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DEUTSCHE ZUSAMMENARBEIT

Study on the opportunities of "Power-to-X" in Tunisia

Published by

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Ministry of Industry Mines and Energy

Imprint

Published by the
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany
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As at
April 2021

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German Federal Ministry for Economic Cooperation and Development (BMZ)

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DIRECTORY OF ABBREVIATIONS, UNITS, AND SYMBOLS

Abbreviations

AEL	Alkaline electrolysis
bbl	Barrels of oil
BMWi	Bundesministerium für Wirtschaft und Energie
BF-BOF	Blast furnace - basic oxygen furnace
CCS	Carbon capture and storage
COVID 19	Coronavirus pandemic 19
CPG	Compagnie des Phosphates de Gafsa
CSP	Concentrated solar power
d	Day
DAC	Direct air capture
DAP	Diammonium phosphate
DCP	Calcium phosphate
DLR	German Aerospace Centre
DRI-EAF	Direct reduced iron electric arc furnace
EAF	Electric arc furnace
EHS	European hydrogen strategy
ETAP	Entreprise Tunisienne d’activités Pétrolières
ETS	European emissions trading scheme
EU	European Union
FCEV	Fuel cell electric vehicle
Fig.	Figure
GCT	Group Chimique Tunisien
ibid.	Ibidem
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelised cost of electricity
LPG	Liquid petroleum gas
MAP	Monoammonium phosphates
NHS	National hydrogen strategy of Germany
PEM	Polymer electrolyte membrane-electrolysis
PtG	Power-to-gas
PtH	Power-to-heat
PtL	Power-to-liquid
PtX	Power-to-X
SNG	Synthetic natural gas
STEG	Société tunisienne de l’électricité et du gaz
STIR	Société Tunisienne des Industries du Raffinage
Tab.	Table
TCO	Total cost of ownership
TSP	Triple super phosphate
USGS	United States Geological Survey
WI	Wuppertal Institut für Klima Umwelt, Energie GmbH

Units and Symbols

US$	US Dollar
%	Percent
€	Euro
°C	Degree Celsius
a	Annum / year
CH_3OH	Methanol
CO_2	Carbon dioxide
GW	Gigawatt
GWh	Gigawatt-hour
h	Hour
H_2	Hydrogen
H_2O	Water
kg	Kilogramme
km	Kilometre
km^2	Square kilometre
kt	Kilo tonne
kWh	Kilowatt-hour
l	Litre
m^2	Square metre
m^3	Cubic metre
Mt	Mega tonne
MW	Megawatt
N_2	Nitrogen
NH_3	Ammonia
t	Tonne
TWh	Terrawatt-hour

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1 Rationale, objectives and methodological approach of the study

Electricity-based fuels, especially hydrogen, are increasingly recognised as a key strategic element for the further progress of the German and European energy transition. This reality is underlined by the "National Hydrogen Strategy" (NHS), recently published by the German government, and the EU's "European Hydrogen Strategy" (EHS). Both strategies aim to support the rapid development of Power-to-X (PtX) value chains, i.e., hydrogen and its downstream products. Green hydrogen produced using renewable electricity is projected to play a particularly important role in ensuring a low-carbon emission development. However, it is already clear that the generation of green hydrogen in Germany and Europe is unlikely to be sufficient to meet the predicted demand, meaning that in the medium to long term substantial quantities of hydrogen will have to be imported (BMWi 2020). Consequently, the NHS and the EHS highlight the importance of cooperation with potential suppliers and exporters beyond European borders.

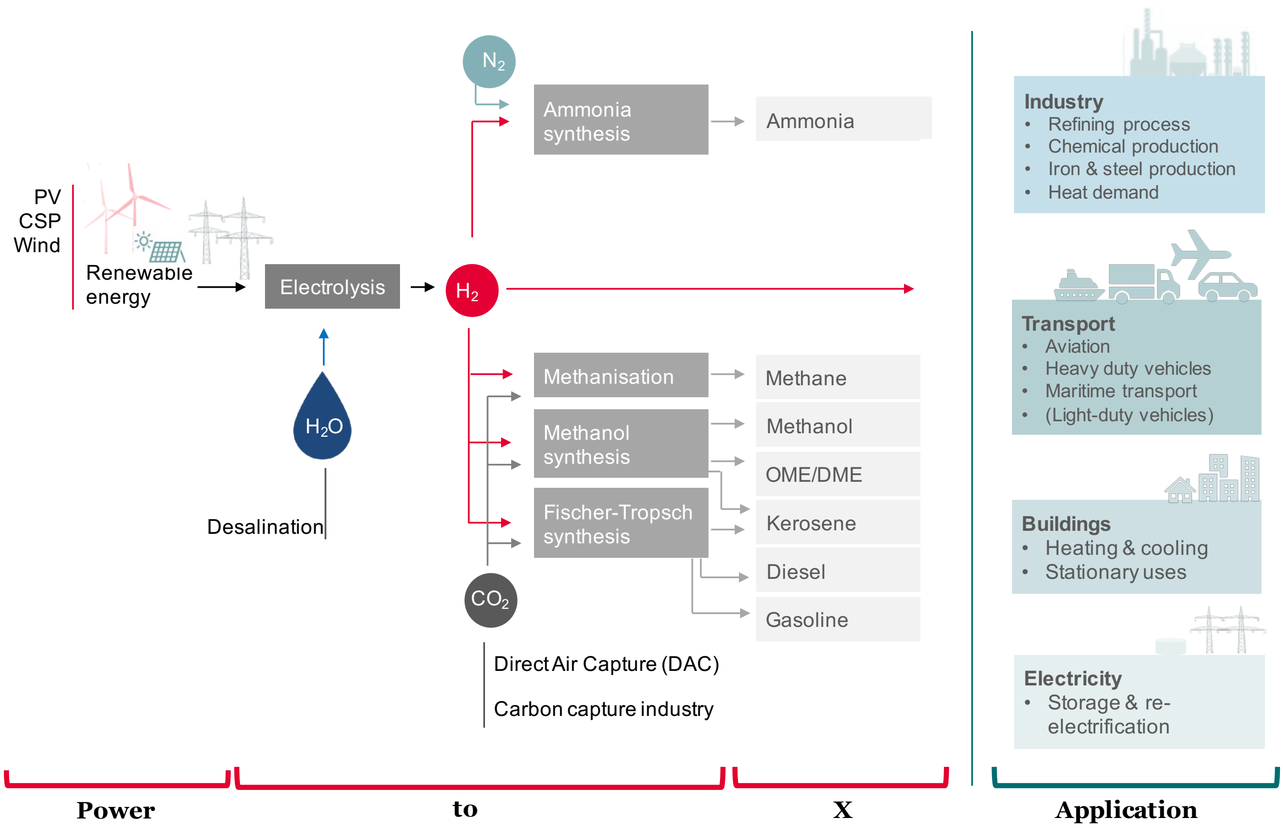
North Africa is highlighted as a potential future producer and exporter of green hydrogen and other PtX fuels due to its proximity to Europe and its abundant solar and wind energy potential. This also applies to Tunisia: with its climatic and geographic conditions, it offers promising technical and economic potential for the development of a national PtX sector that could also play an important long-term role in international hydrogen supply networks and markets. Against this backdrop, the objective of this study is to assess the opportunities of PtX in Tunisia on behalf of the Gesellschaft für Internationale Zusammenarbeit (GIZ). The potential for PtX has not yet been analysed in depth for Tunisia. This study, therefore, provides a first systematic analysis of key aspects relevant to the development of PtX in the country.

A combined approach was applied using comprehensive desk research, including detailed potential and cost analysis, and expert interviews with relevant Tunisian stakeholders from different sectors (conducted in February and March 2021). The expert interviews were designed as dialogue-discourse interviews to capture individual perspectives and knowledge. The input gathered in the interviews is reflected and integrated throughout the study. It was reflected, for example, in the selection of the PtX pathways to be analysed and in the assumptions made and in the formulation of recommendations. In order to evaluate where potential demand for PtX could arise in Tunisia, the current demand for fossil fuel-based hydrogen and other fossil fuels that could be replaced by renewable energy-based hydrogen and its derivatives was first analysed. For this purpose, data and statistics on industrial production and import and export of products requiring hydrogen (e.g., ammonia, methanol or hydrogen itself) were collected and evaluated. Secondly, existing national development plans, industrial expansion plans, regional trajectories and global demand scenarios were used to create bottom-up scenarios for the possible future demand for these products. Based on these demand scenarios and assumptions on the gradual switch to PtX-based products, the potentials for PtX were modelled. The results of the bottom-up analyses provide an overview of possible development paths for PtX in Tunisia for selected PtX products, always under the assumption that a corresponding market for green PtX products will develop. The costs for the production of green hydrogen and its derivates were modelled based on a number of input parameters such as capital investments, electricity costs, full load hours, efficiencies and transport costs. The results of the analysis and the expert interviews are synthesised into recommendations for further support and research on PtX in the Tunisian context.

The study is structured as follows: Following a brief overview in Chapter 2 of what is understood by the term PtX, Chapter 3 summarises why PtX should be considered in the Tunisian context. Chapter 4 presents the techno-economic, legal and regulatory, institutional, and political framework conditions for the development of PtX in Tunisia. Chapter 5 assesses the potential opportunities for PtX in Tunisia in different sectors and illustrates potential development pathways for selected PtX routes and associated renewable energy demands. Chapter 6 provides a cost analysis for PtX in Tunisia, followed by a brief assessment of the environmental risks and potential employment benefits in Chapter 7. Finally, Chapter 8 makes recommendations concerning the various levers identified and how further research to support the discussion on PtX in Tunisia should be prioritised.

2 What is Power-to-X?

Power-to-X (PtX) is an umbrella term that describes different pathways for turning renewable electricity into storable chemical energy carriers, synthetic fuels for the transport sector, reducing agents in steel production, or raw materials for the chemicals industry. Power-to-X technologies can be subdivided, according to the energy carrier, into power-to-gas (PtG), power-to-heat (PtH), or power-to-liquid (PtL). The conversion typically starts with the generation of hydrogen from renewable electricity and water. The green hydrogen can either be used directly or further processed into hydrocarbon fuels (Fig. 2.1). Direct applications include use as a raw material in the industrial sector, as fuel in the transport sector for fuel cell vehicles, as a medium for heat generation, or as a storage medium that can later be used for re-electrification.



(Source: Wuppertal Institut)

Fig. 2.1 Overview of Power-to-X pathways

Hydrogen can be produced by electrolysis using renewably-sourced electricity and water as input. The most mature technology for producing hydrogen via electrolysis, during which water is split into its components (hydrogen (H_2) and oxygen (O_2)), is alkaline electrolysis (AEL). The advantages of AEL are its longevity, technological maturity, high energy efficiency, and the use of non-critical raw materials. On the downside, however, the ability for dynamic operation is limited (Zelt et al. 2021). An alternative electrolysis technology is polymer electrolyte membrane-electrolysis (PEM). This is a newer technology and, therefore, less mature, but it has advantages for coupling with fluctuating renewable power supply, such as larger controllable load range and better efficiencies in the partial load range, and it can be better tailored for integration into existing infrastructures (Merten et al. 2020). As well as these low temperature electrolysis technologies, high temperature electrolysis in the form of solid oxide electrolysis cell (SOEC) could become relevant, although it is not yet as technologically and economically advanced as the two low temperature technologies. SOEC requires much less electricity and promises significantly higher efficiencies but, on the other hand, it is less flexibly applicable and therefore more difficult to link to fluctuant renewable electricity supply (ibid.) (Tab. 2.1). Independent of the technology electrolysis is an electricity-intensive process (IEA 2014).

Tab. 2.1 **Electrical transmission network in 2019**

	Low temperature electrolysis		High temperature electrolysis
	Alkaline electrolysis (AEL)	**Polymer electrolyte membrane-electrolysis (PEM)**	**Solid oxide electrolysis cell (SOEC)**
Advantages	• Commercially available • Widely used in large-scale industry • Lower investment costs • Higher efficiencies compared to PEM • Longer lifetimes (stack)	• Commercially available • System-technical advantages for coupling with fluctuating RE electricity • Larger controllable load range • Better efficiencies in the partial load range compared to AEL • Fast response times • Compact systems	• Higher efficiencies if the high temperatures for splitting the water into hydrogen could be provided by external sources (e.g., industrial heat sources) • Much lower electricity demand
Disadvantages	• Lower electricity density • Larger installations • Capacity for dynamic operation is limited (longer response and cold start times)	• Less mature and currently higher costs than AEL (smaller size classes available, higher costs and a shorter stack life) • Shorter lifetime (stack)	• Research and development stage, therefore technologically and economically much less advanced than the other two technologies

(Source: Based on Zelt et al. 2021; Merten et al. 2020)

By combining hydrogen with carbon dioxide (CO_2), synthetic fuels comparable to fossil fuels can be produced (e.g., methane or methanol). These can be further refined into diesel, petrol, or kerosene-type jet fuel. The required CO_2 can be captured from point sources, such as existing carbon-emitting industries, or from the atmosphere – either directly via direct air capture (DAC) technologies or indirectly via biomass sources.

Another hydrogen conversion pathway is the combination of green hydrogen with nitrogen (N_2) sourced from the atmosphere to produce ammonia. Ammonia is currently the second most produced synthetic chemical worldwide, of which around 80% is used in fertiliser production. For future energy systems, ammonia is increasingly being considered as a storage and transport medium for green hydrogen and as a fuel for maritime shipping.

The various PtX technologies are expected to play an important role in the energy transition, as they can provide solutions to some of the major challenges arising from the shift from a fossil fuel-based energy system to a renewable energy-based system. Until recently, hydrogen has been considered mainly as a transport fuel but green hydrogen and its derivatives also offer flexibility options for balancing electricity supply and demand – not only to absorb short-term peaks but also, for example, long-term fluctuations between seasons. PtX also offers decarbonisation options for hard-to-abate sectors, such as certain industrial processes, heating, and long-distance transportation such as aviation and shipping. The renewed interest in hydrogen and PtX in the industrialised countries in Europe, as well as in Japan and China for example, is not only attributable to climate policy but is also driven by the hope of new value chain development potential and a global market worth billions.

The biggest challenges currently facing PtX development are the high costs and low efficiencies. Without substantial support, green hydrogen and its derivatives will not become competitive with fossil fuel-based products. Moreover, many PtX technologies are still in the development phase, although several are on track to become commercially available in the next ten years. Other technologies are already widely applied in the chemicals industry, such as Fischer-Tropsch and methanol reactors, but full integration into PtX systems is still under development (Kober et al. 2019). Therefore, the first green hydrogen applications are expected to be in existing industrial uses where they will replace fossil hydrogen. Other short to medium-term applications are expected to include heavy-duty transport, especially buses and trucks, and long-distance rail freight.

3 Why Power-to-X in Tunisia?

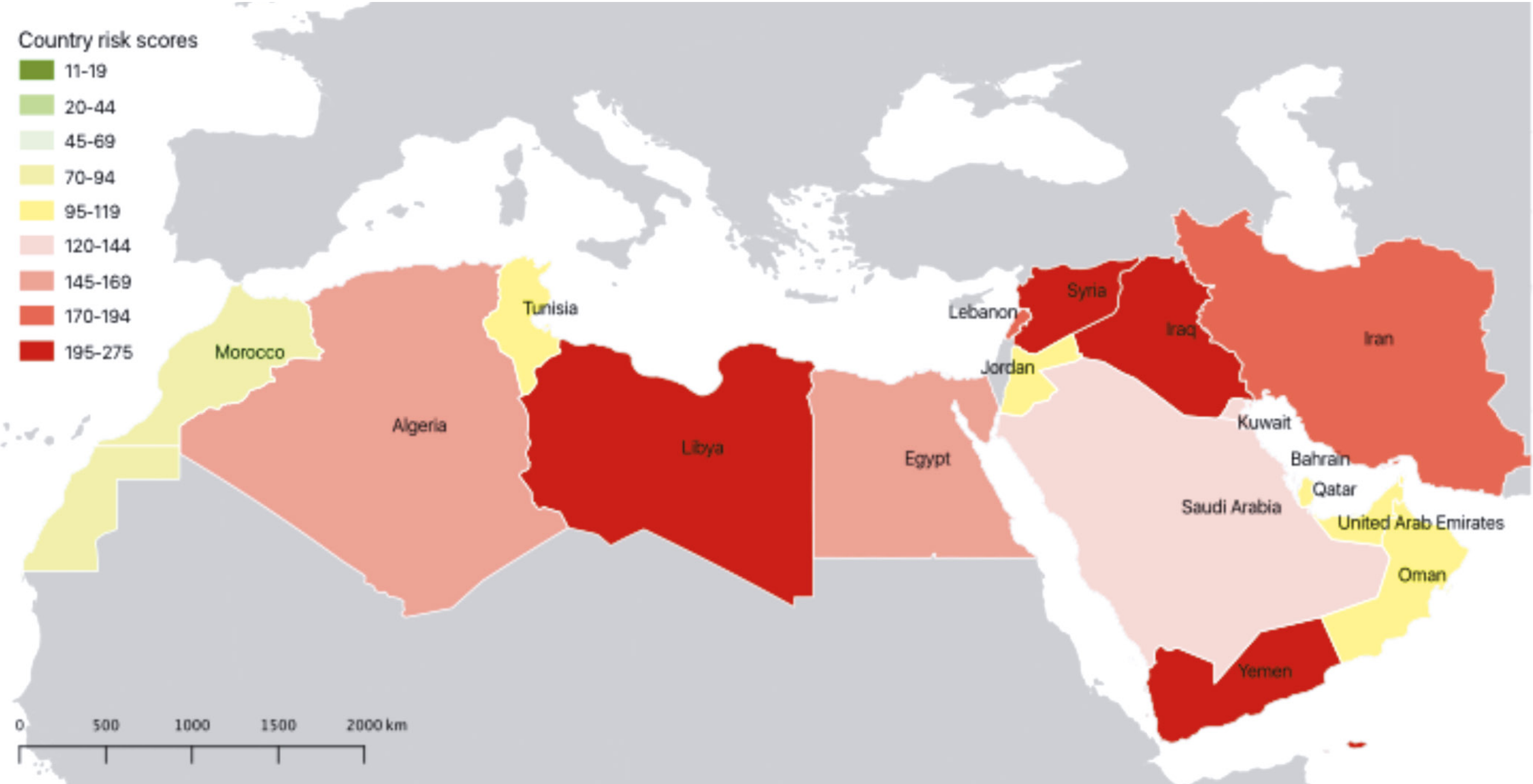
The acceptance of green hydrogen and its derivatives will depend on how the costs develop, which is contingent on the costs and availability of electricity from renewable sources. This will become increasingly pertinent in the future, when technology costs are expected to decrease due to learning processes from the growing number of applications worldwide and the mass market availability of the various technologies. Therefore, countries with high renewable energy potential that can produce renewable electricity at low cost are expected to become the leading producers and exporters of green hydrogen in the future.

In the proximity of Europe, North Africa is highlighted as a potential future producer and exporter of green hydrogen and other PtX fuels due to its abundant solar and wind energy potential. This is also the case for Tunisia: its climatic and geographic conditions offer promising technical and economic potential for the development of a national PtX sector that could also play an important long-term role in international hydrogen supply networks and markets.

The costs and, more generally, the decisions about whether to invest in a particular technology are not only influenced by renewable energy potential: country-specific circumstances also play a crucial role. This is particularly relevant for capital-intensive renewable energies, where investment and financing costs are the primary determinant of the levelised cost of electricity (LCOE) (Egli et al. 2019). As electricity costs are the largest cost factor in the production of hydrogen and synthetic fuels, these costs are also key for the development of the PtX sector. Although other northern African countries have even higher renewable energy potentials based on their surface area, Tunisia has the advantage of favourable political and economic framework conditions. This is illustrated, for example, by a risk assessment of the development of the PtX sector in different MENA countries from an investor perspective, in which Tunisia is evaluated as having lower risk levels than most other countries in the region (Fig. 3.1). Furthermore, in terms of infrastructure, the existing gas pipeline connecting Tunisia to the EU could potentially be used to export hydrogen.

As well as being exported, PtX products could also play a role in decarbonising end-use sectors in Tunisia. In sectors where direct electrification is either not possible or not feasible, such as heavy-duty transport, certain industrial processes, and aviation, PtX will become increasingly relevant for Tunisia to reach carbon neutrality in the long term. However, as PtX products under today's conditions are not cost competitive, initial uses are more likely be in sectors that export their products to markets where there is already today a higher margin to pay for green products.

Overall, the deployment of renewable energy technologies is growing rapidly in the region, which has led to the price of renewable electricity falling to record low levels. Recent bids in Tunisia for the production of electricity from solar power were among the lowest in the world. Moreover, Tunisia has set ambitious targets in its solar plan, aiming for a 30% share of renewable electricity by 2030. However, despite these plans and recent progress in the expansion of renewable energy generation, the share of renewables in Tunisia's electricity mix is still relatively low, at around 3%. Tunisia's energy sector also faces many challenges, including high dependence on imported fossil fuels, high energy subsidies, and weak performance at the utility level (World Bank 2019). At the same time, electricity demand continues to rise, threatening Tunisia's energy security (ibid.)



(Source: Terrapon-Pfaff et al. 2021)

Fig. 3.1 **Country risk levels for the development of the Power-to-X sector – business-as-usual scenario**

Against this backdrop and despite the potential advantages of establishing a new (export) industry branch in Tunisia, the development of PtX also includes risks that must be carefully assessed. One of the obvious risks is the potential for PtX production for export to absorb renewable electricity capacities and, thereby, decelerate the domestic energy transition (Wehinger and Raad 2020). To avoid this and ensure that the Tunisian energy transition benefits from PtX, it would be necessary to develop and implement suitable precautions and regulations to ensure the additionality of renewable energies in new PtX investments. A further significant factor that will determine the extent to which Tunisia could benefit from the development of a PtX sector is how much of the value chain could be established in Tunisia. If green hydrogen is produced using imported technologies and exported as a raw material, with the further processing steps located in the recipient countries, this would create limited jobs and value in Tunisia. Therefore, it is important that Tunisia creates conditions that are attractive for technological development and further value-adding process steps to take place within the country. Countries planning to import green hydrogen, on the other hand, should be held accountable for ensuring effective knowledge and technology transfer. Other risks that need to be considered for Tunisia include, for example, environmental aspects such as water demand for the production of green hydrogen.

Given that the production of green hydrogen and its derivatives is not yet cost competitive with fossil-based fuels, the establishment of PtX will in any case require political support and financial incentives. A number of external factors will also influence the willingness to pay higher prices for products based on green hydrogen in recipient markets and the speed of the technical deployment. These factors include, for example, carbon pricing mechanisms, technology-readiness levels, the international climate change agenda, countries’ decarbonisation targets, and private sector climate strategies (Fig. 3.2).

International and national climate objectives	Global market development of PtX will be largely driven by the international decarbonisation efforts and national policies as well as long-term emission targets.
Carbon price	The level of the carbon price will be decisive in determining whether PtX applications become competitive with conventional fuels. Without carbon pricing, even in the long term, most PtX products will not break even with conventional fuels.
EU carbon border adjustment mechanism	A European carbon border tax could impact, either directly or indirectly, all sectors that export to the EU. Demand for inputs with a lower carbon intensity could significantly increase and value chains could be altered opening entry points for the generation of green feedstocks in Tunisia.
Technology Technology-readiness (TRL)	The various technologies used in PtX systems are currently at different stages of development and implementation, so the further evolution and integration of technologies into overall systems will be crucial for the large-scale application of PtX.

(Source: Wuppertal Institut)

Fig. 3.2 External factors with influence on PtX market development

It would only make sense for Tunisia to push ahead with the broad development of PtX if these framework conditions develop in favour of PtX applications. The considerations of the opportunities for PtX development in Tunisia in this study are also based on these premises. However, although it is difficult to predict how the production and market for PtX will develop in the coming years, it nevertheless seems advisable for Tunisia to prepare for such development at an early stage in order to create the basic conditions for successful implementation at the appropriate time. The example of Morocco shows the advantage of being among the «first movers» when it comes to attracting capital and innovations. To build up know-how and expertise in the country, opportunities for technology transfer (e.g., in the form of pilot plants) and funding measures (e.g., from Germany or the EU) should be leveraged. Furthermore, the early establishment of a regulatory and legal framework for PtX could facilitate future investment in the sector in Tunisia and ensure that PtX development takes place sustainably.

4 Framework conditions for Power-to-X development in Tunisia

To assess PtX opportunities for Tunisia, it is essential to first conduct a systematic analysis of the relevant techno-economic, legal and regulatory, institutional, and political framework conditions for the development of the sector in the country.

4.1 ENERGY SECTOR

4.1.1 Energy supply and demand

Tunisia has oil and natural gas reserves, but domestic production is far from sufficient to meet the country's own needs and production is declining, leading to an energy deficit increase by a factor of almost 10 in the last decade. Over the last decade, the production of fossil primary energy resources has experienced a decline of around 7% per annum, falling from 7.8 Mtoe in 2010 to 3.9 Mtoe in 2019. The analysis of the evolution of crude oil production during the period 2010-2019 shows a significant decrease at an average annual rate of -8.4%. This decline in production is mainly explained by the depletion of reserves in Tunisia's main deposits, namely El Borma and Ashtart, and by the low production of most of the new deposits and the shutdown of around ten concessions over the last few years. The production of natural gas also recorded a significant drop during the period 2010-2019, falling from 2.7 Mtoe in 2010 to 1.6 Mtoe in 2019: a reduction of more than 55% over the period. Despite this situation, most of Tunisia's electricity supply still comes from fossil energy sources (mainly natural gas, followed by oil).

Although production levels decreased, demand grew by an average of 1.6% per annum during the decade 2010-2019 (from 8.4 Mtoe in 2010 to 9.6 Mtoe in 2019). During the same period, demand for natural gas grew at an average annual rate of 1.5%, compared to an annual growth rate of 1.2% for oil products. The following graphs (Fig. 4.1) show the evolution of this demand and its structure.

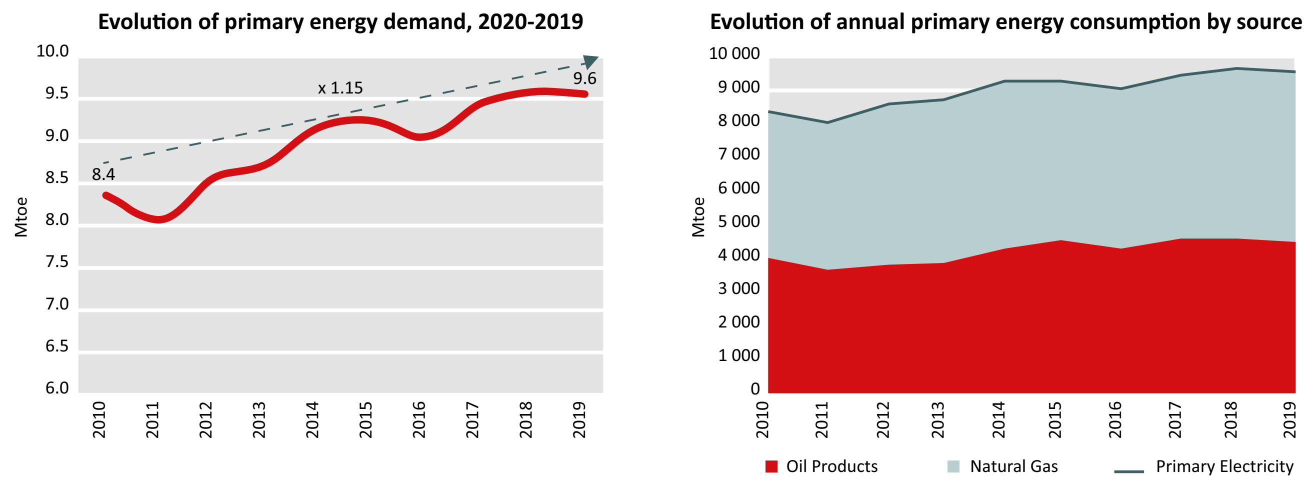
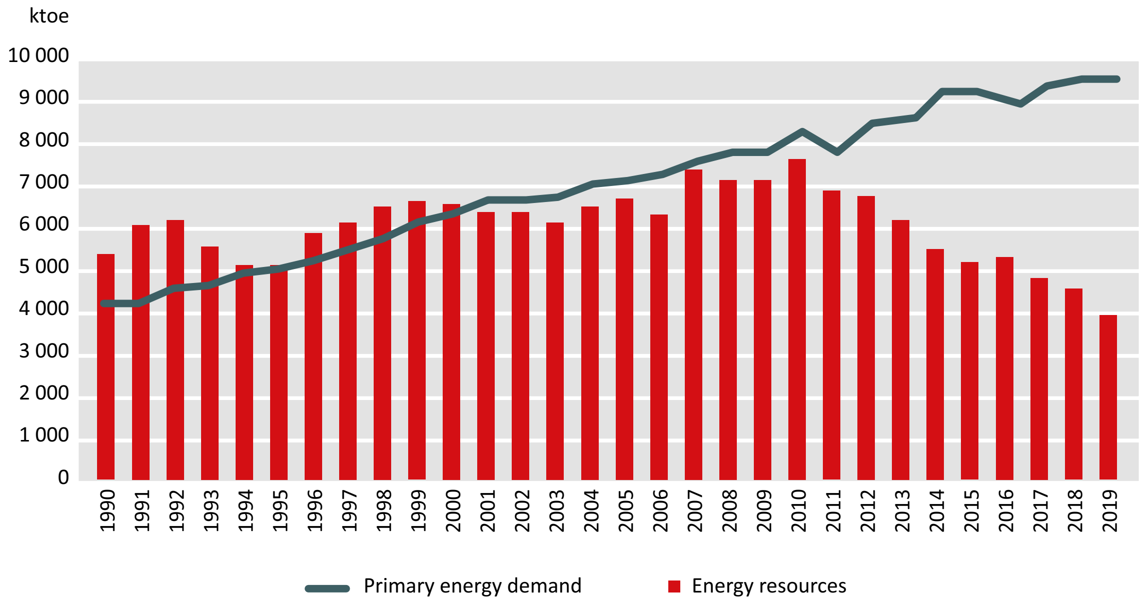


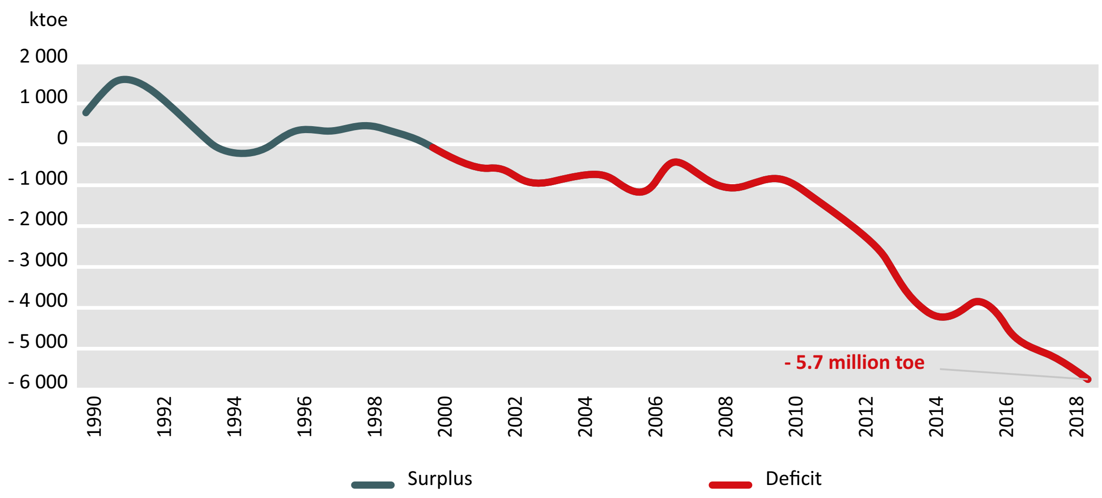
Fig. 4.1 Evolution of annual primary energy consumption

The decline in production of fossil energy resources and the sustained increase in primary energy demand created an energy deficit of 5.7 Mtoe in 2019, equating to 59% of primary energy demand (Fig. 4.2 and Fig. 4.3). In 2010, the deficit was less than 0.6 Mtoe.



(Source: ONE)

Fig. 4.2 Energy resources and demand in Tunisia

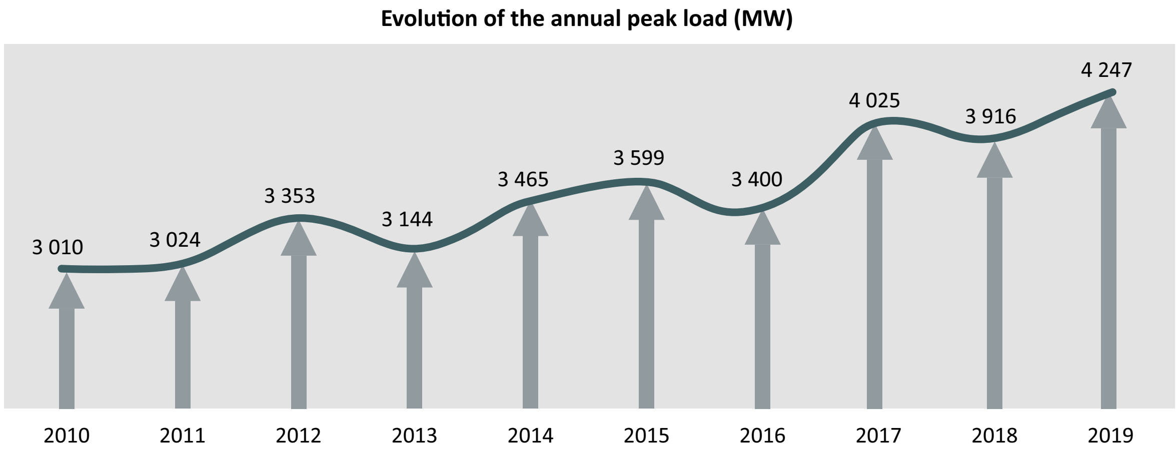


(Source: ONE)

Fig. 4.3 Energy balance deficit in Tunisia

The structure of the electric charge curve has undergone significant changes over the past 20 years. Before 1996, maximum annual demand increased at a similar rate to energy demand, and peak demand occurred overnight in the month of September. Since 1996, the structure of the load curve has changed considerably due to the use of air conditioning.The annual peak in demand is now recorded during the day in summer and its relationship to climate change is becoming increasingly important. Peak electricity demand grew by an average of 4% per annum during the period 2010-2019 and reached 4,247 MW in 2019, compared to 3,010 MW in 2030, as shown in the following graph (Fig. 4.4). Peak load has increased at a pace higher than the power demand (in terms of energy). Consequently, the load factor of power plants declined more than 13% between 1996 and 2019 leading to fossil fuel capacities being underused.

In conclusion, Tunisia is facing a rising energy deficit and this may affect its supply security in the long term. This is particularly concerning for the power sector, which is nearly 100% dependant on gas mainly imported from Algeria.



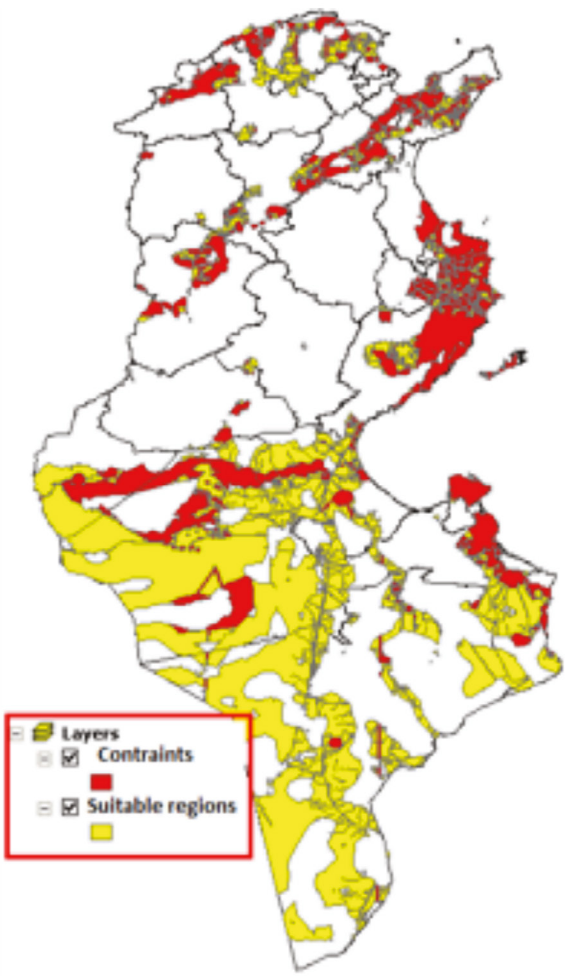
(Source: STEG)

Fig. 4.4 Electricity peak load in Tunisia

4.1.2 Renewable energy

There is significant potential for renewable energy in Tunisia, especially wind and solar photovoltaics (PV). To reduce its dependence on fossil fuels and increase energy security, Tunisia plans to increase its share of renewable energy. The Tunisian Solar Plan (PST) envisages that 30% of Tunisian electricity will come from renewable sources by 2030.

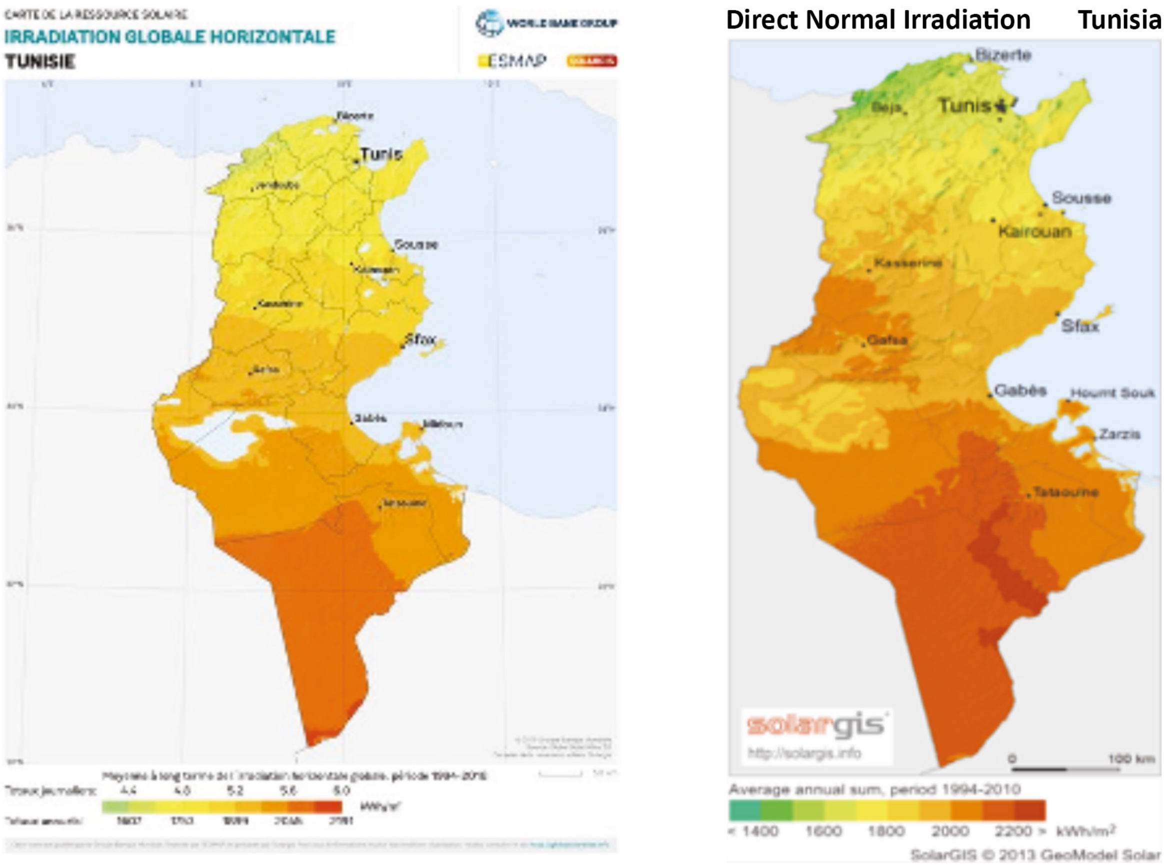
Mapping the potential of Tunisia's renewable energy sources shows that the country has several regions with favourable conditions for the development of wind power, particularly in the northeast, central west and southwest. These regions have a total area of approximately 18,000 km² (11% of Tunisia's surface area). After disregarding areas that may not be conducive to the development of wind power and taking into account the issue of proximity to the electricity grid, this leaves an area of 1,700 km², meaning an exploitable wind potential of around 10,000 MW. Fig. 4.5 shows the best suited regions for the construction of wind farms. Regarding offshore wind potential, the most recent renewable energy strategic study indicates a technical potential of around 250 GW (ANME/UNDP, Alcor, 2020).



