Fraunhofer ISI

STUDY ON THE OPPORTUNITIES OF "POWER-TO-X" IN MOROCCO

10 HYPOTHESES FOR DISCUSSION

REPORT TO

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Executive Summary

Morocco has a very high renewable (RES) energy potential (wind and solar). Since 2009, the Kingdom has developed an ambitious policy of large-scale renewable energy deployment in the power sector. Further, there is a global dynamic observed over the past ten years, which has resulted in an increasing penetration of renewable energies into the energy mix of almost all countries on the planet. This tendency has resulted in a **substantial drop in the kilowatt-hour price of renewable electricity to record low levels**. This important reduction in cost of electricity generated by RES further encourages governments to install even more renewable capacities, inducing further cost degression for RES. Therefore, some RES manufacturers, producers and R&D institutes are considering other uses for the renewable electricity. This is a new paradigm commonly referred to as "Power-to-X" (PtX). The X can stand for: heat, hydrogen, gas, liquid, or chemical elements. Power-to-X has gained increasing interest around the world in recent years. **Hydrogen and, increasingly, ammonia, are among the most interesting molecules for the "Power-to-X" process**. These are raw materials that are used in several industrial processes.

Morocco's strategic geographical proximity to Europe, along with its exceptional potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with very high added value.

The objective of this study is to identify the opportunities of PtX in Morocco. **We formulate for this analysis 10 hypotheses on PtX and its opportunities for Morocco. This approach is taken because there are still quite some uncertainties about the possible future role of PtX, both in Europe and countries like Morocco.** The formulation of such hypotheses, supported by analysis of the present knowledge and uncertainties, helps to feed the necessary discussion processes to determine more precisely the possible future role of PtX technologies in the energy system.

The **ten hypotheses formulated** and discussed in Chapter 5 are the following:

1. Hypothesis 1: The demand for PtX will be driven by the requirements on developed countries to reach a reduction of 95% in view of contributing to the 1.5°C target of the Paris Agreement.
2. Hypothesis 2: If the requirement would only be 80% reduction in GHG (which is possibly compatible with a 2°C scenario) there would be very limited need in developed countries for PtX.
3. Hypothesis 3: Developing countries have lower GHG reduction requirements by 2050, hence less pressure to introduce PtX for own purposes.
4. Hypothesis 4: There is no need for PtX from the pure requirement of a 100% RES share in the power sector. This concerns both Morocco and for example European countries, as long as the power systems are optimised (grid expansions, market arrangements,...).
5. Hypothesis 5: Morocco can capture a non-negligible share in the world-wide demand for PtX.
6. Hypothesis 6: Power exports to Europe is not a strong competitor for PtX exports.

7. Hypothesis 7: PtX products may under favourable conditions become economic compared to fossil competitors beyond 2030.
8. Hypothesis 8: The production of synthetic ammonia offers - under favourable conditions - economic opportunities to Morocco as a producer of green ammonia for own purposes and for export.
9. Hypothesis 9: RES development should be accompanied by a hierarchy principle minimising necessary expansion, even with further falling cost, to minimise broader environmental impacts.
10. Hypothesis 10: Sustainability criteria play an important role for PtX in Morocco.

On the basis of the analysis of the 10 hypotheses the following **recommendations for short- and medium term R&D on PtX in Morocco** can be derived:

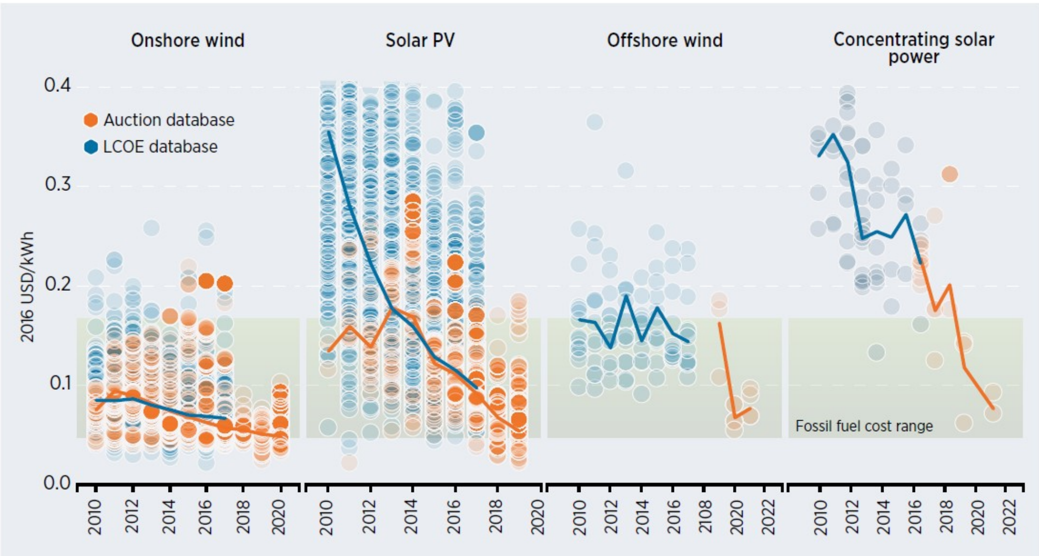
1. Establishment of a detailed 2050 energy and climate strategy and of 2050 energy and climate targets for Morocco.
2. Elaboration of a roadmap for hydrogen and derived PtX products for Morocco.
3. Elaboration of an infrastructure roadmap for hydrogen and derived PtX products for Morocco.
4. Development of sustainability criteria in the frame of the hydrogen/PtX roadmap.
5. Investigation of governance structures for a Moroccan hydrogen and ammonia industry.
6. Investigation of electricity market design to support a Moroccan hydrogen and ammonia industry.
7. Development of technological R&D and demonstration plants of a reasonable size of several MWs which can enhance experience with technologies. Development of a market introduction scheme.

