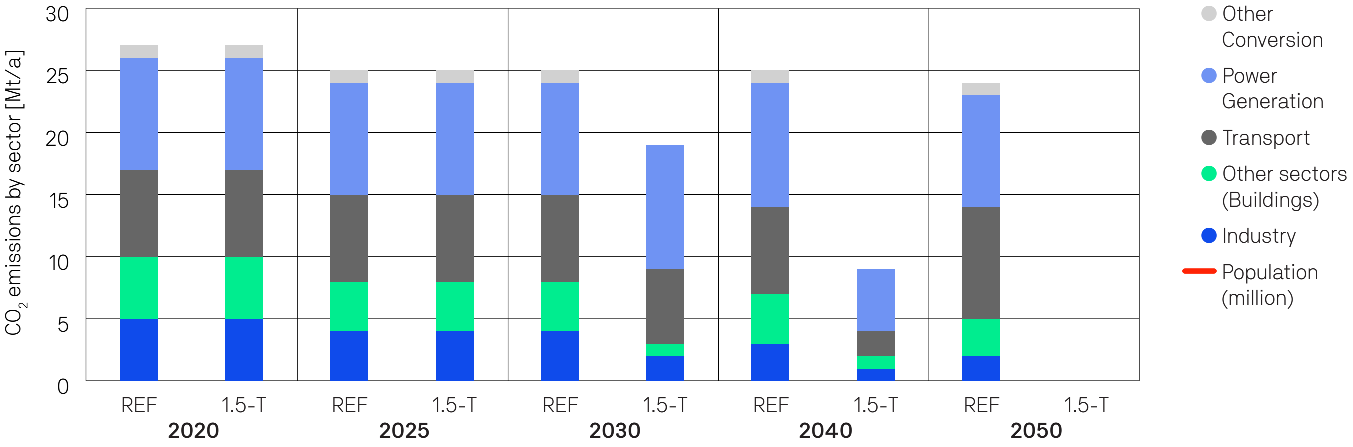
Figure 27: Projection of total primary energy demand by energy carrier (including electricity import balance)



5.2.6 CO_2 emissions trajectories

The T-1.5°C scenario will reverse the trend of increasing energy-related CO_2 emissions from 2025, leading to a reduction of 27% by 2030 relative to 2020– which is the same of order of magnitude specified by the unconditional emissions reduction target of 27% reduction relative to 2010 emissions levels (The T-1.5°C scenario represents 22% emissions reduction relative to the 2010 baseline used). The target of the T-1.5°C scenario increases substantially, and by 2040, reaches an emission reduction of 66% relative to 2020 (64% relative to 2010). In 2050, the full decarbonisation of Tunisia's energy sector will be achieved under the T-1.5°C scenario (Figure 28).

Figure 28: Development of CO_2 emissions by sector



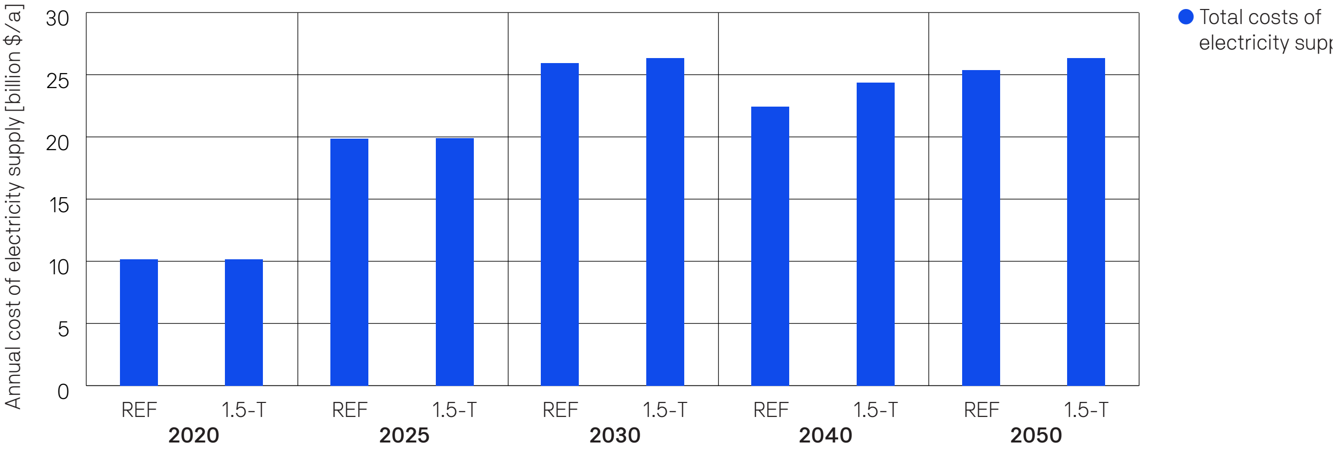
5.2.7 Cost analysis

Future costs of electricity generation

Figure 29 shows that despite the increasing electricity demand under the T-1.5°C scenario, the annual cost of electricity supply will remain on par with that under the REFERENCE scenario. This can be attributed to the fact that although the REFERENCE scenario requires less capital expenditure than the T-1.5°C scenario because it requires fewer generation projects, it experiences significantly more operational costs associated with the purchase of fuel for gas generation.

Under ***both*** scenarios, the full cost of generation will increase by a significant amount, from 0.033 trillion TND/kWh to 0.066 trillion TND/kWh, because both scenarios include an increase in electricity demand associated with economic growth and the varying levels of electrification across the economy (excluding integration costs for storage or other load-balancing measures). In 2030, there will be a mix of fossil fuels and new renewables, so there will be costs in both the procurement of new renewable generation and the ongoing costs arising from the marginal fuel costs of continued gas generation. By 2050, both scenarios will achieve a reduction in costs relative to 2030 because fuel costs will be lower and significant amounts of renewable capacity will already exist in the system. Average electricity generation costs will be 0.071 trillion TND/kWh under the T-1.5°C scenario and 0.068 trillion TND/kWh under the REFERENCE scenario.

Figure 29: Development of total electricity supply costs and specific electricity generation costs



Investments in power generation

Under the T-1.5°C scenario, Tunisia will invest in new power generation – mainly solar PV and wind. Here, the main difference between the T-1.5°C scenario and the REFERENCE scenario is the latter's investment in other technologies, such as fossil gas. Figure 24 and Table 31 show the strong growth in both solar and wind energy in Tunisia, and the following figures highlight the stronger growth in renewables associated with the T-1.5°C scenario.

Figure 30: Shares of cumulative investment in power generation, T-1.5°C scenario, 2020–2050 [billion US$]

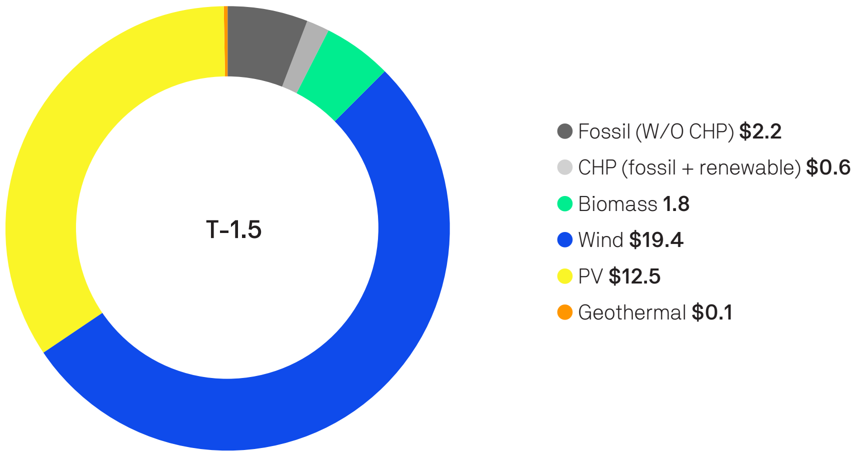


Figure 31: Shares of cumulative investment in power generation, REFERENCE scenario, 2020–2050 [billion US$]

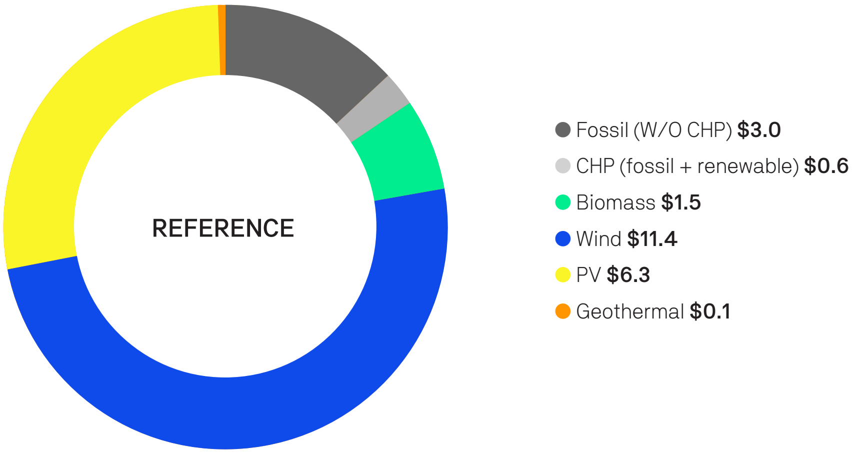


Table 34: Investment costs in new power generation under the T-1.5°C and REFERENCE scenarios (exchange rate: 1 trillion TND = US$0.33, November 2024)

	2020–2050	
T-1.5°C	**[billion US$]**	**[billion TND$]**
Hydro	0	0
Biomass	2	6
PV	13	38
Wind	19	59
Fossil & other	2	7
Total	**36**	**110**
	2020–2050	
REFERENCE	**[billion US$]**	**[billion TND$]**
Hydro	0	0
Biomass	2	5
PV	6	19
Wind	11	34
Fossil & other	3	9
Total	**22**	**68**

The investment in solar PV under the T-1.5°C scenario will amount to around 38 billion trillion TND (US$13 billion) over 30 years. This electricity will primarily be used to electrify the residential and commercial sectors, for end uses such as heating and cooking, and to charge various electric vehicles, from two- and three-wheeler vehicles to cars and small delivery trucks.

Future investments in the heating sector

The main difference between the T-1.5°C scenario and REFERENCE scenario in terms of clean heating technologies is the significant increase in heat-pump deployment under T-1.5°C, because the REFERENCE scenario still retains a significant amount of gas heating. Electrical heat pumps, geothermal heat pumps, and solar thermal applications for space and water heating and drying will lead to a considerable reduction in the demand for biogas and solid biomass, and will therefore reduce fuel costs.

Figure 32 shows the shares of cumulative investments in the heating sector between 2020 and 2050 for the T-1.5°C scenario, for comparison with the cumulative investments for the REFERENCE scenario (see Figure 33).

Figure 32: Cumulative investment in the heating technologies (generation) under the T-1.5°C scenario for 2020–2050 [billion $]

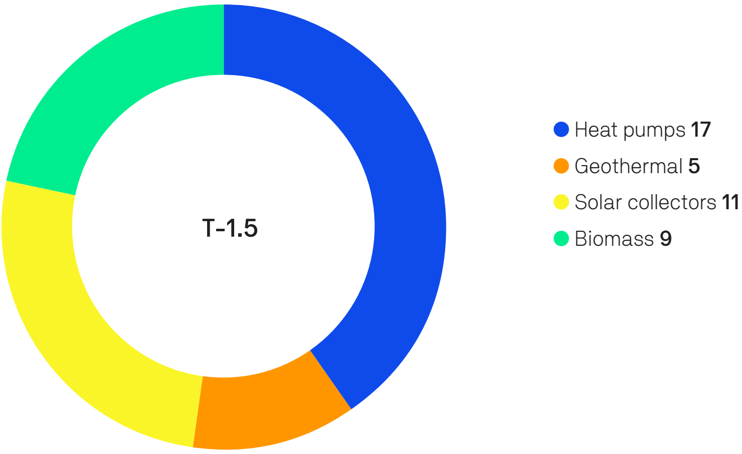


Figure 33: Cumulative investment in the heating technologies (generation) under the REFERENCE scenario for 2020–2050 [billion $]

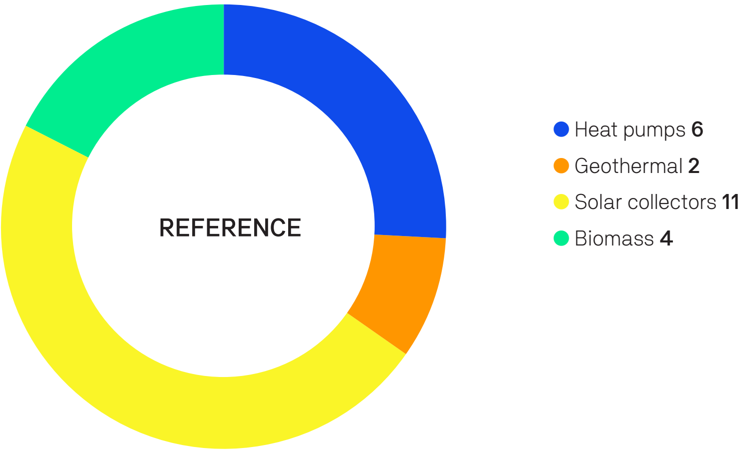


Table 35 shows the cumulative investment and fuel costs in the heating sector for the T-1.5°C scenario and the REFERENCE scenario, together with the total costs associated with new power generation capacity, providing a summary of the cost estimates of the two scenarios. The overall heat sector costs – investment and fuel costs – over the entire scenario period until 2050 will be 13.7 trillion USD for the T-1.5°C scenario.

Table 35: Tunisia – heating, electricity and fuel: cumulative investment and fuel costs in 2020–2050

T-1.5°C Scenario, Costs (2020–2050)	**[billion US$]**	**[billion TND$]**
Cumulative heating investment	42	129
Cumulative fuel cost	436	144
Cumulative electricity investment	36	110
Total	**675**	**222**
REFERENCE scenario (2020–2050)	**[billion US$]**	**[billion TND$]**
Cumulative heating investment	23	71
Cumulative fuel cost	607	200
Cumulative electricity investment	22	68
Total	**746**	**245**

5.2.8 Investment and fuel cost savings

Finally, the fuel costs for the power, heating, and transport sectors are presented. All three sectors will reduce their fuel costs over time because electricity generation will be based on renewables – with significant shares of solar and wind power. Table 36 shows all the accumulated fuel costs by sector and scenario and the calculated fuel cost savings in 10-year intervals between 2020 and 2050 in Tunisian dinar and US dollars.

The T-1.5°C scenario requires an investment of 21 trillion TND (US$135 billion) in power generation and 25 trillion TND (US$166 billion) in heat generation. The total investment in power and heat generation capacities therefore adds up to 46 trillion TND (US$301 billion).