(Source: ANME)

Fig. 4.5 Suitable regions for wind power in Tunisia

Tunisia also benefits from good sunshine conditions, favourable for solar energy applications – particularly those relating to electricity production. With an average sunshine rate of 3,000 hours per annum and solar irradiation that can exceed 2,000 kWh/m² per annum in the south of the country, the Tunisian solar field is ideal for the establishment of different types of PV solar installations and concentrated solar power (CSP) plants. Limiting solar PV to areas in the centre and south of the country (Fig. 4.6), whose daily electrical productivity exceeds 5 kWh/KWp, the gross potential of the capacity of ground-based solar PV plants is estimated to be around 840 GWp. For CSP, the area of Tunisian territory with a DNI favourable to the establishment of power plants (DNI greater than 2,000 kWh/m² per annum) is estimated to be around 17,700 km². The potential of CSP is around 600 GW for plants using cylindro-parabolic sensors and around 400 GW for CSP tower plants.



(Source: SolarGIS)

Fig. 4.6 **Direct and global solar irradiation map of Tunisia**

In conclusion, Tunisia has significant potential for renewable energy, particularly for solar and wind. The technical potential can be summarised as follows:

- Solar PV: 840 GW
- Solar CSP: 600 GW for cylindro-parabolic sensors + 400 GW for tower plants
- Wind onshore: 110 GW
- Wind offshore: 250 GW

Despite this large potential, the share of renewable energy in electricity generation is still very low, around 3%. The installed renewable capacity in 2020 totalled around 400 MW, broken down as follows:

- Wind: 245 MW
- Solar PV: 100 MW (including around 90 MW for self-generation and 10 MW of STEG)

- Hydroelectricity: 62 MW

After deducting solar PV installations intended for self-generation, the installed capacity of renewable energies represents around 5% of the total electricity production capacity.

As part of its energy transition policy, Tunisia plans to increase the share of renewable energies in the electricity production mix, reaching 30% by 2030 and 80% by 2050. This will require the implementation of significant additional electricity production capacities from renewable energies to reach 3,800 MW by 2030, 10,000 MW by 2040 and 21,000 MW by 2050.

To achieve these objectives, the Ministry of Energy and Mines published a notice outlining the planned capacities to be installed by 2022 under three regimes defined by Law No. 2015-12 (self-generation, authorisations, and concessions). These capacities, totalling 1,860 MW, are broken down as follows (Tab.4.1):

Tab. 4.1 Renewable energy programme announced by the Tunisian Government as part of Notice No. 01/2016

Regime	Wind (MW)	Solar PV (MWp)
Concessions	500	500
Authorisations	130	140
Self-generation	80	130
STEG projects	80	300
Total	**790**	**1,070**

(Source: Ministry of Industry, Energy and Mines)

Based on this plan, several projects have been launched under the authorisations and concessions regimes.

Authorisations

For solar PV, four rounds of calls for projects have been launched since May 2017, of which three are now closed and one is in progress. The first three rounds enabled a preliminary agreement to be granted for 18 solar PV projects with a unit capacity of 10 MW and 24 projects with a capacity of 1 MW. Of these, only one 1 MW project is currently in operation, one 10 MW project is pending commissioning and two other projects are at an advanced stage of work. The results of the first three rounds are summarised in Tab.4.2.

In terms of wind power, only one round has been completed. Four projects, with a capacity of 30 MW each, were selected. These projects are located in the regions of Mornag (Governorate of Ben Arous), Jebel Sidi Bchir, Jebel Kchbata, and Batiha (Governorate of Bizerte). The proposed selling prices vary between 111 millimes/kWh and 136 millimes/kWh. These projects are still in the final stages of financing.

Tab. 4.2 Renewable energy programme announced by the Tunisian Government as part of Notice No. 01/2016

		First round	Second Round	Third round
10 MW Projects	Selected projects	6	6	6
	Governorates	Sidi Bouzid (2) - Sfax (1) - Kasserine (1) - Kairouan (1) - Tataouine (1)	Sidi Bouzid (3) - Gabes (2) - Beja (1)	Gabes (2) - Kasserine (2) Medenine (2)
	Selling price	From 117 to 177 millimes/kWh ± 3.5 to 5.4 c€/kWh	From 112 to 147 millimes /kWh ± 3.4 to 4.5 c€/kWh	From 125 to 130 millimes /kWh ± 3.8 to 3.9 c€/kWh
1 MW Pro-jects	Selected projects	4	10	10
	Governorates	Tataouine (1) - Beja (1) - Gafsa (1) - Sousse (1)	Gabes (4) - Tataouine (1) - Sidi Bouzid (1) - Beja (1) - Sfax (1) - Sousse (1) - Kebili (1)	Gabes (1) - Tataouine (1) - Sidi Bouzid (1) - Kairouan (1) - Sfax (2) - Medenine (4) -
	Selling price	From 178 to 248 millimes/kWh ± 5.4 to 7.5 c€/kWh	From 198 to 234 millimes/kWh ± 6 to 7.1 c€/kWh	From 190 to 213 millimes/kWh ± 5.8 to 6.5 c€/kWh

*: 1 € = 3.3 TND - 1 TND = 1,000 millimes

(Source: Ministry of Industry, Energy and Mines)

Concessions

A prequalification call for tenders was launched on 23 May 2018 for the implementation of five solar PV plants with a total capacity of 500 MW. These plants are planned to be installed on state-owned land in Sidi Bouzid (50 MW), Tozeur (50 MW), Kairouan (100 MW), Gafsa (100 MW), and Tataouine (200 MW). These concessions have been assigned and are at an advanced stage of negotiations with the authorities. The prices accepted for the sale of electricity to STEG in these bids range from US$25.12/MWh to US$49.21/MWh.

Main barriers to Renewable Energy market development

The main financial barriers are the following:

- The PPA under the renewable authorization regime is considered non-bankable by financiers and local banks. This is mainly linked to the absence of state guarantees, compensation in case energy is not delivered by STEG and the uncertainty on the period STEG takes for the grid connection of the installation.
- Due to the financial difficulties of STEG and in the absence of sovereign guarantee for the PPA, the off-taker risk is considered high by the developers and banks and make them reluctant to invest.
- The lack of financial capacity of local developers for the authorisation regime is also a high barrier. Due to the limited size of the projects, the bidders to project tenders are small and medium developers with usually limited financial and even technical capacity. This is particularly true for projects with a capacity of 1 MW, where almost all the bidders are local individuals who often lack technical and financial capacity.
- The renewable market in Tunisia suffers also from a lack of suitable local financing options. Banks do not offer appropriate project finance instruments.

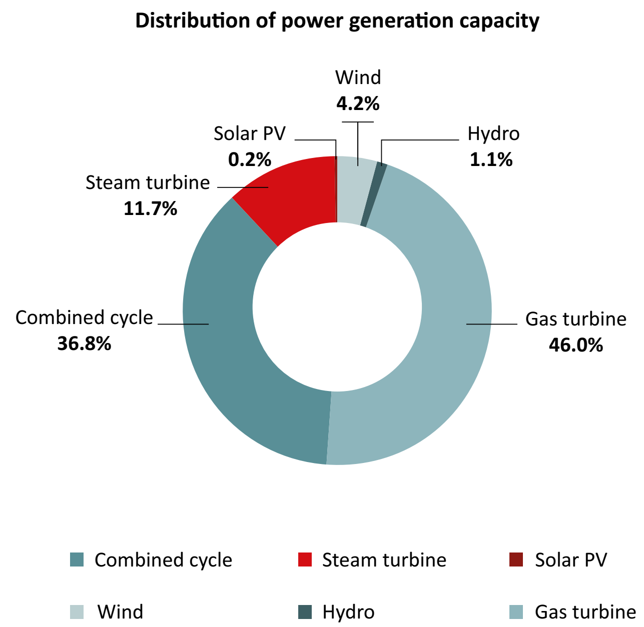
The main non-financial barriers are linked to:

- The absence of an independent power sector regulatory body to give investors a sense of confidence
- The difficulties in accessing land for project installations under the authorisation regime
- The complexity of administrative procedures and the delays in obtaining the necessary permissions during all phases of the projects.

4.1.3 Energy infrastructure

The basic means of electricity production are combined cycle power plants and steam power plants. These means of production generally have low specific consumption. Peak power plants are essentially gas turbines operating in an open cycle. Although their specific consumption is relatively high, these plants have the advantage of flexible operation and can satisfy the «variable» demand between the minimum of the trough and the maximum of the peak.

The electricity generation fleet in Tunisia reached a total capacity of 5,653 MW in 2019, compared to 3,599 MW in 2010, meaning an overall growth over the period 2010-2019 of 57%. In 2019, combustion turbines represented the largest share of installed capacity (46%), compared to 37% for the combined cycle. Fig. 4.7 shows the shares of each technology in the structure of the electricity generation fleet in Tunisia in 2019. The share of STEG power plants represented 92% of the installed capacity in 2019, compared to 8% for the independent combined cycle power plant in Radès (commissioned in 2001 and with an installed capacity of 471 MW) managed by the Carthage Power Company.



(Source: STEG)

Fig. 4.7 Distribution of installed capacity in 2019

The analysis of the evolution of production during the decade 2010-2019 shows an increasingly important orientation towards combined cycle power plants, whose share in production rose from 41% in 2010 to more than 60% in 2016. Despite their high share in installed capacity, combustion turbines produced only 15% of the total electricity produced over the entire period 2010-2019. This is because they are used primarily as peak power plants. Fig. 4.8 shows the evolution of the structure of production by type of equipment.

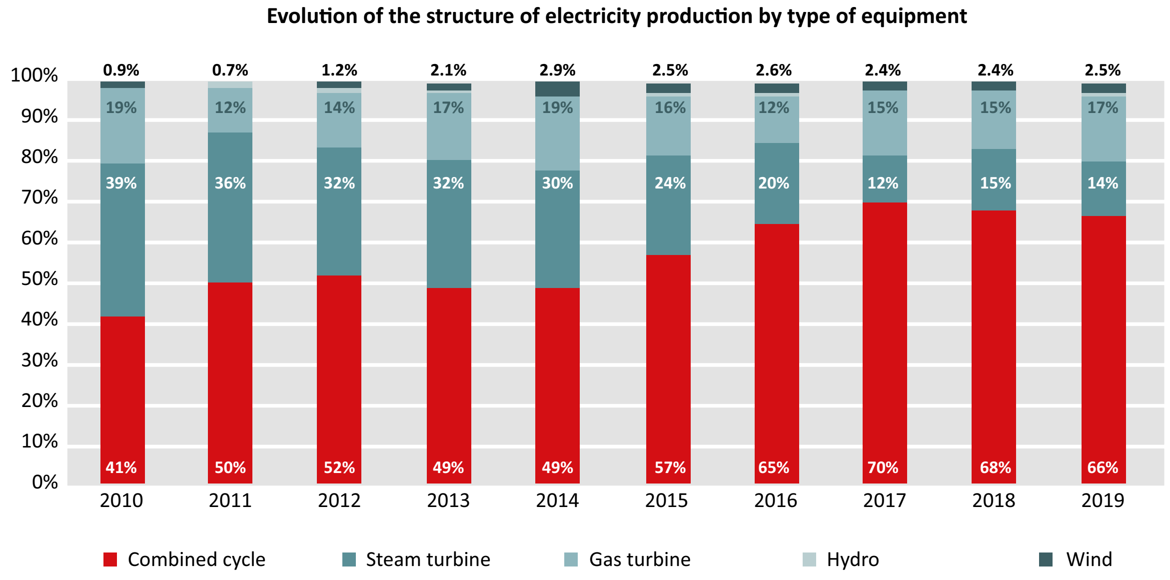


Fig. 4.8 Structure of electricity production by type of equipment

In terms of the transmission network, the voltage levels used for the high voltage grid are 400 kV, 225 kV, 150 kV, and 90 kV. The grid is essentially made up of overhead lines except in the capital, where for town planning and easement considerations some connections are underground.

The high voltage grid is closed and connects all the generation plants to the consumption centres. Over the period 2010-2019, the electricity transmission network grew by around 1,200 km. By 2019 its lines totalled 6,990 km (Tab. 4.3). The distribution of the transmission network for the different levels is given in the following table (year 2019).

Tab. 4.3 Electrical transmission network in 2019

Voltage	Length (km)
400 kV	208
225 kV	2921
150 kV	2382
90 kV	1479
Total	**6990**

(Source: STEG)

The evolution of the distribution network during the decade 2010-2019 is given in Tab 4.4.

Tab. 4.4 Evolution of the electrical distribution network

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
MV lines (km)	50 634	51 699	52 783	53 885	55 049	56 579	57 270	58 417	59 691	60 966
LV lines (km)	92 860	97 413	99 926	102 709	105 855	108 514	110 832	112 899	115 698	119 453
MV/LV transformer substations	60 168	62 296	63 275	64 746	66 996	68 669	70 790	72 770	75 065	78 507

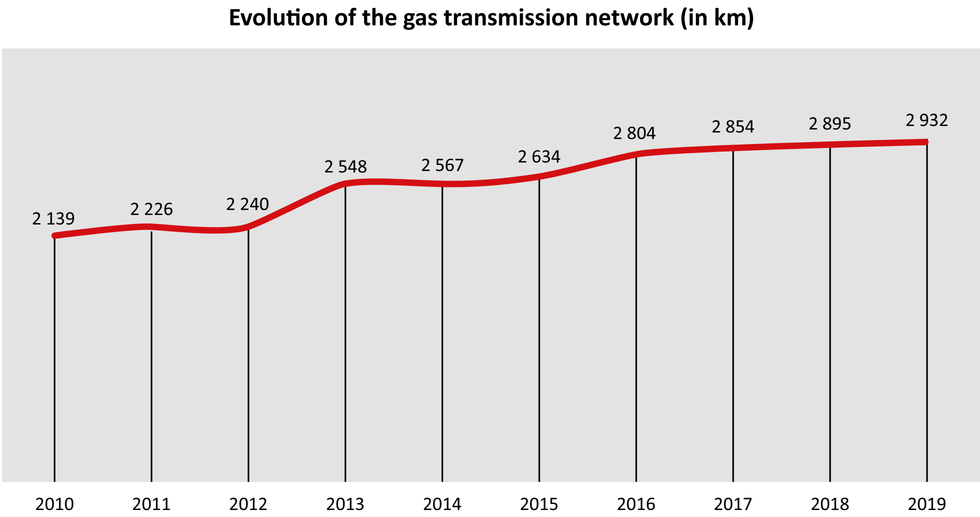
(Source: STEG)

Fig. 4.9 shows the electricity generation and transmission network in Tunisia.

(Source: STEG)

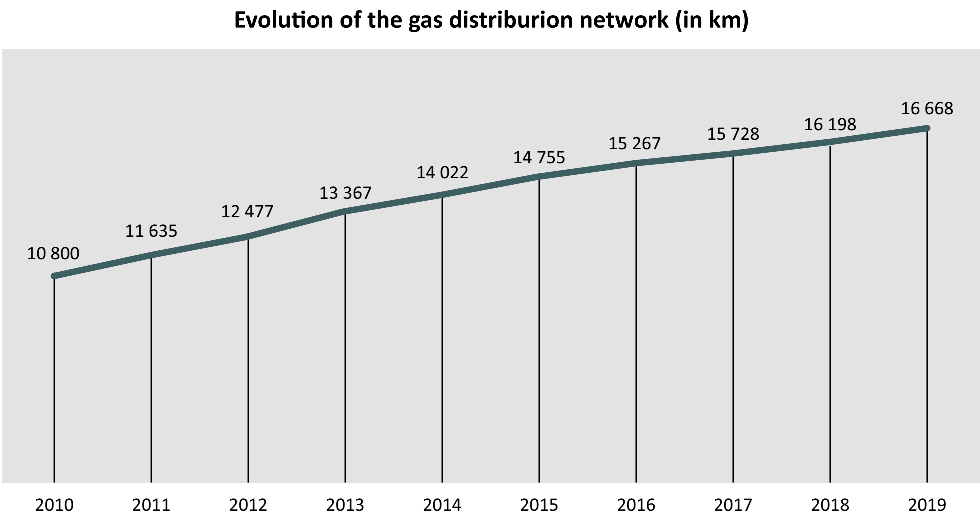
Fig. 4.9 Electrical power generation and transmission network in Tunisia

The total length of the gas transmission network (excluding the transcontinental network) increased to 2,932 km by 2019 compared to 2,139 km in 2010. Regarding the gas distribution network, it grew to 16,668 km by 2019 compared to 10,800 km in 2010. The evolution of the gas transmission and distribution networks is shown in Fig. 4.10 and Fig. 4.11, and an overview of the natural gas infrastructure in Tunisia is given in Fig. 4.12.



(Source: STEG)

Fig. 4.10 Evolution of the gas transmission network in Tunisia



(Source: STEG)

Fig. 4.11 Evolution of the gas distribution network in Tunisia

The Tunisian power grid is connected to the Algerian grid via two 90 kV lines, one 150 kV line, one 225 kV line, and one 400 kV line commissioned in 2014. Two 225 kV interconnections with the Libyan grid have been in place since 2001. Tab. 4.5 shows the characteristics of these different electrical interconnection lines. Although the Tunisian grid interconnects with its neighbouring countries, there is no real electricity market between Tunisia and the Maghreb region. The electricity exchanges with Algeria are non-significant and are designed to limit electricity supply risk at times of high load demand.

(Source: STEG)

Fig. 4.12 Natural gas infrastructure in Tunisia

Tab. 4.5 Interconnection lines with the Maghreb countries

Pays		Nœud 1	Nœud 2	Nbre de circuits	Tension (kV)	Longueur (km)	Imax (A)	Mise en service
Tunisie	Algérie	Tajerouine	El Aouinet	1	90	60	450	1952
		Fernana	El Kala	1	90	35	525	1955
		Tajerouine	El Aouinet	1	220	59	620	1980
		Metlaoui	Jebel Onk	1	150	62	620	1984
		Jendouba	Chefia	1	400	160	1540	2014
Tunisie	Libye	Tataouine	Rowies	1	220	160	620	2001
		Médenine	Abou Kamash	2	220	110	620	2001

(Source: STEG)

In terms of gas pipelines, Tunisian transit pipelines are part of the Transmed system that transports natural gas from Hassi R’Mel (Algeria) to Sicily and the Italian market. The Algerian section is operated by the public company “Sonatrach”. The Tunisian section (two 48-inch pipelines) belongs to «Sotugat» (Société Tunisienne du Gazoduc

Trans-tunisien), which is controlled, operated, and maintained by subsidiaries of Eni TTPC (Trans Tunisian Pipeline Company) and Sergaz. The submarine section between Tunisia and Sicily consists of three 20-inch pipelines and two 26-inch pipelines. It is owned by the Transmediterranean Pipeline Company Limited (TMPC) and is operated by Transmed Sp.A - two joint ventures between Eni and Sonatrach.

Tab. 4.6 **Oil product unloading ports**

Port	Draft (feet)	Dock length (metres)
SKHIRA		60-300
Loading station 1 (PP)	37	
Loading station 2 (crude and PP)	47-50 high tides	100-300
Loading station 1 (PC)	24-27 low tides	
BIZERTE		
Dock A	35	250
Dock B	26	150
RADES	31	170
GABES	10,5	120
ZARZIS	28	175

(Source: Ministry of Transport)

In terms of the harbour infrastructure and capacity for handling different fuel sources, Tunisia has five unloading ports for oil end products, namely:

- Skhira: petrol, gasoil, and fuel
- Bizerte: LPG, petrol, gasoil, and fuel
- Radès: LPG, gasoil, jet aviation, and fuel
- Gabès: LPG
- Zarzis: petrol, gasoil, and jet aviation

The unloading ports and related port infrastructure are summarised in Tab. 4.6. LNG is not currently used and Tunisia does not have specific infrastructure for this product.

4.2 LEGAL AND REGULATORY FRAMEWORK

The PtX value chain involves a number of sectors governed by different legislative areas. The main areas of regulation that may affect the activity of the PtX are:

- Power sector legislation
- Gas sector legislation
- Oil sector legislation
- Industry legislation, including procedures and security
- Environmental legislation, including authorisation & environmental impact studies
- Land legislation

- Water legislation
- Transport legislation, including road, rail, and aviation.

Some of these laws are applicable in their current states to PtX activities; others require marginal adjustments to cover certain areas in the value chain. Other areas in the chain fall into a legal vacuum and would need to be regulated by new frameworks.

Tab. 4.7 Mapping of regulatory/legislative areas related to PtX in Tunisia

Value chain	Power sector legislation	Gas sector legislation	Oil sector legislation	Industry legislation	Environmental legislation	Land and water legislation	Transport legislation		
							Road	Rail	Aviation
RE power generation	Applicable				Marginal adjustment	Marginal adjustment			
Electrolysis (Hydrogen production and storage)		New regulations needed		Applicable	Marginal adjustment	Applicable			
Hydrogen injection in gas network		New regulations needed			Applicable	Marginal adjustment			
Power production from hydrogen	Marginal adjustment				Marginal adjustment				
Use of hydrogen for transportation							New regulations needed	New regulations needed	
Transportation of hydrogen on road for industry use							Applicable		
Manufacturing and use of synthetic fuel for hydrogen			New regulations needed	Applicable	Applicable	Applicable	Marginal adjustment	Marginal adjustment	Marginal adjustment
Ammonia/methanol manufacturing from hydrogen				Applicable	Applicable	Applicable			

- The current regulation is applicable to PtX
- The current regulation needs marginal adjustment to be applicable to PtX
- New specific regulations are needed
- Not applicable

4.2.1 Renewable power generation

Power sector legislation

The legal and regulatory framework for renewable energy generation is covered by power sector legislation. The regulatory framework for the power sector is mainly governed by:

- Law No. 62-8 of 3 April 1962, establishing and organising the Tunisian Electricity and Gas Company and giving it a monopoly in the sector.
- Law No. 96-27 of 1 April 1996, supplementing Law No. 62-8 and abolishing the monopoly of the public utility on power generation activity.

The specific regulatory framework for renewable electricity generation is mainly governed by:

- Law No. 2015-12 of 2015 organising the activity of power generation from renewable energy by private investors.
- The governmental Decree No. 2016-1123 of August 2016 on conditions and procedures for renewable energy project implementation.
- Decision issued on 9 February 2017 related to connection codes.
- Decision issued on 9 February 2017 related to the Power Purchase Agreement for the various production regimes.

In terms of the production of green hydrogen, it is anticipated that electricity generation will fall mainly under the self-generation regime connected to MV grid. In this case, the administrative procedure would be as described in Tab. 4.8.

Tab. 4.8 **Procedures related to renewable electricity self-generation in Tunisia**

Characteristics	Projects connected to MV grid
Eligible self-producers	Any local authority, public, or private establishment operating in the industrial, agricultural, or tertiary sector subscribed to STEG Any facility connected to the MV or HV grid
Renewable power capacity	Installed power capacity must not exceed the subscribed capacity to STEG
Technical requirements	Possibility to install the RE facility out of the consumption site with the right to use the electricity grid to transport the electricity produced to the point of consumption Transmission tariff set at US$ 0.0024/kWh Installation must be technically compliant with the provisions of the specifications related to the technical requirements for connection and evacuation of energy produced from renewable energy installations connected to the MV and HV network
Administrative requirements	Obtain an authorisation signed by the minister in charge of energy
Validity of contract	20 years
Specific provisions for PV solar installations	Sale of surplus power of up to 30% of the annual production of the renewable energy plant Sale tariff of surplus production differs according to the period of the day: Day: US$ 0.04/kWh Morning peak summer: US$ 0.07/kWh Evening peak: US$ 0.06/kWh Night: US$ 0.03/kWh

Environmental legislation

Environmental protection is mainly governed by Law No 88-91 of 2 August 1988 and decrees related to environmental impact studies, namely:

- Decree No. 91-362 of 13 March 1991
- Decree N0. 1991 of 11 July 2005

According to current local legislation, only power facilities of a capacity exceeding 300 MW require an environmental impact study. However, local and international finance institutions require impact studies as part of the documentation required for financing these projects.

Land legislation

Land legislation is governed by the Code of Real Rights promulgated by Law No. 65-5 of 12 February 1965, updated several times since. The availability of land is often a problem for investors in the field of renewables in Tunisia. Indeed, most land suitable for renewable energy are often in undivided, collective, or state ownership. Furthermore, agricultural land is often classified by the Ministry of Agriculture as a prohibited zone that cannot be used for renewable energy installations.

4.2.2 Hydrogen production and storage

- **Gas sector legislation**

The gas sector in Tunisia is governed by two main laws: The Tunisian Hydrocarbon Code, promulged by Law No. 99-93 of 17 August 1999, regulating downstream activity including gas production; and Decree No. 64-10 of 17 January 1964, approving the technical specification of gas supply in Tunisian territory (security, standards, etc.) for upstream activity. The production of hydrogen as an energy product is not covered by any existing provision under gas legislation. For any future development of green hydrogen activity, new regulations would have to be developed.

- **Industry legislation, including procedures and security**

Electrolysis is considered to be an industrial activity and, therefore, must respect industry legislation. This legislation is covered by two main provisions: Law No. 94-16 of 31 January 1994 relating to the development and maintenance of industrial zones, according to which all industrial activity must take place in authorised industrial zones; and Decree No. 2006-2687 of 9 October 2006, relating to the procedures for opening and operating dangerous, hazardous, or complex industries. Should electrolysis be considered as a hazardous industry in Tunisia, it would require specific authorisation for operation.

- **Environmental legislation, including environmental impact studies**

The current environmental legislation does not specify clearly whether the production of hydrogen by electrolysis would require an impact study. However, both gas extraction and gas storage do require an impact study under the legislation. If an environmental impact study were required, it would have to include the issue of water desalination.

- **Water legislation**

Water legislation is covered by the Water Code, promulgated by Law No. 75-16 of March 1975. Where underground resources or surface water are used, permission must be gained from the Ministry of Agriculture.

4.2.3 Hydrogen injection into the gas network

- **Gas sector legislation**

Gas transportation and distribution is regulated by Decree No. 64-10 of 17 January 1964 approving the technical specification of the supply of gas in Tunisian territory (security, standards, etc.). The injection of hydrogen into the gas network is not covered by the existing regulation. The injection of green hydrogen into the gas pipelines would, therefore, require new regulation.

- **Land legislation**

Land legislation does not include easement for private pipelines to connect electrolysis facilities and the gas network. The current land legislation would, there-fore, require adjustment.

4.2.4 Power production from hydrogen

The current power sector legislation does not include any technical provision regard-ing the use of hydrogen for power generation. New legal texts would be required to regulate this potentially future activity. Regarding environmental legislation, power generation from hydrogen would have to be added to the list of activities subject to an environmental impact study.

4.2.5 Use of hydrogen for transport

The authorisation of the use of road vehicles in Tunisia is governed by specific regulations, including the following decrees:

- Decree No. 2000-147 of 24 January 2000 setting out the technical rules for the equipment and fitting out of vehicles.
- Decree No. 2002-2016 of 4 September 2002 setting out the technical rules for the equipment and fitting out of motor vehicles running on LPG.
- Decree No. 2002 - 2017 of 4 September 2002 setting out the technical rules for the equipment and fitting out of motor vehicles running on compressed natural gas.
- Order of the Minister of Transport of 25 January 2000 relating to the reception and approval of vehicles.

The use of hydrogen for fuel in cars would require specific new regulations. Regarding the use of hydrogen for rail transport, this would have to meet the technical standards and specifications for fuel and power trains. Any use of other energy types would require new regulations, including new standards and specifications, including specifications on the use of synthetic fuel for road vehicles, trains, and aviation.

4.2.6 Transportation of hydrogen by road for industry use

As for any hazardous product, the transportation of hydrogen would be administered by Decree No. 2002-2015 of September 2002 on technical rules relating to the equipment and fitting out of vehicles used for the transportation of hazardous products and materials. Finally, specifications on the use of synthetic fuel for road vehi-cles, trains, and aviation would have to be developed in future from the perspective of PtX development.

4.2.7 Manufacture and use of synthetic fuel from hydrogen

The legislation of oil products is governed by Law No. 91.45 of 1 July 1991 relating to petroleum products. This law lays down special provisions relating to import, export, refining, recovery in the refinery, storage, distribution, and pricing. This regulation gives a monopoly on the manufacture and supply of oil products to the state, who also define the price structure of these products. Currently, synthetic fuels are not covered by this regulation and new legal text would have to be promulgated.

The current industrial and environmental regulations would be applicable to the manufacture of synthetic fuel from green hydrogen. This also applies to the manufacture of ammonia and methanol from green hydrogen.

4.3 INSTITUTIONAL SETTINGS

The main institutions involved in the energy and industry sectors and their roles and responsibilities are summarised in Tables 4.9 and 4.10. In addition to these public enterprises, the energy sector has a web of private companies active in the production of electricity, in the exploration and production of hydrocarbons, and in the storage and distribution of petroleum products.

Tab. 4.9 Main institutions in the energy sector

Institution	Roles and responsibilities
Ministry of Industry, Energy and Mines	Head of the energy sector. Roles and responsibilities: 1. preparation of sector policy and strategy; monitoring and evaluation; 2. preparation of regulations and monitoring of their implementation.
National Agency for Energy Conservation - ANME	Numerous missions aimed at implementing concrete measures and energy management strategies. GHG study and inventory missions.
Tunisian Electricity and Gas Company - STEG	Vertically integrated national company (production, transmission, and distribution of electricity) with a monopoly on the transmission and distribution of electricity and gas to customers.
Tunisian Company of Petroleum Activities - ETAP	Promotion of the development of exploration and production of hydrocarbons in Tunisia; partnership in production projects; management of national assets in the field of hydrocarbons; promotion and development of marginal fields; supplying the national market with natural gas and crude oil; carrying out the studies necessary for the exploration and development of Tunisian hydrocarbons.
National Petroleum Distribution Company - SNDP	Marketing of petroleum products and their derivatives on the national territory.
Tunisian Company of Refining Industries - STIR	Import of petroleum products and refining of crude oil.
Sahara Pipeline Transport Company (TRAPSA)	Transportation, storage, and loading of petroleum products. Management and operation of Skhira oil terminal.
Pipeline Hydrocarbon Transport Company (SOTRAPIL)	Transportation of refined products.
Tunisian Company of the Trans-Tunisian Gas Pipeline (SOTUGAT)	Ownership of the gas pipeline which transports gas from Algeria to Italy, via Tunisian territory.

Tab. 4.10 Main actors in the industry sector

Institution	Roles and responsibilities
Ministry of Industry, Energy and Mines	Industry sector policy and strategy.
Industry and Innovation Promotion Agency - API	Implementing government policy relating to the promotion of the industrial sector and innovation as a support structure for businesses and promoters. Provision of information and support to industrial businesses.
Industrial Land Agency - AFI	Carrying out studies and programmes relating to the delimitation, development, and equipment of industrial zones.

4.4 RESOURCE AVAILABILITY

The production of green hydrogen and its conversion into gaseous and liquid fuels requires not only renewable electricity as an input but also other feedstocks. Hydrogen production requires water, and synthetic fuels require CO_2. This section provides an overview of Tunisia’s CO_2 sources and the country’s water situation.

4.4.1 Carbon sources

The energy-intensive industries (IGCE) are those industries responsible for the highest CO_2 emissions from energy combustion in Tunisia. The main industries in this category are cement, brick, and ceramic factories. Table 4.11 lists the plants that emit the highest levels of CO_2 and their locations.

Tab. 4.11 Location, activity, and carbon emissions of the most carbon-intensive industries

#	Factory	Activity	Location	Emissions (t CO_2)
1	SCE	Cement	Sousse	545 646
2	CT	Cement	Ben Arous	487 937
3	CJO	Cement	Zaghouan	435 755
4	SCG	Cement	Gabès	319 238
5	SOTACIB-K	Cement	Kairouan	316 156
6	CAT	Cement	Tunis	250 645
7	CIOK	Cement	Kef	205 648
8	SCB	Cement	Bizerte	186 631
9	SOTACIB-F	Cement	Kasserine	177 061
10	CC	Ceramic	Sfax	66 438
11	BLC	Brick	Monastir	48 262
12	BBM	Brick	Zaghouan	43 761
13	IBZ 1	Brick	Monastir	43 706
14	BCM	Brick	Monastir	38 877
15	BAMI	Brick	Monastir	32 893
16	SBK	Brick	Tataouine	32 649
17	SBM	Brick	Monastir	32 525
18	CBG	Brick	Gafsa	32 017
19	SOMOCER	Ceramic	Monastir	31 672
20	SCS	Ceramic	Medenine	31 434
21	BMT	Brick	Monastir	30 822
22	IBZ 2	Brick	Monastir	29 138
23	INB	Brick	Kef	26 257
24	SBN	Brick	BIZERTE	22 341
25	CI	Ceramic	MONASTIR	22 334
26	BKS	Brick	SOUSSE	21 172
27	SOTUVER	Glass	ZAGHOUAN	21 072
28	BT	Brick	NABEUL	19 177

(Source: Alcor based on ANME data)

Tunisia has nine cement factories, and their energy combustion generates the highest CO_2 emissions levels in the building materials, ceramics, and glass industries sector. These factories are responsible for around 3,000 ktCO_2/annum. Fig. 4.13 gives the geographical location of these sources of CO_2.

(Source: Alcor)

Fig. 4.13 **Location of the most carbon-intensive industries**

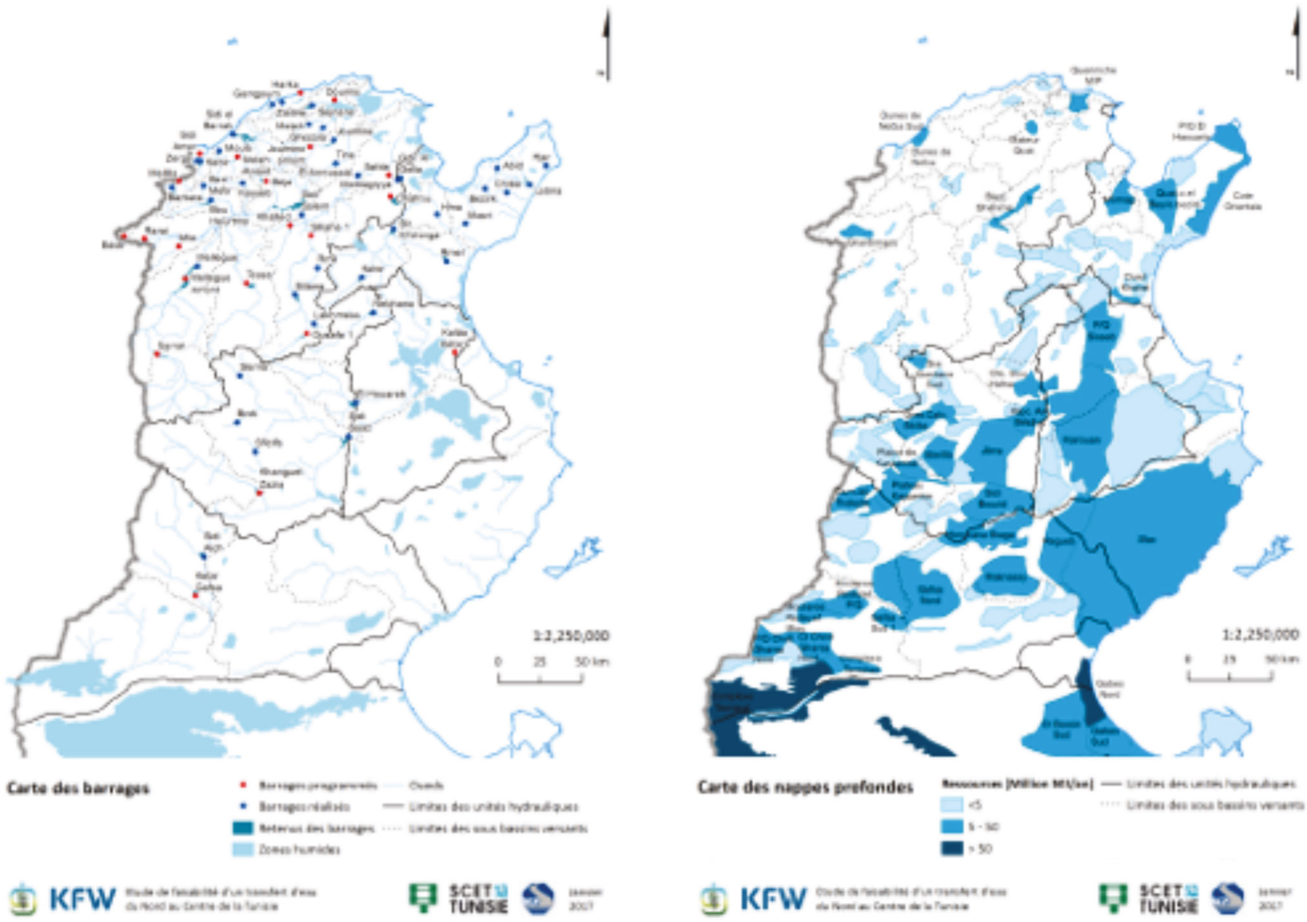
4.4.2 Water resources

Tunisia’s total water resources are estimated to amount to 4.874 billion m^3/annum, including 2.7 billion m^3/annum of surface water, and are characterised by significant annual and regional disparities. The water sector in Tunisia is governed by the Water Code and its implementing texts defined by Law No. 75-16 of 31 March 1975 whose update is currently voted upon in Parliament.