1. Introduction

Morocco has a very high renewable (RES) energy potential (wind and solar). Since 2009, the Kingdom has developed an ambitious policy of large-scale renewable energy deployment. Its vision is to achieve 42% of the electricity capacity from renewable energies by 2020, and 52% by 2030, out of a total installed capacity by then of around 14 and 22 GW respectively. Recently, more ambitious RES targets for the electricity generation of 59% or possibly beyond 60% have been discussed.

Further, there is a global dynamic observed over the past ten years, which has resulted in an increasing penetration of renewable energies into the energy mix of almost all countries on the planet. This tendency has resulted in a substantial drop in the kilowatt-hour price of renewable electricity to record low levels (Figure 1). Indeed, a photovoltaic (PV) solar project in Mexico recently broke the world record for PV by being auctioned at about 1.6 c€/kWh (16€/MWh). Morocco had beaten world records for wind energy for the integrated wind project, with a rate of less than 3 c€/kWh (30€/MWh)[1].

Figure 1: World-wide technology learning for the main-stream renewable energy sources



Source: IRENA Renewable Cost Database and Auctions Database.

Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

Source: IRENA (2018)

[1] As of January 2019, Mexico holds the world record for wind power with a price of 18.14$/MWh

This important reduction in cost of electricity generated by RES further encourages governments to install even more renewable capacities, inducing further cost degression for RES. Therefore, some RES manufacturers, producers and R&D institutes are considering other uses for the renewable electricity. This is a new paradigm commonly referred to as "Power-to-X". The X can stand for: heat, hydrogen, gas, liquid, or chemical elements. Power-to-X has gained increasing interest around the world in recent years, particularly in Germany, the Netherlands and Japan.

Hydrogen and, increasingly, ammonia, are among the most interesting molecules for the "Power-to-X" process. These are raw materials that are used in several industrial processes. Thus, producing them in a green way, using renewable electricity and electrolysis, is a step towards reducing heavy industry emissions.

- Hydrogen, in addition to its direct use (hydrogen vehicles, industrial gases, etc.), could also be used in the recycling of CO_2 into various molecules and hydrocarbons.
- Ammonia has the advantage of being easier to transport than hydrogen. Ammonia is <other hand, it is possible to "crack" the ammonia molecule to return to hydrogen or even generate electricity again.

These processes, however, come with substantial conversion losses along the chain efficiency.

Morocco's strategic geographical proximity to Europe, along with its large potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with high added value.

2. Context and objectives of the study

In September 2017, the Moroccan-German Energy Partnership PAREMA organized the first Moroccan-German Energy Day in Rabat, during which the "Power to X" technology was presented by the Fraunhofer IWES Institute on the basis of a study published in Germany that identified Morocco as a potentially key player in technology, given its geographical location and its unique solar and wind energy resources.

This theme was addressed during the Berlin Energy Transition Dialogue in April 2018, as part of a panel on "Renewable Fuels", in which Mr. Ikken, IRESEN's Director General, participated as a speaker. Alongside this conference, PAREMA held its annual steering committee meeting, and following an intervention by Mr. Ikken, the two parties agreed to collaborate on this theme.

This study is a first step in this collaboration. It follows a visit to Berlin by Mr. Ikken and the representatives of OCP Group, during which a Memorandum of Understanding was signed with the Fraunhofer IWMS Institute on the launch of a research platform on the «Power to X «technology and green fertilizers in Morocco.