Additional power generation investments will be compensated by fuel costs savings in the decade in which they are made. Across the entire scenario period, fuel cost savings under the T-1.5°C scenario relative to the REFERENCE scenario will be

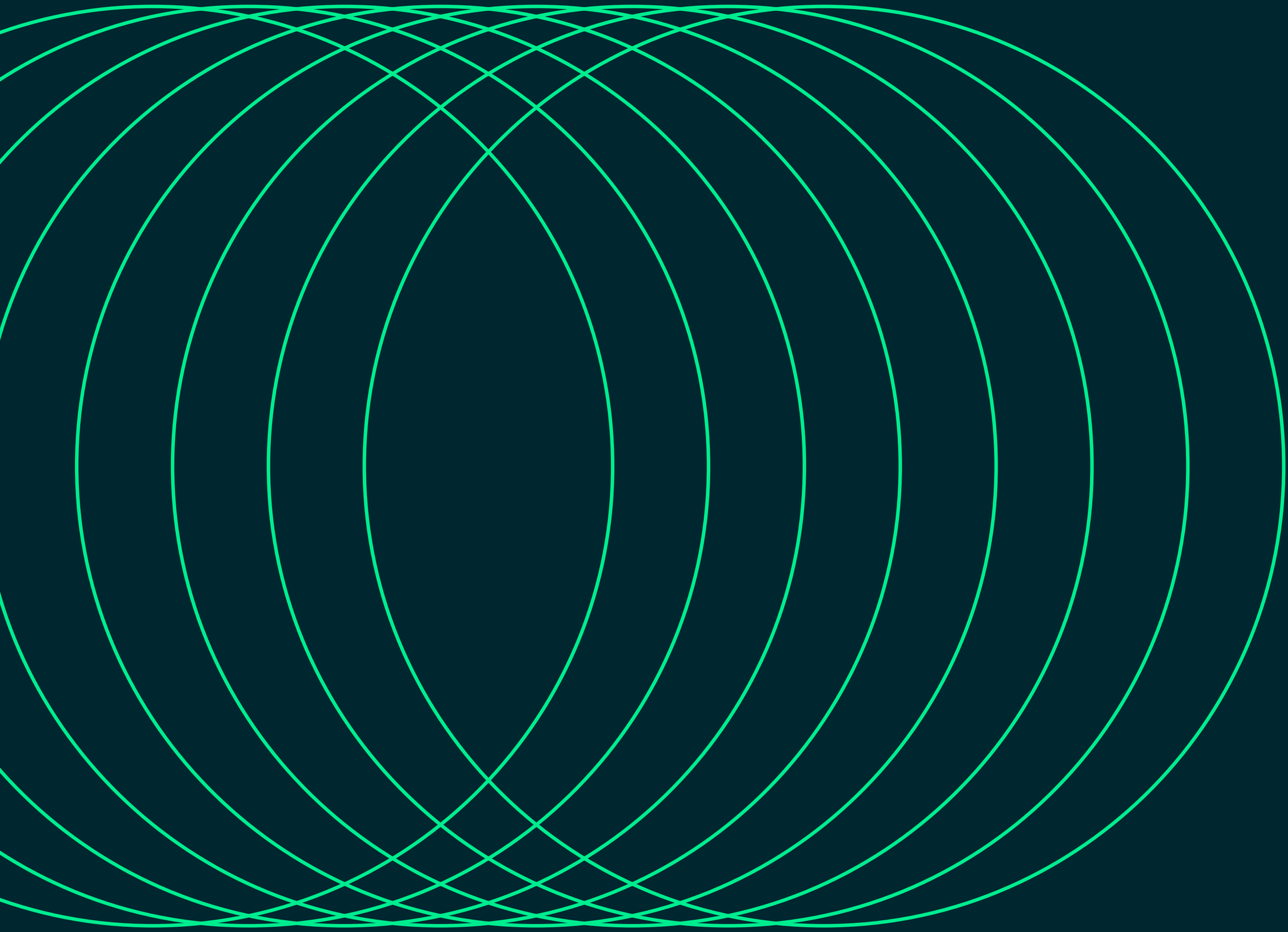
170 billion TND (US$56 billion) – about 4 times higher than the additional investment in power generation capacities until 2050. Although fuel cost predictions are subject to a great deal of uncertainty, this result makes the cost-effectiveness of electrification very clear.

Table 36: Cumulative fuel costs for heat generation under the REFERENCE and T-1.5°C scenarios in billion USD and trillion TND

		2020–2030		2031–2040		2041–2050		2020–2050		2020–2050 average per year	
REFERENCE		[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD	[Billion TND]	Billion USD
Power	Total	56.9	18.8	56.9	18.8	53.1	17.5	166.8	55.1	5.6	1.8
Heat	Total	55.9	18.5	56.8	18.8	47.6	15.7	160.4	52.9	5.3	1.8
Transport	Total	90.4	29.8	99.2	32.7	90.0	29.7	279.5	92.2	9.3	3.1
Summed Costs		**203.2**	**67.0**	**212.9**	**70.3**	**190.7**	**62.9**	**606.7**	**200.2**	**20.2**	**6.7**
		2020–2030		**2031–2040**		**2041–2050**		**2020–2050**		**2020–2050 average per year**	
T-1.5 °C		**[Billion TND]**	**Billion USD**	**[Billion TND]**	**Billion USD**	**[Billion TND]**	**Billion USD**	**[Billion TND]**	**Billion USD**	**[Billion TND]**	**Billion USD**
Power	Total	50.3	16.6	50.3	16.6	24.4	8.1	125.0	41.2	4.2	1.4
Heat	Total	54.4	17.9	46.5	15.4	28.3	9.4	129.3	42.7	4.3	1.4
Transport	Total	89.2	29.4	69.3	22.9	23.4	7.7	181.8	60.0	6.1	2.0
Summed Costs		**193.8**	**64.0**	**166.1**	**54.8**	**76.1**	**25.1**	**436.1**	**143.9**	**14.5**	**4.8**
Difference REFERENCE versus T-1.5°C		**9.3**	**3.1**	**46.8**	**15.4**	**114.5**	**37.8**	**170.6**	**56.3**	**5.7**	**1.9**

6

Tunisia: Power Sector Analysis



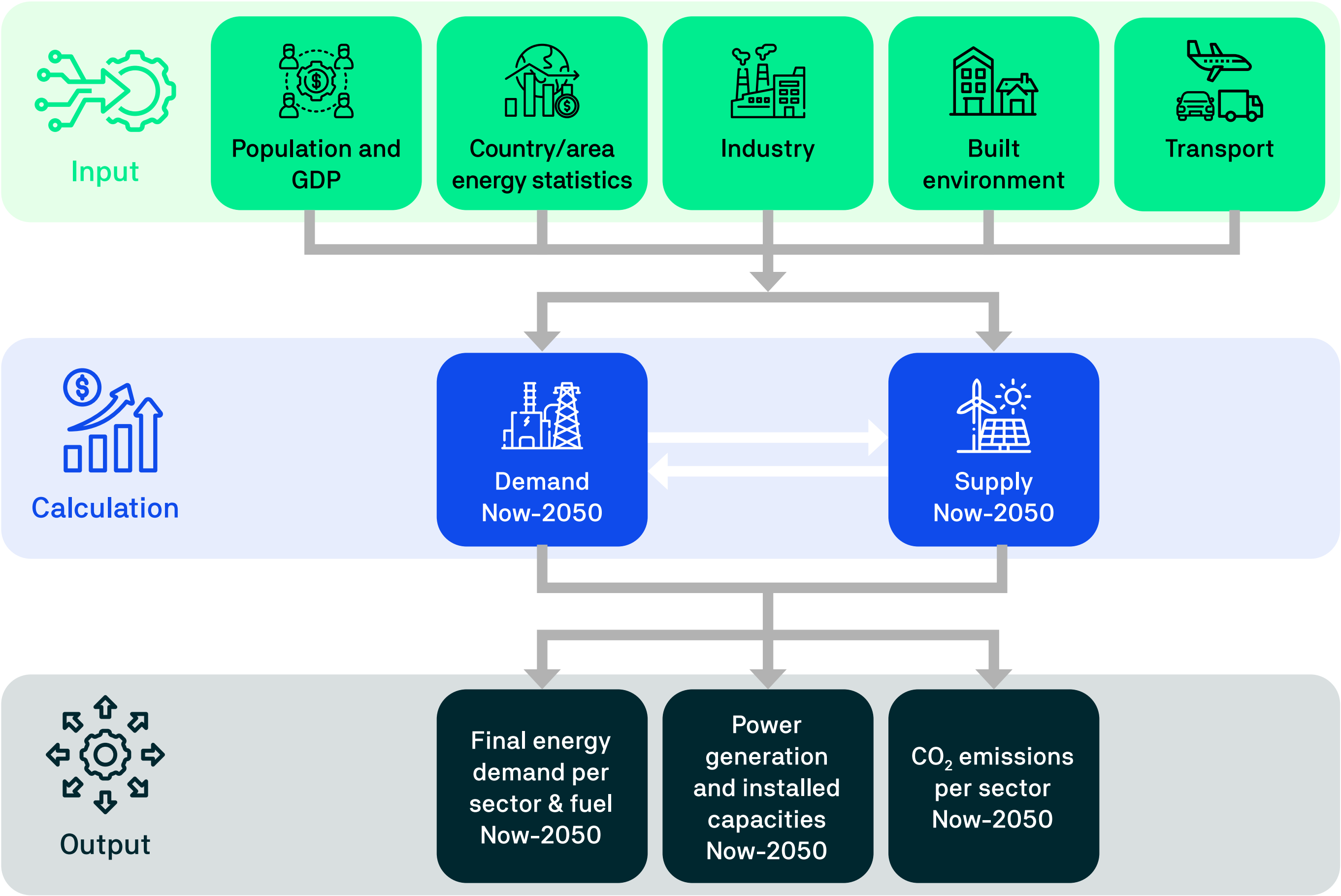
In this chapter, we summarise the results of the hourly simulations of the long-term scenarios (Chapter 5). The One Earth Climate Model (OECM) calculates the demand and supply by cluster. In this section, we provide an overview of the possible increase in electrical load under the T-1.5°C scenario, and the consequent increased demand on the power grid transmission capacities, possible new inter-provincial connections, and/or expanded energy storage facilities.

6.1 Power Sector Analysis – Methodology

After the socio-economic (Chapter 2) and geographic analyses (Chapter 3) and the development of the long-term energy pathways for Tunisia (Chapter 5), the power sector was analysed with the OECM in a third step.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, will allow a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis.

Figure 34: Overview – energy demand and load curve calculation module



6.1.1 Meteorological data

Variable power generation technologies are dependent on the local solar radiation and wind regime. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database renewables.ninja (RE-N DB 2018)[82], which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated. Weather data, such as temperature, precipitation, and snowfall, for the year 2019 were also available. To utilise climatisation technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the cluster-specific temperature time series.

The demand for lighting was connected to the solar time series to accommodate the variability in the lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilised for onshore and/or offshore wind, utility solar, and roof-top solar PV. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future-generation systems, a representative site was selected for each of the five generation types.

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (renewable.ninja, see above). The model methodology used by the renewable.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[83], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[84]; Müller and Pfeifroth, 2015[85]).

Whereas in practice, the utility-scale solar sites will be optimised, the tilt angle was selected within a couple of degrees of the latitude of the representative site, an indicative system tilt of 35° was used for the generation trace for the utility systems. For the roof-top solar calculations, this was left at the default of 35° because it is likely that the panels will match the tilt of the roof.

The onshore wind outputs were calculated at an 110 m hub height to reflect the potential wind resource available in each cluster, and is available to modern turbines with sufficiently high hub heights. It is possible that commercial hub heights will exceed this height before 2050, but 110 m was deemed appropriate as representative of the resource available to both current and future generators. A turbine model of Vestas V90 2000 was used.

Limitations

The solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

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[82] RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position, data viewed and downloaded between September and October 2022, https://www.renewables.ninja/

[83] Pfenninger S, Staffell I (2016a) Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114:1251–1265. doi: 10.1016/j.energy.2016.08.06

Pfenninger S, Staffell I (2016b) Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114:1224–1239. doi: 10.1016/j.energy.2016.08.068

[84] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[85] Müller R, Pfeifroth U, Träger-Chatterjee C, Trentmann J, Cremer R (2015) Digging the METEOSAT treasure – 3 decades of solar surface radiation. Remote Sensing 7:8067–8101. doi: 10.3390/rs70608067

6.1.2 Power Demand Projection and Load Curve Calculation

The OECM power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- Households
- Industry and business
- Transport

Although each sector has its specific consumer groups and applications, the same set of parameters was used to calculate the load curves:

- Electrical applications in use
- Demand pattern (24 h)
- Meteorological data
    - Sunrise and sunset, associated with the use of lighting appliances
    - Temperature and rainfall, associated with climatisation requirements
- Efficiency progress (base year 2018 for 2020 until 2050, in 5-year steps
    - Possibility that the electricity intensity data for each set of appliances will change, e.g., change from compact fluorescent lamp (CFL) light bulbs to light-emitting diodes (LEDs) as the main technology for lighting.

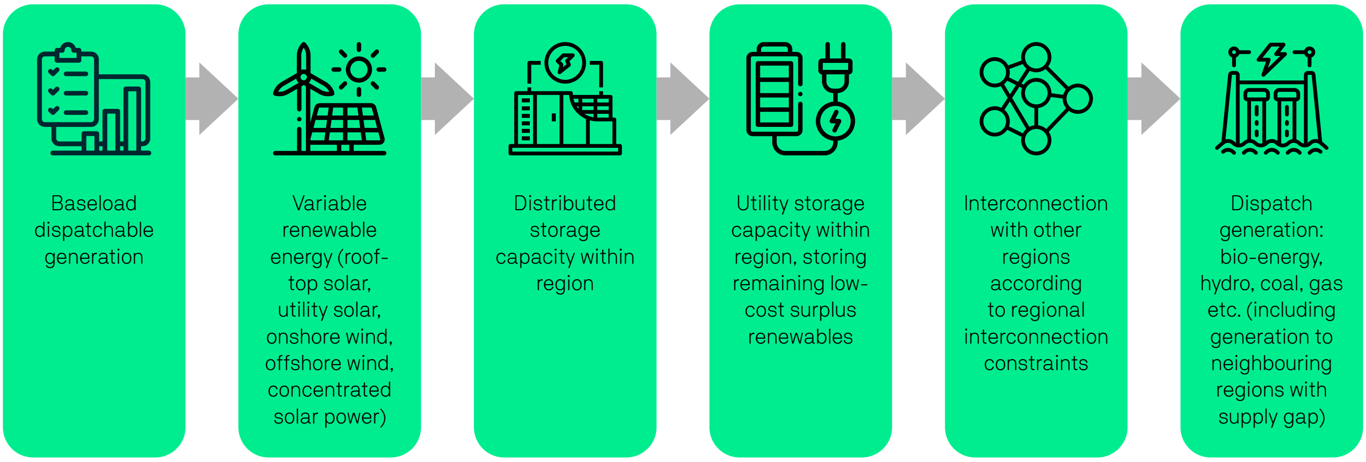
The OECM 24/7 Dispatch Module

The OECM 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can either be moved to storage, moved to other regions (including export to other countries if specified in modelling assumptions), or – if neither option is available – curtailed. In the case of undersupply, electricity will be supplied either from available storage capacities, from neighbouring clusters, or from dispatch power plants.