The country is one of the most arid in the Mediterranean, suffering from high water scarcity levels. With water availability of 380m^3 per capita per annum, Tunisia falls well below the internationally specified critical minimum of 1,000 m^3 per person. The physical water scarcity results largely from the spatio-temporal variability of rainfall. The annual rainfall averages between 400mm and 1500mm, but 60% of the country receives less than 200mm per annum. Most of the surface water is in the north, where the main wadis are located and where most of the rain falls. In terms of water quality, only 72% of the surface water with hydropower potential has a salinity level lower than 1.5 g/l (82% of northern waters, 48% of central waters and 3% of southern waters).

At the end of 2014, surface water was mobilised through 33 dams with a current total retention capacity of 2.237 km^3 (with the volume of the silt deducted), 253 hill dams with a total capacity of 266 million m^3, and 902 hill lakes with a total capacity of 93 million m^3.

Most of Tunisia’s groundwater comes from deep water tables in the south (Fig. 4.14), the most important of which are non-renewable fossil water tables (610 million m^3/annum, representing 42% of deep groundwater resources). These resources are part of the SASS basin, which is shared between Libya and Tunisia.
A consultation mechanism exists for this basin but there is no agreement or common management strategy between the countries. In addition, the quality of the groundwater is poor; 84% has salinity levels exceeding 1.5 g/l. This degradation is the result of overexploitation, which is a particular issue in deep water tables in the governorates of Ben Arous (105%), Nabeul (154%), Kairouan (123%), Kasserine (112%), and Kébili (179%). 78.1% of the total volume of water extracted from the deep-water table is for agricultural use. The main consequences of this overexploitation are a significant reduction in the water levels, the potential for the disappearance of natural wells, as well as the gradual deterioration of the chemical quality of the water. The groundwater water tables, whose potential is estimated to be 846 million m^3, are also suffering from overexploitation which has reached a rate of 139% for certain water tables in the centre of the country. All the water tables are used for irrigation, with only 2% with a salinity of less than 1.5 g/l.



(Source: KfW)

Fig. 4.14 Maps of dams and deep aquifers

The volume of water produced is the volume of potable water from production facilities (treatment station output). It includes the volume of treated water, untreated groundwater, and treated groundwater. According to SONEDE statistical reports, the volume of water produced during the period 2010-2019 evolved as shown in Table 4.12.

Tab. 4.12 **Volume of water produced in Tunisia over the period 2010-2019**

	Unit	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total water produced	million m^3/a	523.9	540.6	579.1	609.3	627.5	646.5	653.8	680.5	698.1	729.9
Surface water	million m^3/a	294.3	307	332.5	347.2	360.5	372.5	377.4	395.1	403.3	412.5
Underground water	million m^3/a	205.7	208.9	220.7	234.3	241	248	238.9	245.8	247.7	268.7
Desalinated water	million m^3/a	19.7	19.3	19.7	19.9	18	18	27.9	30.1	39	42.7
Iron-free water	million m^3/a	4.2	5.4	6.2	7.9	8	8	9.6	9.5	8.1	6

(Source: SONEDE)

In future, water availability is expected to be further affected by climate change. Tab. 4.13 summarises blue water resources (mainly water from groundwater and surface water) by category, taking into account the increased aridity due to climate change. The availability of green water for rain-fed agriculture, rangelands, and forests is presented in Tab. 4.14. One factor that influences the availability of green water resources is the water storage capacity of the soil. Agricultural practices, as well as soil degradation due to climate change, may affect the soil's water storage capacity in the future.

Tab. 4.13 **Blue water resources at different horizons (million m^3)**

Horizons	2014	2030 with CC	2050 with CC
Surface water available for use (million m^3)	1072	1176	843
Groundwater (million m^3)	746	720	705
Deep water tables (million m^3)	1429	1404	1380
Total blue water resource	3247	3300	2928

(Source: GWP)

Tab. 4.14 **Green water resources at different horizons (million m^3)**

Horizons	2014	2030 with CC	2050 with CC
Rainfed crop water (million m^3)	11033	10880	10770
Forest and rangelands water (million m^3)	9011	8800	8822
Total	20044	19680	19592

(Source: GWP)

To meet growing water demand, Tunisia is increasingly turning to non-conventional water resources, including desalination and wastewater treatment. In 2018, about 5.6% of the water produced in Tunisia came from desalination plants (SONEDE 2019). The total production of desalinated water is distributed between brackish water and sea water. It increased from 19.7 million m^3 in 2010 to 42.7 million m^3 in 2019, as shown in Tab. 4.15.

Tab. 4.15 Desalinated water production from 2010 to 2019 (million m^3)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Desalinated water	**19.7**	**19.3**	**19.7**	**19,9**	**18**	**18**	**27.9**	**30.1**	**39**	**42.7**
Brackish water	19.7	19.3	19.7	19,9	18	18	27.9	30.1	31.2	30.3
Sea water	0	0	0	0	0	0	0	0	7.8	12.4

(Source: SONEDE)

The specific energy consumption per cubic metre of seawater is estimated to be 3 kWh/m^3 and desalination in Tunisia is mainly powered by fossil energy sources. Renewable energy is only used in the water desalination station at El Ketf port, Ben Guerdane (governorate of Medenine). It was installed in 2019 and has solar panels with a capacity of 212 kW to power a plant with a capacity of 50 m^3 per day, ex-pandable up to 100 m^3.

The desalination plants are distributed in different regions in Tunisia:

Tunisian south: This region, comprising the governorates of Medenine, Ta-taouine, Kébili, and Tozeur, has 10 brackish water desalination stations: Jerba (4.9 million m^3 in 2019), Zarzis (4.9 million m^3 in 2019), Ben Guerdane (0.3 million m^3 in 2019), Béni Khédache (0.1 million m^3 in 2019), Kébili (3.8 million m^3 in 2019), Douz (2.4 million m^3 in 2019), Souk Lahad (2.5 million m^3 in 2019), Tozeur (3.7 million m^3 in 2019), Nafta (1.2 million m^3 in 2019), and Hezoua (0.3 million m^3 in 2019), as well as the Djerba seawater desalination station (12.4 million m^3 in 2019). The Djerba seawater desalination station, a first of its kind in Tunisia, came into operation in May 2018. The station has a capacity of 50,000 m^3 per day.

Kerkennah: Kerkennah is supplied by the brackish water desalination station from local boreholes (2.1 million m^3 were distributed in 2019).

Gabes: Desalination stations for brackish water in Gabes (2.5 million m^3 in 2019), Mareth (1 million m^3 in 2019), Matmata (0.5 million m^3 in 2019), and Belkhir (0.1 million m^3 in 2019) (it should be taken into account that the latter three stations came into operation at the start of 2016). Two seawater desalination stations will be installed in Gabes: one in Zarat with a capacity of 50,000 m^3/day expandable to 100,000 m^3/day, and the other belonging to the Tunisian Chemical Group with a production capacity of 50,000 m^3/day of reverse osmosis water.

Sfax: A seawater desalination station is being installed in Sfax. This station has a production capacity of 100,000 m^3/day expandable to 200,000 m^3/day. The cost of desalination for a cubic metre of seawater is around 3 dinars. Energy accounts for 40% of the cost, depreciation 40%, and maintenance 10%, with other costs accounting for the remaining 10%.

4.5 EXPERTISE AND HUMAN CAPACITY

The development of renewables and a PtX sector in Tunisia Tunisia have a fairly good job creation and training potential, as it would also require sufficient numbers of skilled workforce. According to the latest INS employment survey from 2017, the energy and mining sector employs around 37,500 people, about half of whom are in the upstream and downstream energy sector. Thus, the contribution of the energy sector to total employment in Tunisia is just over 0.5%. From a gender perspective, employment in the energy sector remains dominated by men, who represent more than 85% of employees in the sector.

Regarding renewable energies and energy efficiency, the number of direct jobs created in Tunisia by the end of 2020 was estimated to be around 4,500, according to the updated data presented by the study on job creation in energy management carried out by GIZ and ANME in 2016. Most of these jobs were in the solar thermal and photovoltaic sectors. According to the same study, the renewable energy and energy efficiency development scenario adopted by Tunisia is expected to lead to more than 25,000 additional jobs between 2015 and 2030.

The Tunisian Agency for Vocational Training «ATFP» is the main public operator of vocational training in Tunisia. The diplomas issued by the ATFP cover four levels, namely:

- Level I (CC degree): Certificate of Competence
- Level II (CAP degree): Certificate of Professional Competence
- Level III (BTP degree): Professional Technician’s Certificate
- Level IV (BTS degree): Superior Technician’s Certificate

The energy training sector covers more than 15 specialisms, including renewable energy and energy efficiency, broken down as follows:

- Three specialisms at CC level
- Three specialisms at CAP level
- Six specialisms at BTP level
- Three specialisms at BTS level

At university level, several MSc degrees and engineering training courses in the public or private sectors focus totally or partially on energy in general and on renewable energy and energy efficiency in particular. In 2020, there were more than 10 training courses in this field. In addition to these training courses, there are training courses in related fields that could be necessary for the future development of PtX, such as skills in electricity, mechanics, chemistry, etc.

In addition to these potential skills, high-level expertise exists in certain public establishments, such as STEG for electricity and gas, STIR for refining, SNDP for the distribution and storage of products (including petroleum products), ETAP for the production and transportation of hydrocarbons, ANME for renewable energy and energy efficiency, etc. Thus, the basic skills necessary to support the development of the PtX sector already exist in Tunisia but specific technology-related capacity-building would be required.

4.6 INDUSTRY SECTOR

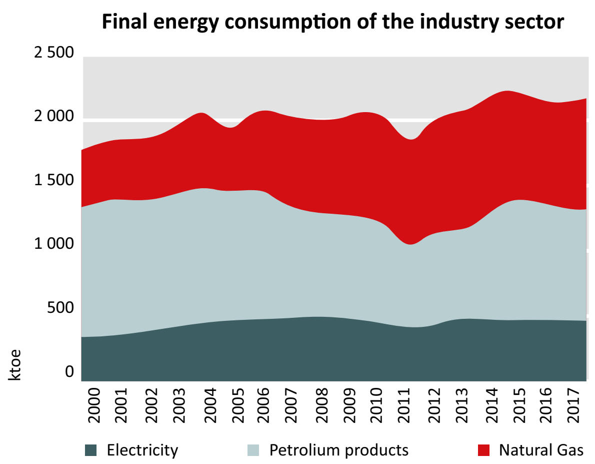
Tunisia's industrial sector comprises about 5,200 companies. The distribution of these companies according to the different sectors is shown in Tab. 4.16.

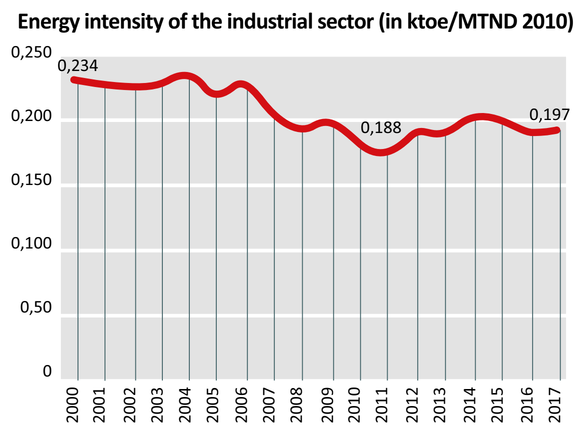
Tab. 4.16 **Distribution of industrial companies according to the different sectors**

Sectors	Exporters	Other	Total	Share (%)
Agrifoods	205	855	1060	20.6%
Ceramic and glass building materials	19	373	392	7.6%
Mechanical and metallurgical	181	433	614	11.9%
Electrical, electronic, and household appliances	224	113	337	6.5%
Chemicals	134	418	552	10.7%
Textile and clothing	1251	279	1530	29.7%
Wood, cork, and furniture	16	159	175	3.4%
Leather and footwear	158	59	217	4.2%
Other	73	208	281	5.4%
Total	2261	2897	5158	100%

(Source: INS)

In terms of the national energy balance for 2017, the final energy consumption of the industry sector amounted to 2,163 ktoe, representing 30% of total national consumption (excluding biomass and renewable energies). This places the industry sector in second position after the transport sector (36%) (Fig. 4.15). Final energy con-sumption in the industry sector increased by 23% over the period 2000-2017, representing an average annual growth of 1.4%. However, the energy intensity of the sec-tor decreased by 15.8% over the same period; an annual decrease of 1%.

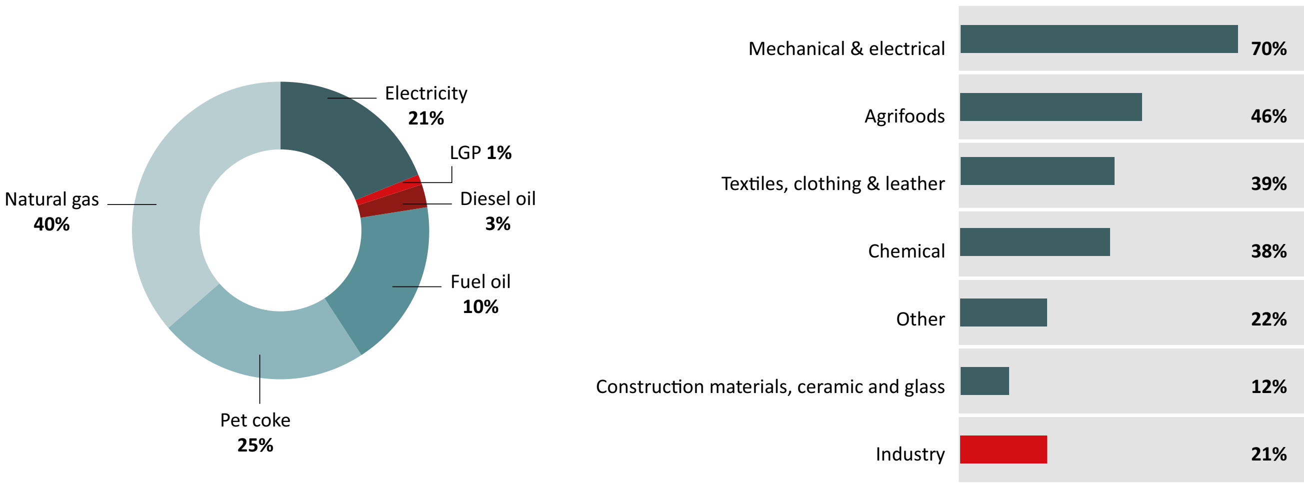




(Source: ANME)

Fig. 4.15 **Evolution of final energy consumption of the industry sector by energy type and the energy-intensity of the industrial sector over the period 2000-2017**

The sector’s final energy consumption mix is dominated by natural gas and oil, which accounted for shares of 40% and 39% respectively in 2017 (Fig. 4.16). Regarding oil products, the most widely used fuel is pet coke, representing 65% of oil products consumption and about 25% of the total consumption for the sector. In terms of the share of electricity in final energy consumption, the building materials, ceram-ics, and glass industry has the lowest share (less than 12% of its total consumption) (Fig. 4.16).



(Source: ANME)

Fig. 4.16 Energy mix of final energy consumption in the industry sector in 2017 and share of electricity in the final energy consumption of industrial branches in 2017

4.7 INVESTMENT CONDITIONS IN TUNISIA

Table 4.17 summaries key factors related to the investment situation in Tunisia.

Tab. 4.17 Overview Investment conditions in Tunisia

Share of equity/debt	It depends on the solvency of the investor and can go from 20% to 40%. It has to be mentioned the approach of project finance is still not developed in Tunisia and banks offer mainly corporate loans.
Cost of equity	Around 15% to 20%
Cost of debt	The interbank market rate in Tunisia is currently around 6.25%; The banks have to add their margin which raises the average interest rate to around 9% to 11% depending on the investors and banks, for loans in Tunisian Dinar.
Availability of public loans (specifically energy and industry sector)	The public indebtment rate in Tunisia is currently around 90% which makes public loans in general little available. This is also true for the energy and industry sectors
Commercial loans (specifically energy and industry sector)	In 2019, the total loans contracted for industry including the energy sector raised to around 26 billion Tunisian dinars and represented a share of 27% of total loans far behind the services sector and households with 92 billion dinars (Central Bank). So, in general, private economic sectors have difficulties to access bank financing because of guarantee requirements.

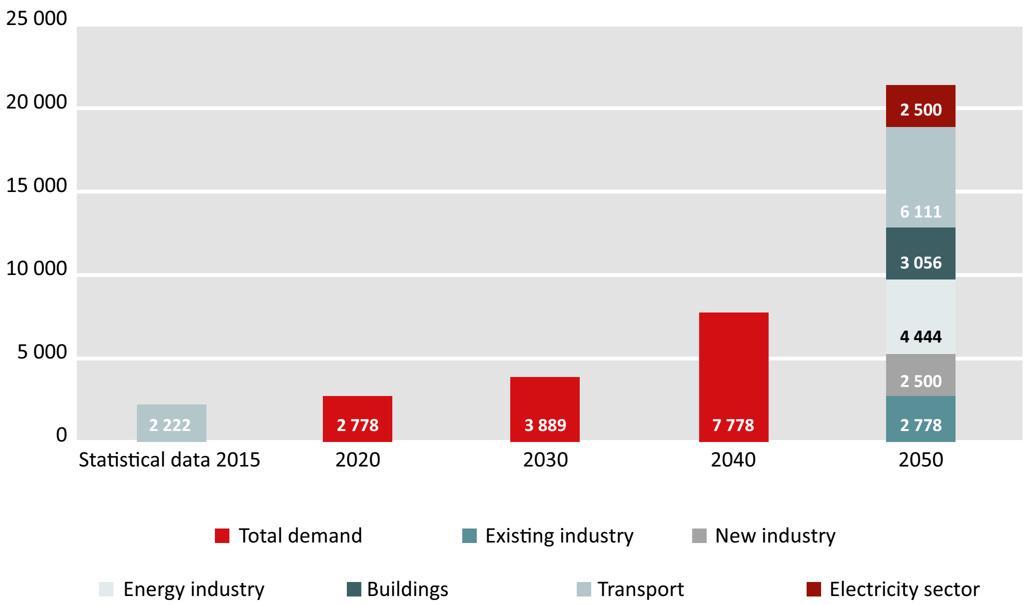
Public guarantees	The guarantee required by the banks is one of the most important obstacles for SMEs to access to financing and consequently to develop their investments. Hence, since early 2000s the Tunisian government has created a public Company (SOTIGAR) whose mission is facilitating the access of SME to financing, by sharing the loan risk with banks. SOTUGAR has managed several Guarantee Funds. The last was the Guarantee Fund set up by ANME and World Bank for energy efficiency projects implemented by energy services companies.
Subsidies to fossil fuels	Most of the energy product prices are fixed by the government in a disconnected way from the international fossil fuel prices. Since Tunisia is importing more than half of its energy needs, almost all the energy products are more or less subsidised. In 2019, the energy subsidy raised to around 2,1 billion dinars (Ministry of finance), so around 50% of the overall subsidy including all products. It represents around 2% of the GDP, in 2019.
The exchange rate	The Tunisian dinar has experienced a significant devaluation in recent years. Compared to the Euro, the rate has fallen from around 1.6 dinars / Euro in 2010 to nearly 3.3 dinars per Euro currently. This increases the cost of investment in industry, whose equipment is often imported. This has also as a direct consequence on the increase of the country’s energy bill because of oil and gas imports.
Investment	The investment rate (investment to GDP) has decreased from 22% in 2013 to 18.5% in 2018 (Central Bank). The investment rate is considered too low to encourage economic growth in the country. Particularly, the foreign investment rate (to GDP) is too low, raising to around 2.2% during the last 5 years (2014-2019) according to central bank. The share of the energy sector in foreign investment has stagnated in recent years at around 35%. However, the manufacturing industry saw its share increase from 18% in 2014 to around 50% in 2019 (Central Bank).

5 Opportunities for Power-to-X in Tunisia

With PtX in general and hydrogen in particular becoming a key strategic element for the further progress of the German and European energy transition and internationally, export markets for PtX are expected to develop rapidly. Tunisia's strategic geographic location close to Europe, together with its extensive renewable energy potential and its stable political situation, create excellent conditions for the country to become a producer and exporter of PtX products. PtX has the potential to be more than simply an export commodity; it could also make an important contribution to Tunisia's long-term decarbonisation efforts. The following sections present an analysis of the development of PtX demand in potential export markets, such as the EU and Germany, as well as the concrete opportunities for PtX in Tunisia.

5.1 FUTURE POWER-TO-X MARKETS

The current market for green hydrogen and its derivatives is vanishingly small. However, the global market for fossil-based hydrogen amounted to 74 million tonnes in 2018 (IEA 2019), with a total estimated value of US$115 billion. The market is expected to grow significantly in the coming years and reach US$155 billion by 2022 (IRENA 2018). With the increasing application of hydrogen in new processes such as transport, as well as its potential as a flexibility option in the electricity sector or as source for generating heat, demand is expected to significantly increase in the coming decades (Fig. 5.1).



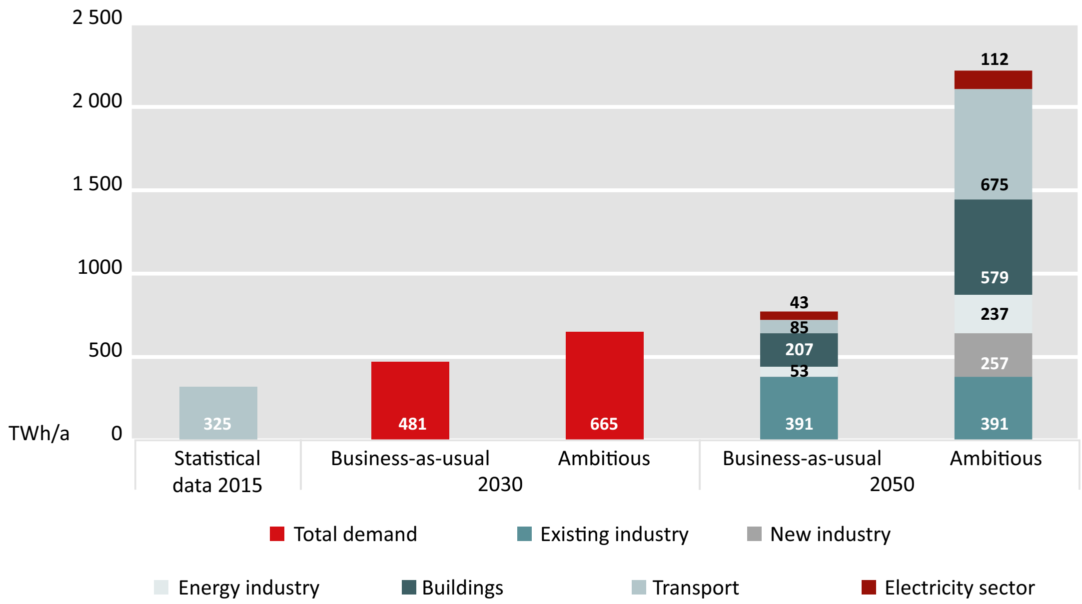
(Source: Based on Hydrogen Council 2017)

Fig. 5.1 Global hydrogen demand scenario up to 2050 (in TWh)

It is anticipated that by 2030, and especially thereafter, there will be significant market growth for hydrogen and a global mass market will be in place. By 2050, it is expected that nearly half the demand will come from the industry sector, followed by the transport sector, heating in buildings, and finally in the electricity sector to buffer the increasing shares of renewables in global energy systems. Total demand is estimated to be about 21,400 TWh in 2050, equating to about 18% of global final energy consumption (Hydrogen Council 2017). Increasingly, green hydrogen from renewable sources will have to meet this demand to achieve global, regional, and national decarbonisation targets. Both the "European Hydrogen Strategy" (EHS) and the German "National Hydrogen Strategy" (NHS), as well as strategies adopted by other countries across the world, underline this fact by aiming to support the rapid development of PtX value chains. Globally, market development is now being driven by a growing number of countries; the leading markets are currently Europe, Japan, China, South Korea, and the USA – particularly in California where hydrogen and (to an extent) PtX are supported via political measures, investments, and government subsidies (Weichenhain et al. 2020). Not only governments are taking action; the private sector is also stepping up its efforts to find solutions for reducing its carbon footprint. The private sector efforts are driven partly by regulations and (future) carbon prices but are also influenced from the consumer side as end-users are increasingly demanding low carbon emission products. Therefore, companies are in-creasingly investing in PtX technologies.

In Europe, in view of current developments, an ambitious scenario foresees the large-scale commercial application of hydrogen by 2050, which would equate to a demand of about 2,250 TWh (Fig. 5.2). This would be about 24% of Europe's final energy demand and would equate roughly to 10% of the predicted global hydrogen demand according to the Hydrogen Council's ambitious scenario (2017). In the business-as-usual scenario, the demand (which corresponds to moderate market development) would be significantly lower at about 780 TWh by 2050. However, this would still represent significant market growth: the 2015 demand of 325 TWh would more than double and would equal about 8% of the European final energy demand by 2050. Until 2030, however, both scenarios assume similar market development. By 2030, demand is expected to reach 481 TWh in the business-as-usual scenario and 665 TWh in the ambitious scenario. Mass market development is only expected from 2030 onwards, which is in line with the assumed pattern of global development.

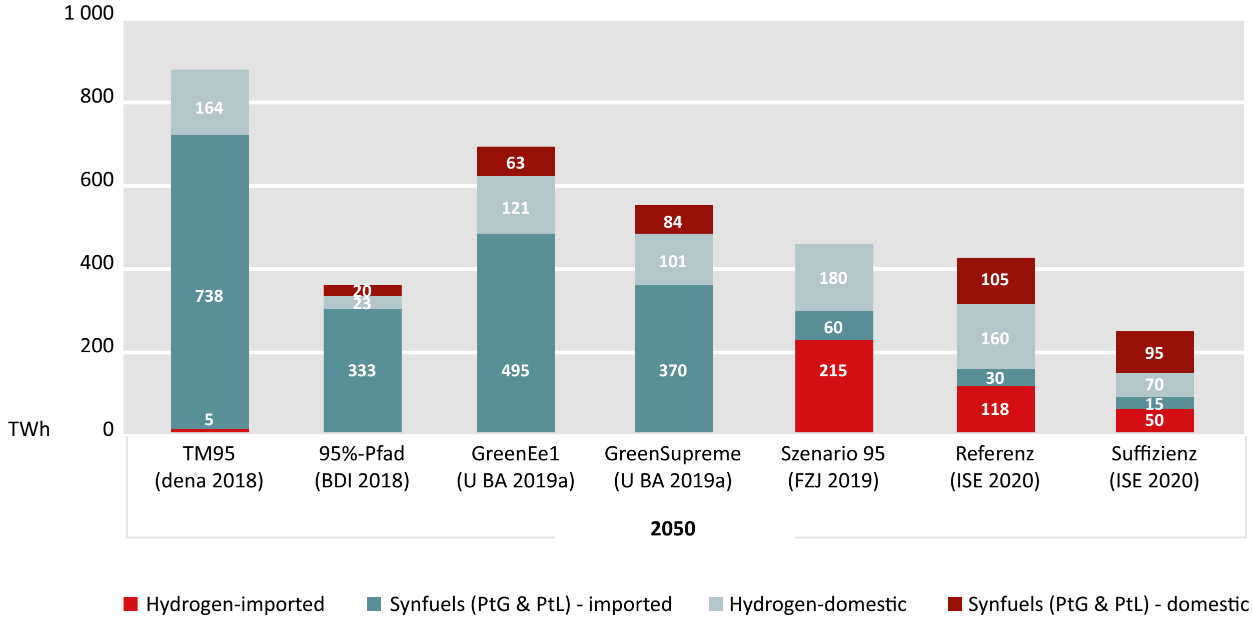
In mid-2020, the EU published the «European Hydrogen Strategy» (EHS), which aims to translate the theoretical contribution of green hydrogen to decarbonisation efforts into practice through investment, regulations, market creation, and research and innovation. Specifically, it envisages the installation of at least 6 GW of renewable hydrogen electrolysers in the EU by 2024, producing up to one million tonnes of renewable hydrogen (EHS 2020). According to the strategy, hydrogen should become an integral part of the European energy system between 2025 and 2030, with 40 GW of renewable hydrogen electrolysers producing up to ten million tonnes of renewable hydrogen. In addition, it is assumed that around 40 GW of renewable hydrogen electrolysers in neighbouring EU countries will be needed to meet European demand. Therefore, the EU aims to have established an open and competitive EU hydrogen market by 2030 with unhindered cross-border trade and efficient allocation of hydrogen supply between sectors. From 2030 to 2050, renewable hydrogen technologies are expected to mature and be deployed on a large scale in all sectors that are difficult to decarbonise.



(Source: Based on FCH 2 JU 2019)

Fig. 5.2 **European hydrogen demand scenarios up to 2050 (in TWh)**

To date, hydrogen has only played a minor role in Germany's energy supply. Around 55 Twh to 60 TWh of hydrogen, mainly produced from fossil sources (natural gas and coal), are currently used per annum in Germany. However, in line with global and European development, Germany expects to see a substantial increase in demand. Different climate protection scenarios assume that by 2050 Germany will have a total demand for hydrogen and gaseous and liquid synthetic energy carriers of between 200 TWh and 900 TWh per annum (Fig. 5.3). The level of demand varies in the scenarios depending on the assumptions made: e.g., level of energy efficiency, extent of electrification in the final energy sectors, changes in behaviour and lifestyle, and the use of carbon capture and storage (CCS) in the energy sector (Wuppertal Institut 2020). Depending on the scenario, demand for hydrogen and synthetic fuels is expected to be met by different shares of either domestic generation or by imports. However, most of the scenarios predict that imports will account for a large share of the demand by 2050 (around 65 TWh to 740 TWh). The share of hydrogen and synthetic fuel imports varies in the different scenarios, as do the costs, which are estimated to range between €40 billion and €77 billion in 2050 depending on the import volumes. This would be in a similar order of magnitude to the current costs of importing fossil fuels to Germany (ibid.).



(Source: Wuppertal Institut 2020 based on the cited scenario studies)

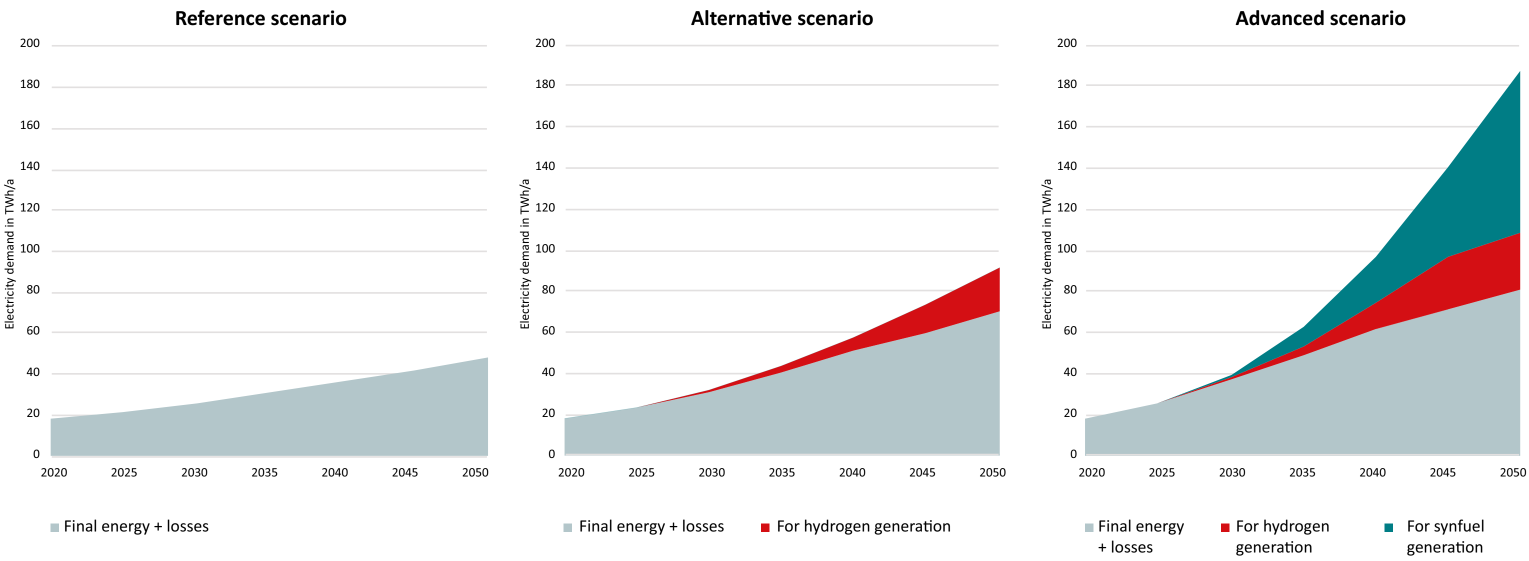
Fig. 5.3 **German hydrogen and synthetic fuels demand according to their origin in different climate protection scenarios up to 2050 (in TWh)**

The German hydrogen strategy, in line with the scenarios outlined above, also expects that the domestic generation of green hydrogen is unlikely to be sufficient to meet the predicted demand, which is why in the medium to long term substantial quantities of hydrogen will need to be imported (BMWi 2020). The strategy, which sets a green hydrogen production capacity target of 5 GW for 2030 with a further 5 GW to be added by 2035-2040, is largely based on the development of hydrogen production outside Germany. The international dimension of the German hydrogen strategy is further underlined by the intended integration of demonstration projects for industrial uses of hydrogen into global value chains, and the identification of potential hydrogen production sites around the world as part of a global green hydrogen atlas project. This import strategy requires early cooperation with potential suppliers and exporters of PtX. In order to foster the development of hydrogen production abroad, Germany needs to provide financial, technical, and logistical support for the construction of plants for power generation from renewable energies and electrolysers, as well as for the establishment of the necessary export infrastructure. Accordingly, the German strategy has earmarked €2 billion for investment in the development of hydrogen technologies in third party countries. Tunisia and Germany have taken a first step to collaborate in this regard by launching the German-Tunisian partnership for the promotion of green hydrogen generation in December 2020.

5.2 FUTURE POWER-TO-X DEMAND IN TUNISIA

Opportunities for green hydrogen in Tunisia could go beyond export to Germany, Europe, and global developing markets: there could also be new demands from within Tunisia. Although Tunisia, as a developing economy, is not obliged under the Paris Agreement to reach the deep decarbonisation levels of 95% required for industrialised countries like Germany, hydrogen and its derivatives could contribute to decarbonation in Tunisia – particularly in sectors that are either impossible or difficult to electrify. These could include industrial applications, as well as air and sea transport. Moreover, hydrogen could also play a role as a flexibility option in electricity systems with a high share of intermittent renewable energy sources, as well as being injected into the national gas grid. Furthermore, the anticipation is that demand for "green" products that are CO_2 neutral, or at least have a reduced carbon footprint, will increase as countries worldwide strengthen their efforts to combat climate change and its impacts. Consequently, even if there is no direct pressure on Tunisia to raise its ambitions beyond the requirements of the Paris Agreement, the development of a PtX sector could nevertheless create opportunities for the country. Provided that the appropriate technical, financial, regulatory and political developments are made, hydrogen and synthetic fuels could also become part of Tunisia's strategy to reduce greenhouse gas emissions due to the growing demand for both electricity and other forms of energy in the transport sector.

First scenarios for Tunisia from the German Aerospace centre (DLR 2020), which are based on regional trajectories, show how demand in Tunisia for electricity to produce hydrogen or synthetic fuels could develop based on different decarbonisation strategies and targets (Fig.5.4).

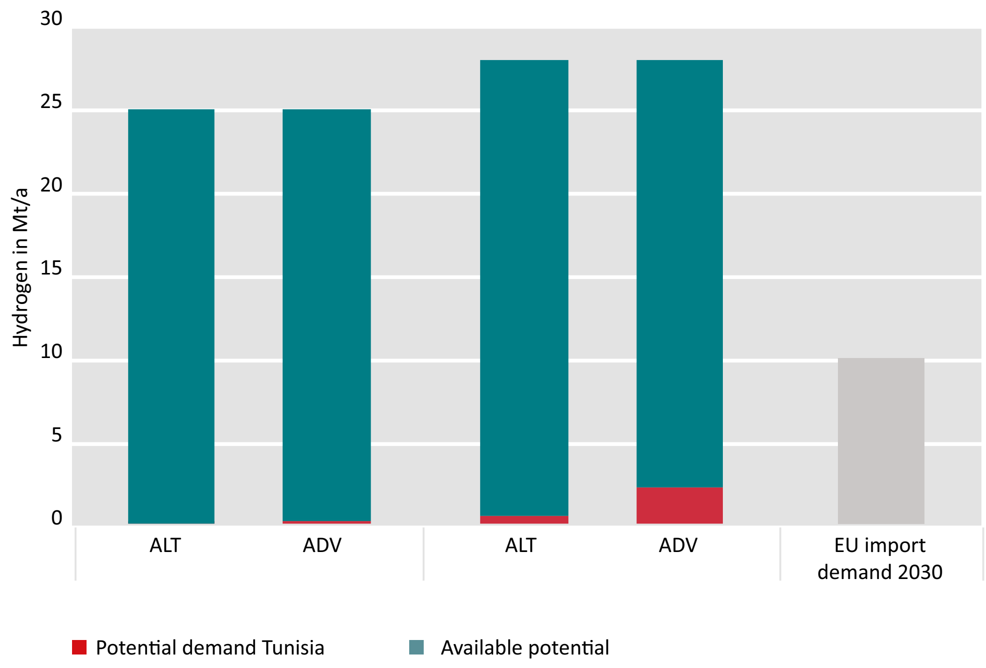


(Source: DLR 2020: Scenario data for Tunisia developed in the framework of the project MENA-Fuels (BMWi FKZ 03EIV181C). T. Pregger, German Aerospace Center (DLR), personal communication 19th November 2020.)

Fig. 5.4 Electricity demand scenarios for Tunisia (TWh/a)

In the reference scenario, which assumes the continuation of current policies and no introduction of new policies, the expectation is that no hydrogen or synthetic fuel demand develops and the energy system continues to be dominated by fossil fuels. The rise in electricity demand is primarily driven by increasing demand for existing appliances. In the alternative scenario (ALT), with moderate pathways for efficiency and the expansion of renewables, electricity demand nearly doubles due to assumed greater electrification efforts in end-use sectors such as transport and, after 2030, the generation of hydrogen for domestic applications. The advanced scenario (ADV), which is in line with a 100% renewables-based energy system by 2050, shows demand for renewable electricity more than quadrupling compared to the reference scenario, with about half of the demand stemming from hydrogen and synthetic fuel production.