The objective of this study is to identify the opportunities of "Power-to-X" and its sub-sectors in Morocco, to discuss the related industrial, economic and social impacts of PtX, and to elaborate and prioritise recommendations, in particular by addressing the following dimensions:

- The potential of "Power-to-X" in Morocco in the medium and long term;
- The various technological, industrial, regulatory, economic and logistical levers likely to influence the deployment of this technology, as well as possible related industrial, economic and social impacts;

After an overview of the present state and expected evolution of the Moroccan power sector up to 2050 in Chapter 3, we provide a definition for PtX in Chapter 4, with a focus on the conversion of electricity to materials. In Chapter 5, we formulate for this analysis 10 hypotheses on PtX and its opportunities for Morocco. This approach is taken because there are still quite some uncertainties about the possible future role of PtX, both in Europe and countries like Morocco. The formulation of such hypotheses, supported by analysis of the present knowledge and uncertainties, helps to feed the necessary discussion processes to determine more precisely the possible future role of PtX technologies in the energy system. The hypotheses are grouped into four main sections:

- Main Drivers for the Demand for PtX
- Morocco’s potential share of world-wide demand for PtX
- Production of synthetic ammonia as a promising economic opportunity for Morocco
- Guiding principles for the development of PtX in Morocco

Finally, in Chapter 6 we derive recommendations concerning the various levers identified, and prioritisation for further research to support the discussion on PtX in Morocco from a systems-analytical perspective.

3. **RES Power Generation in Morocco**

3.1 The present electricity mix of Morocco

Table 1 shows the present power generation mix for Morocco with the following main characteristics:

- It is still dominated by large coal capacities which represent about one third of the total generation capacities.
- Overall, thermal power generation based on fossil fuels covers about two thirds of the generation mix.
- Renewables now present more than one third of capacities with the largest contributor still from hydro power. New renewables, excluding hydro represent 14% of the generation mix with wind being the large non-hydro RES.
- Renewables have been growing rapidly since 2010: 20% on annual average for wind and 27% annual growth for solar, while the power capacities in total grew by 4% annually

Table 1: Present power generation mix of Morocco

	Unit	2010	2011	2012	2013	2014	2015	2016	2017	Annual growth rate
Installed electricity capacity	**MW**	**6444**	**6448**	**6749**	**7370**	**8034**	**8159**	**8261**	**8701**	4%
Thermal electricity capacity	MW	4353	4352	4652	5077	5427	5431	5412	5730	4%
Total electricity capacity oil (multifuel oil/gas included)	*MW*	*1588*	*1587*	*1587*	*1587*	*1587*	*1587*	*1588*	*1588*	0%
Total electricity capacity gas (multifuel oil/gas included)	*MW*	*980*	*980*	*1280*	*1295*	*1295*	*1299*	*1279*	*1279*	4%
Total electricity capacity coal (multifuel included)	*MW*	*1785*	*1785*	*1785*	*2195*	*2545*	*2545*	*2545*	*2863*	7%
Renewables	*MW*	*2091*	*2096*	*2097*	*2293*	*2607*	*2728*	*2849*	*2971*	5%
Hydroelectricity	MW	1771	1771	1771	1770	1770	1770	1770	1770	0%
Wind	*MW*	*286*	*291*	*291*	*487*	*797*	*797*	*898*	*1017*	**20%**
Solar	*MW*	*34*	*34*	*35*	*36*	*40*	*161*	*181*	*184*	**27%**
RES Share in electricity capacity	%	32%	33%	31%	31%	32%	33%	34%	34%	
RES Share excl. hydro in electricity capacity		5%	5%	5%	7%	10%	12%	13%	14%	

Source: ENERDATA Global Stat (2018)