The key objective of the modelling is to calculate the load development by region, modifying the residual load (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. It would be possible to produce an estimate for the additional required storage capacity required to avoid supply gaps, but in reality, the economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and their costs. Given Tunisia's historical reliance on gas, which is dependent upon existing gas networks and power generation units, unmet generation is reported and an equivalence is provided in terms of the additional gas generation required to fill the supply gap (including the implications for emissions).

Figure 35 provides an overview of the dispatch calculation process. The model allows for the dispatch order to be changed in terms of the order of renewables and the dispatch power plant, as well as in terms of the order of the generation categories: variable, dispatch generation, or storage. In this analysis, a fixed dispatch order was used: minimum baseload dispatch, variable renewables, distributed generations sources, utility storage, interconnection with other regions to allow exchange of low-cost surplus renewables, and finally the remaining additional dispatch generation that was not dispatched as part of the minimum baseload output requirement. The 'baseload dispatch generation' represents the minimum amount of a fossil fuel power plant capacity that must run for either economic, technical, or system requirements. For example, a coal plant may only be able to run at 30% capacity due to technical limits on the generation equipment (thermal operating windows/ minimum temperature), whereas a gas plant may be asked to run at 5% or 10% capacity throughout the day because the electrical system operator requires sufficient levels of inertia in a high-renewables system (the remaining capacity is then dispatched as required as step six in the dispatch order).

Figure 35: Dispatch order within one cluster



The following key parameters are used as input: generation capacity by type, the demand projection and load curve for each cluster, interconnections with other clusters, and meteorological data, from which solar and wind power generation are calculated with hourly resolution. The installed capacities are derived from the long-term projections described in Chapter 5, and the resulting annual generation, in megawatt hours, is calculated based on meteorological data (in the cases of solar and wind power) or dispatch requirements.

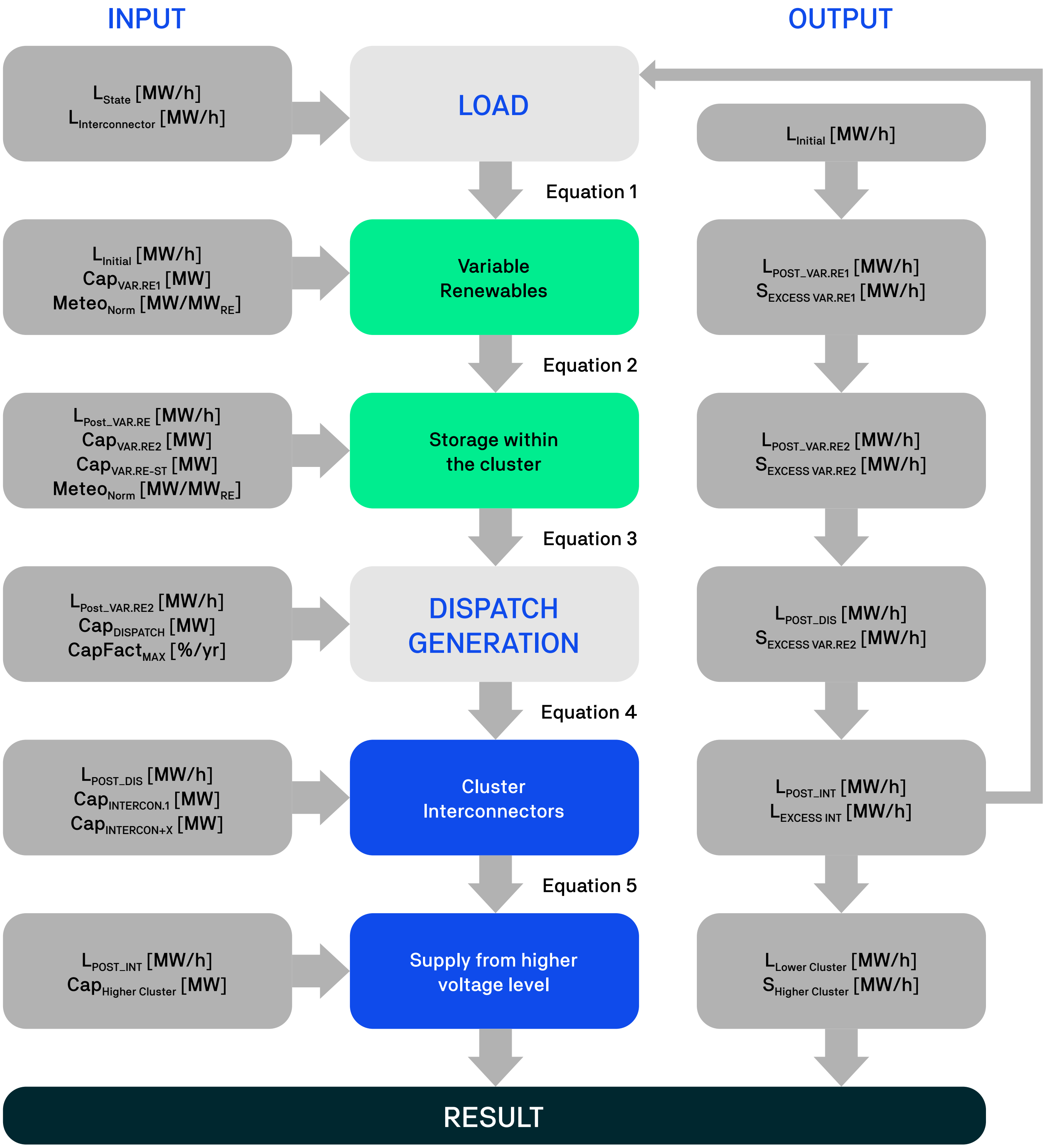
Overview: Input and output – OECM 24/7 energy dispatch model

Figure 36 gives an overview of the input and output parameters and the dispatch order. Although the model allows changes in the dispatch order, a 100% renewable energy analysis always follows the same dispatch logic. The model identifies excess renewable production, which is defined as the potential wind or solar PV generation that exceeds the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be stored with some form of electrical storage technology or exported to a different cluster. Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge the storage within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as 'potential curtailment' (pre-storage). It is assumed that a certain number of behind-the-meter consumer batteries will be installed, independently of the system requirements.

Limitations

The calculated loads are not optimised in terms of local storage, the self-consumption of decentralised producers of solar PV electricity, or demand-side management. Therefore, the actual loads may be well below the calculated values.

Figure 36: Overview – Input, output, and dispatch order



6.2 Development of Power Plant Capacities

As discussed in Chapter 3, Tunisia has substantial untapped renewable energy potential, and its renewable energy potential far exceeds the projected energy demand requirements by 2050. Despite Tunisia's abundance of renewable energy resources, its electricity supply has been historically almost entirely derived from gas generation, with percentages regularly exceeding 95% between 2005 and 2020. (Of the 16 years in that range, gas generation accounted for > 95% of supply in 11 of them).[86] Therefore, until now, variable sources of renewable energy have played a limited role in Tunisia's electrical system.

Under the T-1.5°C scenario, solar PV generators will expand rapidly and provide increasing electricity, alongside wind generation, which is also projected to increase significantly across Tunisia. This will be possible because Tunisia has an existing electrical infrastructure, decarbonisation policies, and sufficient areas of land with suitable resources, which is attractive from the perspective of project development. Given the existing electrical infrastructure, it can be expected that the majority of PV systems installed will be grid-connected, with off-grid micro-grids playing a role in remote areas of the country. In terms of Tunisia's renewable electricity potential, the vast majority of future generation will be solar PV and onshore wind. Because truly sustainable sources of biomass energy are limited, it is envisioned that offshore wind will also be developed by 2050, because Tunisia has high-quality offshore wind resources that can fill supply gaps when there is insufficient onshore wind or solar resources.

Therefore, the capacity for solar PV installations will increase substantially under the T-1.5°C pathway. The average solar PV market will range around 315 MW per year between 2021 and 2035 and increase to around 721 MW per year between 2036 and 2050. Tunisia's wind power market will require a relatively constant installation rate throughout the modelling period, with an average of 223 MW installed/year until 2035 and an installation rate of 300 MW/year until 2050. Tunisia's renewable potential is exceptionally diverse, and not limited to solar and wind power. The values for the full range of renewable technologies is shown below (Table 37).

Table 37:Tunisia – average annual changes in installed power plant capacity (main technologies)

Power Generation: average annual changes in installed capacity [MW/a]							Annual Average	
	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050	2021–2035	2021–2050
Biomass	10	11	26	32	40	47	16	28
Hard coal	0	0	0	0	0	0	0	0
Lignite	0	0	0	0	0	0	0	0
Fuel cell	0	0	0	0	0	0	0	0
Natural gas	15	341	132	-800	-432	-608	163	-225
Oil	2	11	-42	0	0	0	-10	-5
Diesel	0	0	0	0	0	0	0	0
Hydro	0	1	2	1	1	1	1	1
Wind onshore	33	248	390	428	337	366	223	300
Wind offshore	26	48	31	148	145	153	35	92
PV	183	168	595	1,386	886	1,109	315	721
Geothermal	0	1	3	4	5	6	1	3
Total CHP plants	0	0	0	0	0	0	0	0
Biomass & Waste	14	1	1	2	-1	-1	6	3
Hard coal	1	0	0	0	0	0	0	0
Lignite	0	0	0	0	0	0	0	0
Fuel cell	0	0	0	0	0	0	0	0
Gas	-25	-8	-5	-7	-2	-2	-13	-8
Geothermal	-13	1	0	0	0	0	-4	-2
Oil	0	0	0	0	0	0	0	0

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[86] IEA World Energy Balances

6.3 Results: Utilisation of Power Generation Capacities

Table 38 and Table 39 show the installed capacities for roof-top and utility-scale solar PV under the T-1.5°C scenario in 2030 and 2050, respectively. The distributions are based on the regional solar potential for utility PV and according to the population distribution for roof-top solar, with the aim of generating electricity where the demand is located. Whereas roof-top solar PV power generation is modular and can be installed close to the consumer or even integrated into buildings, utility-scale solar PV is usually further away from settlements and close to medium- or high-voltage power lines. Moreover, solar power plants (= utility-scale PV) have double-digit megawatt capacities, on average. The best solar resources are located in the southern areas of the country, in the Southern Desert region and the Southern Coastal region near the Mediterranean Sea.

Table 38: Tunisia T-1.5°C pathway – installed photovoltaic capacity by region (2030)

T-1.5°C pathway 2030	Southern Desert [MW]	Southern Coastal [MW]	South-western [MW]	Central Western [MW]	Central Coastal [MW]	North-western [MW]	North-eastern [MW]	Greater Tunis [MW]
Photovoltaic (roof-top)	14	41	21	68	126	53	74	129
Photovoltaic (utility-scale)	114	188	21	75	130	135	468	99

Table 39: Tunisia T-1.5°C pathway – installed photovoltaic capacity by region (2050)

T-1.5°C pathway 2050	Southern Desert [MW]	Southern Coastal [MW]	South-western [MW]	Central Western [MW]	Central Coastal [MW]	North-western [MW]	North-eastern [MW]	Greater Tunis [MW]
Photovoltaic (roof-top)	177	509	258	837	1,556	652	912	1,589
Photovoltaic (utility-scale)	1,399	2,312	262	928	1,604	1,657	5,767	1,218

In this analysis, we have assumed that approximately 30% of solar PV installations are roof-top and 70% are utility-scale power plants, because there is significant interest in large-scale generation capacity and historically low capacity and economy for roof-top solar across Tunisia. As discussed in previous sections, Tunisia has significant wind generation potential, and this is leveraged under the T-1.5°C scenario. Offshore wind is also utilised in this scenario, and Table 40 shows the percentage of variable generation and the dispatchable sources of power supplied throughout the year (renewable and fossil fuel disaggregated). The percentages shown in Table 41 are the output of the hourly power system modelling outlined in section 6.1, and are therefore indicative of not only the capacity factors, but also the need for generation dependent upon the demand in each hour. Table 40 shows the categorisation of the various generation types used in the power system modelling.

Table 40: Categorisation of generation types

Generation Type	Fuel	Technology
Limited Dispatchable	Fossil, uranium	Coal, brown coal/lignite, (including co-generation)
	Renewable	Hydro power, bio-energy, and synthetic fuels, geothermal, concentrated solar power (including co-generation)
Dispatchable	Fossil	Gas, oil, diesel (including co-generation)
		Storage systems: batteries, pumped hydro power plants, hydrogen- and synthetic-fuelled power and co-generation plants
	Renewable	Bio-energy, hydro, hydrogen- and synthetic-fuelled power, and co-generation plants
Variable	Renewable	Solar photovoltaic, onshore wind

The percentages shown below in Table 41 are dependent on multiple variables: the amount of existing fossil fuel infrastructure, projected solar and wind distributions (based on regional potential), adoption of roof-top solar (based on population), and the installation rate of new renewable capacity.

As discussed in Chapter 3, the Southern Desert and Southern Coastal regions have some of the best solar and wind resources across the country, in terms of both resource quality and availability of land upon which to install capacity across the region. It is interesting to contrast the changing proportions of variable renewable power in these regions. The Southern Desert region is expected to have an increase in renewable penetration of more than two-fold by 2030, reaching a proportion of 94%. The Southern Coastal region will also experience a dramatic increase in renewable penetration by 2030, reaching a value of 71%. Although the Southern Coastal region has a greater amount of renewable capacity installed (shown in Tables 38 and 39), it has lower penetration of renewables because it has a notable existing fossil-fuel capacity, whereas the Southern Desert region does not have the same level of existing generation capacity (evident in the proportion of dispatchable fossil fuel generation). In contrast to these areas of high renewable potential, areas such as Greater Tunis have less potential for installed wind and solar capacity and have larger amounts of existing gas generation assets due to their close proximity to the load centres. Greater Tunis will have the slowest transition from a predominantly dispatchable-based supply to a high renewable penetration system.

Table 41: Tunisia – power system shares of annual generation values by technology group

		T-1.5°C		
Percentage of Annual Supply [%/a]		**Variable Renewable**	**Dispatch Renewable**	**Dispatch Fossil**
Southern Desert	2020	41%	0%	58%
	2030	94%	2%	4%
	2050	98%	2%	0%
Southern Coastal	2020	16%	0%	84%
	2030	71%	1%	29%
	2050	99%	1%	0%
South-western	2020	11%	0%	88%
	2030	49%	20%	30%
	2050	91%	10%	0%
Central Western	2020	6%	0%	94%
	2030	33%	4%	63%
	2050	95%	5%	0%
Central Coastal	2020	3%	0%	97%
	2030	22%	1%	77%
	2050	97%	3%	0%
North-western	2020	12%	3%	85%
	2030	49%	6%	45%
	2050	97%	3%	0%
North-eastern	2020	23%	0%	77%
	2030	83%	2%	16%
	2050	98%	2%	0%
Greater Tunis	2020	2%	1%	97%
	2030	18%	2%	81%
	2050	97%	3%	0%

Ultimately, all regions will transition to a very high variable renewable penetration supply, due to Tunisia's excellent solar and wind resources. In the interim, a mix of regions with high levels of variable renewables will co-exist with regions with more significant levels of existing gas generation assets. The significant regional differences in the power system shares – the ratio between dispatchable and non-dispatchable variable power generation – will require a combination of increased interchange, storage facilities, and demand-side management incentives to ensure that all regions maintain sufficient levels of supply security and system strength. In the long term, grid operators and market bodies must develop their systems and market arrangements to allow the functioning of Tunisia's grid with very high levels of renewable penetration (> 90% supplied energy throughout the year).