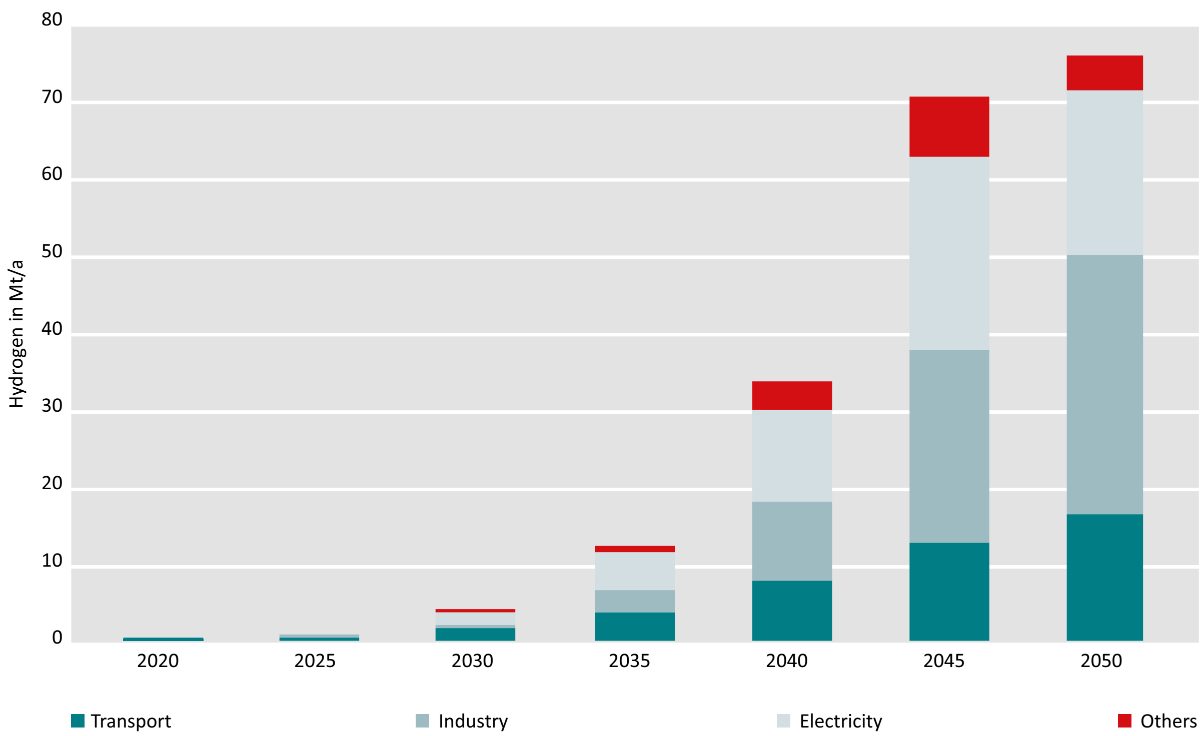
Taking into account the electricity demand generated by hydrogen and synthetic fuel production in the alternative and advanced scenarios, the total electricity demand could range between 0.3 TWh and 3 TWh by 2030 and between 21 TWh and 100 TWh by 2050. Comparing this demand to the technical green hydrogen potential in Tunisia for the best solar energy and onshore wind resources shows that the technical potential is sufficient to meet domestic demand and to produce hydrogen for export (Fig. 5.5)



(Source: Wuppertal Institut, data sources DLR 2020; Brändle et al. 2020; EU hydrogen strategy 2020)

Fig. 5.5 **Comparison of green hydrogen potential and demand scenarios for Tunisia (potential includes solar PV and wind onshore sources with a capacity factor over 20%)**

A closer look at the sectors where demand for green hydrogen could develop in the advanced scenario shows that by 2050 the largest demand could come from applications in the industrial sector, followed by the power sector and the transport sector. In the initial phase up to 2030, demand could develop in the transport sector, followed by the electricity sector. In the latter, hydrogen could compensate for the increasing share of intermittent renewables and could contribute to the decarbonisation of gas-fired electricity generation by injection into the gas grid. Demand in the industrial sector under this scenario rises sharply from 2040 onwards (Fig 5.6).



(Source: DLR 2020: Scenario data for Tunisia developed in the framework of the project MENA-Fuels (BMWi FKZ 03EIV181C). T. Pregger, German Aerospace Center (DLR), personal communication 19th November 2020.)

Fig. 5.6 **Advanced scenario electricity demand for hydrogen by sector in Tunisia (PJ/a)**

5.3 EVALUATING FUTURE POWER-TO-X OPPORTUNITIES IN TUNISIA

The following sections explore further the potential demand and opportunities in Tunisia for different sectors. To estimate the demand for green PtX products and the associated demand for renewable electricity, this study developed three scenarios outlining demand and production for the three most promising applications for Tunisia: ammonia, methanol, and kerosene fuel. These scenarios are all based on the premise that a global market for green PtX products will develop. This would require the development of external factors in favour of PtX applications, such as carbon price mechanisms, the international climate change agenda, and countries’ decarbonisation targets, as well as private sector climate strategies. A PtX market will only develop when PtX products become cost competitive with conventional products or the willingness to pay more for green products increases. The three scenarios developed in this study include a business-as-usual (BAU) scenario, a growth scenario in which Tunisian demand and production are expected to increase significantly (Growth), and an export scenario in which green ammonia, methanol, or kerosene-like jet fuels are also produced for export in Tunisia (Export).

5.4 POWER-TO-X OPPORTUNITIES IN THE INDUSTRY SECTOR

Globally, hydrogen is currently used by several industrial sectors, mainly as a feedstock rather than as an energy carrier. The main applications are in refineries, for ammonia or methanol production, and in first applications in the iron and steel industry. Together these applications account for about 75% of current hydrogen use (IEA 2019). The sectors that consume hydrogen at industrial level are expected to remain the main users for the foreseeable future (ADEME 2019). Other uses in the industry sector (accounting only for a small share of hydrogen applications worldwide) include glass manufacturing, electronics, bulk chemicals, the cooling of electrical generators, and fuel for aerospace rockets (IRENA 2018). Current hydrogen generation is based almost entirely on fossil fuels: mainly natural gas and coal. Natural gas is converted via steam-methane reforming (SMR) and coal via gasification, particularly in China and Australia (IRENA 2018). Replacing fossil fuel-based hydrogen with green hydrogen produced using renewable energy via electrolysis is one option for contributing to the decarbonisation of these existing industry applications. Furthermore, new opportunities for green hydrogen use are emerging in the industry sector. Hydrogen could, for example, replace coal as a reducing agent in steel production, be used in new plastic production processes, or produce high temperature heat for the cement industry (Material Economics 2019). The options for the use of green hydrogen in industry are specific for each industrial segment, ranging from simply replacing fossil-based hydrogen to changing the entire industrial production process. Fig 5.7 gives an overview of the status and potential opportunities in the industry sector in Tunisia. In the following sections these opportunities are discussed for the most relevant industry segments: refining, the iron and steel sector, ammonia and methanol production, and heat applications.

	Current applications of hydrogen	Relevance for Tunisia today	Long-term development potential Tunisia
Refining	Desulphurise and upgrade heavy crude oil via • Hydrocracking • Hydrotreating	The country has one refinery with no further treatment unit so currently no demand for green hydrogen for refining exists in Tunisia.	New refinery or adding treatment units could create limited demand in the future. But these options entail risks like technological lock-in effects or stranded investments.
Iron and steel	Direct reduction of iron (DRI) in primary steel production	Tunisia has one steel mill with secondary steel production from scrap in an electric arc furnace. This process does not require hydrogen.	Establishment of new steel industry with DRI and related hydrogen demand unlikely. Especially as Tunisia has only limited iron ore reserves.
Chemicals	• Ammonia production • Methanol production • Other chemical processes	Currently no ammonia or methanol production in Tunisia, both commodities are imported. Only indirect demand for hydrogen today.	Green ammonia and methanol could be produced in Tunisia from hydrogen generated with renewables to cover domestic demand and for export.
High temperature heat	No application today, but potential application in the future	No application of hydrogen for heat in the industry in Tunisia.	No potential applications in Tunisia in short to medium term. Long-term demand development possible but direct use of concentrated solar heat could be a more feasible option.

Fig. 5.7 Overview of Power-to-X opportunities in the industry sector in Tunisia

5.4.1 Refining

Tunisia is a small producer of crude oil with limited oil reserves compared to its neighbours. The main producer of crude oil is the state-owned Entreprise Tunisienne d'activités Pétrolières (ETAP), which had a share of about 80% of production in 2016 (USGS 2020a). The production of crude oil has been trending downwards from its peak of 120,000 barrels per day (bbl/d) in the mid-1980s to 50,000 bbl/d in 2019 (BP 2020). Crude oil is processed in Tunisia's only oil refinery, which has a crude oil distillation capacity of 34,000 bbl/d. The refinery, which started operation in 1963, is located in the northeast at Bizerte and is operated by the Société Tunisienne des Industries du Raffinage (STIR). The refined products include gasoline, petrol, gasoil, fuel oil, LPG, kerosene, and NGL.

The existing refining capacities are neither sufficient for processing the volume of crude oil produced in Tunisia nor for meeting domestic demand. The refinery output currently meets about 30% of the demand for refined oil products in Tunisia (OBG 2017). Accordingly, Tunisia exports crude oil and imports refined products. Overall, Tunisia is a net importer of oil products, with imports steadily rising since 1990 to over 4,000 kt in 2018, while exports have remained at more or less constant levels averaging between 450 kt and 800 kt per annum (IEA 2020a). In 2012, discussions took place with investors from Qatar and Libya to build a second refinery at Skhira with an initial capacity of 120,000 bbl/d, expanding to 250,000 bbl/d, to include the processing of crude oil from Libya (EIA 2014). However, the $2 billion project was suspended due to the conflict and political uncertainty in Libya, which meant that steady supply could not be ensured (OBG 2017). Furthermore, on a global level, refining capacity is generally thought to be sufficient to meet the global (rising) oil demand (IEA 2019). Therefore, building additional refining capacities in Tunisia is perhaps not the most viable option. Instead of building a new refinery, an alternative would be to invest in hydrocracking or hydrotreatment units so the existing refinery could reduce sulphur ratios and optimise octane ratings to lower the direct emissions of particulate matter (OBG 2017). Hydrocracking or hydrotreatment would generate demand for green hydrogen. However, in light of decarbonisation efforts worldwide, building a new refinery or heavily investing in the current refinery could result in technological lock-in effects or stranded investments. This, in turn, could create barriers to Tunisia’s sustainable energy transition.

In conclusion, there is currently no demand for green hydrogen for refining in Tunisia. Building a new refinery or adding hydrocracking or hydrotreatment units to the existing refinery could create demand in the future. However, against the backdrop of global decarbonisation efforts, these options entail risks such as technological lock-in effects or stranded investments.

5.4.2 Iron and steel

Primary steel can be produced through the blast furnace basic oxygen furnace (BF-BOF) process, which accounts for 90% of global primary steel production, or through direct reduction in combination with an electric arc furnace (DRI-EAF), which accounts for about 7% of global primary steel production (IEA 2019). The BF-BOF path produces hydrogen as a by-product, while the DRI-EAF requires hydrogen and carbon monoxide as reducing agents (ibid.). One option for decarbonising steel production is to use green hydrogen in the iron ore direct reduction (DRI) process, which currently uses natural gas as a reducing agent (Lechtenböhmer et al. 2016).

Secondary steel is produced from scrap steel in an electric arc furnace (EAF). The scrap-based EAF steel production process has the lowest emissions (FCH 2 JU 2019). This process requires high amounts of electricity but no hydrogen, and secondary steel production is mainly located in countries with low natural gas prices (such as the Middle East).

Tunisia after the closure of its sole blast furnace in 2003 has no primary steel production. The country however has infrastructure for secondary steel production. The country’s only steel mill, the state-owned société Tunisienne de sidérurgie, also known as El-Fouladh (USGS 2020a), produces steel from scrap via EAF. The steel mill has two electric furnaces and a total capacity of 200,000 tonnes per annum. Since 2015, however, only around a quarter of the capacity has been used, with an annual production of 50,000 tonnes of crude steel (World Steel Association 2020). Furthermore, there have been discussions in Tunisia about the steel mill as it does not generate profit for the state but actually runs at a loss. Against this background, it can be assumed that there is currently no real demand for hydrogen in Tunisia’s steel sector and that no significant demand will develop by 2050 under current conditions.

5.4.3 Ammonia

Ammonia (NH_3) is a chemical compound formed by one nitrogen (N) and three hydrogen (H) atoms. It is the second most widely produced synthetic chemical in the world, of which around 80% is currently used in the production of fertilisers. Other applications include explosives and other chemical and pharmaceutical feedstocks, such as nitric acid and acrylonitrile (Bazzanella and Ausfelder 2017). As such, ammonia is almost exclusively used as a raw material in the chemicals industry.

In addition to its application as feedstock, in the context of the decarbonisation debate and the growing need to transport and store hydrogen and its derivatives, ammonia is gaining attention as a potential energy carrier. Three characteristics of ammonia make it a promising energy medium: (1) the gross energy density of liquid ammonia is higher than that of liquid hydrogen (11.5 MJ/l, compared to 8.491 MJ/l); (2) the abundance of nitrogen in the atmosphere could make the large-scale production of renewable ammonia easier than the production of CO_2-based fuels; and (3) ammonia has the lowest energy demand for feedstock separation compared to other fuels (Zelt et al. 2021).

Ammonia is currently almost exclusively produced in large-scale facilities (up to 3,300 tonnes per day) by combining nitrogen and hydrogen via the Haber-Bosch process (Zelt et al. 2021). The hydrogen used is commonly derived from reforming natural gas (Lechtenböhmer et al. 2016). Ammonia production is the most energy-intensive process in the fertiliser industry (Batool 2019). Changing the process to use green hydrogen made by the electrolysis of water with electricity from renewables, rather than hydrogen from natural gas, could reduce the intensity of greenhouse gas emissions from ammonia production. The synthesis of ammonia using renewable electricity requires the separate production of both hydrogen and nitrogen as inputs, while the production of the ammonia itself is possible using the same Haber-Bosch process. The technologies to produce hydrogen through electrolysis and nitrogen through air separation are, in principle, available. However, there is significant scope to improve the efficiency of the electrolysis (Material Economics 2019) and the integration of the overall process has not yet reached the commercial stage (Zelt et al. 2021).

The main producers of ammonia are China, India, Russia, and the USA (USGS 2020b). In the Middle East and North Africa, the main producers are Saudi Arabia, Qatar, Iran, Egypt, and Oman: countries where natural gas is inexpensive due to large deposits and local production. Tunisia does not currently produce ammonia but imports it – mainly from Russia and (in very small quantities) from Italy (OEC 2020). Tunisia is the second largest importer of ammonia in Africa after Morocco (ibid.) The main application of ammonia in Tunisia is for producing fertiliser.

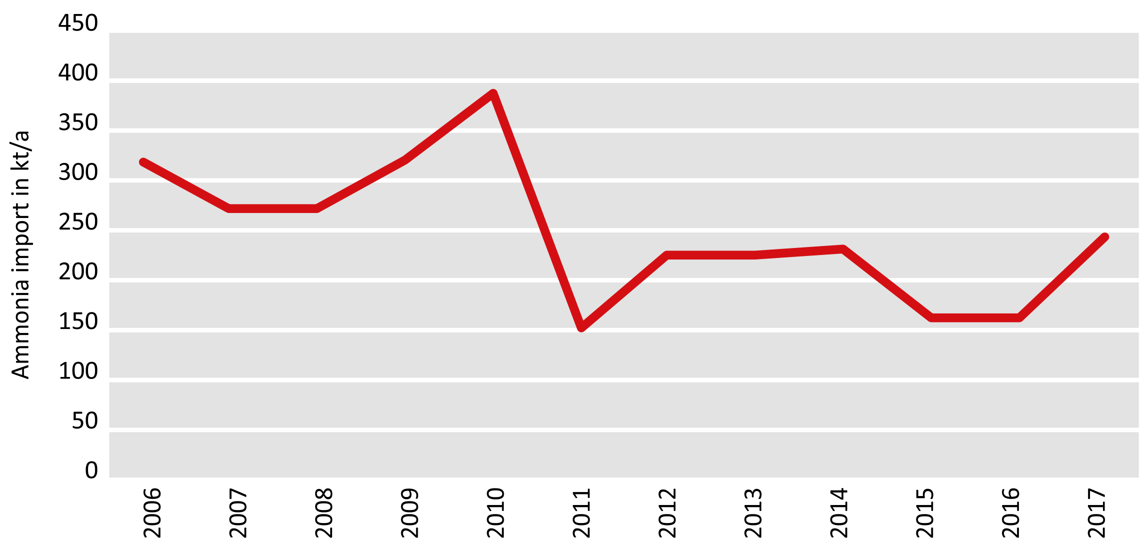
The fertiliser industry in Tunisia is based on its substantial reserves of phosphate rock, estimated to amount to 900 Mt (OBG 2017). The state-owned Compagnie des Phosphates de Gafsa (CPG) carries out all phosphate mining activities in Tunisia, running eight open-cast mines and eleven phosphate rock-washing plants (USGS 2020a). The production of phosphate rock amounted to 3.2 Mt in 2015, which is still below the pre-2011 level of 8 Mt per annum (ibid.). The Tunisian government aims to increase the output of phosphate rock through expansion projects at existing mines in the Metlaoui district in Gafsa Governorate and through the development of new mines in Le Kef Governorate (ibid.).

Most of the phosphate rock is used domestically in Tunisia to manufacture fertiliser. Tunisia has two major manufacturers of fertiliser. One is the Group Chimique Tunisien (GCT), which merged with CPG in 1996.

GCT processes about 6.5 million tonnes of Tunisian phosphate rock annually to produce merchant grade phosphoric acid (MGA), diammonium phosphate (DAP), monoammonium phosphates (MAP), triple super phosphate (TSP), and calcium phosphate (DCP) (GCT 2020). In addition, ammonium nitrate and porous ammonium nitrate are produced as agricultural fertilisers, mainly for the local market. GCT has four production sites in southern Tunisia: Gabès, Sfax, Skhira, and M'dhilla.

The other fertiliser producer is the Tunisian-Indian joint venture between CPG (35% share), GCT (35% share), India's Coromandel International (15% share) and Gujarat State Fertilisers and Chemicals (15% share). It operates a phosphoric acid production plant in Skhira with a capacity of 360,000 tonnes per annum, and the entire production is exported to India as part of a long-term purchase agreement (OBG 2017).

The production of diammonium phosphate (DAP), monoammonium phosphates (MAP), ammonium nitrate, and porous ammonium nitrate, requires ammonia, which Tunisia currently imports. Tunisia imported about 245,000 tonnes of ammo-nia in 2017; this was significantly less than the pre-2011 level of close to 400,000 tonnes due to reductions in fertiliser production after 2011 (Fig. 5.8).



(Source: Data from FAO 2020)

Fig. 5.8 **Ammonia imports for Tunisia (in kilo tonnes per annum)**

Currently, there are no specific measures in Tunisia that explicitly target the reduction of emissions in industrial processes (MRP 2018). Consequently, there are no direct incentives in Tunisia to switch to using green ammonia in fertiliser production.

However, in view of global decarbonisation efforts and their long-term benefits, Tunisia could consider making greater efforts to decarbonise its industrial sector in the future. Demand for CO_2 neutral fertilisers or those with a low carbon footprint is also expected to increase worldwide [1], especially as close to half of global ammonia production could be included in carbon pricing schemes by 2030 (Eichhammer et al. 2019). The EU Emissions Trading Scheme (ETS), for example, has been applicable to the production of ammonia since its third phase (2013-2020). In other countries, such as Canada, USA, China, and Australia, ammonia could be included in GHG emissions trading in the future (ibid.) These developments could encourage the switch to green ammonia in fertiliser production in the EU and in other countries, as well as potential future green fertilizer exporting countries such as Tunisia.

Assuming that Tunisia chooses to support a switch towards fertiliser with a low carbon footprint – as a result of rising demand for low carbon fertiliser, incentives from importing countries, and favourable cost developments – it has two options with regard to ammonia. Tunisia could either import green ammonia or develop the production of green ammonia in the country. The first option means that Tunisia would remain dependent on ammonia imports. No production capacities for green hydrogen would be created in Tunisia. Thus, the expected growing global demand for ammonia (IEA 2019) could offer a chance to establish green ammonia production in locations like Tunisia with the potential to generate large amounts of low-cost renewable electricity. Moreover, if Tunisia aims to export green hydrogen in the long term, ammonia could become relevant as a storage and transportation medium, which would also require the establishment of green ammonia production facilities in Tunisia. Against this backdrop, it could be worth examining how pathways towards green ammonia production in Tunisia could potentially develop.

To evaluate and quantify the potential demand for ammonia in Tunisia, these potential developments are taken into account and three scenarios are developed. A business-as-usual scenario (BAU), a growth scenario (Growth), which assumes that fertiliser production in Tunisia increases significantly, resulting in higher demand for ammonia), and an export scenario, which assumes that Tunisia exports green ammonia (Export). The estimated demand for ammonia along these scenarios is shown in Fig. 5.9.

Tunisia is aiming at increasing its fertilizer production; accordingly this is also reflected in the business-as-usual scenario. Here, demand for ammonia is expected to increase, reaching pre-2011 levels by 2050, which is consistent with a 20% growth compared to 2017. In the Growth scenario, demand for ammonia will increase more rapidly (by 50% by 2040 compared to 2017) and will then plateau until 2050 in line with an expected global slowdown in the growth of demand for fertiliser (Brown 2018). The Export scenario, on the other hand, assumes that Tunisia becomes an exporter of green ammonia, which would triple demand by 2050 compared to 2017.

1 | CO_2 neutral or low carbon fertilisers have distinct advantages over fossil fuel-based fertilisers, but extensive use of nitrogen and phosphorus fertilisers can still have negative impacts on air and downstream water quality. Therefore, to make fertilisation more sustainable, consideration should be given not only to reducing CO_2 but also to adopting alternative agricultural practices to reduce the need for synthetic nitrogen. However, these considerations are outside the scope of this study.

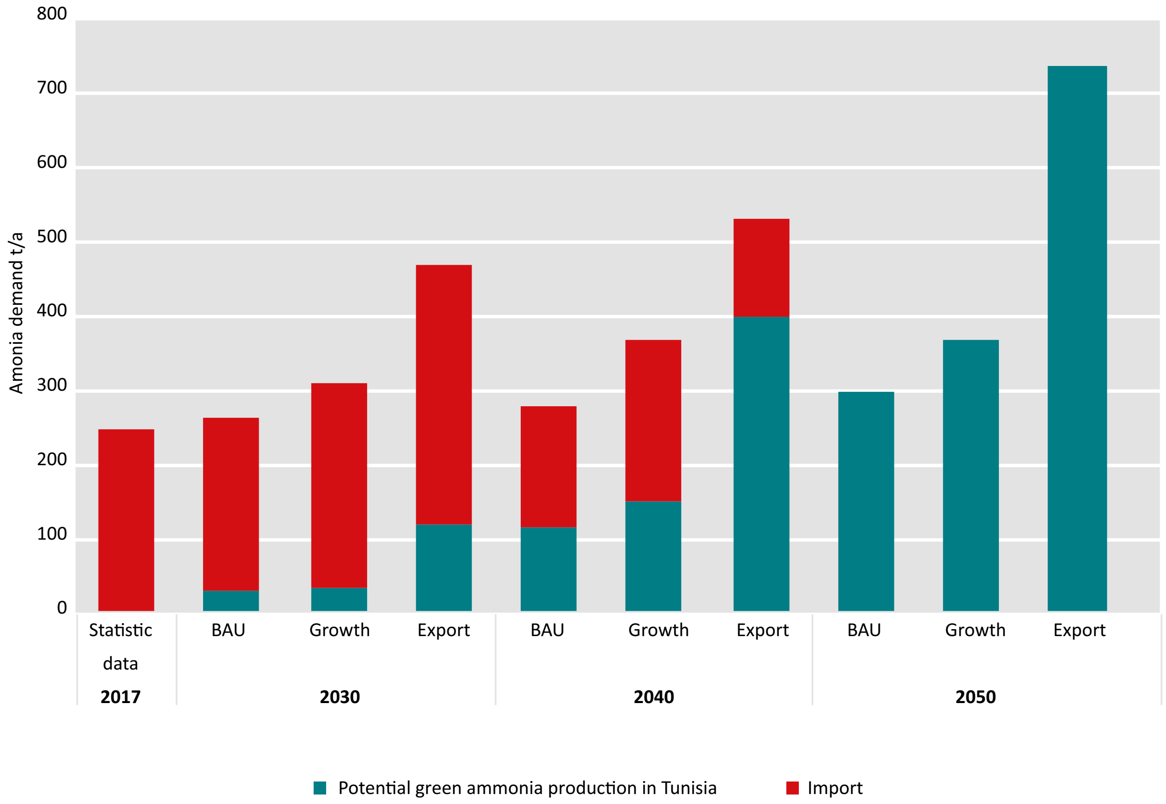


Fig. 5.9 **Ammonia demand and production scenarios for Tunisia (in kilo tonnes per annum)**

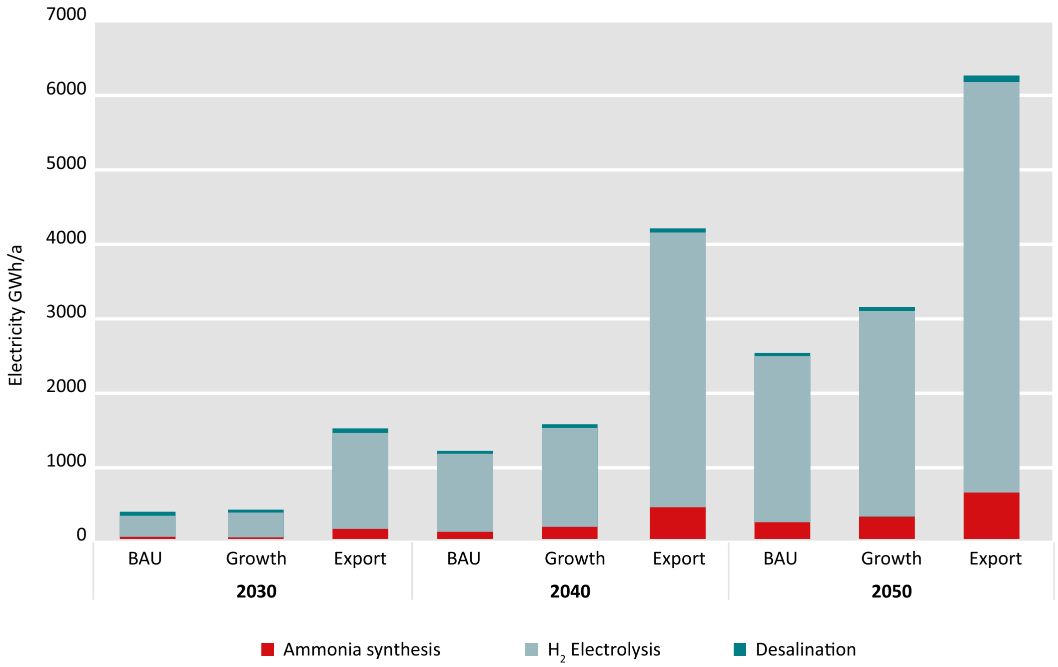


Fig. 5.10 **Ammonia demand and production scenarios for Tunisia (in kilo tonnes per annum)**

As Fig. 5.9 shows, imported ammonia is gradually replaced by green ammonia produced in Tunisia with renewable electricity. To achieve this, it would be necessary to establish green ammonia production capacities in Tunisia and increase renewable energy capacities in line with the developments outlined in the scenarios. Fig. 5.10 shows the electricity demand for the production of green ammonia for each scenario based on the assumed increasing share of green ammonia over time, from 10% to 25% in 2030, to 40% to 75% in 2040, and up to 100% by 2050. The Export scenario requires rapid expansion of green ammonia production capacities to meet 100% of Tunisia’s domestic and export ammonia demand by 2050. A slower expansion path would correspondingly require lower capacities and renewable energies for the share produced in Tunisia. Fig. 5.10 shows the corresponding electricity demand for these production scenarios. The major share of electricity would be needed for the hydrogen generation followed by the electricity demand for the ammonia synthesis. Compared to conventional drinking water treatment plants, water desalination is an energy-intensive process. However, ammonia production is such an energy-intensive process that water desalination with reverse osmosis accounts for only a small share of the total electricity demand.

The investment costs for the ambitious expansion pathway aiming to meet the entire demand for green ammonia through local production in Tunisia by 2050 are estimated to range between €0.95 billion and €2.4 billion, depending on the scenario. Fig. 5.11. illustrates the level of investment and when it would be required for the three different scenarios.

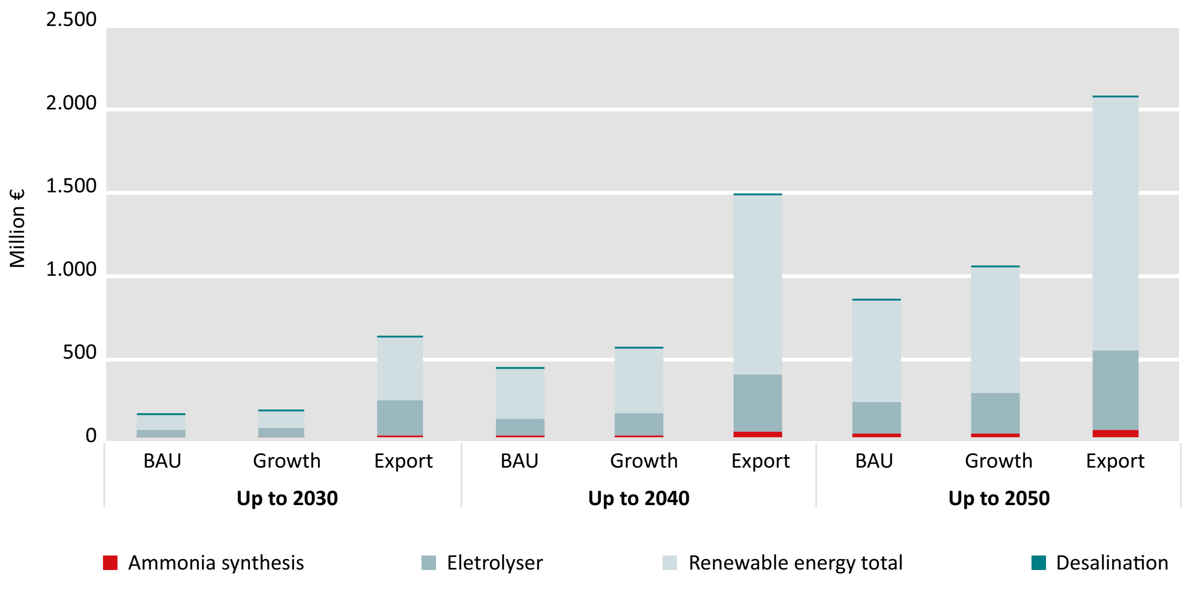


Fig. 5.11 **Cumulative investment needs for ammonia production scenarios for Tunisia (in million €)**

The investment costs include costs for the establishment of renewable energy capacities, electrolysis, ammonia synthesis, and desalination. The major share of the costs is for the expansion of renewable electricity generation (around 60%), with the development of electrolysis capacities accounting for about 30% and ammonia synthesis accounting for about 8%, while desalination represents less than 1% of the overall investment required. Infrastructure development costs (e.g., grid connection and transmission, water transportation, and product transportation) have not been calculated as these will depend on the location and are, therefore, site- and project-specific. A detailed infrastructure needs assessment, possibly combined with techno-economic infrastructure modelling (such as by Reuß et al. 2019 for Germany; Tlili et al. 2020 for France or Moreno-Benito et al. 2017 for the UK), for PtX in Tunisia seems advisable. This would help to better estimate infrastructure needs and costs apart from generation facilities for PtX in Tunisia.

In summary, increasing green ammonia capacities would be capital-intensive and the main challenge is expected to result from financial rather than technical aspects. Therefore, while replacing imported ammonia with locally-produced green ammonia could reduce GHG emissions and provide economic opportunities in the long term, incentives from importing countries and political support will play an important role in the short term for establishing green ammonia production in Tunisia.

5.4.4 Methanol

Second to ammonia production, methanol production is currently one of the largest consumers of hydrogen in the global industrial sector. Methanol (CH_3OH) is a liquid chemical and a key product in the chemicals industry used for a diverse range of industrial applications, including the manufacture of chemicals such as formaldehyde, acetic acid, and plastics, or in high-value chemicals such as ethylene and propylene via the methanol-to-olefin (MTO) route (IRENA 2021). The chemicals produced are further processed and can be found in many products that are part of our daily lives, such as building materials, foams, resins, plastics, paints, polyester, and a variety of health and pharmaceutical products (Methanol Institute 2021). As well as its industrial applications, which account globally for about 60% of methanol use, methanol is also used as fuel for vehicles, ships, industrial boilers, and for cooking (ibid.). It can be used as fuel either on its own, blended, or further converted into methyl-tert-butyl-ether (MTBE) and dimethyl-ether (DME) (IRENA 2021). Methanol as a liquid fuel is easily transportable, like other common petroleum fuels (IEA 2019).

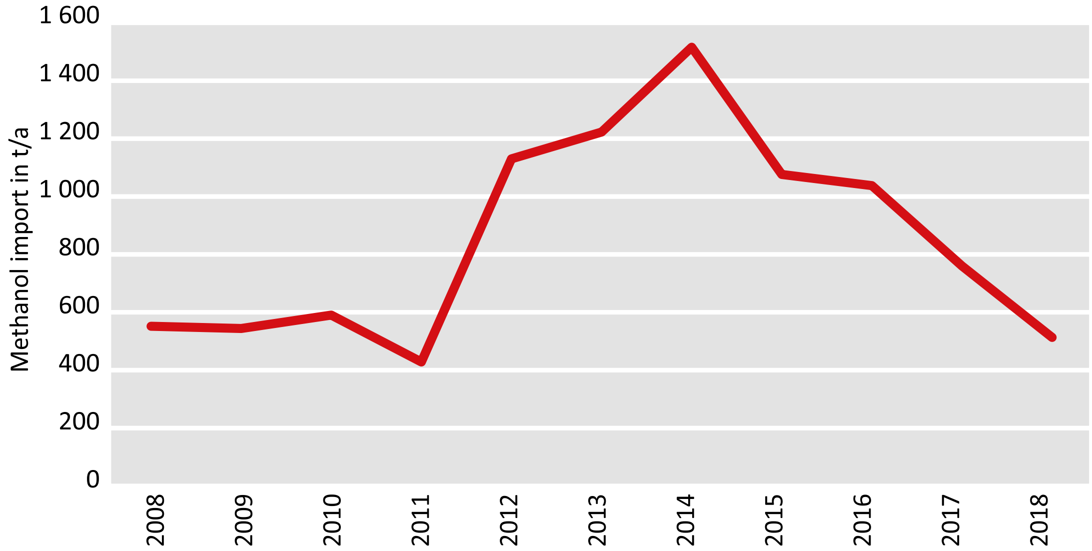
While some of the applications of methanol have been in existence for a long time with production at industrial scale, other applications are relatively new and the technology is, to some extent, still at the demonstration phase. The newer applications in the chemical sector include methanol-to-olefins and methanol-to-aromatics. Methanol-to-olefins, to produce ethylene and propylene, has seen significant growth in the past 10 years (almost exclusively in China) and accounts for about 25% of current global methanol consumption (IRENA 2021). On the other hand, methanol-to-aromatics, which are the starting block for a wide array of consumer products, are still in the demonstration phase (IEA 2019).

Overall, global demand for methanol has more than doubled in the last decade and it is expected to grow significantly by 2050. The Transforming Energy Scenario from IRENA expects global demand to grow from current levels of about 100 Mt per an-num to 500 Mt per annum in 2050 (IRENA 2021). The methanol-to-olefins/methanol-to-aromatics segment is expected to grow more quickly, with most of the demand coming from China (IEA 2019). Demand could be further driven by the use of methanol as a fuel and as an energy carrier for the transmission, distribution, and storage of hydrogen.

Methanol (MeOH) is conventionally produced from synthesis gas (syngas), which is essentially obtained from the reforming or partial oxidation of any fossil carbon source. The process is industrially proven and large-scale methanol plants with capacities of up to 1,000 kt per annum are in operation worldwide on the basis of coal-to-liquid (35% mainly in Asia) or gas-to-liquid (GtL, 65% mainly in the Middle East) technologies (IRENA 2021; Zelt et al. 2021). However, methanol can also be produced using renewable energies: either from biomass (so-called bio-methanol) or from electricity from renewable sources, such as wind, solar or hydro power (so-called green e-methanol) (IRENA 2021). While conventional methanol is produced using syngas, green e-methanol uses CO_2 as a feedstock. There are several ways of producing e-methanol using CO_2, but the simplest and most mature pathway is via the hydrogenation of CO_2, where hydrogen is reacted with CO_2 (Vesterinen 2018). Hydrogen can be produced via electrolysis using renewable electricity and CO_2 can either be captured from point sources (e.g. industrial sources) or from the atmosphere via direct air capture technology (DAC) (Methanol Institute 2018). For methanol to be carbon-neutral, the CO_2 must come from renewable sources – either directly from the atmosphere or indirectly from biomass. Another possible pathway is to produce syngas from CO and H_2 through co-electrolysis, followed by the conversion of the syngas to e-methanol (as in conventional methanol production) (IRENA 2021). A direct methanol synthesis pathway from CO_2 is also under development but has so far only been tested at laboratory scale (Zelt et al. 2021). It should be noted that methanol synthesis can usually be combined with other process steps, such as hydrogen electrolysis, which optimises the combination of heat sources and sinks (ibid.) and achieves better efficiencies.

Tunisia imports methanol. Over the last ten years, Tunisia imported between 500 tonnes and 1,500 tonnes of methanol per annum (Fig. 5.12).

The import volumes increased significantly after 2011 and have since fallen back to pre-2011 levels. The main suppliers in 2018 were Spain, France, the Netherlands, and Belgium. In previous years, Saudi Arabia, Egypt, and the United Arab Emirates were among the main suppliers of methanol (WITS 2021). Overall, Tunisia has imported methanol from many different countries over the years, showing that methanol is not supplied under long-term contracts but is rather sourced based on market price and demand.



(Source: Data from FAO 2020)

Fig. 5.12 **Methanol imports for Tunisia (in tonnes per annum)**

Compared to the worldwide demand for methanol, which is currently about 100Mt per annum, the quantities imported by Tunisia are low. In an optimistic scenario domestic demand could reach about 5,000 tonnes per annum by 2050 (Growth scenario) (Fig. 5.13). This equates to the volume of methanol produced by the largest renewables-based CO_2-methanol plant in operation worldwide, the «George Olah Plant» in Iceland. Conventional methanol production is done at very large scale in around only 90 industrial plants worldwide (Methanol Institute 2021) and, in comparison, the capacity of the "George Olah Plant» is still very low. With the growth in green methanol demand and production, it is assumed that economies of scale will enable green methanol plant sizes to increase. The Port of Rotterdam, for example, has already launched a project with industrial partners that aims to produce 220,000 tonnes of bio-methanol per annum from waste (Zelt et al. 2021). Against this background, it is questionable whether green methanol production would be a viable option for Tunisia due to its limited domestic demand. If green e-methanol production were to be established in Tunisia, its production would have to be directed at the export market, assuming no further industry with substantial methanol demand were established in Tunisia. With demand for green methanol expected to increase in industrialised countries worldwide and in Europe (in light of the EU target of climate-neutrality by 2050), an export strategy could nevertheless have potential based on the low-cost availability of renewable electricity in Tunisia.