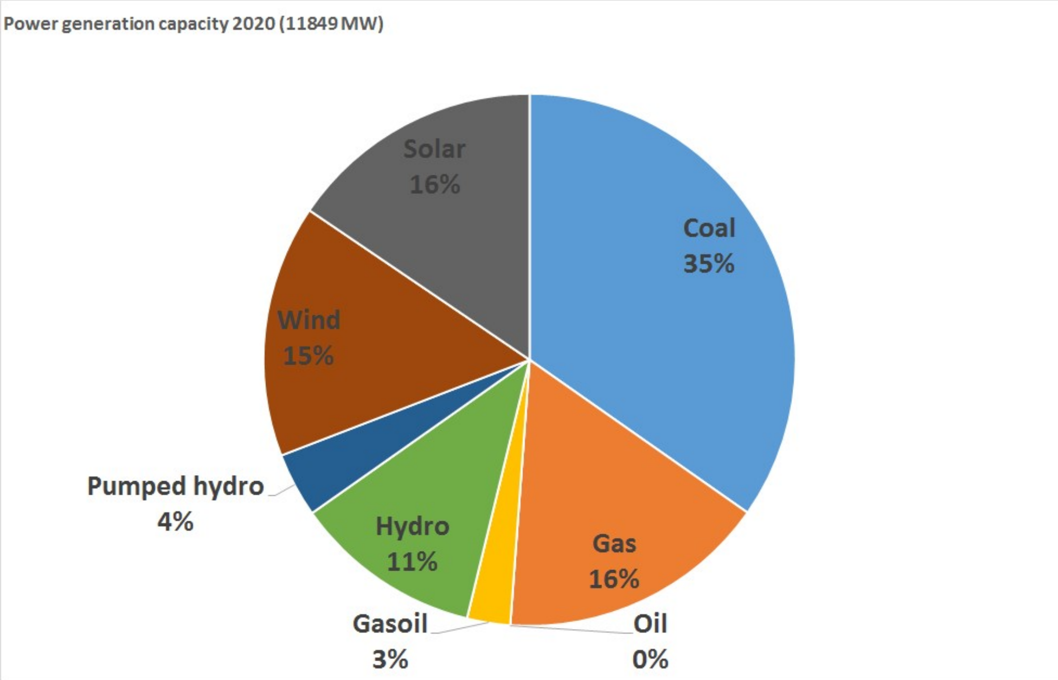
3.2 Electricity mix of Morocco in 2020 and 2030

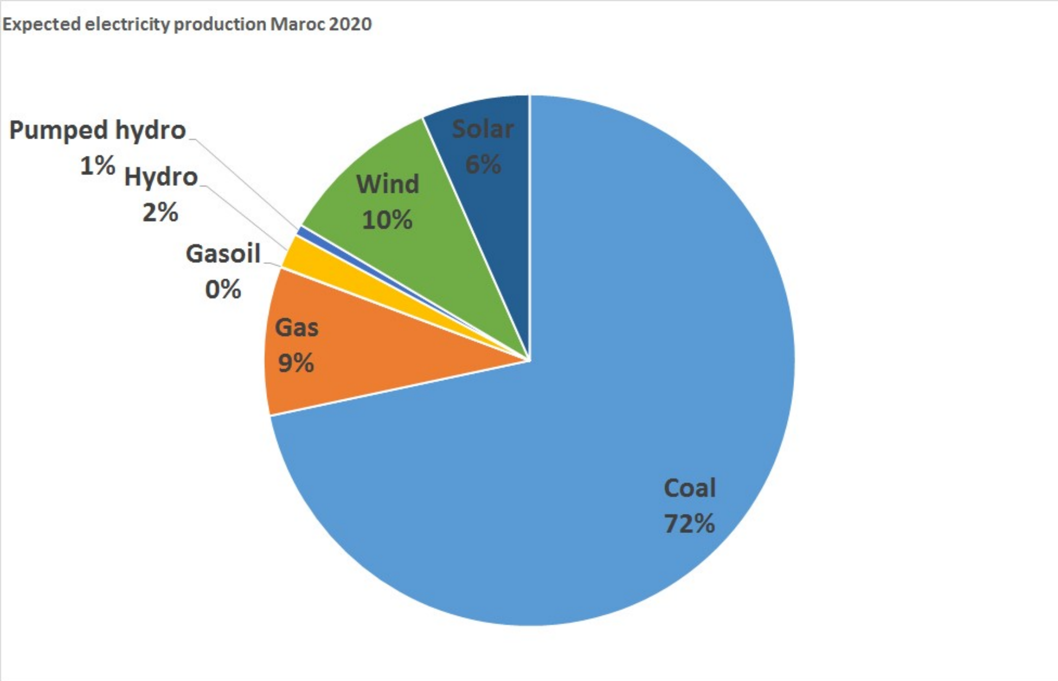
Morocco has ambitious plans for RES in 2020: the country is aiming for a 42% share of renewables (up from 35% in 2018) and is on a good path to achieve this target.

RES Power Generation in Morocco

Figure 2 shows the expected capacity and power production mix in Morocco in 2020. In terms of capacities, wind and solar present already 30%, up from 14% in 2017. In terms of power production, coal is with 60% still the dominating power source, and fossil fuels still cover 75% of the power production. Overall, around 12000 MW of power generation capacities will be installed by 2020.