Experience from other jurisdictions indicates that the integration of large shares of variable power generation will require a more flexible market framework. Those power plants requiring high-capacity factors because of their technical limitations in terms of flexibility ("base-load power plants") will not be desirable to future power system operators. Therefore, capacity factors will become more a technical characteristic than an economic necessity, with flexibility being a commodity that increases in value over time. Future power systems must be structured to leverage the characteristics of each of the different generator categories to ensure sufficient supply and system strength. In Tunisia's case, gas power plants could be operated as peaking plants to cover supply gaps when there is insufficient solar and wind resources, until sufficient levels of interconnection and storage are in place for any reliance on gas peaking to abolished. This may require adaptations or upgrades to existing gas plants that are currently run as base-load generators in Tunisia.

6.4 Results: Analysis of Peak Load, Generation, and Residual Load

Table 42 shows the calculated annual demand, maximum and minimum loads, and the calculated average load by region for 2020. It is based on a historical calibration process, and which is used as the baseline to develop the T-1.5°C scenario projections. To validate the data, we compared our results with real-time data published by the local grid operator.

The statistical data for each province for 2020 were not available at the time of writing, so the values are estimates and may vary by ± 10% for each data point. However, the published online data for Tunisia's power sector is within the same order of magnitude. The calculation of the maximum, minimum, and average loads for the base year (2020/21) is important to calibrate the OECM and to compare the values with future projections.

Table 42: Tunisia – regional breakdown of modelled demand and generation values for 2020

Region	Maximum Load (Domestic) [MW]	Maximum Generation [MW]	Minimum Load [MW]	Average Load [MW]
Southern Desert	70	68	36	46
Southern Coastal	200	215	101	129
South-western	100	58	51	65
Central Western	273	290	129	163
Central Coastal	663	663	347	430
North-western	236	236	116	146
North-eastern	382	382	199	244
Greater Tunis	852	852	477	584
Tunisia-wide Total (non-coincident values)	**2,776**	**2,764**	**1,456**	**1,807**

The calculated load for each province depends on various factors, including the local industrial and commercial activities. A detailed analysis of the planned expansion of economic activity for each province was beyond the scope of this research and the results are therefore estimates based on the regional distribution of GDP and population.

As discussed in the methodology above, the 24/7 model analyses both generation and load on a regional basis, so it is possible to analyse the data outputs to gain insight into the maximum hourly demand and generation values for each region. The results indicate that the peak load will increase by a factor of approximately 1.5 across each region by 2030 under the T-1.5°C scenario, with the maximum regional load increasing by a factor of 3 in each region by 2050. The peak load will increase to a slightly lesser extent than the overall annual electricity demand, but to an equivalent order of magnitude. The increase in load is attributable to the increase in the overall electricity demand with the electrification of cooking, heating, and cooling. Furthermore, the growth of the commercial and industrial sectors of Tunisia and the electrification of transport will lead to a sharp increase in the electricity demand and therefore the overall power load.

Table 43 shows data on the levels of residual load in each region, when 'residual load' is defined as the load remaining after the local generation from variable renewable sources within the analysed region is exhausted. In general, a positive residual load implies that a region has an insufficient amount of variable supply to cover the demand in each time step, and therefore that demand must be met through other supply sources (dispatchable renewables, dispatchable fossil fuel, storage, interconnection). The maximum residual value is the largest positive value experienced throughout the year, indicating the largest mismatch between variable renewable generation and demand to occur during the modelling period.

Table 43: Tunisia – projection of load, generation, and residual load until 2050

Tunisia Development of Load and Generation		T-1.5°C			
		Maximum Load [MW]	Maximum Generation [MW]	Maximum Residual Load [MW]	Peak Load Increase [MW]
Southern Desert	2020	70	68	70	-
	2030	101	243	96	144%
	2050	206	1,903	182	294%
Southern Coastal	2020	200	215	197	-
	2030	287	557	263	144%
	2050	587	2,944	577	294%
South-western	2020	100	58	100	100%
	2030	143	119	142	143%
	2050	294	564	797	294%
Central Western	2020	273	290	272	-
	2030	382	585	911	140%
	2050	791	2,009	619	290%
Central Coastal	2020	663	663	659	-
	2030	959	1,052	911	145%
	2050	1,961	3,736	1,962	296%
North-western	2020	236	236	234	-
	2030	334	513	320	142%
	2050	689	2,895	619	292%
North-eastern	2020	382	382	373	-
	2030	551	1,171	453	144%
	2050	1,128	4,032	867	295%
Greater Tunis	2020	852	852	849	-
	2030	1,260	1,260	1,235	148%
	2050	2,557	3,809	2,360	300%
Tunisia-wide Total (non-coincident values)	**2020**	**2,776**	**2,764**	**2,754**	**-**
	2030	**4,017**	**5,500**	**4,331**	**144%**
	2050	**8,213**	**21,892**	**7,983**	**294%**

In our analysis, power generation is assumed to grow proportionally to the growth in overall demand across Tunisia. A more detailed assessment of the exact locations of power generation will be required to optimise the required expansion of transmission grids and to ensure that generation capacity is installed appropriately to provide system security and strength, congruent with grid operator requirements. A more detailed consideration of generation placement could lead to a reduction in the residual load to avoid over- and/or undersupply in each province, when either increased grid capacity or more storage systems will be required.

6.5 Results: Inter-regional Exchange of Capacity

As discussed in section 2.2, an updated map of Tunisia's electricity infrastructure was used as the basis for the power sector analysis. With the detail provided in the image of Res4Africa Foundation's report, ISF could accurately implement the interconnection limits between modelling regions in the 24-7 MATLAB model, based on conversion factors for the line ratings to MW capacity constraints. The updated infrastructure map (based on mapping conducted by STEG, the national grid operator) shows that Tunisia's electricity infrastructure has been significantly expanded relative to the 2017 data plotted in Figure 2, with a range of interconnection ratings spanning the country (90 kV, 150kV, 225kV, 400kV).[87] An image of the map referenced in the Res4Africa Foundation report is provided below for reference[88]:

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[87] Res4Africa, 'Deploying Battery Energy Storage Solutions in Tunisia', 2023

[88] Ibid.

Figure 37: Map of Tunisia’s electricity network (Image Source: Res4Africa)

Figure 37 provides the basis for the assumptions made regarding the modelling of geographic interconnections. However, line ratings are insufficient to provide exchange limits. Therefore, conversions were made between interconnection line ratings using conversion factors provided by an industry reference partner on previous project work (Table 44).

Table 44: Industry rule-of-thumb conversion factors: line rating to exchange limit

kV Line Rating	MW
132	500
330	1,000
500	3,000
400	2,400

Based on this information (regional interconnection mapping and conversion factors), the regional interconnection limits (shown in Table 44) were applied in the modelling of Tunisia's energy system. Constant interconnection values were used across the modelling time period for a variety of reasons: Res4Africa's map was based on STEG's projection of what Tunisia's network could become by the end of the 2010s[89]; Res4Africa's map shows notable improvement in Tunisia's transmission network relative to the World Bank's 2017 data[90]; given Tunisia's economic context, the resources for public infrastructure spending will be constrained, which may affect expenditure on electrical transmission, particularly given Tunisia's existing strong coverage of transmission infrastructure and rates of household electricity access. Therefore, the interconnection limits detailed in Table 45 describe the interconnection limits used across the years modelled (2020, 2030, 2050), avoiding overly ambitious assumptions around the expansion of the transmission infrastructure but constraining the possible imports/exports into/out of the regions in later years (2050).

Table 45: Interconnector capacities used in modelling Tunisia electrical system

	Southern Desert	Southern Coastal	South-western	Central Western	Central Coastal	North-western	North-eastern	Greater Tunis
Southern Desert		767	568	568	767	341	568	767
Southern Coastal			568	568	767	341	568	767
South-western				568	568	341	568	568
Central Western					767	341	568	568
Central Coastal						341	568	767
North-western							2400	2400
North-eastern								341
Greater Tunis								

As discussed in the methodology section 6.1, the 24/7 model distributes renewable generation capacity according to the regional potential, whereas load is distributed according to the relevant indicator (residential load an demand – are distributed by population; whereas industrial load is distributed according to GDP The locations of existing hydro power plants are fixed, and the installation of new capacities will depend upon geographic conditions and nature conservation requirements. Tunisia's existing gas generation assets were distributed according to their current locations based on publicly available information.[91] In this way, an accurate reconstruction of Tunisia's electricity transmission infrastructure and generation was implemented in the 24/7 MATLAB model.

The following results show the levels on annual energy exchange (TWh/a) on a regional basis for each of the years modelled, demonstrating which regions can export power to surrounding regions, and which regions will be more dependent on their neighbouring areas for imports (Figure 38, not that the x-axis is not constant). Also note the dispatch order in section 6.1.3.

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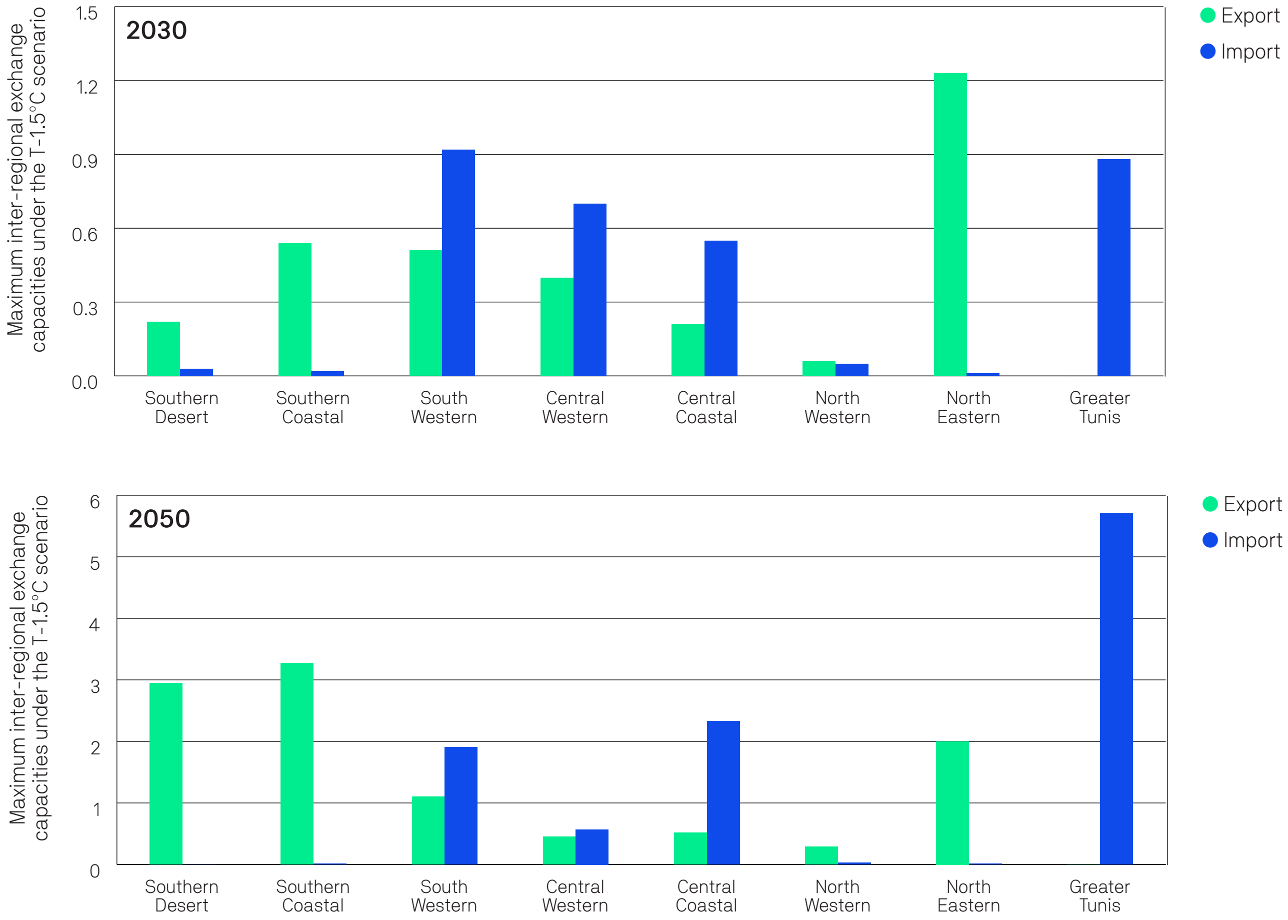
[89] Given Tunisia's economic and political context, it is possible that not all transmission infrastructure included in STEG's map will be able to reach financial closure and construction prior to 2020. Therefore, this map is seen as an appropriate guide for how Tunisia's regions will be connected in the short- medium-term future.

[90] The World Bank: https://datacatalog.worldbank.org/search/dataset/0040234

[91] Open Infrastructure Map, Tunisia Power Plant Statistics, accessed September 2024: https://openinframap.org/stats/area/Tunisia

Figure 38: Annual inter-regional exchange capacities, showing total imports and exports across the year for each region (2030, 2050)



As to be expected, regions with a higher percentage of the county's population, such as Greater Tunis and the Central Coastal region (36% and 24%, respectively) will be net importers of energy throughout the year. This is due to the residential demand of Tunisia's largest population centres, such as the cities of Tunis and Sfax, and to the fact that these two regions contribute to higher proportions of Tunisia's GDP (25% and 24%, respectively). Conversely, regions such as the Southern Desert and Southern Coastal area will be significant exporters of energy throughout the year, because generation assets are distributed according to potential. A comparison of the 2030 and 2050 results clearly shows energy exchange between regions as Tunisia progresses towards a decarbonised economy, reliant on more variable generation and the consumption of electricity in lieu of fossil-fuelled energy (i.e., gas-fuelled end uses and gas-powered electricity generation). Furthermore, Greater Tunis will experience a significant increase in its reliance on electrical imports, whereas areas in the south will also experience increased exports. Therefore, transmission planning must consider the implications of having load centres such as Tunis reliant not only on neighbouring regions in the north-east, but also on the southern exporting regions.