Based on the current situation and an assumed demand for green e-methanol, three scenarios for methanol demand and potential green e-methanol production in Tunisia have been developed. The BAU scenario foresees demand for methanol growing slowly in Tunisia in line with economic and industrial development in the country but assumes no domestic production of green e-methanol. The Growth scenario (Growth) foresees a larger increase in demand for methanol in Tunisia. Assuming (despite the recent decline) that methanol demand in Tunisia develops in parallel with global demand at an annual growth rate of 3.6% (IEA 2019), domestic demand could reach about 5,000 tonnes per year by 2050 in an optimistic scenario. A green e-methanol plant with a capacity of 5,000 tonnes per year is assumed to be built by 2040 to meet domestic demand as part of the decarbonisation efforts in the industrial production in Tunisia. The Export scenario (Export) foresees the potential export of methanol (Fig. 5.13), presuming that first a smaller CO_2-methanol plant with a capacity of 5,000 tonnes per annum (similar in size to the plant in Iceland) would be established. Based on experience gained by 2040, a further renewables-based e-methanol plant with a capacity of 50,000 tonnes would be built to export green methanol. The feasibility of such a development, however, would have to be analysed based on a concrete project proposal.

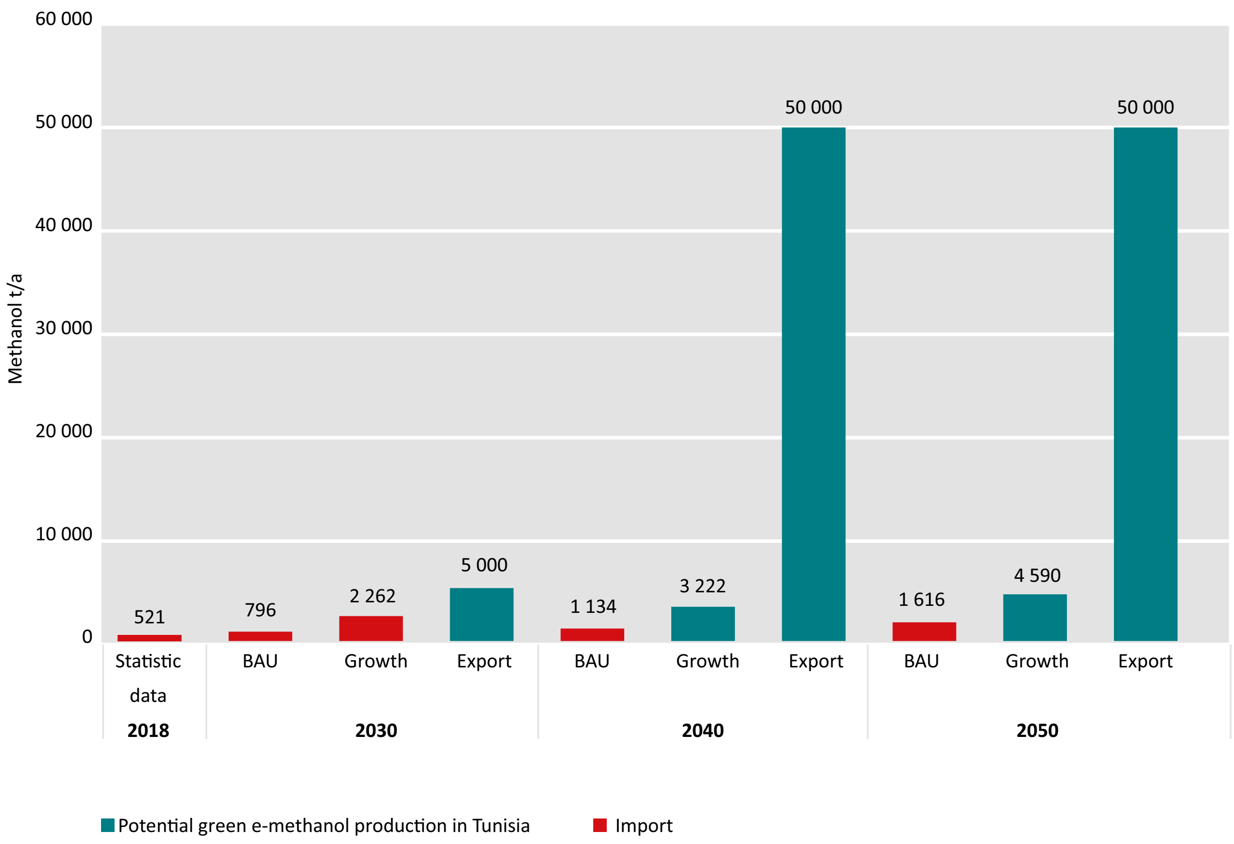


Fig. 5.13 **Green e-methanol demand and production scenarios for Tunisia (in tonnes per annum)**

To produce methanol under the different scenarios would require between 40 GWh and 625 GWh of renewable electricity (Fig. 5.14). Renewable capacities would have to be increased accordingly in Tunisia for the production of green e-methanol.

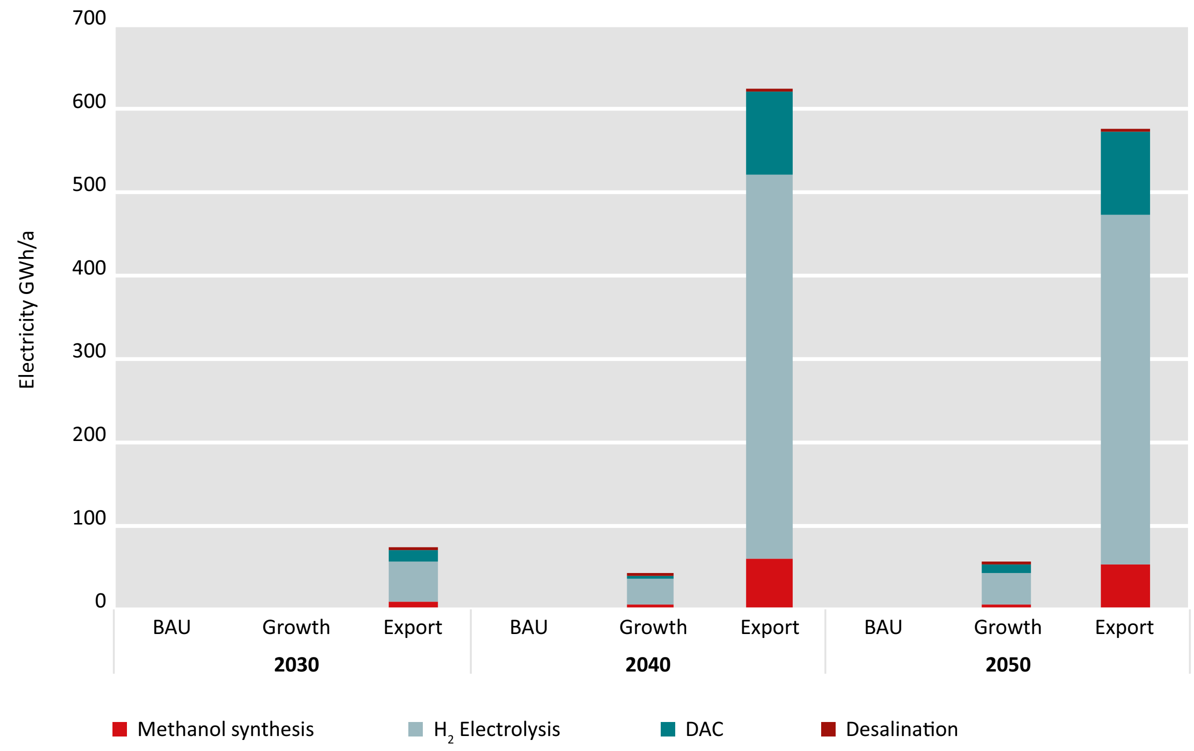


Fig. 5.14 Renewable electricity demand for methanol demand/production scenarios for Tunisia (in GWh per annum)

Furthermore, CO_2 would be required, either in the transition phase captured from point sources (e.g., cement production) or directly or indirectly captured from the atmosphere. As the biomass potential for the generation of CO_2 is limited in Tunisia, in the long-term CO_2 would have to be obtained via direct air capture (DAC) technologies for the e-methanol to be renewable and sustainable. DAC technologies have been developed and commercialised by companies such as Climeworks (Switzerland), Global Thermostat (USA), and Hydrocell (Finland) (Zelt et al. 2021). The advantage of DAC plants is they can be located anywhere, as air offers an almost endless source of sustainable CO_2 (IRENA 2021). However, from an economic perspective, but also for technological reasons, existing designs are still far from large-scale implementation and are likely to rely on market incentive programmes to mature into competitive products (Zelt et al. 2021). Therefore, conservative assumptions predict that DAC is unlikely to be commercially available on a large scale before 2030 (ibid.). Due to its high investment and generation costs, the production of green e-methanol in Tunisia would only make sense if a market for highly priced green e-methanol developed due to global decarbonisation efforts.

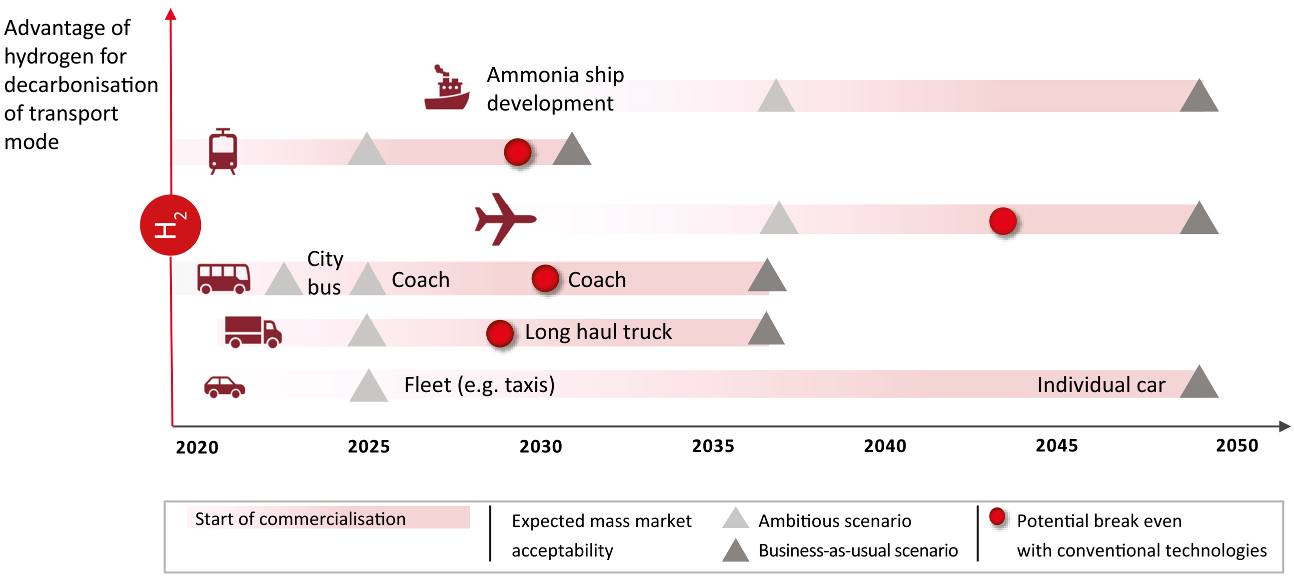
5.4.5 High temperature heat

Heat accounts for a large share of industrial energy demand and fossil fuels are the main source of heat generation in the industrial sector. For lower to medium temperatures (<400°C), the direct use of solar thermal energy can be a viable solution, especially in countries like Tunisia with high solar radiation.

Furthermore, several research and development projects are currently investigating the use of concentrated solar power to generate high temperature process heat, which could become an interesting option for countries such as Tunisia. Hydrogen could also be an option for generating the high temperature heat needed for certain industrial applications including smelting, gasification, and drying (IEA 2019). In the cement industry, for example, high temperatures are necessary to produce clinker; in the metal industry, high temperatures are needed for melting purposes; and the glass and ceramics industries need high temperatures in their furnaces. In theory, green hydrogen could be used as a heat source to replace fossil fuels in these sectors; however, this application of hydrogen is almost non-existent (IEA 2019) because hydrogen cannot easily replace fossil fuels in most sectors, due to the specific processes and special properties of hydrogen (e.g., high combustion velocity, low radiative heat transfer, corrosivity, and special storage conditions) (ibid.). Consequently, the use of hydrogen would require a change in processes and the modification of production systems, which would entail considerable investment. In most cases, this would be technologically and economically unviable (FCH 2 JU 2019). Accordingly, there does not appear to be the potential for hydrogen to be used to generate high temperature heat in Tunisia in the short to medium term. In the long term, technological development could provide opportunities, especially in terms of the construction of new industrial plants. These potential opportunities would have to be investigated and evaluated in comparison to direct heat generation from solar power in detail at a later stage.

5.5 POWER-TO-X OPPORTUNITIES IN THE TRANSPORT SECTOR

Outside the industry sector, the use of hydrogen and hydrogen-based fuels could also play an important role in decarbonising the transport sector. Theoretically, means of transport including cars, buses, trucks, ships, and aircrafts could in future be directly or indirectly powered by hydrogen (IEA 2019). Hydrogen has actually already been discussed for quite some time as fuel for road transport in form of fuel cell electric vehicles (FCEVs). Furthermore, hydrogen can be converted to methane, methanol, and ammonia, which can be used directly as fuel or further converted and upgraded into synthetic diesel, gasoline, or kerosene. Synthetic fuels are technically no different from their conventional counterparts and can, therefore, be used directly in combustion engines without the requirement of technology change for the end-user or new infrastructure. These technologies are not yet cost competitive with conventional fuels and the technology-readiness levels still vary between the different applications. But many of the technologies are expected to be ready for commercial applications by 2030 (Fig. 5.15). FCEVs in the form of light-duty vehicles are already commercially available and heavy-duty vehicles, like trucks and buses, have also been successfully tested, with China leading the way in actual and planned deployment.



(Source: Based on FCH 2 JU 2019; Hydrogen Council 2021 and 2017)

Fig. 5.15 Horizon for the commercial deployment of PtX for different modes of transport

In the maritime, rail, and aviation sectors, some small demonstration projects are under implementation (IEA 2019). However, although light-duty FCEVs are commercially available, they require around double the energy input compared to direct electrification via batteries (Agora 2017). Synthetic fuels based on renewables (which have the advantage of being able to use the existing end-user appliances and infra-structure) demonstrate even lower efficiency levels compared with the direct use of electricity in battery-electric vehicles (BEVs), requiring five to seven times more electricity (ibid.). Therefore, direct electrification in the form of battery electric vehicles

(BEVs) has significant advantages over FCEVs and synthetic fuels and should be prioritised for passenger cars and vans wherever possible. However, in the long-haul and heavy-duty transport sector, as well as for long-distance buses and trains, the use of hydrogen has several advantages over battery vehicles. These advantages include larger ranges, shorter refuelling times, and hydrogen's higher energy density requiring smaller storage tanks. Consequently, FCEVs are the better solution for decarbonising these modes of transport (FCH 2 JU 2019). For aircraft and freight ships, synthetic fuels are seen by many researchers as the only current feasible decarbonisation option, although in the long-term hydrogen-powered aviation could become an option for short to medium range flights (FCH 2 JU 2020). Overall, the theoretical potential for the future use of hydrogen and fuels based on hydrogen in the transport sector is promising: the question is what role could green hydrogen and hydrogen-based fuels play in improving the sustainability of the transport sector in Tunisia?

The transport sector in Tunisia accounts for about 26% of Tunisia's CO_2 emissions of the energy sector (ANME 2019) and for about 31% of national energy consumption (ONE 2019). Economic development is expected to drive up the rate of motorisation, and passenger and freight transport kilometres are expected to increase. The sector already plays a key role in the economic development of the country, with shipping and air transport lines being essential for trade and tourism. With its favourable geographic position in the centre of the Mediterranean and close to major shipping routes, the transport sector is also expected to play a vital role in future economic growth. Accordingly, the Tunisian government has established an ambitious transport roadmap to 2040, with investments of US$22 billion for projects in rail, road, and air transport (TMO 2019). The aim is to improve efficiency and effectiveness in the transport sector, as well as its sustainability. Green hydrogen and synthetic fuels could become a future option for sustainable transport in Tunisia, but the technology is not currently cost competitive with conventional fuels. Major support structures, incentives mechanisms, and regulations would be required to make these fuels competitive.

The transport sector segments in Tunisia that could be suitable for the introduction of green hydrogen and synthetic fuels based on green hydrogen are aviation, maritime traffic, rail transport, and heavy-duty vehicles such as coaches and trucks. Aviation and maritime traffic could be possibilities due to their international orientation and integration in global climate protection efforts. Rail transport could be an interesting option due to planned investments in the coming years that could allow for innovative low carbon technology to be implemented instead of investing in fossil fuel technologies, which could create lock-in effects and potential stranded investments. Coaches and trucks travelling long distances could benefit from PtX solutions as it offers several advantages for decarbonising these segments compared to direct electrification. Fig 5.16 gives an overview of the status and potential opportunities in the transport sector in Tunisia, which are briefly discussed in the following sections.

	PtX applications	Development status	Long-term development potential Tunisia
Aviation	• PtL (jet fuel) production via Fischer-Tropsch or methanol synthesis • Hydrogen planes	Feasibility studies, research and pilot projects planned	Decarbonisation efforts of aviation industry and potentially increasing costs to offset emissions for flights to and from Tunisia could create interest to produce PtL in Tunisia.
Maritime transport	• Ammonia as fuel • Hydrogen ships	Research and pilot projects. Companies expect ammonia-fuelled ships to come on the market before 2030.	IMO and EU efforts to decarbonise shipping, could create potential demand for ammonia as fuel e.g. for shipping from Tunisia. Potential to use existing infrastructure for handling ammonia at Gabés port to be explored.
Rail transport	• Hydrogen trains • PtL as drop-in fuel for diesel locomotives	First hydrogen trains running in a number of countries. Several companies working on bringing trains on the market.	Only a small share of tracks electrified. Hydrogen trains as alternative on long-distance freight lines to decarbonize the rail sector. Chance to focus current investments in the rail sector on green technology to avoid technological lock-in effects.
Road transport	• FCEVs cars • FCEVs trucks • FCEVs buses • PtL as drop in fuels	Light-duty FCEVs commercially available. Heavy-duty FCEVs several demonstration projects and growing demand	Highest potential for heavy-duty vehicles in dedicated fleets, with high daily milage on fixed routes and centralised refuelling. National bus service could be potential segment to drive an early uptake with government support.

Fig. 5.16 Overview of Power-to-X opportunities in the transport sector in Tunisia

5.5.1 Aviation

Tunisia has nine airports and a small number of airfields and airstrips. International flights constitute most of Tunisia’s air traffic. In 2018, an all-time high of 9.4 million tourists visited Tunisia, of which a large share arrived by air, which made the country one of the fastest-growing air markets in Africa (World Bank 2021; OBG 2017). And these numbers were expected to increase until the impact of the COVID 19 pandemic. On a global level, international air traffic was growing by 6.2% annually and was expected to double by the middle of the century before the COVID19 pandemic hit (IEA 2020b). Although currently air traffic is significantly reduced due to the pandemic and longer-term effects on aviation cannot be ruled out, general expectations are that air traffic will resume and, albeit with some delay, growth is expected to pick up again.

The aviation sector is strongly internationalised, interconnected, and widely standardised. Accordingly, the targets for reducing the industry’s CO_2 emissions set by the International Air Transport Association (IATA), whose members represent 82% of global air traffic, are relevant for Tunisia – especially as the two major Tunisian airlines, Tunisair and Nouvelair, are members of IATA. The targets include a cap on net aviation CO_2 emissions from 2020 (carbon neutral growth) and a reduction in net aviation CO_2 emissions of 50% by 2050 (relative to 2005 levels) (IATA 2020). Renewable-based energy carriers are an essential pillar for reaching these targets.

Based on these targets, the carbon offsetting and reduction scheme for international aviation (CORSIA) was introduced in 2016 as a market-based measure. The CORSIA obligations came into force in 2019, with a pilot phase in place from 2021 until 2026.

Since January 2021, flights between states that volunteer to participate are subject to offsetting requirements (IATA 2020). From 2027, the intention is to offset all international flights operated by member states of the International Civil Aviation Organization (ICAO). Tunisia is a member state of the IAOC and has already volunteered to participate in the pilot phase. This means that, in future, airlines flying to and from Tunisia will be required to offset their emissions. With carbon prices expected to significantly increase, this could result in a growing interest in sustainable aviation fuels (SAF), such as synthetic fuels based on hydrogen produced using renewable electricity. Synthetic fuels that are drop-in capable, which means they can be distributed and used within existing technology, are expected to play a particularly important role (Schmidt et al. 2018) as the long lifetimes of aircrafts, engine technologies, and infrastructure make the introduction of new technologies challenging in the short term (Scheelhaase et al. 2019).

Tunisia currently imports nearly all its kerosene. In 2018, Tunisia imported 284,000 tonnes of kerosene-type jet fuel, which is stored in international aviation bunkers. The import and storage amounts vary, but have stayed within a range of 200,000 to 300,000 tonnes over the last twenty years (Fig. 5.17).

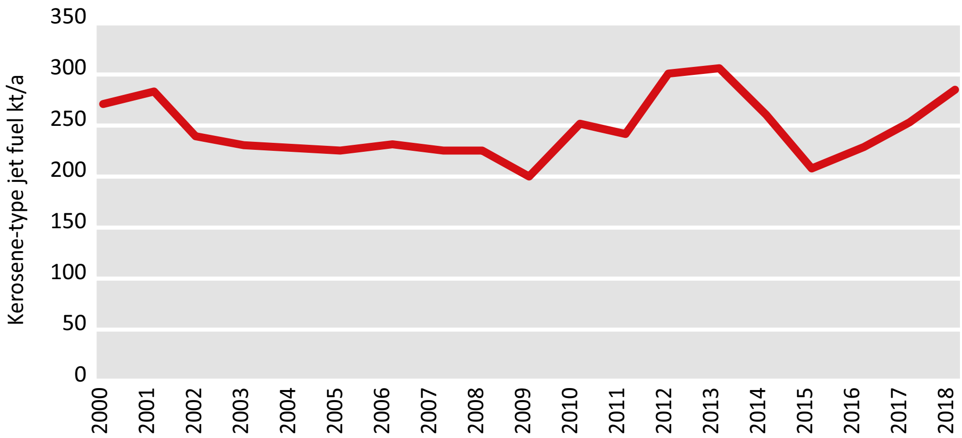


Fig. 5.17 **Import of kerosene-type jet fuel in Tunisia 2000-2018 (in tonnes)**

Therefore, in the medium to long term an option could be to investigate the opportunities for jet fuel production based on renewable electricity in Tunisia. However, it should be noted that at current production prices, renewable energy-based kerosene is expected to be 4 to 6 times more expensive than conventional kerosene. In the long term, technological advances are expected to reduce this difference to about 1.5 to 2 (IEA 2019). Therefore, any introduction of renewable electricity-based kerosene would have to be accompanied by financial incentives or other supporting measures, either at policy level or aviation industry level. Furthermore, although technology for producing such electricity-based fuels has been tested, these fuels have not yet been produced on an industrial scale. The German Aerospace Centre (DLR), supported by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), has recently (in 2021) commissioned a pilot plant to produce electricity-based renewable kerosene for aviation (DLR 2021). Another project is taking place in Norway, where a consortium of industry partners is planning the construction of Europe's first commercial plant for hydrogen-based renewable aviation fuel (Sunfire 2020). Various airlines have shown interest in kerosene produced using renewable electricity: for example, in 2019, Lufthansa signed a joint declaration of intent with the refinery Heide in Germany for the future production and acceptance of electricity-based kerosene.

From the technical side there are two principal pathways for producing renewable jet fuel: Fischer-Tropsch synthesis and methanol synthesis. Renewable electricity, water, and carbon dioxide (CO_2) are the main inputs in both pathways. Fischer-Tropsch synthesis is a process for CO polymerisation and hydrogenation, producing long-chain hydrocarbons from carbon monoxide and hydrogen (Zelt et al. 2021). The main product, a synthetic oil (also known as «Syncrude»), needs further upgrading in the form of hydrocracking, isomerisation, and distillation for use as jet fuel (Schmidt et al. 2016). Only about half of the output from Fischer-Tropsch synthesis can be used in the production of jet fuel (ibid.). The technology-readiness level of Fischer-Tropsch synthesis and subsequent refining processes is currently estimated to be between five and seven on a nine-point scale (Zelt et al. 2021). Some of the components are already deployable, but there are no commercial plants of industrial size. However, it seems plausible that, with intensive development, commercial plants of industrial size could be available by 2030 (ibid.). On the end-user side, Fischer-Tropsch synthetic paraffinic kerosene has already been approved for up to 50% use in jet fuel blends (Schmidt et al. 2016).

An alternative pathway for the production of jet fuel is via the intermediate product methanol (Schmidt et al. 2016). Methanol can also be produced using renewable en-ergy (see also section 5.3.4). To produce jet fuel from methanol, several conversion and upgrading steps are necessary. These include DME synthesis, olefin synthesis, oligomerisation, and hydrotreating (Schmidt et al. 2016). The methanol-to-kerosene process is still being developed, with a current technology-readiness level of between 5 and 6. On the end-user side, kerosene derived via the methanol pathway has not yet been approved for use in commercial aviation but it is expected to have similar characteristics to Fischer-Tropsch-derived products (EASA 2019).

The electricity demand for producing a unit of jet fuel is about the same for both pathways, meaning that if jet fuel from renewable electricity were produced in the future in Tunisia, the electricity demand would be comparable for both technologies. The efficiencies of the two pathways depend heavily on how heat from syntheses can be reused in other processes, such as electrolysis or CO_2 provision (Schmidt et al. 2016).

Fig. 5.18 shows how jet fuel demand could develop according to three scenarios. Overall, it is assumed that demand for jet fuel in Tunisia will increase in the long term, as air travel and transport are expected to grow, albeit with some delays, af-ter the COVID 19 pandemic. As the technology is still under development, it is assumed that until 2030 green kerosene would at best only be produced by a large pilot plant in Tunisia.

After 2030, the BAU scenario shows only a slight increase in demand in relation to pre-COVID 19 pandemic levels. The growth scenario (Growth) assumes that air traffic in Tunisia will double by 2050. This assumption is based on different forecasts for air traffic, which foresee a growth rate between 3.4 to 6.2% for the Middle East and Africa (ICAO 2018). The growth of the Tunisian aviation sector leads to an increase in demand for aviation fuel with an average annual growth rate of 2.4 %, so that demand roughly doubles from 2018 to 2050. A third scenario, the Export scenario (Export), foresees Tunisia exporting green kerosene by 2050 as well as meeting domestic demand. In all three scenarios, green kerosene gradually replaces conventional kerosene in aviation in Tunisia. Until 2040, it is assumed that a blend of only 50% green kerosene is allowed in jet fuels, meaning the remaining 50% (in the form of conventional kerosene-type jet fuel) must be imported. It is assumed that by 2050, 100% of kerosene would be produced using renewable energy in Tunisia. The faster or slower adoption of renewable-based kerosene would accordingly result in higher or lower electricity demand in the given years.

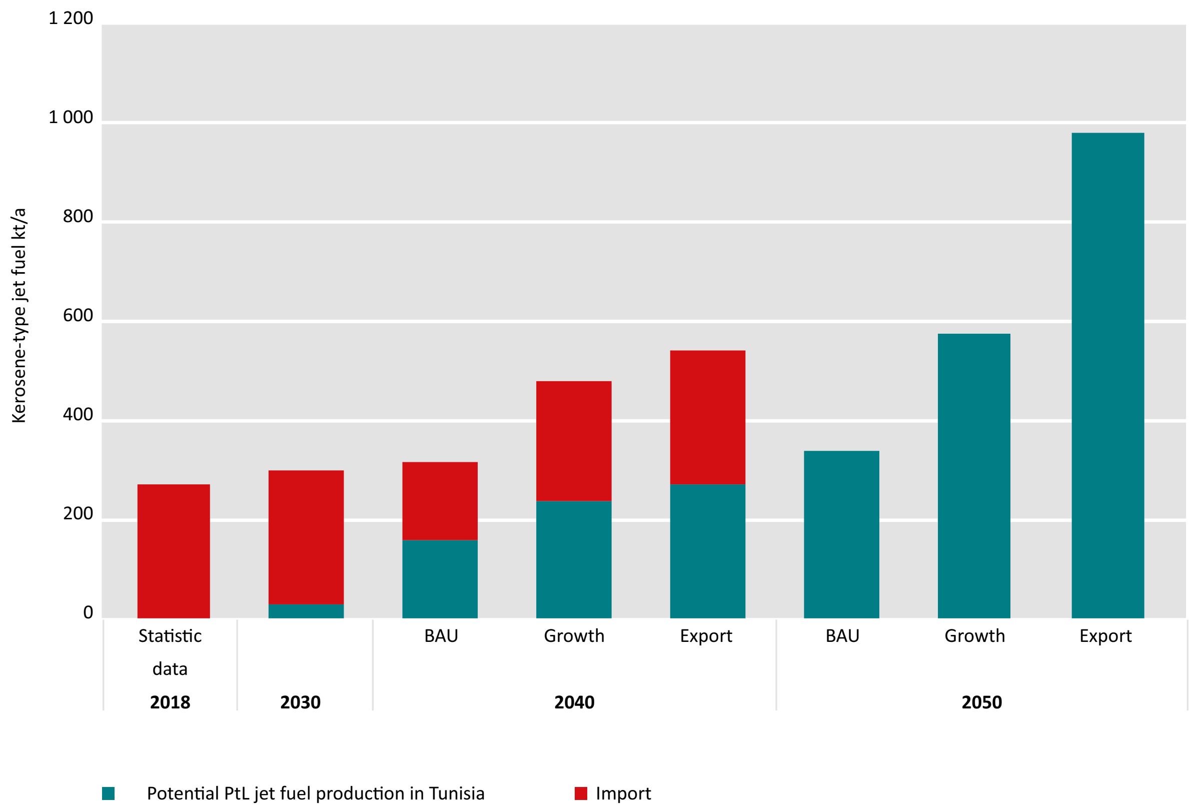
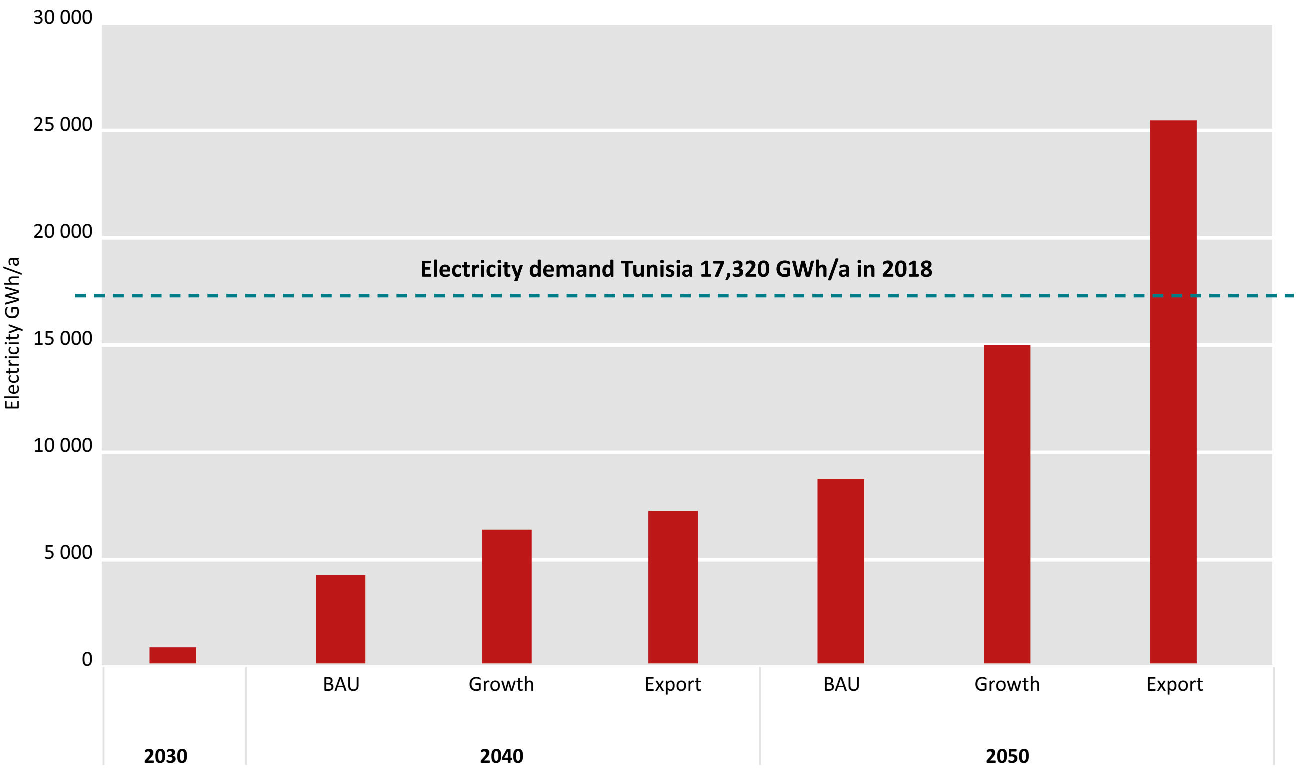


Fig. 5.18 **Renewable PtL jet fuel demand and production scenarios for Tunisia (in tonnes per annum)**

Electricity demand associated with the different development pathways for Power-to-Liquid (PtL) fuel production is displayed in Fig. 5.19. Demand for renewable electricity would start to increase after 2030 as the production of PtL would become more mature and could be applied on an industrial scale. Prior to this, smaller-scale production in the form of a pilot project is assumed. To meet 100% of the modelled kerosene-type jet fuel demand in Tunisia in 2050, between about 9,000 GWh and 25,000 GWh would be required by 2050 depending on the scenario (Fig. 5.19).

The investments necessary for building renewable capacities and synthesis capacities would include investment in renewable energy capacities, electrolysis, synthesis plants, and desalination. The expansion of renewable electricity generation is expected to account for the major share of the costs.



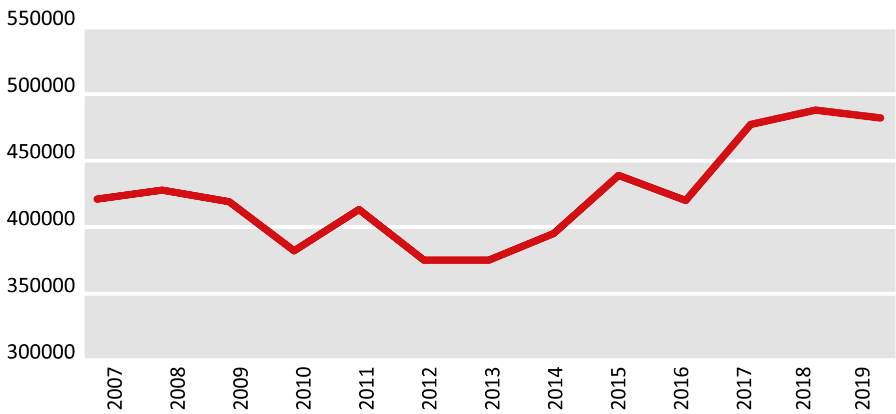
(Source: Wuppertal Institut)

Fig. 5.19 **Potential renewable electricity demand for PtL jet fuel production in Tunisia for different scenarios (in GWh per annum)**

5.5.2 Maritime transport

Hydrogen-based fuels could also offer advantages for long-distance shipping, where it is more difficult to use either hydrogen or electricity. The maritime sector currently accounts for around 5% of global oil demand. Most of the fuel (80%) is used in international shipping, of which 90% is used for freight transport (IEA 2019). Based on the targets adopted in 2018 by the International Maritime Organisation (IMO) to cut international shipping's annual greenhouse gas emissions by at least 50% by 2050 (compared to 2008 levels) and to reduce the carbon intensity of international shipping by 40% by 2030, the shipping industry is looking for alternatives to cut fossil fuel use in ocean-going vessels. Ammonia is attracting particular interest in the shipping industry as a potential alternative fuel. To date, however, the use of hydrogen-based fuels, including ammonia, in shipping has been limited to research and demonstration projects. Industry stakeholders expect that ongoing engine development by different companies will enable the use of ammonia in conventional marine engines as early as 2023 (Stevens 2020). However, cost is – and will remain – a major barrier, especially as fuel costs are a key factor in shipping. Furthermore, hydrogen and ammonia both have a lower energy density and would need larger storage space, resulting in reduced cargo volume. Therefore, it seems unlikely that a switch to low carbon fuels would occur in the absence of policy support, whether through regulations or carbon pricing (IEA 2019). The EU is moving ahead with its plans to include shipping in the EU Emissions Trading System (ETS): certain issues have not yet been finalised, but the necessary legislation could come into force as early as 1 January 2022 (Lexology 2020).

As the EU is one of Tunisia's major trading partners, this legislation could affect shipping to and from Tunisia, especially as Tunisia conducts 90% of its foreign trade by sea (OBG 2017). Tunisia has an extensive network of maritime infrastructure, with two container ports in Tunis and Sfax and seven smaller, specialised commercial ports (ibid.). Overall global freight shipping is expected to significantly increase by around 45% by 2030 and more than triple by 2050 (IEA 2019). This global trend is reflected in the container traffic at Tunisia's ports, as shown in Fig. 5.20.



(Source: UNCTAD 2020)

Fig. 5.20 **Tunisia container port traffic 2007-2019 (in TEU: 20-foot equivalent units)**

However, although maritime transport is growing, Tunisian ports are becoming a bottleneck for the Tunisian economy as they are saturated and suffer from a lack of adequate equipment and infrastructure, as well as a lack of appropriate support services (Morsy et al. 2018).

The commercial port of Gabès could be a starting point for investigating the future opportunities that could arise from producing ammonia for use as shipping fuel. The port already handles ammonia imports and the infrastructure could be used to handle ammonia as a shipping fuel or to export ammonia as an energy resource, as discussed in the industry section of this report. If ammonia or other PtX fuels are to be produced and exported by sea from Tunisia in the long term (not only via pipeline), also the carbon footprint of maritime transport would need to be reduced. In order to determine whether supplying ammonia as a fuel for maritime transport in Tunisian ports could become an interesting development option, more detailed analysis would be required. It would, for example, be important to assess whether existing infrastructure could be used and what adaptations (like bunkering facilities) would be required to handle ammonia as a shipping fuel. Furthermore, information about the types of ships that frequent the port and how much fuel they use should be collected and analysed. Analysis of the main shipping routes would also be opportune to determine whether potential carbon pricing mechanisms, resulting in demand for low emissions shipping, would apply in the future.

5.5.3 Rail

Globally, rail is the most electrified mode of transport. However, in Tunisia only small sections of the railway are electrified. The passenger and freight networks cover 2,165 km across 23 lines, of which 90 km are electrified (65 km from Sousse to Mahdia and 25 km from Tunis to Borj Cédria) (SNCFT 2021). Tunisia has about 140 diesel powered locomotives in operation (Medstat 2020).