Figure 2: Expected capacity and power production mix in Morocco in 2020

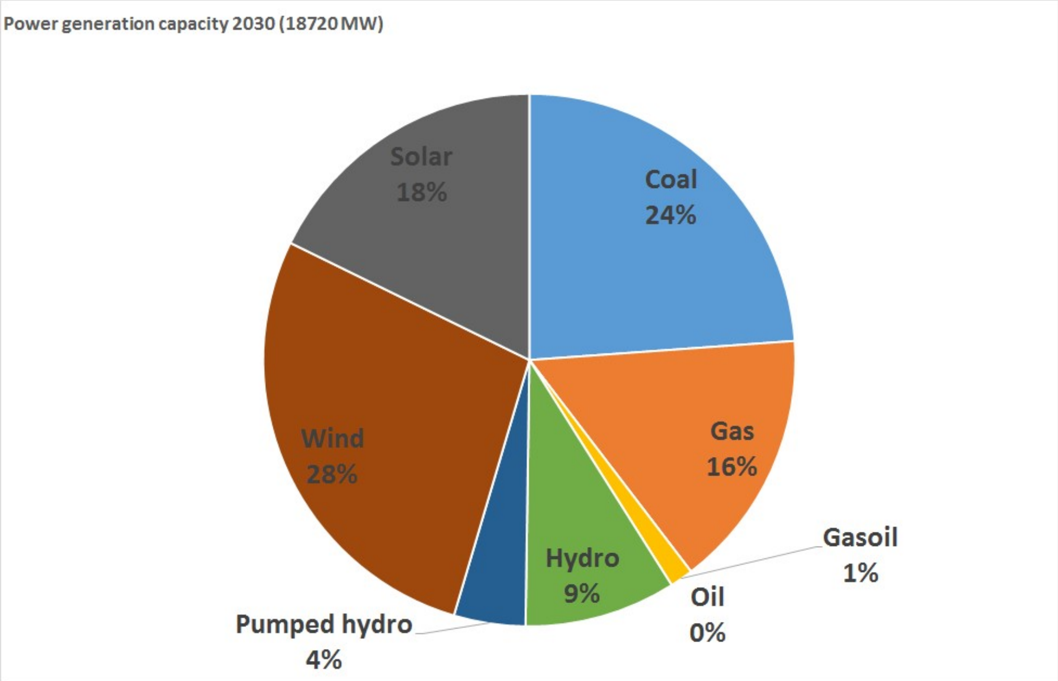


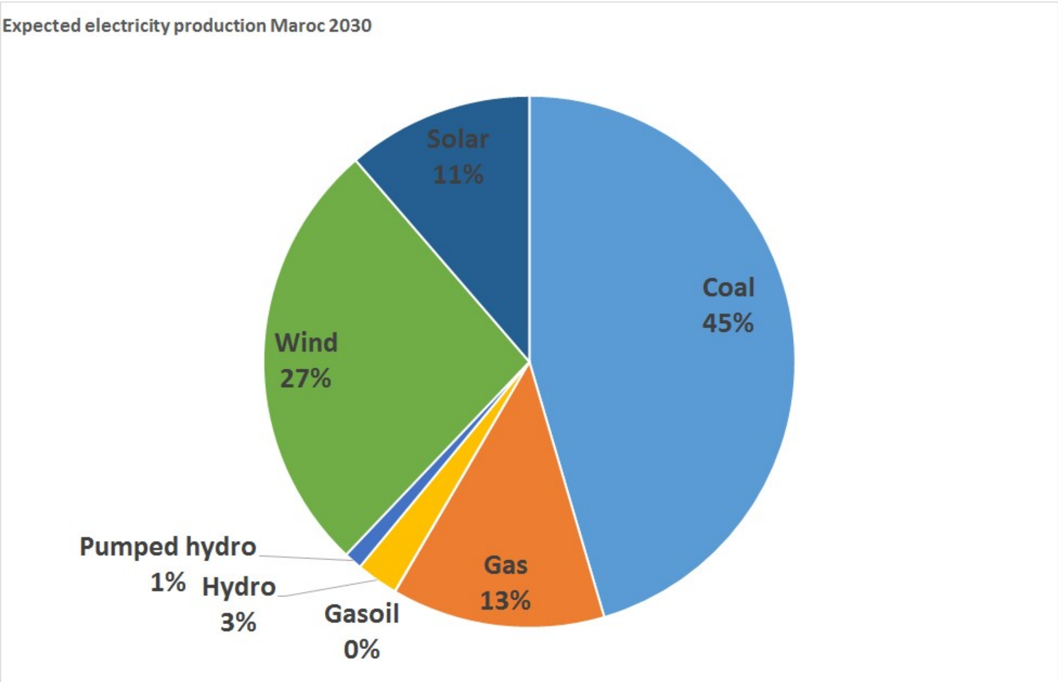


Source: own calculations based on ONEE/MEMDD

By 2030, renewables shall present, at least, 52% of the total generation capacities with wind and solar (both PV and CSP but with a stronger focus on PV) providing 38%. The 52% target shall even be increased at more than 59% according to the last Royal instructions. The share of coal will have decreased to 21%, while natural gas will have expanded. RES altogether will provide more than 40% of the power generation. At present, there is discussion in Morocco to increase the share of RES capacities to even beyond 60% by 2030. Overall installed capacities will be close to 20000 MW by 2030.