To prevent unnecessary expansion of the electricity grid, the projected increase in the regional electricity demand and additional electricity export plans should inform the expansion of the local power generation capacity. Grid operators can utilise a mixture of load management via demand-side measures and storage to regulate the exports and imports shown in Figure 38. Note that the interconnection values displayed above are dependent upon the assumed levels of distributed and utility storage, because interconnection comes after these energy sources in the fixed dispatch order. These results indicate that Tunisia should be able to leverage the existing transmission infrastructure to allow the transition pathway set out in the T-1.5°C OECM model. By appropriately managing the transition, ensuring sufficient levels of storage and load management (demand-side, electric vehicle charging), government bodies and grid-operating agencies will leverage the existing transmission infrastructure while ensuring security of supply for the regions. It was beyond the scope of this project to analyse the low- and medium-voltage distribution systems, so the quantification of the effects of micro-grids and other such arrangements are also beyond the scope of this study.

Limitations

The calculated loads are not optimised in terms of local storage, self-consumption by decentralised producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may differ from the actual values. Furthermore, the calculated export/import loads to neighbouring countries are not included in the regional interconnection analysis in this chapter. Peak load and peak generation events do not occur at the same time, so their values cannot simply be summed. Moreover, peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole country. The maximum residual load[92] shows the maximum undersupply in a region and indicates the maximum load that will be imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnections for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by one or more of the following options:

- Imports from other regions through interconnections;
- Battery storage facilities on-site at solar PV installations and for electric vehicles;
- Available back-up capacities, such as gas peaking plants;
- Load- and demand-side management.

In practice, security of supply will be achieved with a combination of several measures and will require the in-depth analysis of regional technical possibilities.

6.6 Results: Annual variation in renewable energy generation

Solar and wind power generation have different annual variation pattern, which are dependent on the climate zone and geographic location. This section provides a high-level analysis of the electricity import and/or export needs under the T-1.5°C scenario with high shares of variable power generation. In practice, electricity demand ('load') and generation ('supply') must be balanced at all times. If local generation cannot meet demand, electricity must be either imported from other regions or taken from existing storage facilities. If the generation is higher than the load, either the surplus electricity can be exported to other regions, stored, the load increased, or production reduced. The term 'curtailment' is defined as the forced reduction of electricity generation, and is the energy generated by renewable resources in excess of demand that cannot be stored or transmitted within Tunisia to other regions in a given time period. To determine the annual distribution of Tunisia's solar and wind power generation, generation and expected load were simulated with 1-hourly resolution (8760 h/a).

Figure 39 shows the weekly values of supply imbalances in terms of both curtailment and the additional imports required. During times of high generation, generation exceeds demand (green line); the red line shows when demand exceeds generation (i.e., when additional electricity generated must be imported into Tunisia). The modelling of Tunisia's transmission connections to its neighbouring countries (Algeria and Libya) was beyond the scope of this study, so further research must be undertaken to assess the availability of electricity imports at those times, or other measures that could address such supply imbalances. The operation of state-of-the-art power systems for renewable power generation will dominate the grid, utilizing a combination of demand- and generation-side management, export and import from neighbouring regions, and a cascade of different storage technologies, such as batteries, hydro pump storage, and at a later time, hydrogen/synthetic fuel production – which is beyond the scope of the 24/7 modelling undertaken.

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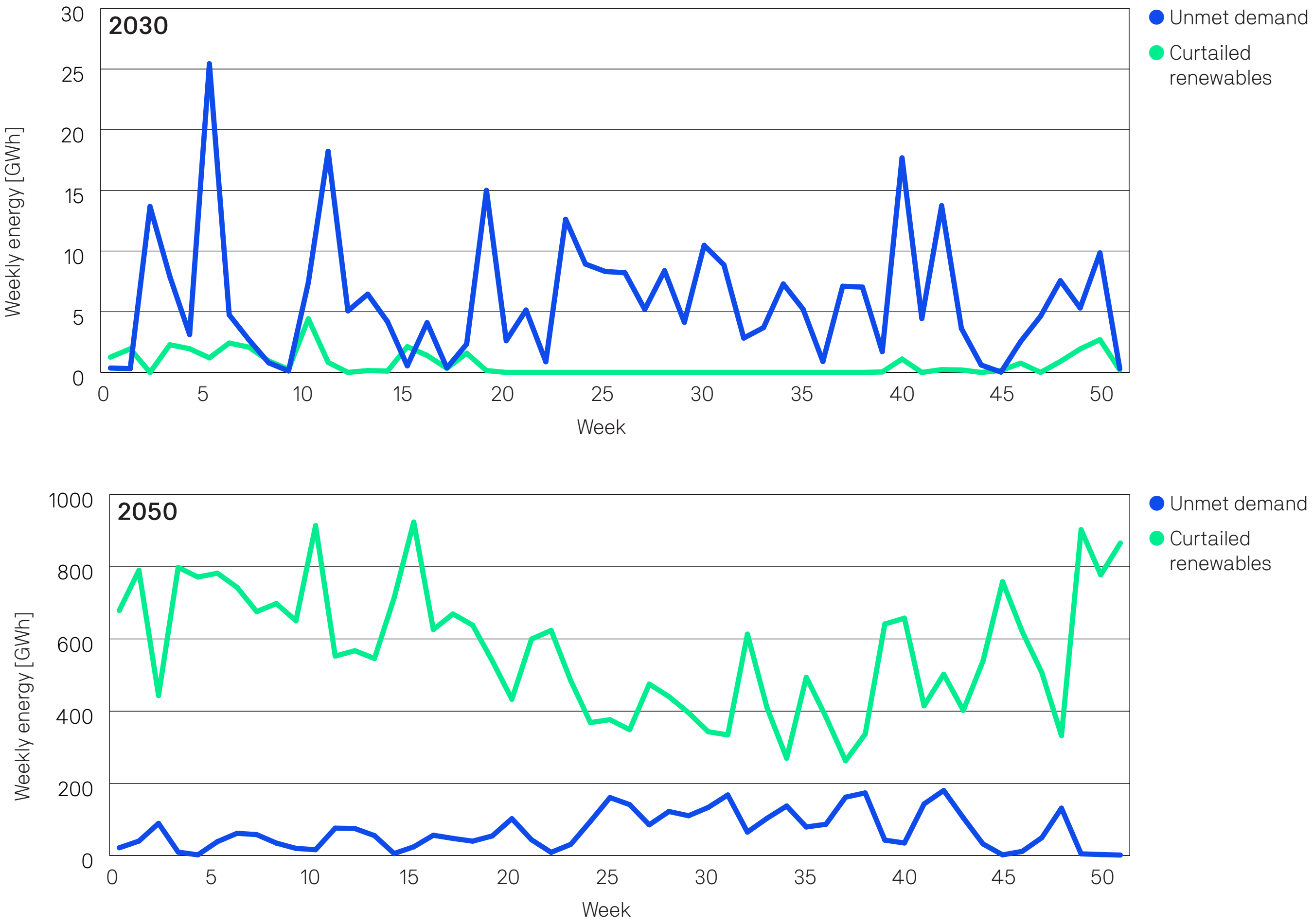
[92] Residual load is the load remaining after the local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and/or solar power plants.

Figure 39: Tunisia: weekly values for electricity import and export – 2030 and 2050



The results shown in Figure 39 underpin the significant amount of change that can be expected under the T-1.5°C scenario, with the values on of the y-axis changing by a factor of 40. Although there is increased use of renewable energy in 2030, there is limited curtailment because this capacity supplies a small proportion of the overall load and is only added to meet marginal increases in load and some reductions in fossil-fuel consumption. However, by 2050, a significant build-out of capacity is required to cover the energy demand throughout the year, leading to overbuilding/excess capacity throughout the year. The combination of significant increases in demand (both peak and annual consumption will increase 3–3.5-fold) and the reliance on variable resources means that a consistently high level of excess power is produced throughout the year, given the load assumptions used in the 24/7 modelling. Because load and generation necessarily vary over time, any coincidence in peak demand and generation cannot be assumed, leading to unmet demand occurring even in weeks with excess renewable generation.

Therefore, Figure 39 demonstrates the importance of the 'state-of-the-art power system operation' mentioned in this chapter. Optimisation was beyond the scope of this work, so further research is required to understand the trade-offs between the oversupply of renewable generation, additional investments in storage options, the assessment of additional inter-regional and international electrical transmission infrastructure, and demand-side management.

Figure 40: Weekly values for inter-province transmission – 2030 and 2050

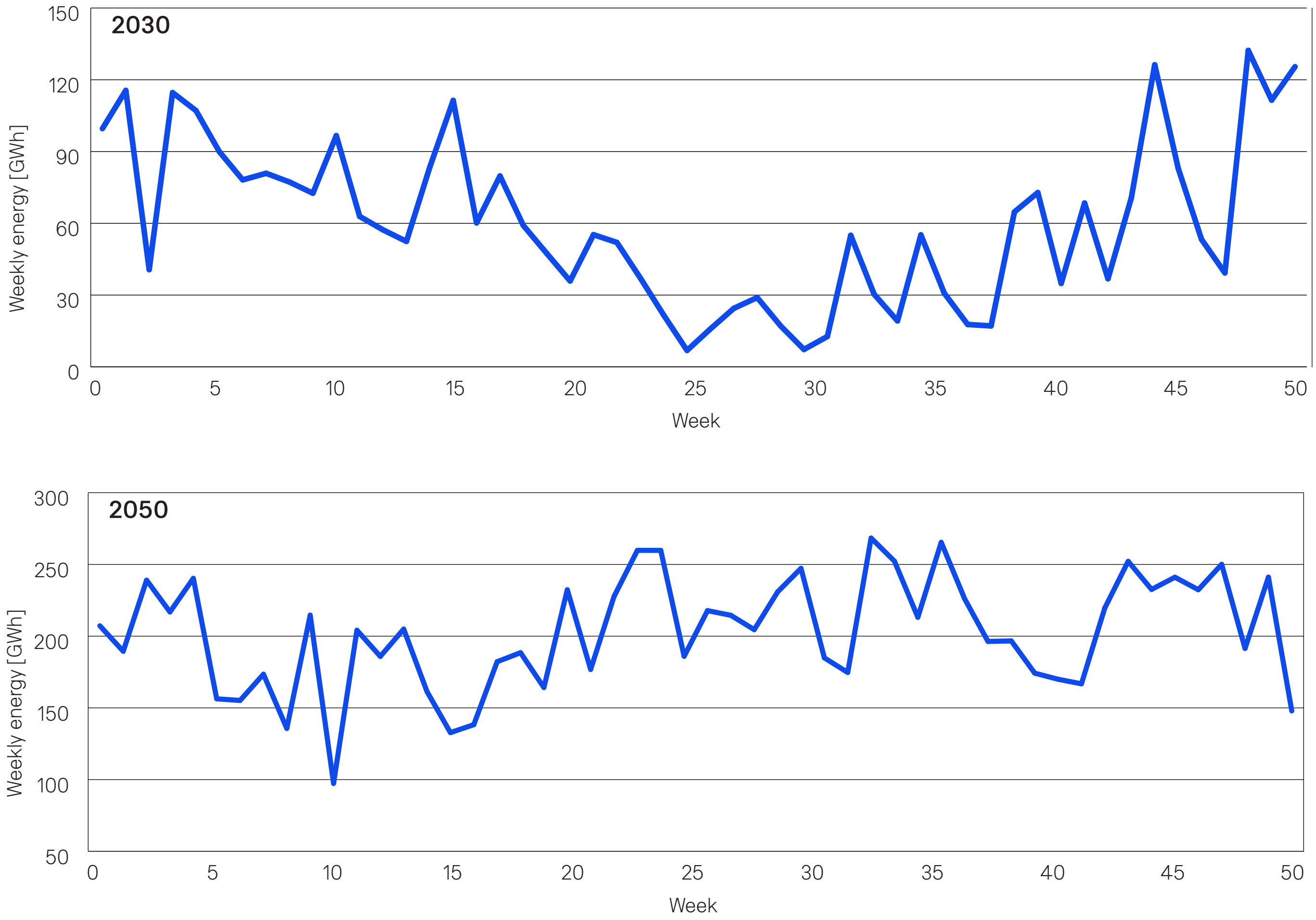
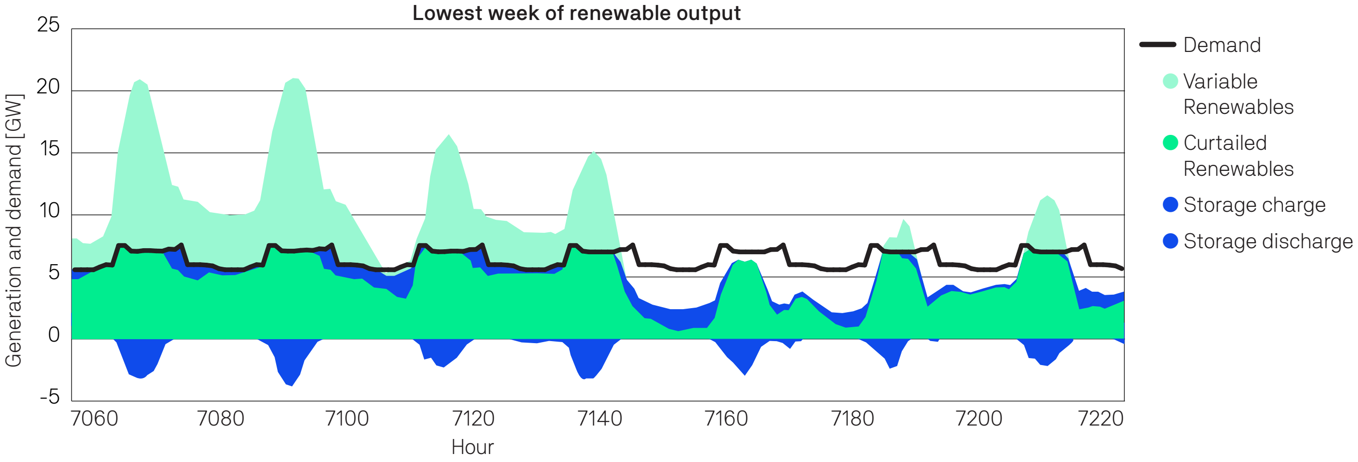


Figure 40 shows the weekly values for the inter-province transmission requirements in 2030 and 2050 under the T-1.5°C scenario, which are a function of the import and export requirements on the national level. Therefore, this figure shows the weekly variations in the inter-provincial energy exchanges shown in Figure 38. It can be inferred from this figure that during the period between 2030 and 2050, the interconnections between regions will be more consistently relied upon than at other times and to a greater proportion of its maximal capacity rating. The energy exchange between regions will become more important in times of greater mismatch between supply and demand. Note: the inverse relation occurs between interconnection and unmet demand in weeks 25–40 in 2050.

The following section looks deeper into two representative weeks from the 2050 modelling undertaken, contrasting the weeks of lowest and highest renewable generation relative to demand. The purple areas in Figure 41 and Figure 42 show the charging (negative values) and discharging (positive values) of the storage systems. Brown areas specify the times with dispatch needs (import or export of electricity) and green areas indicate renewable power generation. The white areas, which indicate periods of unmet demand, are further investigated. Therefore, the analysis of the variations in local annual solar and wind power generation is the first step in determining the technical storage requirements.