Electrification via overhead lines would require large infrastructure investments, which are usually only viable for high-traffic routes (Zenith et al. 2019). However, there are other options for replacing diesel-powered locomotives and decarbonising rail transport. These include battery-powered trains and hydrogen fuel cell trains (IEA 2019). On low-traffic routes, electrification by battery or hydrogen offers an alternative to track electrification. While battery-powered trains use significantly less energy than hydrogen trains, the latter have the advantage of being able to travel long distances without recharging (up to 800 km) and the refuelling time is comparable to that of diesel engines. This makes them particularly suitable for long and low-traffic routes. However, additional investment for the production and storage of hydrogen would be required.

Several countries, including Germany, have already successfully tested hydrogen trains and others are planning to introduce such trains in the near future. Currently, at least three companies (e.g., Alstom) are developing and manufacturing hydrogen trains (IEA 2019) and, in California, a first electric freight train is being tested (BNSF 2019). However, although the first trains are commercially available, mass market adoption is not expected before 2025 and, in a business-as-usual scenario, only after 2030 (FCH 2 JU 2019). Depending on the circumstances, however, hydrogen trains can be cost competitive with trains running on electric overhead lines (Hydrogen Council 2020). This applies for long distances and long trains; conditions that are mainly found in rail freight transport (Zenith et al. 2019). In Tunisia, these conditions apply for instance to the long freight routes from the interior to the coast and from the south to the north (Fig. 5.21), along which goods such as phosphate, fertiliser, sulphur, building materials, foodstuffs, petroleum coke, and containers are transported (SNCFT 2021). In view of the planned investments in Tunisia's rail sector, it could be advisable to consider hydrogen train options for long-distance freight transport to avoid technological lock-in effects resulting from the extension of the rail fleet based on diesel engine trains. In the best-case scenario, imported refined oil products could be replaced by locally produced renewable fuels in rail freight transport in Tunisia. At the very least, the possibility of retrofitting diesel locomotives to run on hydrogen at a later date should be considered in the procurement process. Under optimistic assumptions about cost reductions for fuel cells, hydrogen trains could also become competitive in the future for low-traffic passenger rail transport; for example, in suburban and rural areas (IEA, 2019b).

(Source: Lowside 2018)

Fig. 5.21 Tunisia’s rail network

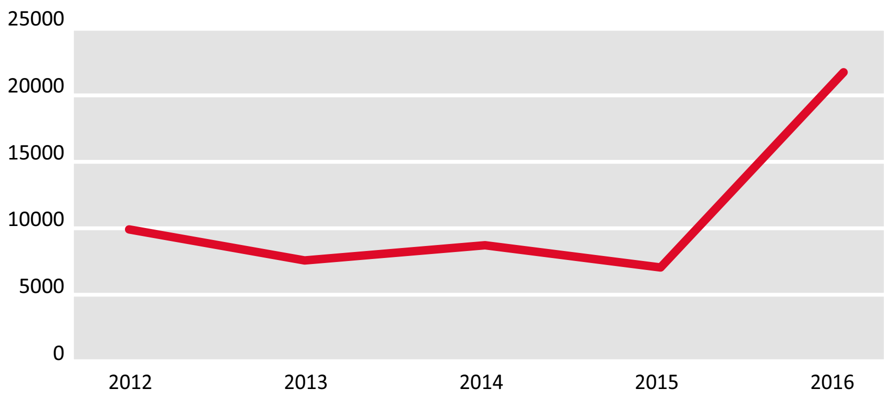
5.5.4 Road transport

Good potential for PtX applications in the road transport sector emerges when considering the commercial availability of fuel cell vehicles (FCEVs) and the drop-in quality of PtX fuels for existing vehicle fleets, as well as the need for additional efforts to reduce greenhouse gas emissions in road transport. In an ambitious scenario, mass market acceptability for FCEVs is foreseen for cars, buses, coaches and trucks as early as 2025 (FCH 2 JU 2019). Currently, over 12,000 cars globally run on hydrogen fuel – but this is marginal compared to the global fleet size. For light-duty vehicles, direct electrification is more efficient than FCEVs, but even more so compared to vehicles running on synthetic fuels. Consequently, direct electrification should be prioritised for passenger cars and vans. However, in the long-haul and heavy-duty transport sector, and for buses and coaches, the use of hydrogen has several advantages compared to battery vehicles. These advantages include larger ranges, shorter refuelling times and the higher energy density of hydrogen. FCEVs are, therefore, the better solution for decarbonising these modes of transport (FCH 2 JU 2019).

In terms of buses and coaches, the number of fuel cell electric buses is growing worldwide, especially in China, and such vehicles have been developed by at least 11 companies (IEA 2019). However, compared to BEVs (which are expected to account for over 65% of the global bus fleet), FCEVs are expected to play only a limited role with a share of about 6.5% in the bus sector (BloombergNEF 2019). FCEVs are, nevertheless, particularly suitable for bus routes with high daily mileage, larger bus fleets, and where flexibility in operation is required. The Tunisian national bus service (Société Nationale du Transport Rural et Interurbain - SNTRI), which operates about 121 coaches from Tunis to nearly every other town in the country, would be a suitable sector for the introduction of hydrogen-fuelled coaches. However, these vehicles are not yet cost competitive with conventionally-fuelled coaches and, consequently, their introduction in other countries has been widely fostered by government-supported initiatives (IEA 2019). As the SNTRI is a state-owned company subsidised by the state, this could be a segment with the potential to drive the early up-take of FCEVs – for example, when old vehicles need to be replaced. This would, of course, require political decisions and financial support. Although it is anticipated that, by 2030, for longer distances, buses and coaches running on hydrogen will achieve cost parity with buses running on conventional fuels (Hydrogen Council 2020), additional investments to set up the infrastructure and establish hydrogen production in Tunisia would still be required.

Hydrogen-fuelled trucks are also not yet cost competitive with conventional trucks, and Tunisia does not yet have the necessary refuelling infrastructure. However, depending on the price evolution for green hydrogen, medium and heavy-duty FCEVs could become cost comparable with conventional trucks even before 2030. An analysis of the costs to decarbonise freight transport suggests that fuel cell trucks are the lowest-cost option for the medium and heavy-duty segments (Hydrogen Council 2020). This will strongly depend on the development of vehicle costs, fuel costs, and the availability of refuelling stations. The most likely segment to adopt hydrogen trucks would be a dedicated fleet operating on fixed routes that could refuel at a single centralised hydrogen refuelling station; for example, at ports to which the trucks deliver their goods (IEA 2019).

Fostering the introduction of heavy-duty FCEVs could be an option for Tunisia to reduce emissions and, at the same time, replace imported refined oil products by a locally produced clean and green energy source. Particularly, as being an emerging economy the demand for transport services in the country is expected to increase. Road transport is currently already the main mode of freight transport in Tunisia accounting for around 75% (Abbes and Bulteau 2018). The number of vehicles has already more than doubled since 2012 (Fig. 5.22). Freight transport is therewith responsible for a large share of the rise of fossil fuel demand, and CO_2 emissions (Mraïh et al. 2014). Against this backdrop, road freight transport should be seen as an important field of action for reducing CO_2 emissions in Tunisia.



(Source: based on data from INS 2020)

Fig. 5.22 **Number of new medium and heavy-duty vehicle registrations in Tunisia per annum**

5.6 POWER-TO-X OPPORTUNITIES IN THE ELECTRICITY AND GAS SECTORS

As the share of intermittent renewables in the electricity mix increases, the challenges of balancing supply and demand will intensify. A high share of renewables requires flexibility options to ensure the stability of the grid and the power supply. This is because a temporal mismatch between electricity supply and demand can occur in the short term between day and night, as well as seasonally (e.g., between summer and winter). Spatial mismatches between supply and demand can also be a concern. With increasing shares of renewables in the electricity mix, peak generation – if it is not to be curtailed – must either be stored and reused as electricity or converted into other energy carriers, such as gases and liquid fuels, to be used in other sectors (Kober et al. 2019). Likewise, to meet the demand peaks, flexibility and storage options will become increasingly important.

Converting electricity into hydrogen is considered to be one option to help offset these mismatches by increasing the flexibility of the power system. Other options include for example pumped storage, batteries, grid expansion, and cross-border trading (IEA 2019). In concrete terms, PtX technologies can support the power grid in two ways: a) by balancing supply and demand by managing surplus electricity generated from non-dispatchable fluctuating renewable electricity sources; and b) by providing ancillary services to stabilise the grid frequency (Kober et al. 2019). In theory, converting «surplus» renewable electricity into hydrogen and re-electrification would allow energy to be stored and used at times when it is most needed, rather than when it is produced, thus balancing energy supply and demand.

Hydrogen can also be injected into existing natural gas pipeline networks, either directly or through conversion into green synthetic natural gas (SNG). The amount of hydrogen that can be added into the natural gas network depends on the characteristics of the existing network, the composition of the natural gas, and the end-use applications (IRENA 2018). It is currently assumed that a share of up to 20% hydrogen would not require any technical adjustments to the natural gas transmission and distribution infrastructure. However, end-use applications are more sensitive and often only allow for a lesser share of hydrogen in the mix. Accordingly, many countries have adopted a cap of between 2% and 6% on natural gas blending (IEA 2019). In Germany, a maximum of 10% is possible, but various restrictions apply (ibid). Higher shares or pure hydrogen storage, transmission, and application would require modifications to the existing infrastructure, or the construction of new infrastructure, which would require significant investment. Green SNG, on the other hand, could be fed into the grid without limitations. The conversion from hydrogen to methane (SNG) in a methanation reactor requires the addition of CO_2. With a current process efficiency of about 70% (Zelt et al. 2021), energy is lost during the transformation. Both factors add to the cost of generating methane, making green SNG more expensive than the direct use of hydrogen.

In Tunisia, the balancing of both temporal and spatial mismatches between electricity supply and demand could become relevant in the future if the share of renewables significantly increases. As previously outlined, renewable energy potentials are mainly located inland in the south, while the main demand centres are located on the coast in the north (Section 2). Furthermore, blending green hydrogen into the existing natural gas infrastructure could help to reduce the carbon footprint of the current electricity mix. Currently there is however no regulation on gas blending.

However, it should be noted that renewables today only account for a 3% share in the Tunisian electricity mix. The need for flexibility options due to the variability of renewables is, therefore, currently very limited. At the same time the demand for electricity is rapidly increasing (Section 2) and Tunisia currently does not generate a surplus of electricity. In the literature, it is assumed that hydrogen only becomes relevant as a storage medium when there is a share of renewables higher than 70% in the electricity mix. Based on FCH 2 JU (2019), with a share of 70% renewables about 5% should be converted to hydrogen; with an 80% share, 10% should be converted to hydrogen; and in a 100% renewables-based electricity system, 14% should ideally be converted to hydrogen. With lower shares of renewables other flexibility options are deemed more feasible. Although these estimations are based on more integrated electricity systems than the Tunisian electricity grid, the share of renewables would still have to increase significantly for hydrogen to become a viable option in Tunisia. Analyses have shown that for an electrolyser to be economically feasible it needs to run for about 5,000 hours per annum (Urbansky 2020). But even if a lower running time of 3,000 hours per annum (Merten et al. 2020) is assumed it is unlikely that sufficient surplus electricity from renewables will be generated to run an electrolyser economically in Tunisia in the foreseeable future. Although higher surplus electricity quantities are expected to arise, these are often widely distributed in terms of location and time of availability. To determine if and where the use of surplus electricity to produce hydrogen could make sense in the future, more detailed site-specific analyses would be required. At present, however, there do not appear to be sizeable opportunities in the electricity and gas sector.

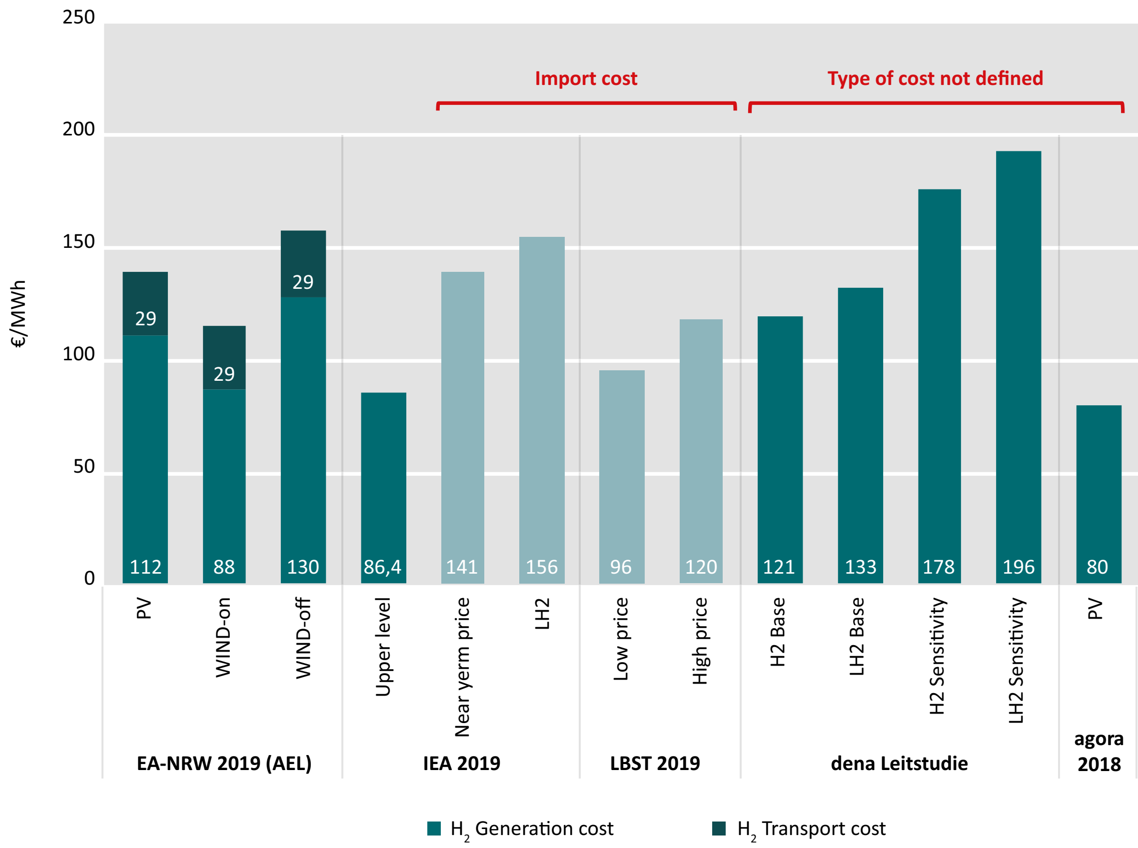
6 Costs and financing of Power-to-X in Tunisia

Costs play a decisive role when evaluating the opportunities for Tunisia to produce PtX products on a large scale and, ultimately, to export these. The costs for green hydrogen depend on many factors that can vary greatly from region to region and can develop differently over time. Cost assumptions for the distant future are also subject to fundamental uncertainties. The following subchapter, 6.1, gives an overview of the technical and financial assumptions and resulting costs for the production of green hydrogen and selected derivatives in Tunisia. To reflect the uncertainties associated with these cost assumptions, the costs are calculated for two scenarios based on optimistic and more conservative assumptions about cost development. In the Progressive Scenario, the costs of the initial investments decrease more rapidly over time, while in the Conservative Scenario, the price reduction rates are assumed to be slower. Consequently, the two scenarios illustrate potential future cost development pathways for PtX in Tunisia.

The costs and, more generally, the decision to invest in a particular technology are influenced not only by technical developments and cost decreases over time based on economics of scale, but also by country-specific conditions. This is particularly true for capital-intensive systems and, therefore, for the production of PtX fuels from renewable energies. Therefore, subchapter 6.2 presents an analysis of the effects of de-risking measures and the level of country risks in Tunisia.

6.1 HYDROGEN COST ANALYSIS

Green hydrogen is currently about two to three times more expensive than hydrogen generated from fossil fuels. The costs for green hydrogen essentially consist of the electricity costs as well as the investment costs for the electrolysis plant and its operating costs. Renewable electricity is by far the largest cost factor. Low electricity costs are, therefore, a necessary prerequisite for the production of competitively priced green hydrogen (IRENA 2020). Thus, locations with optimal conditions for the production of renewable electricity have an important role to play in the competitive production of green hydrogen. As renewable energy costs fall, so will the cost of green hydrogen. Costs for the electrolyser, which is the second-largest cost component, are also expected to decrease over time due to economies of scale and learning effects (ibid). Overall, there is still a great deal of uncertainty about the future costs of green hydrogen and the existing literature on green hydrogen and PtX technologies presents a wide range of expected future costs – due partly to the widely different assumptions made. Fig. 6.1 summarises the production and import costs for green hydrogen from North Africa to Germany assumed in various studies for the year 2050 (Merten et al. 2020). The cost data varies in terms of types of costs included: some studies provide production costs and transportation costs; some only details the total import costs; and others do not specify which costs were considered in detail. These costs range from €45 to €138/MWh, which corresponds to a range of more than €90.



(Source: Merten et al. 2020)

Fig. 6.1 **Comparison of green hydrogen (supply) costs for imports from North Africa to Germany in 2050**

6.1.1 Cost assumptions

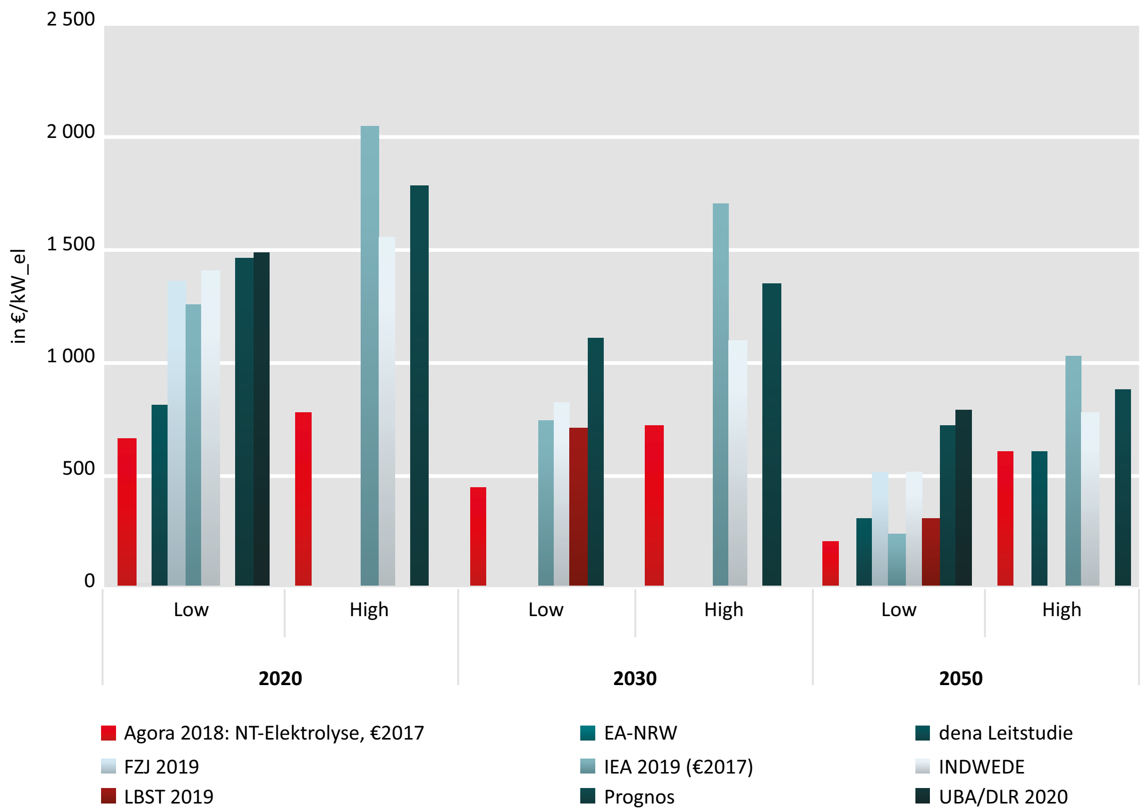
Seven different cost factors (specific investment, technical lifetime, efficiency, fixed operating costs, electricity generation costs from renewable energy sources, full load hours of the plants, and interest rate) are taken into account for the analyses that follow. The technical cost factors are based on the assumption that the electrolysis plants are a globally uniform investment product available in all countries under the same techno-economic conditions (Merten et al. 2020).

The cost factors of electricity production costs, full load hours, and interest rate are influencing factors that can differ significantly from country to country or region to region and thus reflect the regional influence on the resulting production costs. A distinction is made between the supply-side factors related to the renewable energy sources, which influence the operating costs, and the interest rate for financing. The latter indirectly serves to take into account the different political, legal, and economic framework conditions for the investments.

Cost assumptions are calculated for two scenarios to illustrate possible future cost development paths for PtX in Tunisia. In the Progressive Scenario, the costs of initial investments decrease faster over time, while in the Conservative Scenario, the rates of price decrease are assumed to be slower. Table 6-1 summarises the different techno-economic assumptions between the progressive and conservative scenarios.

Investment and fixed operating costs

Hydrogen from electrolysis can be produced using various low temperature processes (AEL, PEM) or high temperature processes (SOEL). As shown in Figure 6.2, a wide range of investment costs are cited in the literature. Low temperature processes are commercially available and well advanced compared to high temperature electrolysis.



(Source: Merten et al. 2020)

Fig. 6.2 Specific investment cost range assumptions for PEM technology in €/kWel

To calculate future costs, cost assumptions for PEM technology are used due to its technological advantages in terms of coupling with fluctuating renewable electricity (cf. Merten et al 2020). Based on a meta-analysis of studies on hydrogen production costs carried out by the Wuppertal Institut and DIWecon (Merten et al. 2020), a slection of techno-economic parameters was made for our own calculations (Table 6.1). The selection of our own cost assumptions (ranges) for the investments over time (2030: €670/kW_{el} to €1,100/kW_{el} and 2050: €300/kW_{el} to €500/kW_{el}) is based on the mean values from the study data.

Full load hours

A significant locational advantage of Tunisia compared to Europe is the possibility to use both solar and wind power and, consequently, to achieve particularly high full load hours. Therefore, a hybrid PV/onshore wind system with full load hours of 5,400 h/a is used as the basis for our own calculations.

According to two studies, Navigant et al. (2019) and Fraunhofer IEE (2020), up to 6,000 h/a will be achievable by 2050. This value for the full load hours is above the assumptions applied in this study and should be regarded as rather optimistic. However, the observed impact of increased full load hours on the resulting costs is quite low according to the sensitivity analysis of Merten et al. (2020). Only when full load hours fall below a certain threshold (<3,000 h/a) does the impact on the overall costs become a more relevant factor (ibid).

Tab. 6.1 Summary of the selected techno-economic parameters for the cost calculation of green hydrogen in Tunisia

	2030		2040		2050	
	Progressive	Conservative	Progressive	Conservative	Progressive	Conservative
Investment costs (in €/kW_{el})	670	1100	485	800	300	500
Tech. lifetime (in a)	23		25		27	
Efficiency (in %)	62		65		68	
Fixed operating costs (in % of the investment costs)	1.70		1.70		1.70	
Full load hours (in h/a)	5400		5400		5400	
Electricity generating costs (in €/MWh)	31	68	26.5	64.5	22	61
WACC	14.9%	16%	13.16%	16%	11.41%	16%

(Source: own assumptions based on Merten et al. 2020)

Average electricity generating costs from renewable sources

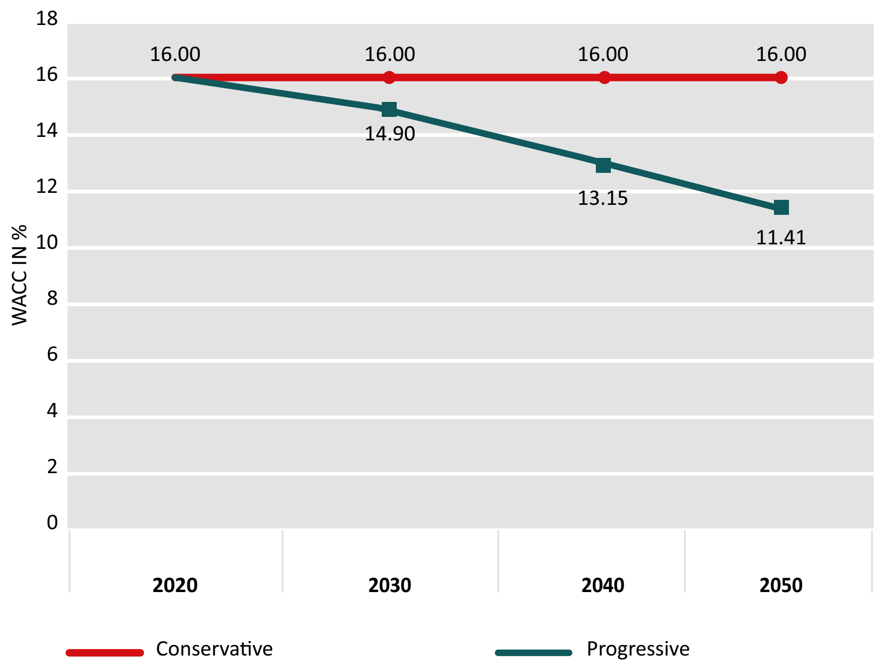
Tunisia, as a North African country, offers good site conditions for electricity production from solar and wind power. Nevertheless, the Tunisian renewable energy sector is still quite young, with the result that the number of available forecasts on future renewable electricity generation costs are very limited. Consequently, our assumptions for average electricity generation costs from renewable energy sources are based on general forecasts for North Africa and Morocco.

We follow the approach of the studies by Merten et al. (2020) and Agora and Frontier Economics (2018) and adopt their assumptions for electricity generation costs (cf. Tab. 6.1).

Costs of capital

With regards to investment security, the MENA region tends to be viewed with a certain level of scepticism. Tunisia is at least partially exempt from this due to its stable and democratic political situation since 2011 and its strong bilateral relations with Germany and the EU. In addition to literature analysis, findings from an ongoing research project at the Wuppertal Institut were taken into account to determine the cost of capital. As a result of these calculations, the average weighted cost of capital (WACC) for PtX technologies in Tunisia is assumed to be about 16%.

As part of this project, scenarios were developed and analysed to determine the impact that decreasing the country risks and increasing the technological maturity of PtX could have on the cost of capital in Tunisia. One of the scenarios describes the overall positive development in which the country risks are reduced and, therefore, the cost of capital decreases in Tunisia. Based on the results we can assume a decrease in WACC from 16% to 11.4% by 2050 (in Fig.6.3). Section 6.3 provides a more detailed analysis of the measures that could be taken to reduce these country risks.



(Source: based on Terrapon-Pfaff et al. 2021)

Fig. 6.3 Assumptions of cost of capital for private sector investments in PtX technologies in Tunisia

Water requirement for electrolysis

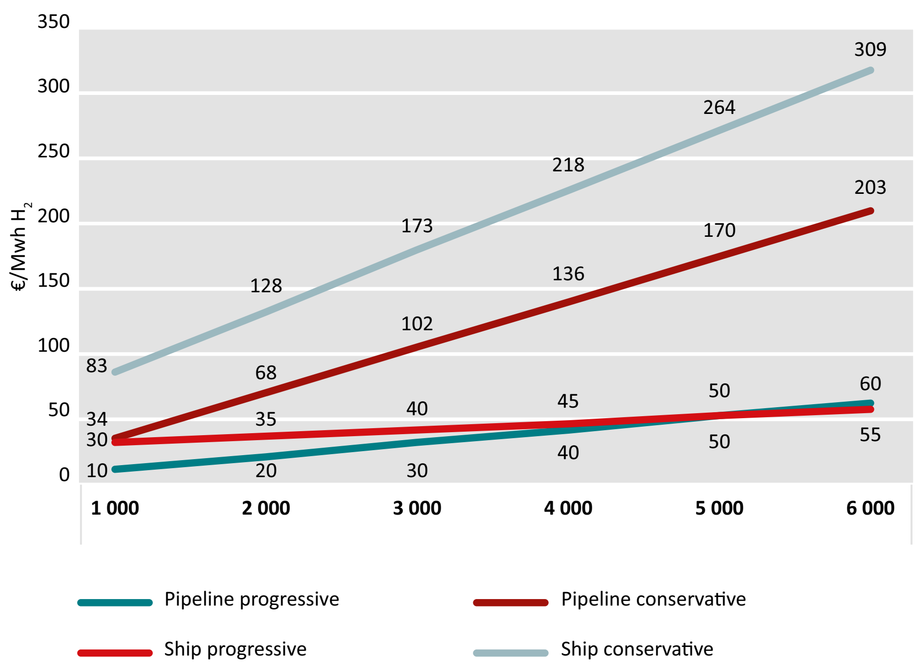
Another relevant factor for the production of green hydrogen is the water demand for electrolysis. Hydrogen production should not threaten the drinking water supply; therefore, the water needs must be met from desalinated seawater resources. Desalination technologies are already commercially available; however, their operation is largely based on fossil fuels. Therefore, for the production of green hydrogen, a switch to renewable energies would be necessary.

Although seawater desalination has associated costs, these represent a very small share of the cost of green hydrogen production. Agora and Frontier Economics (2018) and Merten et al. (2020) assume that seawater desalination does not represent a significant cost component and calculate only €-cent 0.0001/kWh_{H_2} for the total costs of desalination. Our own calculations show a higher share of desalination cost, but still well below 1% of the total PtX costs.

Cost assumptions for hydrogen transportation from Tunisia to Germany

To supply green hydrogen from Tunisia to, for example, Germany, additional costs for transportation (over longer distances) and distribution (for shorter distances) must be considered. These costs increase with distance and play an important role for imports from Tunisia. For long-distance imports, both transmission options (by pipeline and by ship) should be considered.

Transporting hydrogen via pipeline is already a well-established technology. Pipelines can deliver large quantities of hydrogen over long distances at relatively low operating costs and losses. The pipelines also act as storage for the gaseous hydrogen. In addition, existing natural gas pipelines can be converted for hydrogen transport. The disadvantage of using pipelines is the high investment required for new construction or retrofitting.



(Source: based on Merten et al. 2020)

Fig. 6.4 **Specific hydrogen transportation costs via pipeline and ship depending on distance**

Hydrogen transport by ship could be scaled up and adapted to the decentralised expansion paths of hydrogen production, and bridge much longer distances than pipelines.

However, one of the main problems with this option is that there are still no commercial ships for hydrogen transport (IEA 2019a), meaning investments in shipping transport are associated with high uncertainties and costs. A second major disadvantage for transport via ship is that hydrogen must be liquefied [2] (i.e., cooled down to -253°C) for this purpose. This conversion step is expensive and energy or electricity-intensive. Fig. 6.4 shows the additional transportation costs for pipeline and ship by distance.

The distance between Tunisia and Germany (estimated to be 4,115 km) is around the break-even point in an optimistic scenario where transportation by ship becomes reasonable compared to transportation by pipeline, even if it involves significantly higher cost uncertainties and risks. For our cost calculations we estimated the costs of transporting hydrogen to Germany at €-cent 4.1/kWh in the Progressive Scenario and €-cent 13.95/kWh in the Conservative Scenario, based on the assumed cost for transportation via pipeline.

6.1.2 Hydrogen production costs in Tunisia

Based on these assumptions, the costs for the generation and potential supply of green hydrogen to Germany were calculated. Fig. 6.5 shows the total production costs for green hydrogen in Tunisia in 2030, 2040, and 2050 based on these calculations.

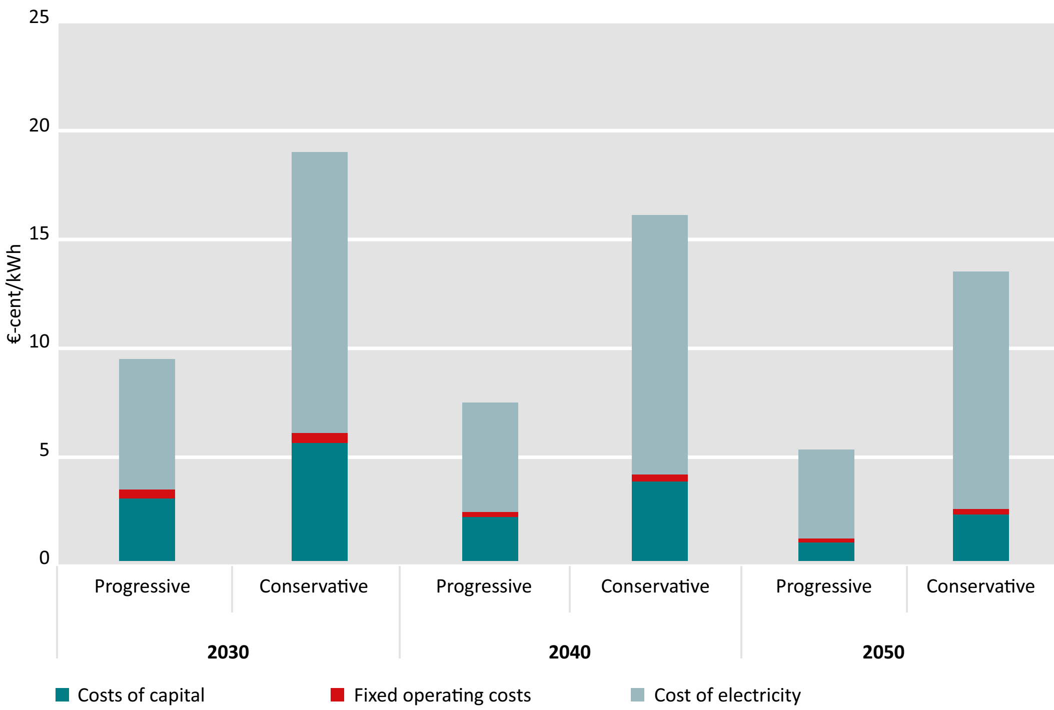


Fig. 6.5 Hydrogen generation costs in Tunisia based on two cost development scenarios

Estimated generation costs of green hydrogen in Tunisia range from €-cent 9.50/kWh to €-cent 19.24/kWh in 2030. In 2050, the lowest estimated hydrogen generation costs were €-cent 5.41/kWh (without transport)

2 The option of hydrogen transport via liquid organic hydrogen carrier was beyond the scope of this cost calculation.

in the Progressive Scenario and €-cent 13.60/kWh (without transport) in the Conservative Scenario.

The major cost driver for green hydrogen is the cost of electricity from renewable energy sources used during the water electrolysis process. The decreasing costs of solar PV and wind electricity make the generation of green hydrogen increasingly economically attractive (IRENA 2020). Cost reductions in the renewable sector will, therefore, directly result in reduced costs in hydrogen production.

The second most important cost driver is the initial investment cost in the water electrolysis process. Electrolysis plants currently require high investment costs; these are expected to significantly decrease over time when plants grow in scale and the number of applications worldwide increases. Furthermore, electrolysis is expected to become more efficient with further technological advances. Taking all the different cost reductions potentials into account, Fig. 6.6. illustrates the cost decrease over time.

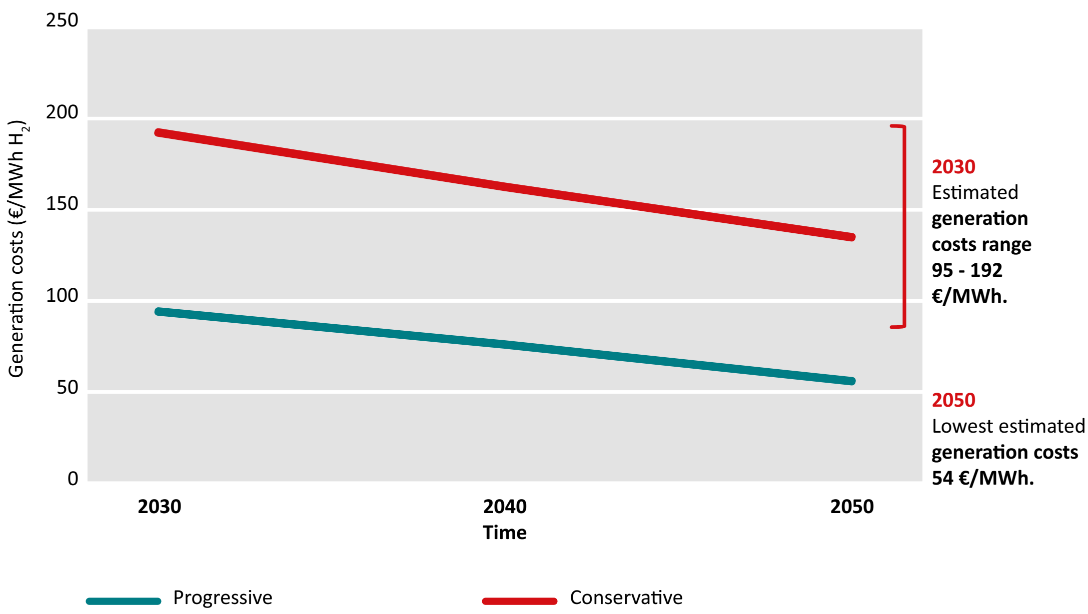


Fig. 6.6 **Illustration of cost decreases for hydrogen generation in Tunisia for two cost development scenarios**

However, in 2050, hydrogen produced from renewable energy sources will still be more expensive than hydrogen produced from natural gas. Agora and Frontier Economics (2018) expect the purchase costs for conventional natural gas to remain much lower for the entire period to 2050, at between €-cent 2.25/kWh and €-cent 3.81/kWh. However, it should be taken into account that the production of hydrogen from renewable energy sources does not lead to any direct CO_2 emissions. The financing of green hydrogen becomes more economical when this green value is reflected in the revenue. Recent developments in various countries in terms of putting a cost on CO_2 emissions through different mechanisms can be expected to significantly increase the price of CO_2 by 2050, making green hydrogen more competitive.