Figure 3: Expected capacity and power production mix in Morocco in 2030





Source: own calculations based on ONEE/MEMDD

Table 2: Summary Mix MW of Morocco

Power Plants	End 2017	End 2020	End 2030	End 2040
Yearly Peak	**6180**	**6770**	**9853**	**13622**
Thermal power plants	**5850**	**6373**	**7679**	**10082**
Oil	600	0	0	0
Coal	2895	4116	4466	4166
CCGT	836	836	2036	2636
TG20 + TG33 + TG100	1230	1110	912	615
OCGT-400MW	0	0	0	2400
Gas Oil	289	311	265	265
Renewables (excluding pumped storage)	**2501**	**5012**	**10227**	**18977**
Classical hydro	1306	1356	1724	1724
Wind	1015	1819	5180	10063
PV	0	1307	2493	6360
CSP	180	530	830	830
Pumped storage	**464**	**464**	**814**	**814**
Total System Capacity	**8815**	**11849**	**18720**	**29873**
Share renewables (excl. pumped st.)	28,4%	42,3%	54,6%	63,5%
Share renewables (incl. pumped st.)	33,6%	46,2%	59,0%	66,3%

Source: ONEE/MEMDD

3.3 Electricity mix of Morocco in the 2050 perspective

No targets exist yet for RES generation at a time horizon 2050. However, various scenarios have been investigated with RES shares in the range of 80-100% in 2050For example Fraunhofer ISI (2018) investigated with the ENERTILE model integrated EU-MENA scenarios with RES shares of 100% in 2050 (see Table 7 later on).

All in all, RES capacities will considerably expand after 2030, and even before 2030 if original coal and gas power plans are reduced.

4. Definition of PtX

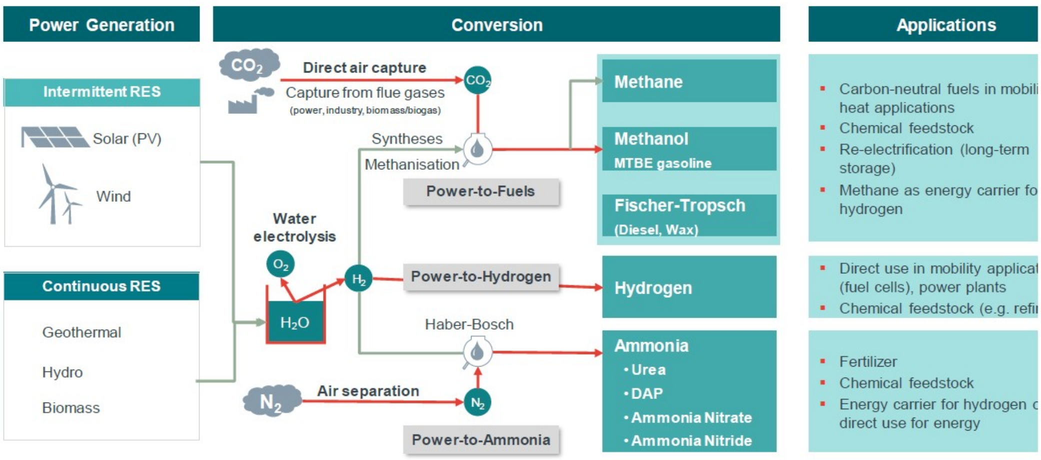
Power-to-X (PtX) generally describes the **conversion of electricity into another form of energy**, for example from Power-to-Heat, Power-to-Mobility or from Power-to-Materials. Storage of power in batteries is not PtX properly spoken. The conversion from power to electricity storage may become necessary in a sustainable energy system, based on renewable energy sources:

- when electricity cannot be directly used
- when the energy carriers generated can more easily be transported than electricity
- when the power generated by a carbon-free energy source is not needed in a given moment.