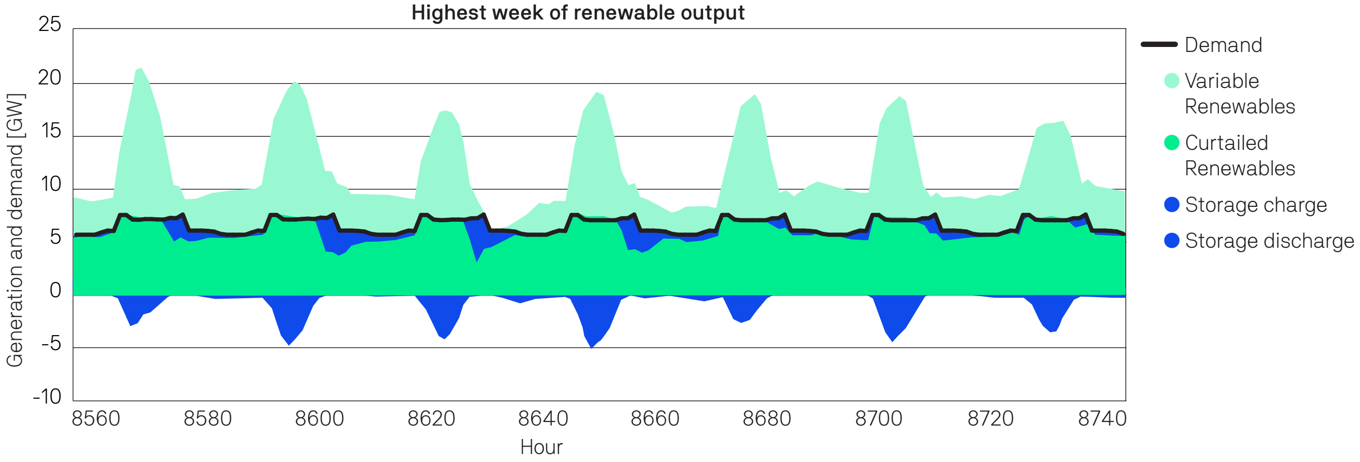
The modelling undertaken – based on historical meteorological data (section 6.1.1) – indicates that there may be cloudy periods of the year in Tunisia that are accompanied by low wind speeds, as shown in Figure 41, when power generation from both wind and solar is at the lowest level throughout the entire year (in October). The production by onshore wind generators is consistently limited to < 25% of their nominal capacity for a period of over 2.5 days (due to low wind resource), and solar output is constrained to approximately a quarter of its output in the first 2 days of the week. This event may be an anomaly given in that only 1 year's worth of data was used in the analysis and that consecutive periods of low wind are not characteristic of other weeks in October. Further analysis is required to examine the extent to which this could affect Tunisia's security of supply.

Figure 41: Tunisia – lowest renewable electricity production under the T-1.5°C scenario in 2050



The other extreme – a period with very high-power generation rates – occurred a mere month and a half later (December). In this week, wind speeds were consistently high, as can be seen by the excess generation outside daylight hours across the entire week (Figure 42). This figure indicates sufficient transmission to neighbouring countries (existing interconnections to Algeria and Libya), so new interconnections to Italy will provide significant economic benefit to Tunisia through the export of excess generation. This excess generation may also be utilised for the production of clean fuels and chemical feedstock.

Figure 42: Tunisia – highest renewable electricity production under the T-1.5°C scenario in 2050



Comparing Figures 41 and 42 indicates that additional storage capacity may benefit Tunisia's supply security, and perhaps play an important role in reducing the amount of generation capacity by 2050 by reducing the need for overbuilding capacity. As discussed, optimisation of the relationship between generation assets, transmission infrastructure, and additional storage capacity is beyond the scope of the modelling undertaken. The following section provides insights into the usage of the projected levels of storage capacity assumed in the modelling.

6.7 Storage Requirements

6.7.1 Introduction

The quantity of storage required will be largely dependent upon the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wei 2016)[93]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than the storage costs. Cebulla et al. (2018)[94] reported that "in general terms, photovoltaic-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap". In an analysis of 400 scenarios for Europe and the USA, they also found that once the share of variable renewables exceeds 40% of the total generation, the increase in electrical energy storage power capacity is about 1–2 GW for each percentage of variable renewable power generation in wind-dominated scenarios and 4–9 GW in solar-PV-dominated scenarios.

When the shares of variable power generation exceed 30%, storage requirements increase. The share of variable generation will exceed 30% between 2025 and 2030 under both scenarios in all regions. Therefore, a smart -integration strategy that includes demand-side management, and the installation of additional decentralised and centralised storage capacities must be established.

Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. However, solar PV costs have also declined significantly. Storage is economic when the cost per kilowatt-hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are several reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[95]. The California Independent System Operator (CISO)[96] defines economic curtailment during times of oversupply as a market-based decision. "During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can 'bid' into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritised using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered 'market-based'".

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[93] Wei W, et al. (2016) Regional study on investment for transmission infrastructure in China based on the State Grid data,10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016.

[94] Cebulla et al. (2018), How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

[95] Wind and Solar Energy Curtailment: Experience and Practices in the United States; Lori Bird, Jaquelin Cochran, and Xi Wang, National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

[96] Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/documents/sb350study-renewableintegrationgridreliability-fastfacts.pdf

6.7.2 Analysis of Energy Storage

Tunisia currently has a limited base of dispatchable renewable generation (such as hydro power) and negligible amounts of storage capacity. According to the Global Pumped Hydro Atlas (ANU 2022)[97], Tunisia has a limited number of high-quality pumped hydro sites, with the most attractive sites located in the mountain ranges of neighbouring Algeria. Therefore, the T-1.5°C scenario does not rely heavily on the expansion of hydro power for generation or on pumped hydro storage for the development of storage capacity.

Our analysis is performed on an hourly basis, so the modelling of demand spikes that occur for a limited time – from minutes to hours – is modelled at less-fine resolution, and peak demand is caused by heating or cooling loads and the tendency of households to use electricity to a greater extent in the morning and evening. Therefore, our model captures peaks, but these are smoother than would occur in reality, so actual grid and storage capacities must react to those changes. In reality, 'peak-shaving' could be used to avoid peak generation events. The term 'peak-shaving' refers to the reduction in the solar or hydro generation capacity in times of high production. Peak-shaving involves pro-actively managing solar generation by reducing the output – e.g., from utility-scale PV – to eliminate short-term spikes.

To build up the additional required storage capacity, we assume that a percentage of the solar PV capacity will be installed with battery storage. The suggested solar battery system must be able to store the entire peak capacity for 4 full load hours. The T-1.5°C scenario uses an ambitious growth trajectory, such that on aggregate, sufficient battery capacity exists that its nominal storage depth in GWh is the same order of magnitude as the aforementioned ratio of aggregate solar capacity x 4 full load hours (i.e., approximately 16 GW of utility battery storage by 2050).

The estimates provided for storage requirements also presuppose that variable renewables, such as solar PV and wind, will be first in the dispatch order, ahead all other types of power generation. Priority dispatch is the economic basis for investment in utility-scale solar PV and wind projects. The curtailment rates or storage rates will be significantly higher when priority dispatch is given to, for example, hydro power plants in 'baseload' generation mode. This case has not been calculated because it would involve a lack of investment in solar in the first place. With decreasing storage costs, as projected by Bloomberg (2019)[98], interconnections may become less economically favourable than batteries. The storage estimates provided are technology neutral and do not favour any specific battery technology.

Table 46 shows the storage assumptions utilised in the T-1.5°C scenario. Given that Tunisia has limited capacity for pumped hydro storage, no specific level of economic curtailment is targeted. Instead, curtailment is allowed to remain dependent upon the modelling assumptions, and the additional generation is shown to highlight Tunisia's potential to export power to neighbouring countries and also become an important nation in the production of H_2 and other clean fuels (note: the H_2 value in Table 46 refers to the H_2 used for the generation of electricity and is therefore restrained to a low value).

The storage demand for micro-grids and off-grid systems must be calculated individually and are not part of this assessment. However, micro-grids always require either a storage system with a capacity large enough (in terms of both the electricity supply in kilowatt-hours and the required load in kilowatts) to bridge the gap in times of low or no generation possibilities.

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[97] ANU (2022), Australian National University, 100% Renewable Energy Group, Global Pumped Hydro Energy Storage Atlas, https://re100.eng.anu.edu.au/global/

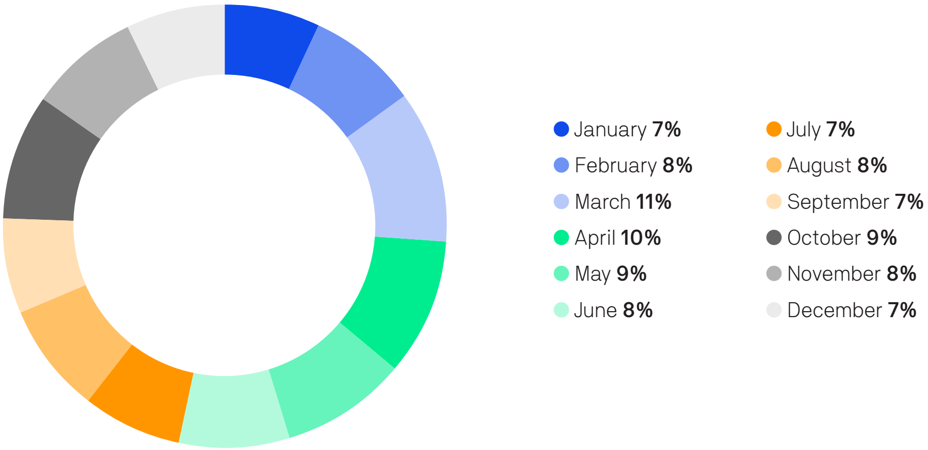
[98] Bloomberg (2019), A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldi-Scot, Bloomberg NEF, March 5 2019, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Table 46: Tunisia: Calculated electricity storage capacities by technology and year

Storage Capacity	Units	2020	2025	2030	2035	2040	2045	2050
Battery – distributed	[MW]	-	5	10	16	26	42	67
Electric Vehicle – V2G	[MW]	-	-	-	-	-	-	-
Battery-utility scale	[MW]	-	300	2,100	5,550	9,100	12,650	16,200
Hydro Pump Storage	[MW]	-	-	600	646	696	750	808
H_2	[MW]	-	5	6	7	8	10	12
Total	**[MW]**	**-**	**310**	**2,716**	**6,220**	**9,831**	**13,452**	**17,087**

The outcomes of the above modelling assumptions are illustrated below in Figure 43 and given Table 47, which show that the assumed levels of utility storage are used consistently throughout the year, dealing with the kind of supply gaps discussed in section 6.6. This is also indicative of the shallow nature of the storage capacity used, because without long-term storage, there is limited ability to shift energy generation from lull periods of variable power to high-demand periods.

Figure 43: Storage usage by month in 2050



The results in Table 47 are surprising, particularly because the utility battery storage capacity was distributed evenly across all regions. Table 47 shows that only the areas that are net exporters to other regions in Figure 38 have excess generation relative to the local regional load required to charge the storage capacity within their own boundaries. These net exporter regions are therefore able to store excess generation within their boundaries and then supply their own needs at a later time of supply mismatch. These net exporter areas (Southern Desert, Southern Coastal, North-western, North-eastern) are also allowed in the model to discharge to their immediate neighbours on condition that their own supply is already balanced and their neighbour requires additional supply to address a demand mismatch. Given that Greater Tunis has the highest load, future grid and storage capacities should be developed according to the need to sufficiently supply the capital.

Table 47: Storage Usage – Annual charge and discharge

	Total Charge [GWh]	Total Discharge [GWh]
Southern Desert	-79	58
Southern Coastal	-100	81
South-western	0	0.0
Central Western	0	0.0
Central Coastal	0	0.0
North-western	-12	12
North-eastern	-144	135
Greater Tunis	**0**	**0.0**

6.7.3 Cost development – Battery storage technologies

Battery technologies have developed significantly over the past decade, and the global annual market increased from 700 MW in 2015 to close to 16,000 MW in 2021 (IEA-BAT 2024)[99]. The market is split roughly equally between grid-scale storage and 'behind-the-meter' storage for solar PV projects. The rapidly growing demand for electric vehicles has significantly accelerated the development of battery technologies, and manufacturing capacities have grown by double digits, with costs decreasing accordingly. The battery costs per kilowatt-hour storage capacity decreased from US$668 (trillion TND 2,024) in 2013 to US$137 (trillion TND 415) in 2020 – a reduction of 79% over 7 years. Bloomberg New Energy Finance estimates that battery costs will decline further to around US$58 (trillion TND 176) by 2030.

6.7.4 Further research Required

A calculation of the investment costs in storage technologies that will be required after 2030 and by 2050 entail high levels of uncertainty and would require both a range of scenarios and optimisations to provide meaningful insights into low-cost system solutions for Tunisia. This level of detail is beyond the scope of this study. More-detailed storage technology assessments will be required if stand-alone grids are considered in the modelling of the T-1.5°C scenario.