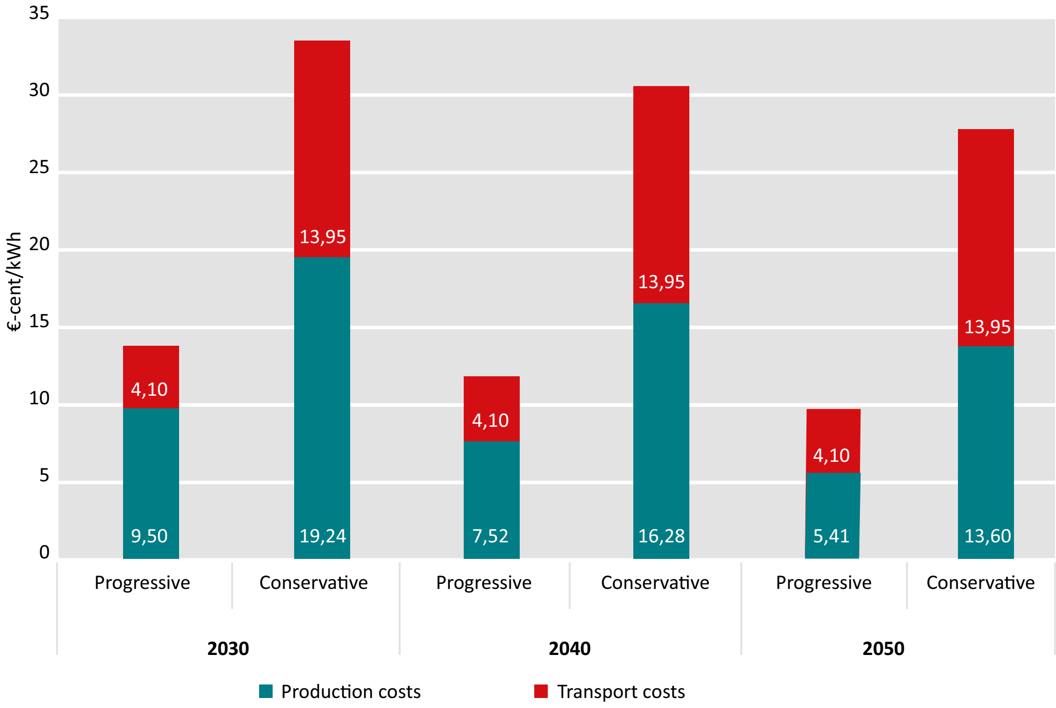


Fig. 6.7 Supply costs of green hydrogen from Tunisia to Germany

Fig. 6.8 Comparison of green hydrogen supply costs from Tunisia and Morocco in 2050

As shown in Fig. 6.7, another cost factor associated with high uncertainties and risks is the cost of transportation to Germany. Accordingly, the costs for 2030 range between €-cent 15.05/kWh and €-cent 33.01/kWh and for 2050 between €-cent 9.86/kWh and €-cent 27.47 /kWh for hydrogen after transportation to Germany.
Fig. 6.8 compares green hydrogen supply costs from Tunisia and from Morocco in 2050. The differences in the estimated transportation costs are based mainly on the longer distance from Tunisia to Germany. The lower investment costs in Morocco reflect the more favourable investment situation represented by a lower WACC.

6.2 SYNTHETIC FUELS COST ANALYSIS

Instead of producing and potentially exporting green hydrogen, it could be used as an input feedstock for conversion into products such as synthetic methane, methanol, ammonia, or PtL fuels for the transport sector. Due to the high costs and uncertainties in terms of the transportation of hydrogen, processing green hydrogen into more easily storable and transportable PtX products for domestic use or export could be a viable alternative. In this subchapter, the costs associated with the production of selected PtX products are evaluated.

6.2.1 Cost assumptions

The costs are analysed for ammonia, methanol, methane, and kerosene-type jet fuel. The different assumptions on which the cost analysis is based are detailed in the following sections.

Ammonia production

Ammonia is produced through the Haber-Bosch synthesis process. This is a well-established process; therefore, significant cost reductions are not expected by 2050. In addition to hydrogen, nitrogen is needed to produce ammonia. The nitrogen can be taken from the air via an air separation unit. The investment cost for the air separation unit presents only a small share of the total investment costs for ammonia synthesis. In the Haber-Bosch synthesis, the two substances react at high temperature and high pressure to form liquid ammonia. This process requires electricity, which is assumed to be obtained from a PV-wind combination as described in section 6.1. For the cost calculation we made the following assumptions, as displayed in Tab. 6.2.

Tab. 6.2 Selected techno-economic parameters for ammonia production

	2030 - 2050
Investment costs [€/t_ammonia]	600
Tech. lifetime [a]	25
Efficiency (in %)	81.9
Fixed operating costs (in % of investment costs)	1
Full load hours (h/a)	8000
Electricity needs (in kWh_{el}/kWh_ammonia)	1700
Spec. H_2 requirements (in t_H_2/t_ammonia)	0.178
Transportation costs (in €-cent/kWh)	0.68

(Source: Based on Frontier Economic 2020)

Methanol synthesis

Methanol is produced from the methanol synthesis process from hydrogen and carbon dioxide. As with Fischer-Tropsch synthesis, we assume that the carbon dioxide is obtained by means of direct air capture (for the assumptions, see Tab. 6.6). For synthetic methanol production, we used the assumptions shown in Tab. 6.3.

Tab. 6.3 **Selected techno-economic parameters for the cost calculation of synthetic methanol production in Tunisia**

	2030	2040	2050
Investment costs [€/kW_{el}]	726	653	588
Tech. lifetime [a]	30	30	30
Efficiency (in %)	80.3	80.3	80.3
Fixed operating costs (in % of investment costs)	4	4	4
Full load hours (h/a)	8000	8000	8000
Spec. CO_2 requirements (in t_CO_2/t_fuel)	1.46	1.46	1.46
Spec. H_2 requirements (in t_H_2/t_fuel)	0.2	0.2	0.2
Transportation costs (in €-cent/kWh)	0.69	0.69	0.69

(Source: Based on Fasihi et al. 2016)

Fischer-Tropsch synthesis

Synthetic kerosene and synthetic heavy marine fuel are obtained by Fischer-Tropsch synthesis. This is an established technology; therefore, we do not assume any cost reduction by 2050. As in the refining of crude oil, several products (i.e., not only kerosene or heavy fuel oil) are produced simultaneously during the further processing of the syncrude. For the simplified calculation, we do not take the cost effects of this co-production into account. Our assumptions for the cost calculation of Fischer-Tropsch synthesis are summarised in Tab 6.4. As in the production of methanol, CO_2 is required as input feedstock for Fischer-Tropsch synthesis. We assume that the CO_2 required is obtained via direct air capture technology (see Tab 6.6 for the cost assumptions).

Tab. 6.4 **Selected techno-economic parameters for the cost calculation of Fischer-Tropsch synthesis in Tunisia**

	2030 - 2050
Investment costs [€/kW_{el}]	2.317
Tech. lifetime [a]	25
Efficiency (in %)	73.4%
Fixed operating costs (in % of investment costs)	5.3%
Full load hours (h/a)	8000

(Source: based on Fasihi et al. 2016; König 2016; Albrecht 2016)

Methanation

In the process of methanation, methane, water, and heat are generated from hydrogen and carbon dioxide. The methanation process is largely based on catalytic (thermochemical) methanation. In the literature, there is a large variation in the future cost assumptions of methanation technology. Therefore, we based our calculations on both progressive and conservative assumptions. Tab 6.5 shows the selected techno-economic parameters for the cost calculation of methanation in Tunisia. The CO_2 needed for the methanation process is assumed to be provided by direct air capture technology (see Tab 6.6 for the cost assumptions).

Tab. 6.5 Selected techno-economic parameters for the cost calculation of methanation in Tunisia

	2030		2040		2050	
	Progressive	Conservative	Progressive	Conservative	Progressive	Conservative
Investment costs [€/kW_{el}]	432	756	311	728	190	700
Tech. lifetime [a]	26		27		28	
Efficiency (in %)	81%		83%		83%	
Fixed operating costs (in % of investment costs)	3%		3%		3%	
Full load hours (h/a)	8000		8000		8000	
spec. CO_2 requirements (t_CO_2/t_CH_4)	1.75		1.75		1.75	
spec. H_2 requirements (t_H_2/t_CH_4)	0.125		0.125		0.125	

(Source: Child et al. 2019; DENA Leitstudie Intergrierte Energiewende 2018; Agora und Frontier Economics 2018)

CO_2 production from direct air capture

For methanol synthesis, Fischer-Tropsch synthesis, and methanation we assume that the necessary CO_2 is captured through direct air capture technology (DAC) (see Tab. 6.6). Where carbon monoxide is required for synthesis it can be extracted from the captured CO_2. For the cost calculation, we use the estimation of CO_2 capture costs in Morocco, for which the necessary electricity is supplied by hybrid PV-wind-battery plants and heat pumps.

The development of the leveraged cost of direct air capture in the next decades mainly depend on how the cost of capital, the learning curve of capital expenditures and the costs of renewable electricity will decrease in the future. Today the costs for DAC are with US$300 to US$600 per tonne for CO_2 three and twelve times higher than the estimated costs for capturing CO_2 from point sources, such as the cement industry, with around US$50 and US$100 per tonne (IRENA 2021). Therefore, conservative assumptions predict that DAC is unlikely to be commercially available on a large scale before 2030 (Zelt et al. 2021). Fasihi et al. (2019) who analysed the future technical and economic perspectives of large-scale CO_2 DAC systems in Morocco, on the other hand expect that the costs for high temperature solid sorbent-based direct air capture technologies (HT DAC) and low temperature solid sorbent-based direct air capture technologies (LT DAC) will decrease significantly until 2030. Fasihi et al (2019) assume that the energy demand for DAC technologies could be met by relatively low-cost PV-wind-battery plants and heat pumps (or from waste heat) from 2030 onwards. Therefore, LT DAC systems could be economically (and technically) more favourable in the long term. For our cost calculation we use the estimates of the conservative and the base case scenarios from Fasihi et al. (2019) to show a cost corridor for our progressive and conservative scenarios. Compared to other studies (e.g. IRENA 2021) the estimated costs are rather optimistic. In order to be able to achieve these cost decreases it is important that both low-cost renewable energy sources are available and the large-scale implementation of DAC systems starts already before 2030 (in order to make them cost competitive).

Tab. 6.6 Levelised cost of direct air capture in North Africa

	2030		2040		2050	
	Progressive	Conservative	Progressive	Conservative	Progressive	Conservative
Levelized cost of Direct Air Capture (in €-cent/t_CO_2)	0.84	1.33	0.53	0.91	0.38	0.71

(Source: Based on M. Fasihi et al. 2019)

Full load hours and hydrogen storage assumptions

To enable high utilisation rates of the PtX conversion plants (8,000 h/a in our assumptions), we assume that hydrogen storage is needed downstream of the electrolysis. The assumed costs for hydrogen storage are simplified and estimated at €-cent 0.28/kWh for every PtX technology over the entire time period (Agora and Frontier Economics 2018).

Transportation costs assumptions

There are two basic options available for transporting synthetic methane: transport using natural gas pipelines or transport as LNG. For the cost calculation, we assume that synthetic fuels will be transported to Germany using tankers. The LNG transportation costs of synthetic methane include the costs of liquefying the gas in Tunisia, the direct transportation costs, and the costs of regasification in Germany. The estimated LNG transportation costs are shown in Tab. 6 7.

Tab. 6.7 Assumption of transportation costs of synthetic LNG

	Transportation costs (in €-cent/kWh)
Liquefaction	0.69
Transportation	0.12
Regasification	0.15
Total	0.96

(Source: based on Agora and Frontier Economics 2018)

Liquefied PtX products, such as kerosene, marine fuel, methanol, and ammonia have a higher volumetric energy density, therefore transportation is less complicated than hydrogen transportation. Large quantities of these fuels can be shipped using existing infrastructure. Kerosene, marine fuel, and methanol are liquids and can be transported by conventional tankers. Ammonia can be shipped in liquefied gas tankers. For all liquefied PtX products, we assume transportation from Tunisia to Germany by ship. For the cost calculation, we use the assumptions shown in Tab. 6.8.

Tab. 6.8 **Assumption of transportation costs of liquefied PtX products**

	Transportation costs (in €-cent/kWh)
Kerosene, marine fuel	0.3
Methanol	0.69
Ammonia	0.68

(Source: Based on Frontier Economics 2020)

For the simplified calculation, the costs associated with blending and distribution are not included for any of the PtX products.

6.2.2 Costs of synthetic fuel production in Tunisia

Based on the assumptions, the cost analysis for the production of green hydrogen derivatives in Tunisia and their export to Germany was calculated. The analysis shows that transportation costs play a minor role in the overall cost share, which makes their production in Tunisia potentially more competitive than for other locations closer to Germany (such as Morocco or Eastern Europe). On the other hand, the advantage of Tunisia’s proximity to Europe is also reduced compared to more distant producers.

Ammonia

The Haber-Bosch synthesis, which provides the technical background for ammonia production, is a widely used and established process. The associated investment and fixed operating costs are low. Therefore, the cost of the ammonia produced depends largely on the price of hydrogen (Fig. 6.9). Advantages of exporting ammonia as opposed to hydrogen are that the corresponding infrastructures already exist, international ammonia trade is established, and transportation costs are lower than for liquid hydrogen. The costs of reconversion would correspond to around 16% of the total (EWI 2020). According to IEA (2019), ammonia-based transportation via LNG tanker could be the most cost-efficient solution for long-distance hydrogen trade in the long term.

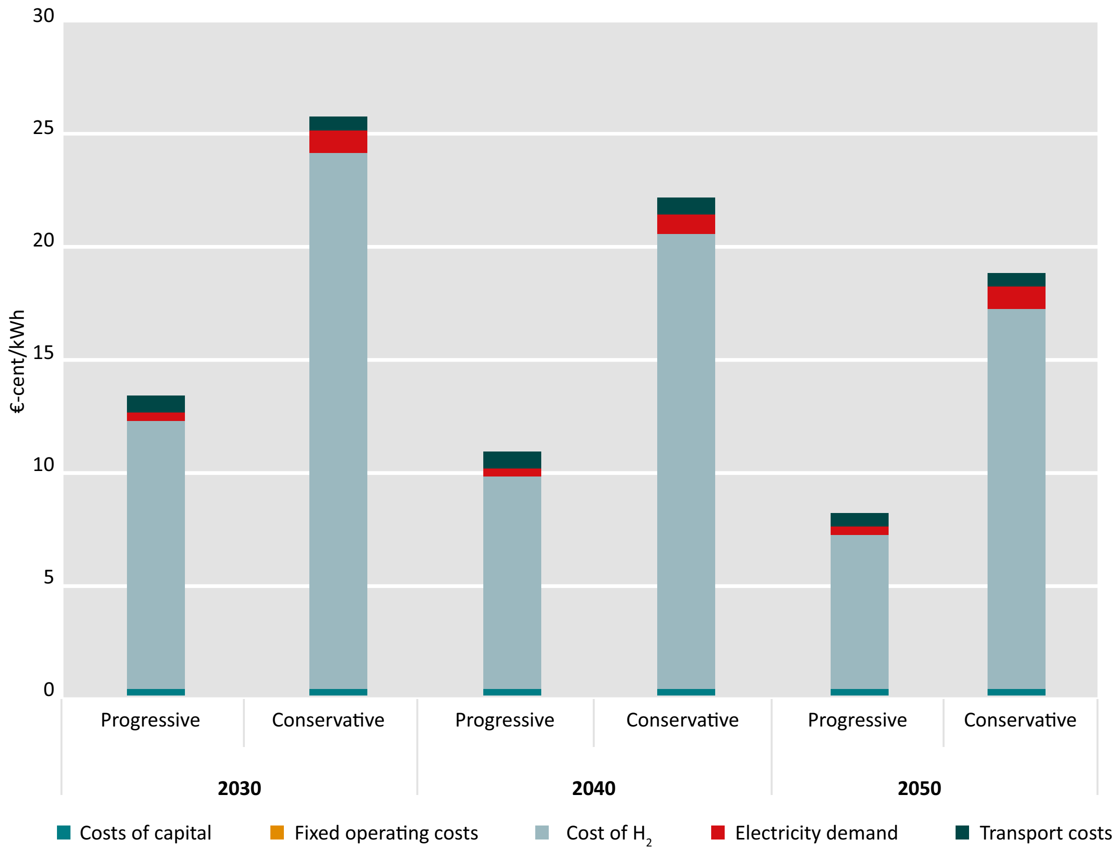


Fig. 6.9 Total costs of green ammonia

Methanol and synthetic kerosene

The total costs of methanol and synthetic liquid fuels like kerosene (Fig. 6.10 and Fig. 6.11) are dominated by the costs of green hydrogen. However, the costs are expected to fall significantly over time for both products. The main driver for the cost decrease is the expected reduction of investment costs for hydrogen generation. The transportation costs only represent a small share of the overall costs for both methanol and synthetic kerosene. Both processes require CO_2, which also only represents a small share of the overall costs, but they are more than twice as high for synthetic kerosene than for methanol. The cost for CO_2 is expected to fall significantly by 2050.

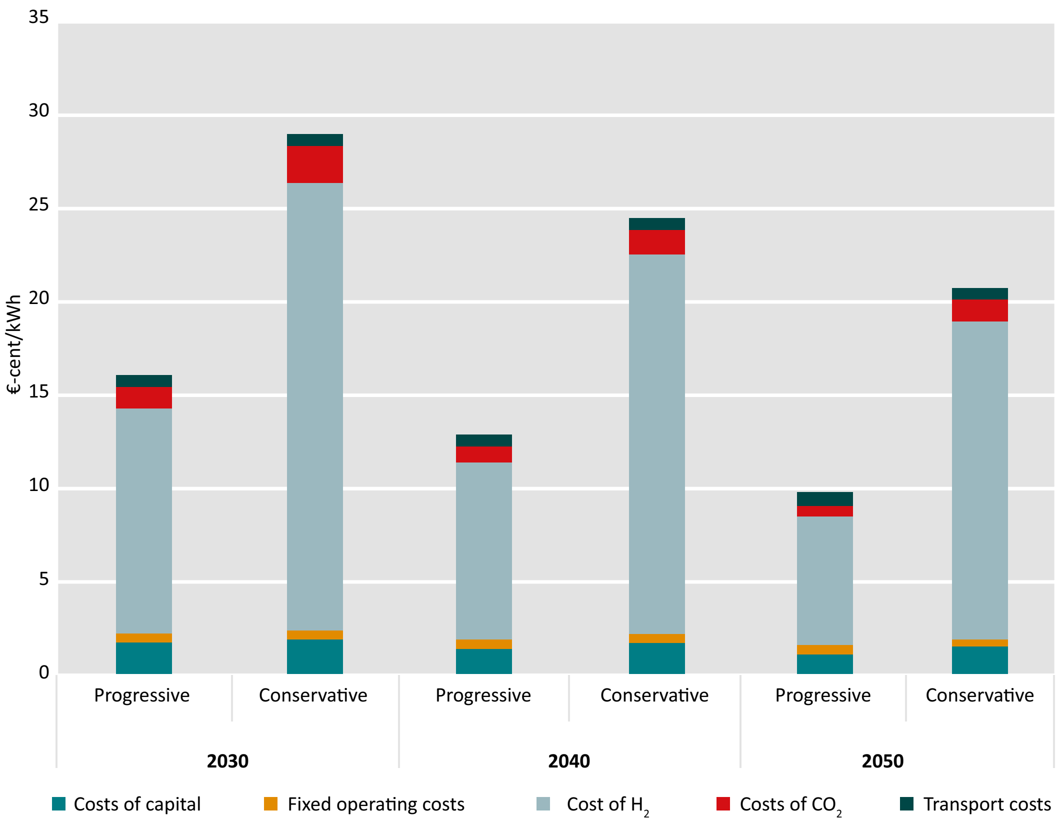


Fig. 6.10 Total costs of green methanol

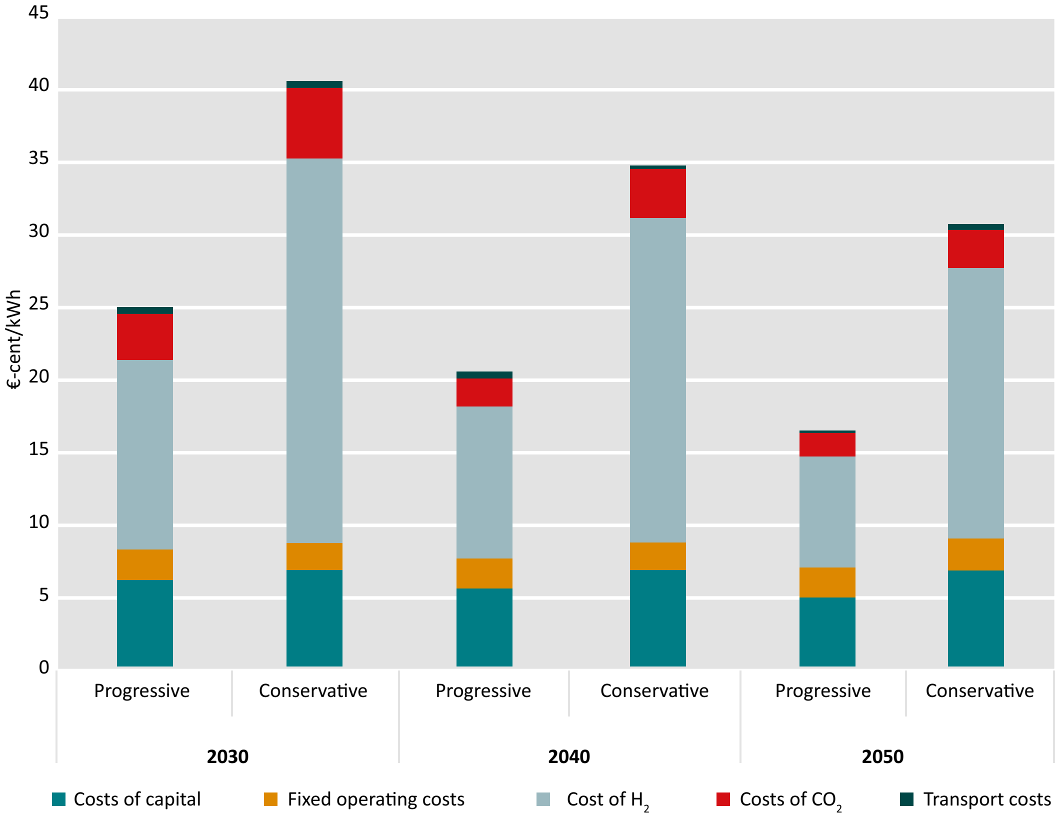


Fig. 6.11 Total costs of green synthetic kerosene

Methane

Estimated total costs for the production and transportation of synthetic methane are shown in Fig. 6.12. Agora and Frontier Economics (2018) estimate the production costs of synthetic methane from offshore wind sources in sites of the North Sea and the Baltic Sea to be around €-cent 10/kWh to €-cent 18/kWh. Compared to our calculation, this would mean that, in the long term, synthetic methane production in Tunisia and its export to Germany (or Europe) could have a cost advantage. Cheaper electricity generation costs in Tunisia compensate for the higher transportation costs to Germany. The magnitude of this cost advantage will depend largely on how the investment costs for renewable electricity and hydrogen production develop in the future.

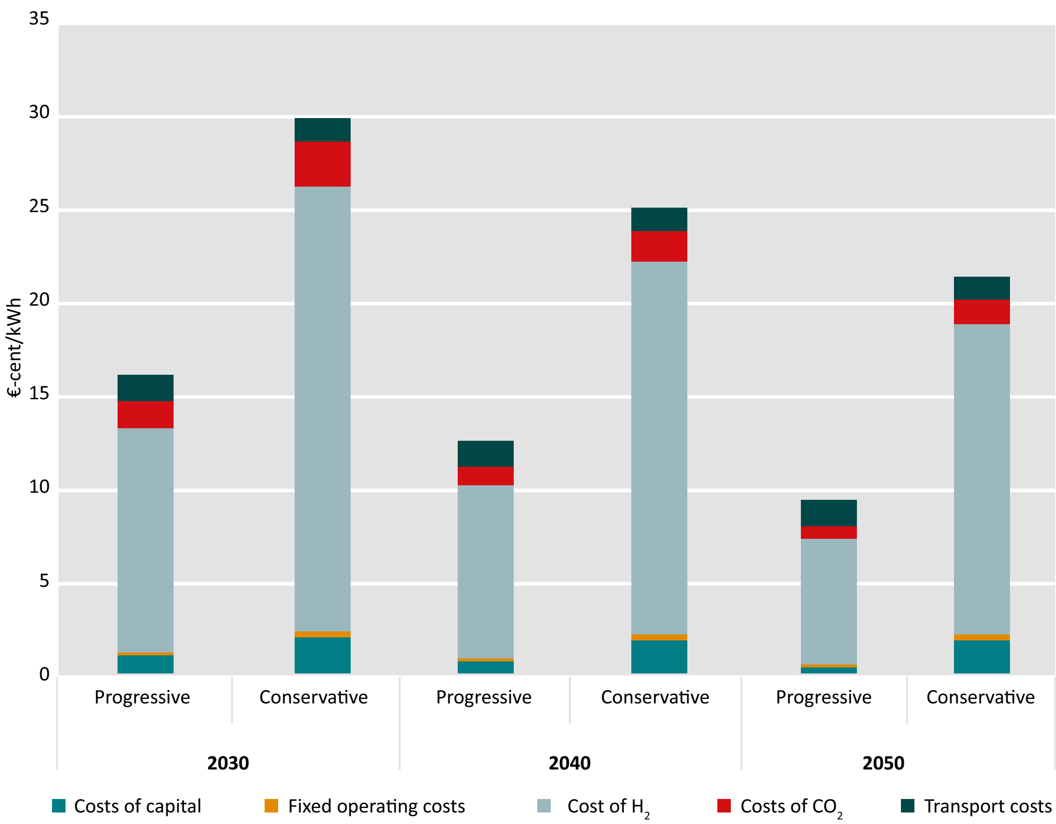


Fig. 6.12 Total costs of synthetic methane

Although the transportation costs of liquid fuels are lower than those of synthetic methane, synthetic liquid fuels have slightly higher CO_2 input costs, which means the resulting cost estimates for these PtX fuels are comparable. However, the purchase costs for conventional natural gas are expected to remain much lower for the entire period (estimated between €-cent 2.25/kWh and €-cent 3.81/kWh in 2050 (Agora and Frontier Economics 2018)). With the introduction of sufficient pricing mechanisms for CO_2 emissions, synthetic methane could become more cost competitive with conventional natural gas as it is a carbon neutral fuel.

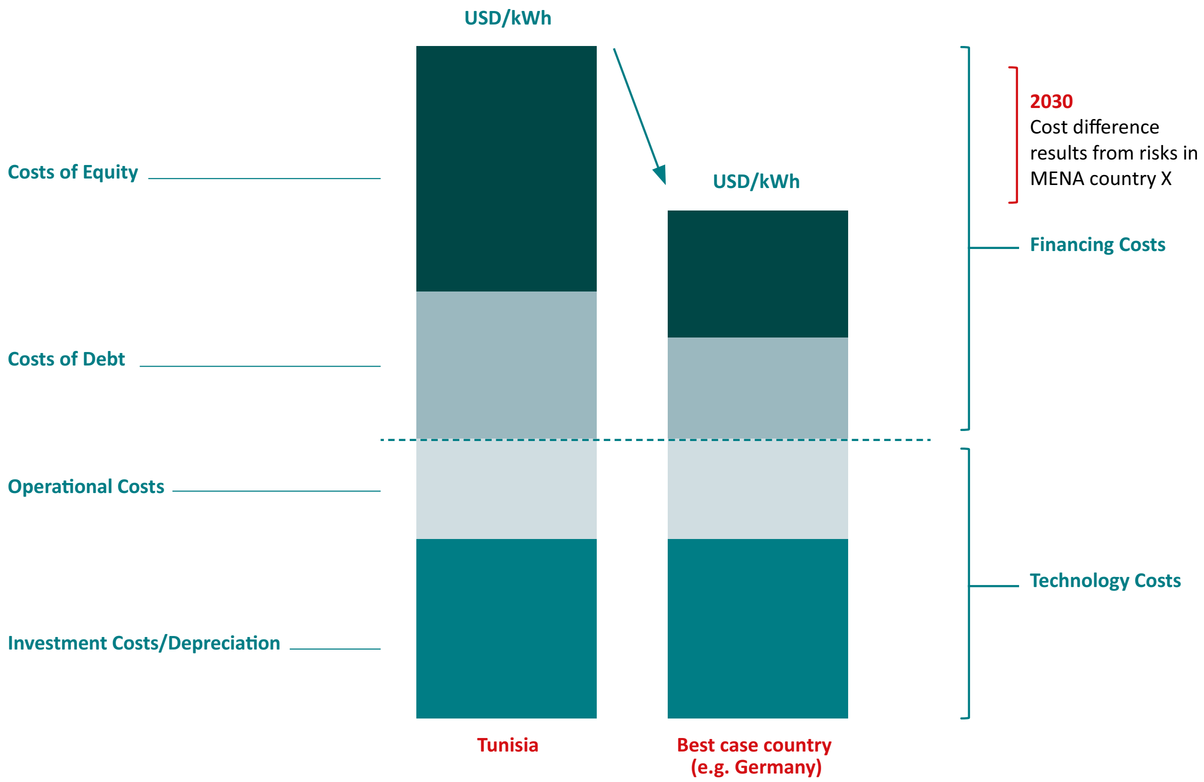
Overall, our calculations show that it is likely to be more economically viable to produce and export PtX products such as ammonia, methanol, and kerosene from Tunisia to Germany – rather than transporting green hydrogen. From a cost perspective, therefore, green hydrogen produced in Tunisia should be further processed into PtX products and then exported, or used directly in Tunisia. This would also have the benefit of locating more added value steps in Tunisia.

6.3 DE-RISKING FINANCING COSTS

Financing costs for renewable energy, and especially for PtX projects, are high in Tunisia compared to developed countries. According to scientific analyses (e.g., Mazzucato 2016), industries with high risks and high capital-intensity tend to attract lower levels of private financing. Therefore, it is necessary to introduce de-risking measures to attract risk-averse investors. In this chapter, the potential de-risking effects of public measures to support green hydrogen investments in Tunisia are analysed. For the analysis we adapted the de-risking renewable energy investments (DREI) methodology of UNEP (2018) for public measures for green hydrogen production. The DREI methodology is based on the assumption that high financing costs for private investors reflect the investment risks that exist in early-stage markets. We assume in our analysis, from a simplified perspective, that risks that are purely technology-inherent and related capital costs are identical in all countries, with the capital cost differences between developing and developed countries reflecting the country-specific risk costs. Investors can be partially compensated for these risks if a well-adjusted mix of public measures is introduced.

By using UNEP’s waterfall method, the financing costs of a «best-in-class» country are compared with those of the analysed country (see Fig. 6.13). The difference between the interest rates for the «best-in-class» country and the analysed country corresponds to the country risk, which can be further broken down into different risk categories. This allows the contribution of each risk to the cost of financing to be quantified. Originally, the UNEP study looked at de-risking renewable energy investments in Tunisia. Here this methodology was further developed to give an estimation of how public measures can affect the cost of capital for green hydrogen production in Tunisia.

The analysis of de-risking instruments is based on the risk assessment by Terrapon-Pfaff et al. (2021), who conducted a comprehensive analysis of over 100 indicators for eleven risks for the development of the PtX sector in Tunisia (including risks stemming from conflicts and violence; government interventions; conditions for doing business; quality of governance, political and trade relations with Germany/EU; framework conditions for renewables, hydrogen, or synthetic fuels; investment conditions; approval, licensing, and permission processes; availability of labour and expertise, as well as social acceptance and natural hazards) and predicted the impact of these risks on the cost of capital.



(Source: based on UNEP 2013)

Fig. 6.13 **Structure of financing costs: comparison between Tunisia and a "best-in-class" country**

The calculation was carried out separately for equity and debt capital costs, as equity and debt capital investors are exposed to different risks. While equity investors are affected by risks at the planning phase, debt investors are usually only involved at a later stage – for example, once business plans and licences are available (Waissbein et al. 2013). The five risks identified as contributing significantly to higher financing costs in Tunisia are (Terrapon-Pfaff et al. 2021):

- Quality of governance;
- Framework conditions for hydrogen and synthetic fuels;
- Investment conditions;
- Project approval, licensing, and permission processes;
- Labour and expertise availability.

With the introduction of public instruments, these key investment risks can be addressed to lower the overall costs of capital. The DREI methodology (UNEP 2014) categorises the types of public measures that can lower the risks of renewable energy (and PtX technology) investments into three types:

- Instruments that reduce risk (policy de-risking);
- Instruments that transfer risk from the private sector to the public sector (such as development banks) (financial de-risking);
- Instruments that compensate for risk (direct financial incentives).

Policy and financial de-risking measures can be understood as interventions by the government and its partners to address specific investment risks in the form of policies, programmes, or financial products. To support the green hydrogen industry, IRENA (2020) suggests an integrated policy approach using various public measures to overcome initial resistance to market penetration. Supporting policies can affect aspects of green hydrogen production, such as the electrolysis sector, the hydrogen infrastructure, industrial applications using hydrogen, maritime shipping, and aviation. This report only analyses the effects of public measures on the cost of capital for green hydrogen production. To kick-start the green hydrogen sector, IRENA (2020) suggests the following public incentives:

- Set capacity targets for electrolyser capacity similar to renewable energy targets. These goals will provide assurance to private investors of Tunisia's commitment. An integrated plan with the activities needed to better assess the potential for hydrogen can be defined in a roadmap. It can include both short-term actions that are needed to advance deployment and research areas with the highest priority.
- Offer government loans, capital grants, and other forms of financial assistance to decrease the initially high capital costs. A national hydrogen strategy defines the targets, addresses concrete policies and evaluates their coherence with other fields of energy policy.
- Improve tax schemes for electrolysers and reduce taxes and fees on electricity, both of which can lower the production costs of green hydrogen;
- Introduce feed-in premiums for green hydrogen through feed-in tariffs or other subsidies.

Using the estimations of the UNEP study (2018), assumptions can be made to evaluate the effects of targeted public measures for green hydrogen production, as displayed in Tab. 6.9. According to UNEP's estimation (2018), the impact of the de-risking instruments shows to what extent the de-risking measure can reduce the level of the risk components. The DREI methodology assumes that the effects of the de-risking instruments would be complete by 2050. The effectiveness shows how far the de-risking effect can be achieved by 2030.

Tab. 6.9 De-risking instruments and their estimated impact and effectiveness on the cost

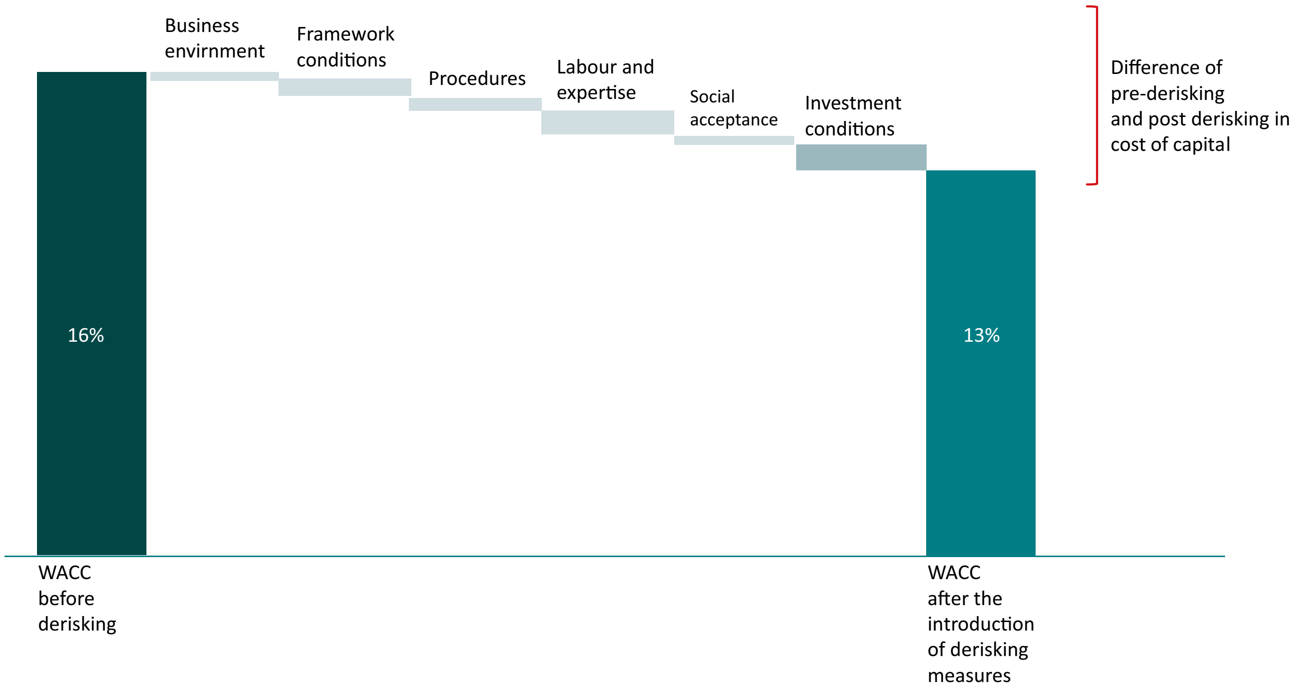
Risk	De-risking instruments	Instrument impact	Instrument effectiveness by 2030
Political de-risking instruments			
Business environment	• Contract enforcement, • Introduction of transparent practices, fraud avoidance mechanisms, • Recourse mechanism (UNEP 2018) • Domestic financial sector reform favourable to long-term investments	50%	50%
Framework conditions for renewables, hydrogen/ synthetic fuels	• Establish a harmonised, well-regulated energy market, ongoing legislative reform with cornerstone instruments to address price and market-access risk for renewable energy projects • Establish an independent energy market regulator • PPA tenders and well-designed standard PPAs	75%	50%

	• Strengthen transmission operator’s operational performance, grid management, and formulation of grid code • Policy support for national grid infrastructure (e.g., development and regular update of a long-term national grid plan to include intermittent renewable energy)		
Approval procedures, authorisation, licensing processes	• Streamline processes for renewable energy and green hydrogen permits (reduction of process steps, clear timelines for processing, harmonisation of requirements) • Funding for feasibility studies	50%	50%
Availability of labour and expertise	• Capacity-building activities • Training programmes to build skills	75%	50%
Social acceptance	• Awareness-raising campaigns • Local support policies	50%	50%
Financial de-risking instruments			
Business environment	• Risk sharing to address currency risk (e.g., partial indexing of local currency tariffs in PPAs)	50%	
Investment conditions	• Include a “take-or-pay” clause in the standard PPA to decrease grid/transmission risks • Government guarantees for PPA payments to reduce investment condition risks • Public loans from international financial institutions to investors to reduce financing risks • Financial products (e.g., public loans) by development banks or other international financial institutions to assist project developers	75%	

(Source: own estimation adapted from UNEP 2018)

The collection of policy and financial instruments is grouped to systematically target the identified risks. The list of de-risking instruments is not exhaustive; it is an example of how tailored public measures influence the cost of capital. The modelling assumptions are simplified to show general impacts of policy and financial de-risking instruments. The assumed impact 0f the measures on selected risks and, consequently, on reducing financing costs for green hydrogen generation in Tunisia is shown in Fig. 6.15. The introduction of de-risking measures could decrease much of the investment, economic, and business risk. The results of the de-risking calculations indicate that a combination of public instruments could serve to reduce the average cost of equity to 19.05% by 2030 and to 16.99% by 2050. The cost of debt would be reduced to 14.26% (under the assumption that the fiscal de-risking instruments introduced have immediate impacts). According to the modelling, this reduces the WACC by 2030 to 13.68% and by 2050 to 13.08%. With further favourable developments (beyond the direct sphere of influence of de-risking measures), the overall WACC could further decrease to 11.41%: the level assumed in the optimistic development scenario for cost development.

Beyond the general contribution of financing instruments to de-risking assumed in the modelling, dedicated financing mechanisms for specific projects or selected areas could further reduce financing costs.