This report focusses on PtX as the **conversion of electricity to materials**. Such conversions are often characterized with respect to the target molecule (Figure 4):

- **Power-to-Gas (PtG)** is the production of a synthetic gaseous target product, such as hydrogen (H2) or methane (CH4),
- **Power-to-Liquid (PtL)** is the production of a synthetic liquid energy carrier, such as gasoline or diesel fuel, kerosene, etc.
- **Power-to-Chemicals (PtC)** describes the production of chemicals, such as methanol (CH3OH), ammonia (NH3), etc.. The latter are usually also liquid or gaseous, so that the nomenclature is not always unambiguous.

Figure 4: Overview of PtX as the conversion of electricity to materials



Source: AGORA/Frontier Economics (2018)

In most cases, the conversion of electricity into material is done via electrolytic processes. One focus is water electrolysis, which splits water into hydrogen (H2) and oxygen (O2) by supplying electric current. However, other processes are also conceivable, such as the co-electrolysis of water and carbon dioxide (CO2) with the aim of producing a synthesis gas (a mixture of hydrogen and carbon monoxide CO) or a pyrolysis of methane (CH4) into carbon (C) and hydrogen (H2).

5. Ten Hypotheses for PtX in Morocco

In this Chapter, we formulate for this analysis 10 hypotheses on PtX and its opportunities for Morocco. This approach is taken because there are still quite some uncertainties about the possible future role of PtX, both in Europe and countries like Morocco. The formulation of such hypotheses, supported by analysis of the present knowledge and uncertainties, helps to feed the necessary discussion processes to determine more precisely the possible future role of PtX technologies in the energy system. For each hypothesis we follow the same approach: **after having formulated the hypothesis, we cumulate the evidence which we know so far and the hypothesis is formulated in such a manner that - from the current perspective - the hypothesis appears as verified, but given the uncertainties**.

The hypotheses formulated and discussed in this chapter are the following:

1. Hypothesis 1: The demand for PtX will be driven by the requirements on developed countries to reach a reduction of 95% in view of contributing to the 1.5°C target of the Paris Agreement.
2. Hypothesis 2: If the requirement would only be 80% reduction in GHG (which is possibly compatible with a 2°C scenario) there would be very limited need in developed countries for PtX.
3. Hypothesis 3: Developing countries have lower GHG reduction requirements by 2050, hence less pressure to introduce PtX for own purposes.
4. Hypothesis 4: There is no need for PtX from the pure requirement of a 100% RES share in the power sector. This concerns both Morocco and for example European countries, as long as the power systems are optimised (grid expansions, market arrangements,...).
5. Hypothesis 5: Morocco can capture a non-negligible share in the world-wide demand for PtX.
6. Hypothesis 6: Power exports to Europe is not a strong competitor for PtX exports.
7. Hypothesis 7: PtX products may under favourable conditions become economic compared to fossil competitors beyond 2030.
8. Hypothesis 8: The production of synthetic ammonia offers - under favourable conditions - economic opportunities to Morocco as a producer of green ammonia for own purposes and for export.
9. Hypothesis 9: RES development should be accompanied by a hierarchy principle minimising necessary expansion, even with fur-ther falling cost, to minimise broader environmental impacts.
10. Hypothesis 10: Sustainability criteria play an important role for PtX in Morocco.

5.1 Main Drivers for the Demand for PtX

5.1.1 Hypothesis 1: The demand for PtX will be driven by the requirements on developed countries to reach a reduction of 95% in view of contributing to the 1.5°C target of the Paris Agreement.

Main messages

- Quite a number of studies come up with fairly high worldwide potentials for PtX in the range 10-40000 TWh in 2050.
- By applying the hierarchical principle of Hypothesis 9 (see there), we estimate PtX potentials in the range of 320 - 726 TWh for 2030 and 972 - 6180 TWh by 2050.
- This corresponds to a market size of 45 – 102 Billion Euro annually in 2030 and 107 – 680 Billion Euro annually in 2050 (for comparison: the size of oil markets at present prices is around 2000 Billion Euro annually).
- A major determinant for the own estimates is the realisation of an ambitious energy efficiency strategy which reduces primary energy demand by 2050 to half of the present value in developed countries. Detailed studies show that such a reduction is economically feasible.
- The estimated world-wide market potential for PtX is smaller than some of the more generous potential estimates come up, which do not apply the hierarchical principle from Hypothesis 9. However, it still presents a considerable mar-ket opportunity for potential PtX producers such as Morocco.

This hypothesis investigates the possible world-wide demand for PtX worldwide. There is a wide spread of ranges in the recent literature on the potential for PtX. The world-wide market demand for PtX based on chemicals (H2, synthetic fuels, synthetic methane, and synthetic methanol) depends on three main factors of influence:

- the evolution of energy demand
- the share of the energy demand that can be covered by direct electricity uses, combined with a decarbonisation of the power sector, as well as by RES heating/cooling applications
- the required GHG reduction (or in other words, the remaining fossil fuels which could still be used to cover energy uses difficult to replace by direct direct electricity uses.