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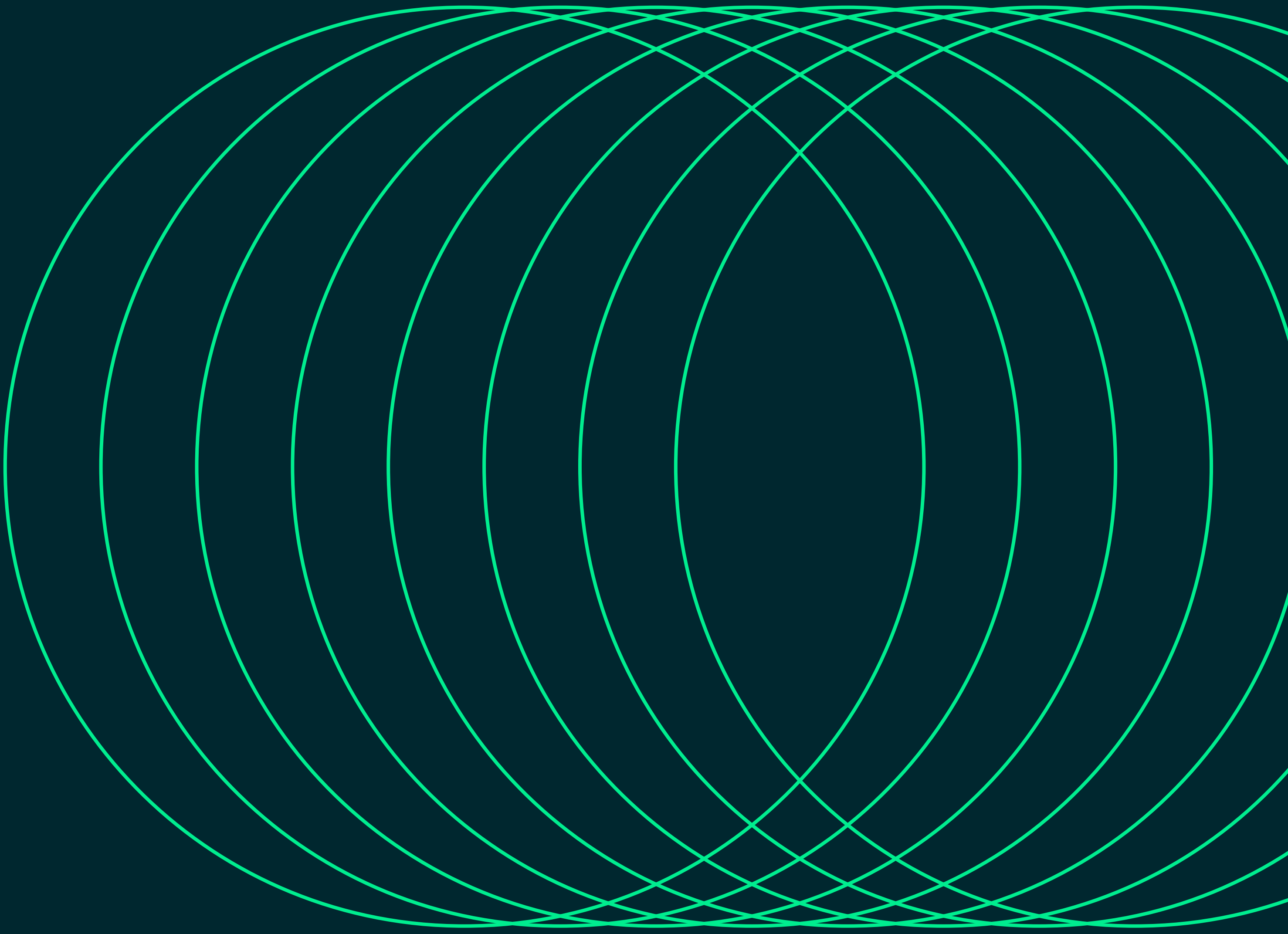
[99] IEA-BAT (2024) – website viewed April 2024. https://www.iea.org/reports/batteries-and-secure-energy-transitions

7

Tunisia: Data Appendix



Tunisia: Electricity generation [TWh/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Power plants	21	21	23	34	47	58	69	79
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	20	20	20	25	27	15	9	0
of which from H_2	0	0	0	0	0	0	0	0
– Oil	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0
– Biomass (& renewable waste)	0	0	0	0	1	2	3	4
– Hydro	0	0	0	0	0	0	0	0
– Wind	1	0	1	5	11	21	29	37
of which wind offshore	0	0	0	1	2	5	8	11
– PV	0	0	2	3	8	20	28	38
– Geothermal	0	0	0	0	0	0	0	1
– Solar thermal power plants	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0
Combined heat and power plants	1	1	1	1	1	0	0	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	1	1	0	0	0	0	0	0
of which from H_2	0	0	0	0	0	0	0	0
– Oil	0	0	0	0	0	0	0	0
– Biomass (& renewable waste)	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0
CHP by producer								
– Main activity producers	0	0	0	0	0	0	0	0
– Autoproducers	1	1	1	1	1	0	0	0
Total generation	22	21	24	34	48	59	69	80
– Fossil	21	20	20	25	27	15	9	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	21	20	20	25	27	15	9	0
– Oil	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0
– of which renewable H_2	0	0	0	0	0	0	0	0
– Renewables (w/o renewable hydrogen)	1	1	3	9	21	43	61	80
– Hydro	0	0	0	0	0	0	0	0
– Wind	1	0	1	5	11	21	29	37
– PV	0	0	2	3	8	20	28	38
– Biomass (& renewable waste)	0	0	0	1	1	2	3	4
– Geothermal	0	0	0	0	0	0	0	1
– Solar thermal power plants	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0
Distribution losses	4	4	1	2	2	3	3	4
Own consumption electricity	1	1	2	2	3	3	4	4
Electricity for hydrogen production	0	0	1	4	6	8	11	13
Electricity for synfuel production	0	0	0	0	0	0	0	0
Final energy consumption (electricity)	17	16	19	26	36	43	50	57
Variable RES (PV, Wind, Ocean)	1	1	3	9	20	41	57	75
Share of variable RES	3%	4%	12%	25%	41%	70%	82%	94%
RES share (domestic generation)	4%	4%	14%	27%	44%	74%	87%	100%

Tunisia: Transport – Final Energy [PJ/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Road	97	93	100	93	67	64	59	63
– Fossil fuels	97	93	95	78	32	20	3	0
– Biofuels	0	0	4	6	8	9	10	11
– Synfuels	0	0	0	0	0	0	0	0
– Natural gas	0	0	1	1	1	1	1	0
– Hydrogen	0	0	0	0	0	0	0	0
– Electricity	0	0	1	8	26	35	45	52
Rail	1	1	1	1	1	1	1	1
– Fossil fuels	0	1	1	1	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0
– Electricity	0	0	0	0	1	1	1	1
Navigation	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0
Aviation	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0
Total (incl. Pipelines)	102	94	101	95	68	65	60	64
– Fossil fuels	98	94	97	81	34	21	4	0
– Biofuels (incl. Biogas)	0	0	4	6	8	9	10	11
– Synfuels	0	0	0	0	0	0	0	0
– Natural gas	0	0	1	1	1	1	1	0
– Hydrogen	0	0	0	0	0	0	0	0
– Electricity	0	0	1	8	27	36	46	53
Total RES	0	0	4	8	19	35	50	64
RES share	0%	0%	4%	9%	29%	54%	84%	100%

Tunisia: Heat supply and air conditioning [PJ/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
District heating plants	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0
– Biomass	0	0	0	0	0	0	0	0
– Solar collectors	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0
Heat from CHP 1)	1	1	1	0	0	0	0	0
– Fossil fuels	1	1	1	0	0	0	0	0
– Biomass	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0
Direct heating	137	143	147	153	151	156	162	171
– Fossil fuels	109	113	105	35	31	22	9	0
– Biomass	21	22	18	75	51	44	44	38
– Solar collectors	2	3	6	11	16	19	22	27
– Geothermal	0	0	3	4	7	10	13	18
– Heat pumps 2)	0	0	6	10	26	35	42	47
– Electric direct heating	5	5	7	7	6	6	6	6
– Hydrogen	0	0	0	0	1	2	3	6
Total heat supply 3)	138	144	148	154	152	156	162	171
– Fossil fuels	111	115	106	36	31	22	9	0
– Biomass	21	22	18	75	51	44	44	38
– Solar collectors	2	3	6	11	16	19	22	27
– Geothermal	0	0	3	4	7	10	13	18
– Heat pumps 2)	0	0	6	10	26	35	42	47
– Electric direct heating (incl. process heat)	5	5	9	17	21	25	29	34
– Hydrogen	0	0	0	0	1	2	3	6
RES share (including RES electricity)	17%	17%	20%	64%	63%	76%	89%	100%
Electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Tunisia: Installed Capacity [GW] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Total generation	8	7	8	13	18	24	29	35
– Fossil	8	7	7	9	9	5	3	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas (w/o H2)	8	7	7	9	9	5	3	0
– Oil & Diesel	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0
– Hydrogen (fuel cells, gas power plants, gas CHP)	0	0	0	0	0	0	0	0
– Renewables	0	0	1	4	9	19	26	35
– Hydro	0	0	0	0	0	0	0	0
– Wind	0	0	0	2	4	7	9	12
of which wind offshore	0	0	0	0	1	1	2	3
– PV	0	0	1	2	5	12	16	22
– Biomass (& renewable waste)	0.0	0.000	0.097	0.159	0.296	0.467	0.7	0.9
– Geothermal	0	0	0	0	0	0	0	0
– Solar thermal power plants	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	0	1	4	9	19	25	34
Share of variable RES	5%	6%	16%	29%	48%	76%	87%	97%
RES share (domestic generation)	5%	7%	18%	31%	50%	79%	90%	100%

Tunisia: Final Energy Demand [PJ/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-Energy use)	326	333	345	358	322	329	334	354
Total Energy use 1)	316	302	313	323	289	293	297	315
Transport	102	94	101	95	68	65	60	64
– Oil products	98	94	97	81	34	21	4	0
– Natural gas	0	0	1	1	1	1	1	0
– Biofuels	0	0	4	6	8	9	10	11
– Synfuels	0	0	0	0	0	0	0	0
– Electricity	0	0	1	8	27	36	46	53
– RES electricity	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0
– RES share Transport	0%	0%	4%	9%	29%	54%	84%	100%
Industry	87	80	85	93	97	100	109	118
– Electricity	21	20	26	39	51	63	73	83
– RES electricity	1	1	4	11	23	47	64	83
– Public district heat	0	0	0	0	0	0	0	0
– RES district heat	0	0	0	0	0	0	0	0
– Hard coal & lignite	0	0	0	0	0	0	0	0
– Oil products	32	32	26	2	1	0	0	0
– Gas	34	29	29	20	15	12	6	0
– Solar	0	0	2	4	5	6	7	9
– Biomass	0	0	1	25	21	12	11	14
– Geothermal	0	0	1	1	3	3	4	5
– Hydrogen	0	0	0	1	2	4	6	7
RES share Industry	1%	1%	10%	46%	55%	72%	86%	100%
Other Sectors	127	127	126	136	124	128	129	133
– Electricity	42	38	42	46	51	56	62	68
– RES electricity	2	1	6	12	22	42	54	68
– Public district heat	0	0	0	0	0	0	0	0
– RES district heat	0	0	0	0	0	0	0	0
– Hard coal & lignite	0	0	0	0	0	0	0	0
– Oil products	40	39	39	3	1	0	0	0
– Gas	20	20	19	13	17	12	4	0
– Solar	2	3	4	7	10	13	14	18
– Biomass	22	27	21	64	40	41	40	31
– Geothermal	0	0	2	3	4	6	9	13
– Hydrogen	0	0	0	0	0	0	0	3
RES share Other Sectors	21%	25%	26%	63%	62%	79%	91%	100%
Total RES	27	32	45	134	138	182	220	262
RES share	9%	11%	14%	42%	48%	62%	74%	83%
Non energy use	10	31	33	35	33	35	37	39
– Oil	10	31	33	35	33	35	36	38
– Gas	0	0	0	0	0	0	0	0
– Coal	0	0	0	0	0	0	0	0

Tunisia: Energy-Releated CO_2 Emissions [Million tons/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Condensation power plants	9	10	9	10	10	5	3	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	9	9	9	10	10	5	3	0
– Oil + Diesel	0	0	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0	0	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	0	0	0	0	0	0	0	0
– Oil	0	0	0	0	0	0	0	0
CO_2 emissions power and CHP plants	10	10	10	10	10	6	3	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Gas	9	9	9	10	10	6	3	0
– Oil + Diesel	0	0	0	0	0	0	0	0
CO_2 intensity (g/kWh)	0	0	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0	0	0
– CO_2 intensity fossil electr. generation	451	486	470	401	379	368	359	0
– CO_2 intensity total electr. generation	434	467	403	292	211	95	46	0
CO_2 emissions by sector	27	27	25	19	15	9	4	0
– Industry 1)	5	5	4	2	1	1	0	0
– Other sectors 1)	5	5	4	1	1	1	0	0
– Transport	8	7	7	6	3	2	0	0
– Power generation 2)	9	10	9	10	10	5	3	0
Other conversion 3) - part of industry & transport	1	1	1	0	0	0	0	0
Population (Mill.)	12	12	0	0	0	0	0	0
CO_2 emissions per capita (t/capita)	2	2	0	0	0	0	0	0

Tunisia: Primary Energy Demand [PJ/a] – 1.5°C

	2019	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-energy-use)	461	489	467	478	446	408	395	395
– Fossil (excluding on-energy use)	407	402	386	307	257	149	72	0
– Hard coal	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0
– Natural gas	229	226	218	215	221	128	69	0
– Crude oil	178	176	168	92	36	21	3	0
– Nuclear	0	0	0	0	0	0	0	0
– Renewables	44	55	48	136	155	224	286	356
– Hydro	0	0	0	0	0	0	0	1
– Wind	2	2	2	10	27	55	79	103
– Solar	3	4	10	17	38	82	110	148
– Biomass	39	50	33	104	83	76	82	84
– Geothermal	0	0	3	5	7	11	15	21
– Ocean energy	0	0	0	0	0	0	0	0
Total RES	44	55	49	137	157	228	292	363
RES share	10%	12%	11%	31%	38%	61%	80%	100%

Tunisia: Electricity generation [TWh/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Power plants	18	19	19	20	20	21	21	23	31	40	48	58	68
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	17	18	19	19	19	20	20	19	23	27	27	25	21
of which from H_2	0	0	0	0	0	0	0	0	0	0	1	1	2
– Oil	0	1	0	0	0	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0
– Biomass (& renewable waste)	0	0	0	0	0	0	0	0	0	1	1	2	3
– Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0
– Wind	0	0	0	0	0	1	0	1	4	7	10	15	22
of which wind offshore	0	0	0	0	0	0	0	0	1	2	3	4	7
– PV	0	0	0	0	0	0	0	2	3	5	8	14	19
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	1
– Solar thermal power plants	0	0	0	0	0	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	1	1	1	1	1	1	0	0	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	0	0	0	0	1	1	1	0	0	0	0	0	0
of which from H_2	0	0	0	0	0	0	0	0	0	0	0	0	0
– Oil	0	0	0	0	0	0	0	0	0	0	0	0	0
– Biomass (& renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0
CHP by producer													
– Main activity producers	0	0	0	0	0	0	0	0	0	0	0	0	0
– Autoproducers	0	0	0	0	1	1	1	1	1	1	0	0	0
Total generation	18	20	20	20	21	22	21	23	31	40	49	59	68
– Fossil	18	19	19	20	20	21	20	20	23	27	28	26	22
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	18	18	19	20	20	21	20	20	23	27	27	25	21
– Oil	0	1	0	0	0	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0	0	0	1	1	2
of which renewable H_2	0	0	0	0	0	0	0	0	0	0	0	0	0
– Renewables (w/o renewable hydrogen)	0	1	1	1	1	1	1	3	8	13	21	33	47
– Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0
– Wind	0	0	0	0	0	1	0	1	4	7	10	15	22
– PV	0	0	0	0	0	0	0	2	3	5	8	14	19
– Biomass (& renewable waste)	0	0	0	0	0	0	0	0	1	1	2	2	3
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	1
– Solar thermal power plants	0	0	0	0	0	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution losses	3	3	3	4	4	4	4	1	1	2	2	2	3
Own consumption electricity	1	1	1	1	1	1	1	2	2	2	3	3	3
Electricity for hydrogen production	0	0	0	0	0	0	0	1	4	7	9	12	15
Electricity for synfuel production	0	0	0	0	0	0	0	0	0	0	0	0	0
Final energy consumption (electricity)	14	15	16	16	16	17	16	19	23	29	34	40	45
Variable RES (PV, Wind, Ocean)	0	1	1	1	1	1	1	3	7	12	18	29	41
Share of variable RES	1%	3%	3%	3%	3%	3%	4%	12%	23%	29%	37%	49%	60%
RES share (domestic generation)	2%	3%	3%	3%	3%	4%	4%	14%	26%	33%	43%	56%	68%