(Source: own calculation based on method described in UNEP 2014)

Fig. 6.14 **De-risking effects of public measures on weighted average cost of capital**

7 Risks and benefits of Power-to-X in Tunisia

Strategic decisions regarding the development of the PtX sector require the consideration of a range of technical, environmental, social, and economic issues. Therefore, to contribute to sustainable development, the prospective technology pathways must be evaluated not only in terms of their technical and economic performance, but also in terms of their environmental and socio-economic consequences. The following section briefly describes the potential environmental and employment benefits and risks that could be linked to the development of PtX in Tunisia.

7.1 ENVIRONMENTAL IMPACTS

7.1.1 Water

The production of hydrogen using renewables – and, therefore, the production of the downstream PtX fuels – requires significant volumes of water (Tab. 7.1). Stoichiometrically, 8.94 litres of water are required to produce one kilogramme of hydrogen (Zelt et al. 2021). PEM electrolysers require about 10 litres of water per kg of hydrogen, equating to a high water use efficiency (89%) (ibid.) However, according to IRENA (2020), the water consumption could be significantly higher due to process inefficiencies, meaning that between 18 litres and 24 litres of water could be required to produce 1kg of hydrogen. On the other hand, some synthesis steps (for example methanol synthesis) generate small volumes of water (Tab. 7.1), which could potentially be reused in the hydrogen production process and contribute to improving the overall water balance of the final PtX product.

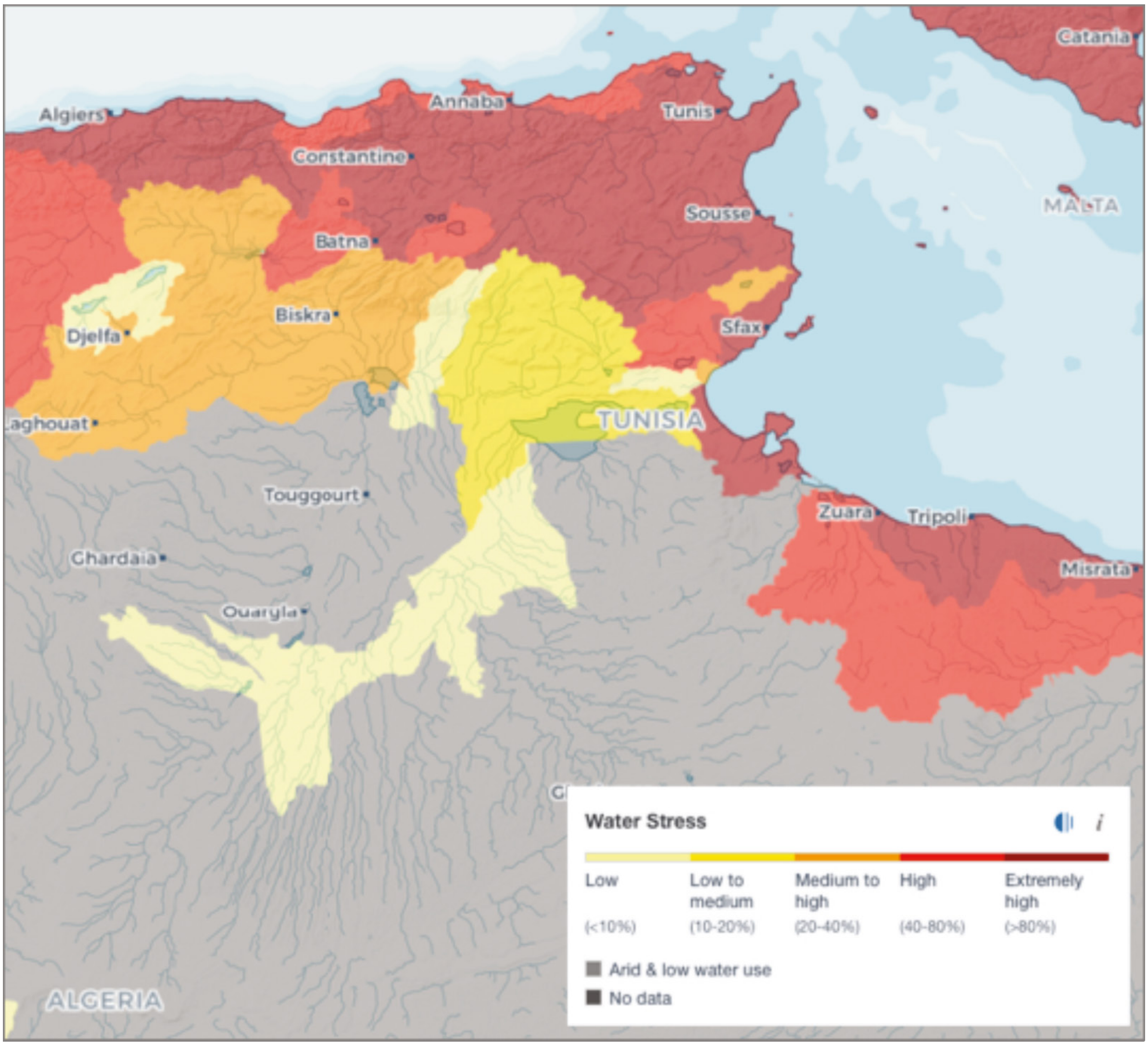
Tab. 7.1 **Overview of water demand of different PtX technologies**

Technology	Unit	Water demand		Reference
Electrolysis (AEL/PEM)	m^3 H_2O /t H_2	10-24	Assumptions on operational water demand vary considerably	Siemens AG, IRENA 2020
Methanation	t H_2O /t Syngas	-2.25	Water is produced as by-product	Swalus et al. 2012
Methanol synthesis	t H_2O/ t MeOH	-0.56	Water is produced as by-product	Niklaß et al. 2016
Fischer-Tropsch synthesis	t H_2O/ t Syncrude	-1.3	Water is produced as by-product	Fasihi et al. 2016
Syncrude upgrading	t H_2O/ Fuel	-1.3	Water is produced as by-product and partly used to generate steam	Bergins et al. 2019
Ammonia synthesis		-	Water demand negligible	

(Source: Based on Zelt et al. 2021)

It may be necessary to purify the water, as different technologies require different levels of water purity. In general, the highest level of purity is desirable to ensure that the performance and consistency of the reaction is maintained. For electrolysis in particular, high purity is necessary as impurities can impact on the lifetime of the electrolyser stack and the need to replace the stack more often due to damage would increase the cost of producing hydrogen (IRENA 2020). Compared to alternative fuels from biomass, however, all PtX products demand significantly lower volumes of water (Schmidt et al. 2016). Nevertheless, local water availability and existing uses are also relevant aspects that must be taken into account.

Tunisia is one of the most arid countries in the Mediterranean, suffering from high water scarcity levels. With water availability of 380m³ per capita per annum, Tunisia falls well below the internationally specified critical limit of 1,000 m³ per person. The country's territory spans across different hydrological regimes but largely experiences annual cycles of water surplus and drought. Tunisia's challenging water supply situation has led to it being quite advanced in terms of water storage, resource planning, and water management, meaning that available water resources are already almost fully mobilised (Chahed et al. 2010). Tunisia is also one of the top-ranking countries in North Africa in terms of drinking water access, at close to 98%. Despite these positive aspects, the condition of the water infrastructure has deteriorated over recent years, meaning that in some regions almost half of the water is currently lost (Reuters 2019).



(Source: WRI 2021)

Fig. 7.1 **Water stress levels in Tunisia by 2040: business-as-usual scenario**

Climate change is further accelerating the critical water situation by prolonging drought periods, increasing temperatures, and altering rainfall patterns. As such, Tunisia is expected to remain one of the most water-stressed countries in the world in 2040, with even more areas experiencing extremely high water stress (WRI 2015). According to a business-as-usual scenario by the World Resources Institute (2021), most of the northern parts of the country will experience extreme water stress levels (Fig. 7.1). At the same time, water demand is rising and is expected to increase in the future.

To meet its growing water demand, Tunisia is increasingly turning to non-conventional water resources, which include desalination and wastewater treatment. In 2018, about 5.6% of the water produced in Tunisia came from desalination plants (SONEDE 2019). Currently, a number smaller desalination plants are in operation in Tunisia (see Section 2) and in 2018 one of four large-scale plants to meet the growing municipal water demand came into operation in Djerba. The three other plants are scheduled to be built in Sousse, Sfax, and Zarat (Gabes Governorate) (Water World 2018). Desalinated water in Tunisia is mainly used to meet drinking water demand but also, to some extent, for industrial applications.

To ensure that the production of hydrogen is sustainable, especially in water-stressed regions such as Tunisia, water as a resource must be explicitly considered in development strategies, further elaborated in project planning, and subject to local impact assessments (IRENA 2020). Although it is frequently argued that water is not a barrier for large-scale hydrogen production (ibid.) in dry regions, a limited water supply could be a relevant factor in siting decisions. For the MENA region (and, therefore, Tunisia), desalination is widely acknowledged in most cases to be the only solution for sourcing water for hydrogen generation without putting additional stress on local ground and surface water resources. The impact of adding desalination facilities in terms of cost and efficiency is modest, with desalination generally representing less than 1% of the investments needs. However, Tunisia would have to evaluate where the optimal sites for the location of the hydrogen and synthesis plants would be: close to the coast and potential demand centres or close to the re-newable energy sources mainly located inland? In the latter case, water would have to be transported inland, which could add to the costs. For water supply to be green and sustainable, desalination should be powered by renewable energy, at least on a balance sheet basis (e.g., through bilateral PPAs). To date, however, only a limited number of desalination plants use renewable energy – the vast majority in the MENA region use fossil fuels. This could be an obstacle for the implementation of renewable desalination, as Tunisia (in common with other countries) lacks experience in this area.

Furthermore, in order to avoid or manage potential environmental impacts of desalination from the outset, environmental risks need to be evaluated. These risks vary depending on the location, technology, type of feed water and management of the brine (Elsaid et al. 2020) and are mainly related to the discharge of concentrates and chemicals into the marine environment (e.g., increase in seawater temperature, salinity and water flow (Lattermann et al. 2008)). Tunisia already requires an environmental impact assessment for desalination plants. In the new desalination plant in Djerba, for example, technical measures have been implemented to counter the risks through rapid dilution of the effluents. If desalination is concentrated in a specific area – e.g., close to industrial and urban centres, which potentially offer favourable conditions for the establishment of a new PtX industry – the environmental side effects must be analysed not only for individual desalination plants but for the development of the entire sector. Furthermore, to avoid conflict and create local benefits, desalination plants should be built to serve multiple water needs – not only to supply water for the production of hydrogen (IRENA 2020). In general, the question of allocation priorities with regards to water should be worked out at the political level with the involvement of stakeholder groups and citizens in order to support consensus building and avoid (or at least reduce) conflicts over water.

7.1.2 Land

As well as water, land is required to establish PtX production capacities, to generate renewable electricity, and to capture CO_2 from the atmosphere for the synthesis processes. As only a limited number of smaller-scale hydrogen and synthesis plants have so far been built, figures relating to the land area required vary significantly. The general assumption is that the land area required will vary according to the plant type, but the area demand per output unit for larger plants will be lower. For electrolysers, estimates from the literature suggest that 100MW plants require a land area between 35 m^2 and 60 m^2/MW (IRENA 2020, Noack 2014), while 1000MW plants require about 13 m^2 to 17 m^2/MW, which could decrease to between 8 m^2 and 10 m^2/MW in the future (IRENA 2020). The land requirements vary slightly depending on the type of electrolyser: AEL needs more space than the more compact PEM technology. Based on existing plants, the land requirements for AEL are quantified at 0.92 m^2 per tonne of hydrogen per annum, while PEM requires 0.79 m^2 for an equivalent output (Zelt et al. 2021). With technological development and large-scale implementation, however, in the future both technologies are expected to require less than 0.39 m^2 of space per tonne of hydrogen per annum (ibid.). About three quarters of the area is required for the electrolyser building and the electrical equipment (e.g., switchgear and transformers) (IRENA 2020). There is no detailed information available about the land requirements of synthesis plants, but it would be fair to assume that the requirements are similar to other chemical facilities and account only for a limited share of the overall land demand for PtX production. For the synthesis processes that require CO_2 as feedstock, such as Fischer-Tropsch or methanol synthesis, additional land would be required to capture CO_2 from the atmosphere (point sources would not require relevant land resources but to be net CO_2 neutral, carbon must be sourced from the atmosphere). To capture CO_2 directly from the air it is es-timated that a land area of 0.1 m2 per tonne of CO_2 per annum would be required (Zelt et al. 2021), but as the technology is still in the development stage this area could decrease in the future.

Compared to the land required for hydrogen and synthesis plants, the area required for the renewable energy capacities is much larger. In the MENA region with its high radiation levels, about 20,000 m^2 would be required per MW photovoltaic installation (Zelt et al. 2021). In the future, the specific area requirements of PV projects could decrease to 17,000 m^2/MW if increases in efficiency are achieved (ibid). Concentrated solar power (CSP) projects currently have an estimated average land requirement of 40,000 m^2/MW, with potential further reductions of up to 20% if increases in conversion efficiency are achieved (ibid.). Wind power projects currently have an estimated land requirement of about 200,000 m^2/MW (based on operational wind projects in the MENA region) but in the future the land requirements could decrease to 80,000 m^2/MW (ibid.). For wind power in particular, however, the land coverage is relatively low and theoretically the land can still be used for other purposes (Schmidt et al. 2016). In Tunisia, because the renewable energy potential is largely located in the less populated inland areas and in the southern desert areas, there is likely to be only limited demand for other uses of the land. Overall, land requirements for the installation of renewable energy capacities are expected to be less of a challenge in Tunisia than siting industrial facilities and desalination plants in the densely populated and touristic coastal areas. Nevertheless, local land use patterns and the potential impacts of renewable energy installations must be evaluated on a site-specific project basis to avoid land use conflicts. Plants are usually constructed in the vicinity of built-up areas, as opposed to in completely unpopulated areas, which can have impacts at local level that are not immediately obvious.

7.1.3 Greenhouse gas emissions

National, international, and private sector decarbonisation efforts are the main drivers for the increased interest in PtX. As such, the level of GHG emissions stemming from PtX products over their life cycle is an important indicator for measuring the environmental benefits compared to fossil fuel use. Two input factors are particularly relevant for the performance of PtX in terms of GHG emissions: the electricity input and the origin of the CO_2 for the synthesis processes.

In terms of electricity input, the environmental impact of PtX on GHG emissions will depend heavily on the hydrogen production pathways. A prerequisite for hydrogen to be classified as ''green'' is the use of electricity from renewable sources. In practice, however, industrial plants are generally not self-sustaining and source at least some of their electricity from the grid: today electricity supplied from the grid is a mix of fossil and renewable power. As the demand centres and renewable energy potentials are located in different parts of Tunisia, it is unlikely that all the hydrogen and synthesis plants will be located adjacent to (or directly connected to) renewable energy plants. As there is currently a limited share of renewables in the Tunisian electricity mix, the electricity sourced from the grid will be mainly fossil-fuel based (at least in the short to medium term). It is, therefore, important to ensure that the development of hydrogen is coupled with the respective development of renewable capacity, so the hydrogen can be considered "green" from an accounting point of view. This so-called «additionality» means that any renewable electricity used to produce hydrogen and downstream PtX products, especially for export, must be linked to the addition of new renewables capacity, in contrast to buy-ins in existing or planned capacity.

In terms of the second aspect relating to the overall climate benefit of PtX (i.e., the source of the CO_2 for synthesis processes), there are various options. CO_2 can either be obtained from point sources, such as existing carbon-intensive industries, (e.g., cement production), or extracted from the atmosphere – either directly using DAC technologies or indirectly from biomass. For PtX fuels to become sustainable, fossil-based CO_2 point sources are not a long-term option. However, recycling a portion of the CO_2 emitted by the industry could still support emission reductions in the short and medium term. Given that Tunisia is challenged by water scarcity, which already limits agricultural production, the use of biomass as an indirect source of CO_2 is not realistically a sustainable option. Therefore, for long term sustainability, extracting CO_2 directly from the air using DAC technology appears to be the only option. However, this technology is currently still in the development stage and is much more expensive than the other two options. Consequently, recycling CO_2 emitted by the industry is widely regarded as a potential bridging technology for the short to medium term, until DAC technology matures and costs for the generation of CO_2 become more competitive.

7.2 EMPLOYMENT CREATION

One of the main socio-economic benefits expected from the development of the PtX sector in Tunisia is the creation of expertise and employment. It is expected that the production of green hydrogen will support job creation and potentially create multiplier effects if further downstream processing steps are to take place in Tunisia to create higher value-added commodities for export (e.g., green ammonia instead of hydrogen) (IRENA 2019). Consequently, the number of jobs created will depend on the extent to which activities along the value chain can be relocated to Tunisia, based on lower costs and high potential for renewable electricity generation. These activities could include research and development (R&D), technology manufacture, and the construction and operation of PtX plants. Currently, in the technology and sector development stage, most jobs are allocated in R&D; the manufacture of emerging technologies is not expected to create significant job opportunities in the short term (IEA 2020c). However, in future the manufacture of components and the construction and operation of PtX plants will become the main sectors of employment (Guidehouse 2019). It is anticipated that a large share of the jobs (about two thirds) will be in the construction and operation of the renewable energy plants to generate the electricity required to produce green hydrogen (ibid.). A larger number of these jobs are expected to be temporary, in the construction phase.

It is expected that skilled professionals will be required for most activities, ranging from highly qualified engineers to application-oriented technicians (FCH 2 JU 2019). Many of these jobs do not currently exist in Tunisia and will require new skills and education/training. This implies the need for significant levels of training and capacity-building to develop an educated and skilled workforce (Bezdek 2019).

As the sector is in an early phase of development, little is known about the actual potential for job creation, but some studies have made estimations. FCH 2 JU (2019) based its assumption on the number of jobs created in similar industries and predicts the creation of an average of 13 jobs/€1 million revenue. About 70% of these jobs are in the manufacture of hydrogen production and distribution equipment and implementation, while about 30% of the jobs relate to specialised components and end use applications (ibid.). The IEA (2020) estimates the number of jobs based on the volume of capital investment, with between 3 and 8 new jobs per US$1 million invested in technology innovation and 5.5 jobs per US$1 million of capital investment for the hydrogen sector specifically. Another estimation is based on the production of hydrogen in TWh, assuming an employment factor of between 575 and 775 jobs/TWh (Guidehouse 2019). The two latter studies point out that the capital-intensity of the renewable energy generation required to produce hydrogen means the number of jobs per investment and per output unit is lower than for other technologies. Ram et al. (2019) estimate the creation of about 4.75 jobs per MW by power to gas (including 1.86 jobs in manufacturing, 2.6 jobs in construction and installation, and 0.28 jobs in operations and maintenance), excluding jobs created from renewable energy installations. In addition, they estimate a regional employment multiplier for the MENA region of 1.51 in 2030 and 1.23 in 2050 based on assumptions on labour productivity. Another estimation is based on the plans for one of the largest green hydrogen complexes for industrial use in Europe, scheduled to be built in Spain. €1.8 billion is being invested in the project over seven years, which is designed to have 800 MW green hydrogen production capacity. The expectation is that almost 4,000 qualified jobs will be created (REVE 2020). This equates to 5 jobs/MW or 2.2 jobs per €1 million, which is much lower than the IEA's estimation (2020). Taking the different ranges of job creation ratios into account (Tab. 7.2), if electrolysers and the corresponding renewable energy capacities were to be installed in Tunisia to generate about 4GW of hydrogen – which represents 10% of the foreseen import by the EU by 2030 – between 20,000 and 32,000 jobs could be created. The share of jobs located in Tunisia would depend on the value chain development within in the country.

Tab. 7.2 **Employment effect estimates for the hydrogen sector**

Employment factor	Source
• 13 jobs/€1 million revenue	FCH 2 JU (2019)
• 5.5 jobs per US$1 million of capital investment in hydrogen	IEA (2020)
• 575-775 jobs/TWh hydrogen	Guidehouse (2019)
• 4.75 jobs per MW power to gas (excluding jobs for renewable energy generation)	Ram et al. (2019)
• 5 jobs per MW	REVE (2020)
• 2.2 jobs per €1 million of capital investment in hydrogen	

To summarise, to develop a PtX sector in Tunisia, additionality of renewable energy capacities must be ensured. To avoid additional pressure on the already scarce water resources, water for the production of hydrogen should be sourced from desalination powered by renewables. Ideally, multi-purpose desalination plants that provide a share of water for local uses should be built. The environmental impacts of the wide-scale deployment of desalination need to be considered. Land requirements will arise from the expansion of renewable energy capacities and, to some extent, for electrolysis plants. In terms of employment effects, the sector is still in its early stages globally so the actual job creation potential is unknown. What is clear, however, is that to create multiplier effects, Tunisia should aim not only to produce and export green hydrogen, but also to locate downstream processing steps in Tunisia and export higher value-added products.

8 Synthesis and recommendations

Based on the results of the analysis presented in the previous sections, this chapter summarises the most important findings and derives recommendations for Tunisia to develop a sustainable PtX sector.

PtX and particularly green hydrogen have recently attracted a great deal of attention as a potential central pillar of the global energy transition. This interest is rooted in the numerous advantages that the conversion of renewably generated electricity into hydrogen and its derivatives offers for advancing the energy transition. Storable and transportable, hydrogen can be used flexibly and offers solutions for applications for which other decarbonisation technologies are not realistically available; for example, in heavy-duty transport, industrial processes, or parts of the heating sector. However, currently green hydrogen represents a niche market. Although many of the technologies are close to being ready for commercial use, large-scale implementation and the combination of the different components into integrated production systems are still lacking. Furthermore, renewable-based hydrogen and PtX products are not yet cost competitive with fossil-based fuels. Nevertheless, many new projects and investments in PtX have been announced and numerous countries are developing strategies. Companies and industry experts expect significant market growth for hydrogen worldwide by 2030 and especially thereafter. This is also underlined by the analysis of the global, European and German hydrogen/PtX demand scenarios. Initially, demand is expected to develop primarily in the industrialised countries with ambitious decarbonisation targets and related regulations – such as in Europe, which aims to become carbon neutral by 2050. Even if global demand is smaller than in the more ambitious scenarios, the market is still expected to grow to a notable size in the long term, which could offer economic development opportunities for Tunisia as a possible producer and exporter of hydrogen.

The analysis of the framework conditions shows that Tunisia, due to its renewable energy potential, proximity to Europe, and qualified workforce, benefits from good conditions to become a PtX producer and exporter. As outlined, the technical potential of renewable energies is sufficient to meet domestic demand and to produce green hydrogen for export. However, the low share of exploited renewable energy in the electricity mix (currently only 3%) creates doubt over Tunisia's ability to rapidly expand renewable energy capacities, which could be a limiting factor for the development of a PtX sector. Therefore, first and foremost the focus should be on converting the Tunisian power sector to a renewable basis. It is inevitable for its sustainability to design the PtX development for export in a way that leads to additional capacities for renewables and thus, does not decelerate but accelerate the domestic energy transition in Tunisia.

For Tunisia itself, the need for the introduction of PtX applications would be limited under the current climate targets. However, as shown in the scenarios with ambitious decarbonisation targets, hydrogen and synthetic fuels could become relevant for the Tunisian energy transition in the medium and long term. For example, as a flexibility option for balancing fluctuating renewable electricity generation and demand (either to absorb short-term generation peaks or to balance seasonal supply and demand discrepancies). Optimisation of the electricity system would however have to take place in parallel with the expansion of renewable capacities. Renewable energy capacities for the production of PtX would have to be constructed in addition to the capacities already planned to meet direct electricity demand.

Furthermore, replacing fossil-based input feedstocks in industries that export to countries with (planned) strict carbon regulations and pricing schemes could make Tunisian products more competitive in the future. Especially as the introduction of the European carbon border adjustment mechanism has the potential to alter the competitive landscape of different sectors by putting carbon-intensive products at a disadvantage. Another potential driver could be to replace imported fossil-based products in existing applications with domestically produced products based on renewable electricity, which would contribute to energy security and the resilience of the affected sectors. The analysis has shown that for existing applications of hydrogen the most likely opportunities in Tunisia could be in the fertiliser industry, where imported ammonia could be replaced with green ammonia produced domestically from renewable electricity. This development would of course depend on the cost development of the technology and the market willingness to pay for green products, which are initially expected to be mainly export markets. Imported fossil-based methanol could also, in theory, be replaced with green methanol but the opportunities are smaller due to the limited demand for methanol in Tunisia compared to the average plant size in industrial methanol production. Green methanol production would, therefore, only make sense with an export focus.

As well as replacing existing applications, a range of new applications for PtX are under development – many of them in the transport sector. Following the principle of efficiency first, the main applications can be expected in the sectors where direct electrification is difficult or impossible. This is the case in heavy-duty transport, including trucks, coaches, rail, maritime transport, and aviation. Based on the technological-readiness level, mass market acceptability of PtX for maritime transport and aviation is only expected in the long term (after 2035). However, these sectors are more likely to adopt PtX due to their international integration and the lack of alternatives. For example, flights to and from Tunisia are already subject to carbon offsetting on a voluntary basis. In the long term, the decarbonisation efforts of the aviation industry and the potentially increased costs for offsetting emissions for flights to and from Tunisia could create interest in the production of green jet fuel in Tunisia. Other modes of transport, like fuel cell trucks, buses, coaches and trains, are already in later stages of development and could become cost competitive with conventional fuelled vehicles by 2030. For these modes of transport, today's investment decisions should be evaluated regarding the risks of potential lock-in effects and stranded investments in fossil-based technologies. The long lifetimes of infrastructure and, to an extent, vehicle fleets could result in technology and infrastructure that is built or purchased today still being in operation in 2050. This would also apply to for example, the investment currently planned in the Tunisian rail transport sector. If new diesel locomotives are purchased these would be expected to have an average lifetime of a minimum of 25 to 30 years and will still be in operation in 2050. While fuel-cell electric locomotives as an alternative investment option are not yet cost competitive today, they could be by 2030.

The risks are not limited to technological lock-in effects and potential stranded investments in both fossil fuels and PtX technologies; environmental factors also need to be considered when discussing PtX development in Tunisia. Important parameters in this context are water and land requirements. Water, in particular, plays an important role in a water-scarce country such as Tunisia. To be sustainable, the water required to produce green hydrogen would have to be obtained from desalination plants powered by renewable energy. However, Tunisia lacks experience in desalination using renewable electricity, and consideration must also be given to the man-agement of possible environmental impacts from the effluents and potential conflicts when using desalinated water for export purposes. Technical solutions such as rapid dilution of effluents, as implemented in the desalination plant in Djerba, can help reduce environmental risks. Meanwhile, stakeholder participation in the planning process or the construction of multipurpose desalination plants that also directly benefit the local population can be options that help reduce the risk of water resource conflicts.

In contrast to these risks, one of the main emerging opportunities related to the development of the PtX sector in Tunisia is the creation of know-how and employment. These opportunities certainly exist, but it is crucial to create the right framework conditions for Tunisia to capitalise on these benefits.

In terms of cost and financing, under an optimistic scenario green hydrogen production in Tunisia could be cost competitive with its peers. However, transportation costs, which present a high share in the green hydrogen supply costs to Germany, are a major influencing factor. The more promising options, therefore, appear to be the conversion of green hydrogen to PtX fuels that are more easily transportable and storable. As shown by the cost calculations, transportation costs represent only a small share of the overall costs for products like green ammonia, methanol, and synthetic kerosene. Furthermore, locating value-added process steps within Tunisia would create greater benefits for the country in terms of economic and industrial development. The hydrogen input is the main cost factor for these PtX products. In this respect, a significant price drop for hydrogen is expected with the growing number and scale of electrolysers installed worldwide. Similarly, the cost of providing CO_2 via direct air capture (required as an input for the synthesis of methanol, methane, and synthetic kerosene) is expected to fall substantially over time. However, from a cost perspective, PtX products will still not be competitive with conventional fossil-based fuels without either carbon pricing schemes or greater willingness to pay for the "green" value of green hydrogen and its derivatives.

Although there are many uncertainties regarding PtX development, and it is difficult to predict how the sector will develop, it would appear worthwhile for Tunisia to assess the opportunities in more detail and position itself at an early stage. Tunisia should take advantage of the support offered by potential importing countries to build up know-how and expertise in the country. Furthermore, the early establishment of a regulatory and legal framework for PtX could facilitate future investments in the sector in Tunisia and ensure that PtX development takes place in a sustainable manner.

A number of recommendations for PtX development in Tunisia can be derived based on the results of this analysis:

Technology and industrial development

- Due to the high uncertainties related to PtX, a step-by-step approach to building hydrogen supply chains, experience, and infrastructure is recommended for Tunisia. The most promising opportunities for PtX are to build on existing uses where a market already exists; in the long term this could help to trigger deployment in other related sectors. In Tunisia this strategy could primarily be based on ammonia, which is currently imported and used in the fertiliser industry. By producing fertiliser using green ammonia, the fertiliser industry could be strengthened and align its business with long-term global decarboni-sation efforts.

- For sectors that currently use hydrogen indirectly, detailed analysis should be conducted concerning the feasibility of replacing imported products like ammonia or methanol with locally produced green products. A detailed analysis of the use and target markets of the end products would be required to assess the potential profitability of the green products.

- Other opportunities could open up for new applications, especially in heavy-duty road transport comprising trucks, coaches, and rail freight transport. The most promising applications are for long distance transportation in dedicated fleets that could refuel at centralised points – for example at the ports to which good are delivered – or for regular bus connections between Tunis and other cities. In optimistic scenarios, these FCEVs could become cost competitive with conventional fuels as early as 2030, depending on the global development of the PtX sector. With the current planned investments in the rail sector in Tunisia, it is recommended to assess the opportunities for fuel cell trains, otherwise Tunisia might risk technological lock-in to fossil-based rail transport due to the long lifetimes of the locomotives.

- Other potential applications include the production of fuels for aviation and the maritime sector; however, these are long-term opportunities due to their early technological development stage. The international nature of these sectors means they will be directly affected by international and regional decarbonisation strategies. It could be possible to develop concrete pilot projects in cooperation with the private sector for these applications. In general, the aviation industry appears more interested in the development of green synthetic fuel than the international maritime sector.

- More detailed and integrated energy and industrial development scenarios showing different pathways for domestic uses and export of PtX products against the backdrop of the energy transition in Tunisia should be modelled.

- To determine the infrastructure needs (e.g., grid extensions, storage capacities, pipelines), it would be crucial to undertake detailed analysis of the potential to use existing infrastructure and the need for additional infrastructure for the transportation, storage, and export of PtX products. For example, the options to use existing infrastructure originally constructed for the import of ammonia also for export purposes should be assessed. In general the potential of Tunisian ports to handle PtX products as commodity but also as fuel for the maritime sector should be analysed.

- The potential to produce ammonia not primarily as a chemical but as an energy carrier for exporting green hydrogen/renewable energy should be analysed in more detail. Compared to exporting green hydrogen, this could offer better opportunities for Tunisia due to reduced transport costs compared to the direct export of green hydrogen.

- In order to derive the greatest possible benefit from the potential development of a PtX sector, Tunisia should try to establish as many steps of the value chain as possible in its own country. This entails building up the necessary know-how as well as designing the appropriate legal and regulatory framework. Here a detailed analysis of the value chains and the local opportunities along these value chains should be conducted in further studies.

- Developing strategic demonstration projects in Tunisia to gain experience, build knowledge, and showcase how PtX could work in Tunisia could be a way of putting Tunisia on the map in terms of PtX. An initial demonstration project should be of a reasonable size (in the range of several MW) in order to gain the necessary operational experience for potential future large-scale industrial applications. This pilot project should be used also as platform for research and training.

- Country-wide and local site analyses should be carried out to determine where it would be most feasible to locate electrolysers, e.g., near renewable power plants or near the coast where the main demand centres are located and from where PtX products could be exported. The options would require different transport infrastructures, as either electricity or water and the PtX product would have to be transported. In addition, consideration should be given to whether PtX plants should be developed as stand-alone systems, which would require additional storage capacity for renewable energy, or whether they should be connected to the grid, which raises questions about ensuring renewable electricity supply for the hydrogen production.

Institutional and regulatory development

- Governments have a central role to play in setting the overarching long-term policy framework. One step to demonstrate to investors and other stakeholders that Tunisia is taking PtX seriously would be to establish targets for green hydrogen or/and develop a PtX roadmap and strategies to provide long-term policy signals.

- In addition to an overall strategy, it is crucial to adapt international standards and develop and align regulations, legislation, and support programmes for PtX. These could, for example, concern technical aspects such as the blending of hydrogen into the gas grid, as well as processes such as licensing and permits for the establishment of electrolysers. Removing regulatory barriers reduces the risks for investors. The basis for developing these regulations could be a detailed analysis of existing regulations in other countries on green hydrogen and PtX – or those currently under development – as well as an assessment with industry players of aspects that would encourage them to invest in PtX and green hydrogen in Tunisia.

- Another important step would be the phase-out of the high energy subsidies for fossil fuels in Tunisia to reduce the cost gap between green hydrogen and conventional fuels in the heavy-duty transport sector.

Costs and financing options

- The most significant cost driver of PtX is electricity generation to produce green hydrogen. Although the costs of renewable electricity are expected to further decrease by 2050, electricity will remain a major cost factor in both of the modelled scenarios. Accordingly, measures that enable the rapid and widespread deployment of renewable energy in Tunisia would also support the development of the green hydrogen sector.

- For export markets, transportation costs play an important role. High uncertainties exist in regard to the transportation costs of green hydrogen. Under current conditions these costs could be the decisive factor regarding Tunisia's competitivity. In contrast, for PtX products converted from green hydrogen the transportation costs represent a small share of the overall costs. This could make these products more competitive even if transported over longer distances. The cost advantage of renewable electricity production in Tunisia compared to locations with less favourable renewable energy conditions could therewith have a more pronounced cost effect.

- Most PtX products are not expected to become cost competitive with conventional fuels in the short term without the support of additional measures, such as increasing carbon prices or an increased willingness to pay for products that are carbon neutral or have a much smaller carbon footprint. These developments depend on external factors that Tunisia would only be able to influence to a limited extent. Therefore, in the beginning it will be important for Tunisia to establish direct partnerships with/between companies or with countries who guarantee the offtake of PtX products. To guarantee offtakers that the PtX products are carbon neutral, the introduction of a guarantee of origin is recommended.

- PtX is at an early development stage and investments in the sector have high risks and are capital-intensive. Therefore, to attract investors it will be necessary to introduce de-risking instruments both on the political and the financing side. The design of these measures in concrete terms would depend on the PtX product and sector concerned. Further research into suitable financing options is required. Initially, individual financing models on a project basis will be required, given that technologies are not yet commercially viable and there is not yet a market or pricing for green products.

Sustainability

- To ensure that PtX development in Tunisia takes place in a sustainable manner, it is recommended that Tunisia develops sustainability criteria including aspects such as water use, land requirements, and priorities for the use of renewable electricity.

- A major requirement concerning sustainability is the need to ensure that Tunisia’s domestic energy transition benefits from the PtX development. Tunisia must ensure that renewable capacities for the generation of green hydrogen are in addition to the foreseen capacities needed to generate electricity for direct applications. Furthermore, an area allocation for certain uses would also be advisable, so the cheapest renewable potential is used for domestic power generation and not for electricity generation for the export of PtX.

- For a water-stressed country such as Tunisia, the assumption is that water for PtX would have to be obtained via desalination to ensure sustainability. It is recommended that Tunisia regulates the use of water for the production of green hydrogen to avoid use conflict.

- To ensure carbon neutrality, Tunisia should introduce a requirement for desalination to be powered by renewable electricity. This would also advance the know-how in the country of renewable desalination, which could support the greening of desalination operations and, consequently, the water supply in other sectors.

- Desalination can have a range of negative environmental impacts, mainly stemming from the discharge of the brine containing high levels of salts and dissolved minerals. Therefore, the possible environmental effects of the scale-up of desalination capacities for PtX should be assessed. Tunisia should note that it would also bear the environmental costs for exported PtX products.

- To avoid conflict and create benefits for Tunisia above and beyond the PtX sector, the desalination plants built to provide water for hydrogen production should be required to be multi-purpose plants, of which a defined share of water is allocated for other local uses.

- To provide the CO_2 required for the conversion of green hydrogen to PtX products, carbon capture at point sources in existing carbon-intensive industries could be a suitable bridging technology but, in the long term, CO_2 would have to be captured directly from the air (DAC). The use of biomass to generate CO_2 is deemed unsustainable for Tunisia due to its limited water resources.

Capacity-building

- Supporting research in the field of PtX in Tunisia would be crucial to develop know-how in the country and, therefore, to rely less on external experts. To achieve this, Tunisia could support existing public research and development in institutions already working on renewable energy, namely:

    - The National School of Engineering of Tunis (ENIT)
    - The National School of Engineering of Monastir (ENIM)
    - The Ecopark of Borj Cedria

  Tunisia should design and implement a common specific programme of capacity building in these research institutions within the next few years. For example, a specialised research centre for PtX technologies could be established (as it was done for example in Oman).

- In addition to these research institutions, the capacity of public operators who could be interested in PtX should be reinforced in order to gradually integrate this new technology into their long-term strategies. These should include:

  - The Electricity and Gas utility (STEG), which could become involved in several parts of the PtX value chain, such as renewable power generation, hydrogen injection in the gas network, the use of hydrogen production to absorb excess renewable electricity, etc;
  - The National Company of Oil Products (SNDP), which could be interested to integrate the commercialisation of synthetic fuels, particularly for aviation, in its long-term development strategy;
  - The Tunisian Refinery (STIR), which could be interested in the use of green hydrogen for its processes;
  - The Tunisian Chemical Group (Groupe Chimique Tunisien), which is the main producer of fertiliser and imports large quantities of ammonia for its production.

- Next to research and public institutions, capacity building would also be important for the relevant industries that are potential producers, users or transporters of PtX products. Furthermore, training or retraining in the oil and gas sector could be an option to develop technical expertise rather swiftly.

- Finally, it would be crucial to integrate modules on PtX in existing master courses specialising in renewables or energy more generally, and in a next step to establish specified bachelor and master courses at universities. This could be complemented by financing PhD research on this subject.

- These different capacity building elements could be jointly supported by a comprehensive national research and development programme that is implemented alongside regulation development.

Stakeholder involvement

- PtX development requires the interplay of different sectors in terms of technical developments, system integration, market development, infrastructure development, regulations, and standards. Accordingly, a wide range of stakeholders from different sectors would be involved in the development of a PtX sector in Tunisia. It would, therefore, be advisable to establish a dialogue between the different stakeholders to identify knowledge demand, joint opportunities, and potential bottlenecks.

- A wide range of stakeholders should also be involved in the elaboration of sustainability criteria for the development of the PtX sector in Tunisia. The involvement of these stakeholders should be integrated in form of a specific group of representatives from relevant government departments, national energy companies, and environmental agencies but also civil society organisations. This group should include at least the main following stakeholders:

  - The Ministry of Energy, as PtX must be integrated into the energy sector's long-term low carbon strategy;
  - The Ministry of Industry, particularly for industrial security aspects;

- The Ministry of Transport, to integrate PtX in the transport sector;
- The Ministry of Agriculture, for the water and land issues;
- The Electricity and Gas company (STEG);
- The National Agency for Energy Conservation (ANME).

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