Tunisia: Transport– Final Energy [PJ/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Road	77	89	89	97	98	97	93	100	105	109	120	133	150
– Fossil fuels	77	89	89	97	98	97	93	95	97	90	97	103	114
– Biofuels	0	0	0	0	0	0	0	4	5	8	9	11	14
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Natural gas	0	0	0	0	0	0	0	1	1	1	1	2	2
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0
– Electricity	0	0	0	0	0	0	0	1	1	10	13	17	19
Rail	1	1	1	1	1	1	1	1	1	1	1	1	1
– Fossil fuels	1	1	1	1	1	0	1	1	1	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Electricity	0	0	0	0	0	0	0	0	0	1	1	1	1
Navigation	0	0	0	0	0	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
Aviation	0	0	0	0	0	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Biofuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (incl. Pipelines)	91	94	100	107	107	102	94	101	106	110	121	134	151
– Fossil fuels	79	90	90	98	99	98	94	97	100	92	99	105	116
– Biofuels (incl. Biogas)	0	0	0	0	0	0	0	4	5	8	9	11	14
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Natural gas	0	0	0	0	0	0	0	1	1	1	1	2	2
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0
– Electricity	0	0	0	0	0	0	0	1	2	10	13	18	20
Total RES	0	0	0	0	0	0	0	4	6	11	15	21	28
RES share	0%	0%	0%	0%	0%	0%	0%	4%	5%	10%	12%	16%	18%

Tunisia: Heat supply and air conditioning [PJ/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
District heating plants	0	0	0	0	0	0	0	0	0	0	0	0	0
– Fossil fuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0
– Solar collectors	0	0	0	0	0	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat from CHP 1)	0	0	1	1	1	1	1	1	0	0	0	0	0
– Fossil fuels	0	0	1	1	1	1	1	1	0	0	0	0	0
– Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0
Direct heating	121	133	129	133	138	137	143	148	164	175	186	191	197
– Fossil fuels	94	104	102	107	110	109	113	108	99	96	91	78	68
– Biomass	21	20	20	20	21	21	22	22	31	37	40	40	30
– Solar collectors	1	2	2	2	2	2	3	6	11	16	19	22	27
– Geothermal	0	0	0	0	0	0	0	2	3	4	5	8	10
– Heat pumps 2)	0	0	0	0	0	0	0	1	2	2	5	12	21
– Electric direct heating	4	8	4	4	5	5	5	7	7	6	6	6	6
– Hydrogen	0	0	0	0	0	0	0	0	0	1	2	3	6
Total heat supply 3)	121	134	129	134	139	138	144	149	164	176	186	191	197
– Fossil fuels	95	104	103	107	111	111	115	109	100	96	91	78	68
– Biomass	21	20	20	20	21	21	22	22	31	37	40	40	30
– Solar collectors	1	2	2	2	2	2	3	6	11	16	19	22	27
– Geothermal	0	0	0	0	0	0	0	2	3	4	5	8	10
– Heat pumps 2)	0	0	0	0	0	0	0	1	2	2	5	12	21
– Electric direct heating (incl. process heat)	4	8	4	4	5	5	5	9	17	21	25	29	34
– Hydrogen	0	0	0	0	0	0	0	0	0	1	2	3	6
RES share (including RES electricity)	19%	17%	17%	16%	17%	17%	17%	21%	31%	37%	42%	50%	57%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Tunisia: Installed Capacity [GW] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Total generation	6	8	8	8	8	8	7	8	11	15	18	23	27
– Fossil	6	8	7	8	8	8	7	7	8	9	10	9	8
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas (w/o H2)	6	7	7	7	7	8	7	7	8	9	9	9	7
– Oil & Diesel	0	1	0	0	0	0	0	0	0	0	0	0	0
– Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0
– Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hydrogen (fuel cells, gas power plants, gas CHP)	0	0	0	0	0	0	0	0	0	0	0	0	1
– Renewables	0	0	0	0	0	0	0	1	3	5	8	13	19
– Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0
– Wind	0	0	0	0	0	0	0	0	2	2	3	5	7
of which wind offshore	0	0	0	0	0	0	0	0	0	1	1	1	2
– PV	0	0	0	0	0	0	0	1	2	3	5	8	11
– Biomass (& renewable waste)	0	0.0	0.0	0.0	0.0	0.0	0.000	0.097	0.149	0.251	0.381	0.5	0.7
– Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0
– Solar thermal power plants	0	0	0	0	0	0	0	0	0	0	0	0	0
– Ocean energy	0	0	0	0	0	0	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	0	0	0	0	0	0	1	3	5	8	13	18
Share of variable RES	2%	3%	4%	4%	4%	5%	6%	16%	27%	34%	43%	56%	66%
RES share (domestic generation)	2%	3%	4%	4%	4%	5%	7%	18%	29%	36%	46%	58%	71%

Tunisia: Final Energy Demand [PJ/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-Energy use)	291	310	316	331	332	326	333	353	383	412	446	476	502
Total Energy use 1)	282	299	303	317	319	316	302	319	347	373	403	429	453
Transport	91	94	100	107	107	102	94	101	106	110	121	134	151
– Oil products	79	90	90	98	99	98	94	97	100	92	99	105	116
– Natural gas	0	0	0	0	0	0	0	1	1	1	1	2	2
– Biofuels	0	0	0	0	0	0	0	4	5	8	9	11	14
– Synfuels	0	0	0	0	0	0	0	0	0	0	0	0	0
– Electricity	0	0	0	0	0	0	0	1	2	10	13	18	20
– RES electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0
– RES share Transport	0%	0%	0%	0%	0%	0%	0%	4%	5%	10%	12%	16%	18%
Industry	85	90	88	89	88	87	80	86	95	105	113	120	127
– Electricity	19	20	19	19	21	21	20	25	35	43	52	63	74
– RES electricity	0	1	1	1	1	1	1	4	9	14	22	36	51
– Public district heat	0	0	0	0	0	0	0	0	0	0	0	0	0
– RES district heat	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hard coal & lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Oil products	28	37	36	34	30	32	32	27	20	20	18	14	5
– Gas	37	33	33	36	38	34	29	30	31	31	30	23	22
– Solar	0	0	0	0	0	0	0	2	4	5	6	7	9
– Biomass	0	0	0	0	0	0	0	1	1	3	1	2	5
– Geothermal	0	0	0	0	0	0	0	1	1	3	3	4	5
– Hydrogen	0	0	0	0	0	0	0	0	1	2	4	6	7
– RES share Industry	1%	1%	1%	1%	1%	1%	1%	9%	18%	25%	32%	47%	60%
Other Sectors	107	115	115	121	123	127	127	132	146	157	169	176	175
– Electricity	33	36	36	38	38	42	38	42	46	51	56	62	68
– RES electricity	1	1	1	1	1	2	1	6	12	17	24	35	47
– Public district heat	0	0	0	0	0	0	0	0	0	0	0	0	0
– RES district heat	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hard coal & lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Oil products	33	37	38	41	40	40	39	39	36	34	33	32	31
– Gas	15	17	16	18	20	20	20	20	20	20	20	20	20
– Solar	1	2	2	2	2	2	3	4	7	10	13	14	18
– Biomass	25	24	23	23	23	22	27	26	36	41	45	44	31
– Geothermal	0	0	0	0	0	0	0	1	1	2	2	3	5
– Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	3
– RES share Other Sectors	25%	23%	23%	21%	21%	21%	25%	28%	38%	44%	50%	55%	59%
Total RES	27	27	27	27	27	27	32	49	78	103	130	164	194
RES share	10%	9%	9%	8%	8%	9%	11%	15%	22%	28%	32%	38%	43%
Non energy use	8	12	12	13	13	10	31	33	36	39	42	46	50
– Oil	8	12	12	13	13	10	31	33	36	39	42	46	49
– Gas	0	0	0	0	0	0	0	0	0	0	0	0	1
– Coal	0	0	0	0	0	0	0	0	0	0	0	0	0

Tunisia: Energy-Releated CO_2 Emissions [Million tons/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Condensation power plants	8	9	9	9	9	9	10	9	9	10	10	10	9
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	8	8	8	9	9	9	9	9	9	10	10	9	8
– Oil + Diesel	0	1	0	0	0	0	0	0	0	0	0	1	1
Combined heat and power plants	0	0	0	0	0	0	0	0	0	0	0	0	0
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	0	0	0	0	0	0	0	0	0	0	0	0	0
– Oil	0	0	0	0	0	0	0	0	0	0	0	0	0
CO_2 emissions power and CHP plants	8	9	9	9	9	10	10	9	9	11	10	10	9
– Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Gas	8	8	9	9	9	9	9	9	9	10	10	9	8
– Oil + Diesel	0	1	0	0	0	0	0	0	0	0	0	1	1
CO_2 intensity (g/kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0	0	0	0	0	0	0	0
– CO_2 intensity fossil electr. generation	476	488	458	451	452	451	486	470	401	390	379	372	411
– CO2 intensity total electr. generation	468	473	443	438	438	434	467	402	298	261	215	163	130
CO_2 emissions by sector	24	27	26	27	27	27	27	25	24	25	25	23	23
– Industry 1)	5	5	5	5	5	5	5	4	4	3	3	2	2
– Other sectors 1)	4	4	4	5	5	5	5	4	4	4	4	4	3
– Transport	7	7	7	8	8	8	7	7	7	7	7	8	9
– Power generation 2)	8	9	9	9	9	9	10	9	9	10	10	10	9
– Other conversion 3) – part of industry & transport	1	1	1	1	1	1	1	1	1	1	1	1	1
Population (Mill.)	11	11	11	11	12	12	12	0	0	0	0	0	0
CO_2 emissions per capita (t/capita)	2	2	2	2	2	2	2	0	0	0	0	0	0

Tunisia: Primary Energy Demand [PJ/a] – REFERENCE

	2012	2015	2016	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-energy-use)	430	443	452	463	471	461	489	489	494	534	558	577	609
– Fossil (excluding on-energy use)	378	389	397	407	414	407	402	388	382	394	392	365	353
– Hard coal	0	0	0	0	0	0	0	0	0	0	0	0	0
– Lignite	0	0	0	0	0	0	0	0	0	0	0	0	0
– Natural gas	213	209	226	227	237	229	226	219	221	240	236	210	194
– Crude oil	165	180	171	180	177	178	176	169	161	153	156	156	159
– Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0
– Renewables	43	43	43	43	44	44	55	67	76	101	124	165	206
– Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0
– Wind	2	2	2	2	2	2	2	2	6	7	14	23	44
– Solar	2	2	2	2	3	3	4	10	16	26	36	58	78
– Biomass	39	39	39	39	39	39	50	53	51	63	67	75	72
– Geothermal	0	0	0	0	0	0	0	2	3	4	6	9	12
– Ocean energy	0	0	0	0	0	0	0	0	0	0	0	0	0
Total RES	41	43	43	43	44	44	55	68	77	103	126	168	210
RES share	10%	10%	10%	10%	10%	10%	12%	15%	17%	21%	24%	32%	37%

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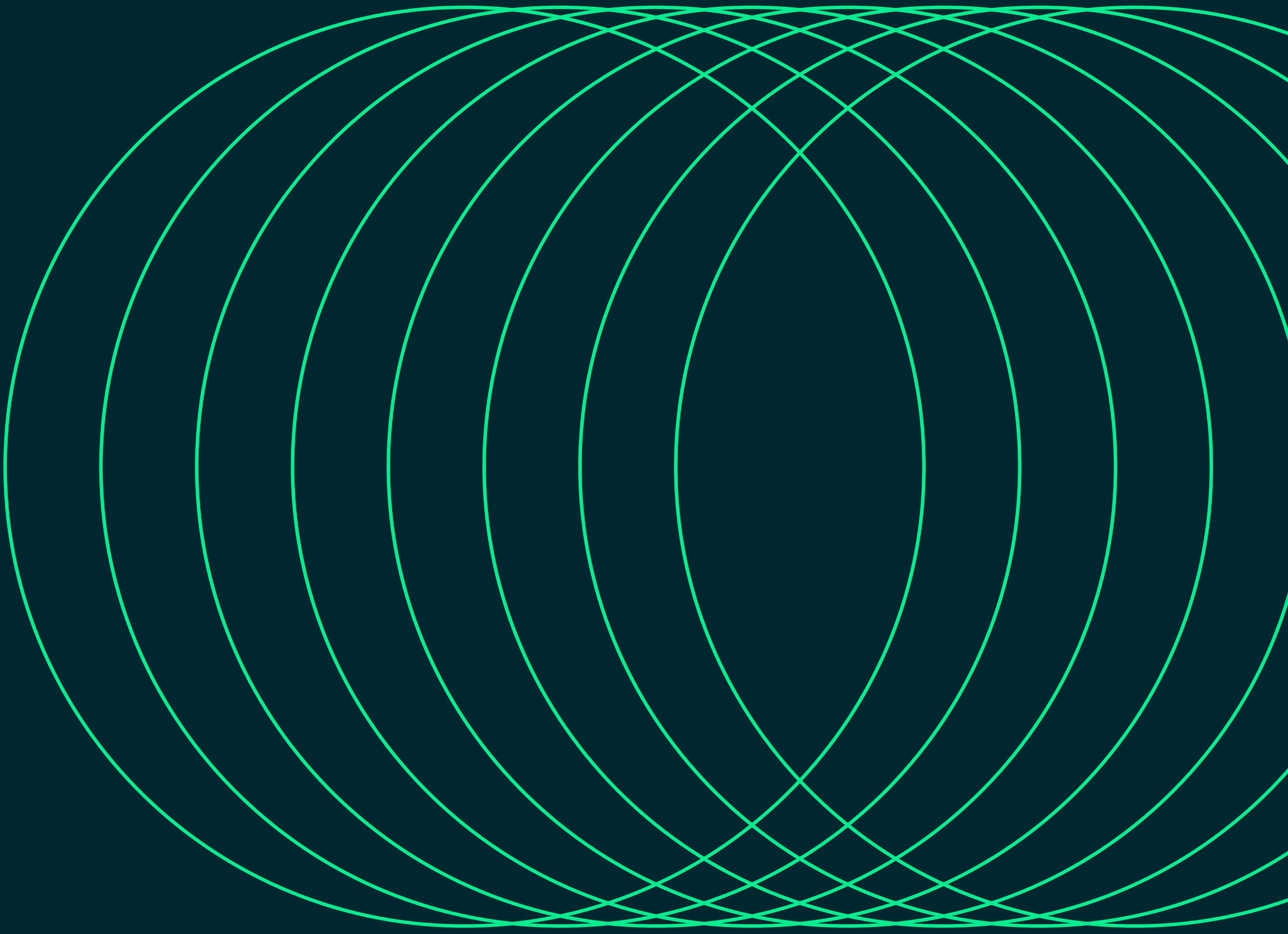

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