The above mentioned order corresponds to the hierarchy among options established under Hypothesis 9. It is evident, if all today's energy consumption, notably in transport, should be satisfied by PtX, there would not be enough surfaces for the RES capacities to satisfy the demand for electricity, or rather: there would not be enough surfaces available in a sustainable manner, with the previously cited side effects. Hypothesis 1 is therefore seeking to determine the word-wide PtX potential in a conservative manner.

A rather broad range of potentials for PtX is provided by Agora/Frontier Economics (2018). They estimate the worldwide PtX demand in a low case scenario 10,000 TWh, in a medium case 20,000 TWh and in a high case 41,000 TWh for 2050. This potentials is largely determined by the above mentioned three factors, notably the evolution of energy demand.

Energy Demand can be strongly impacted by Energy Efficiency Policies. Agora/Frontier Economics (2018) base their analysis on scenarios provided by the IEA (Table 3). We make the case for OECD Europe: While the Current Policy Scenario of the IEA hardly leads to any reduction in demand until 2040, it decreases by 9% in the New Policies Scenario and by 19% in the 450 ppm scenario. Frontier Economics/WEC (2018) to conclude for *"Since Germany's energy demand is expected to be at least 75% of current demand in 2050 – even if the highest energy efficiency targets are achieved – the question as to how to meet this demand remains*". That is, it seems unlikely that energy consumption in Europe can be reduced by more than about 25%.

Table 3: Development of Total Primary Energy Demand (TPED) in two main scenarios of the IEA used to estimate PtX potentials

OECD Europe: New Policies Scenario

	Energy demand (Mtoe)							Shares (%)		CAAGR (%)
	1990	2014	2020	2025	2030	2035	2040	2014	2040	2014-40
TPED	1 631	1 697	1 690	1 641	1 601	1 568	1 540	100	100	-0.4

OECD Europe: Current Policies and 450 Scenarios

	Energy demand (Mtoe)						Shares (%)		CAAGR (%)	
	2020	2030	2040	2020	2030	2040	2040		2014-40	
	Current Policies Scenario			450 Scenario			CPS	450	CPS	450
TPED	1 723	1 720	1 724	1 660	1 486	1 364	100	100	0.1	-0.8

Source: IEA (2016)

Own scenario analysis in the frame of Long-term Climate Scenarios for Germany (Fraunhofer ISI, 2018a and b) comes up with demand reductions of over 50% (Table 4). These scenarios reach at least 80% GHG reduction by 2050. A similar reduction of energy demand appears as feasible at European level in economic terms (Fraunhofer ISI, 2012).

Table 4: Projected reduction of primary energy in Germany in the 80% GHG reduction scenario for 2050 (in TWh)

	2008	2010	2020	2030	2040	2050
Mineral oil products	1.362	1.301	1.039	801	581	436
Hard coal	500	476	528	277	162	109
Lignite	432	420	317	221	67	4
Natural gas (fossil)	895	881	762	704	534	363
Nuclear energy	451	426	183	0	0	0
Renewable energy	319	393	556	634	817	882
Net electricity imports	-22	-18	-113	-46	-19	105
Other	58	70	79	60	41	25
Total primary energy	**3.994**	**3.949**	**3.351**	**2.650**	**2.184**	**1.923**
Reduction to 2008	-	*1%*	*16%*	*34%*	*45%*	***52%***

Source: Fraunhofer ISI (2018a)

In the 95% reduction scenarios for Germany (Fraunhofer ISI, 2018b) the need for PtX arises. Table 5 determines energy demand in the different sectors which cannot be avoided after energy efficiency and direct electric uses have been privileged. In total these are around 600 TWh. Partly, this may be covered by sustainable biomass/biogas, partly by synthetic fuels. A minimum estimate for synthetic energy carrier demand in a 95% reduction scenario for Germany is 200 TWh, while the upper range is around 525 TWh, if only a smaller part of the sustainable biomass is used.

Table 5: Demand for PtX and sustainable biomass/gas in Germany in a 95% reduction scenario (in TWh)

TWh	Total	Syn-fuels/synthetic methane	H2	Sustainable Biomass/-gas
Building	57			57
Transport	239	Share of 3 options open		
Industry	143	Share open	60	Share open
Service Sector	19			19
Transformation sector	50	Share open	50	Share open
Material use	94	Share open	61	Share open
	602	0-50	~ 170	<=400

Source: Fraunhofer ISI (2018b)

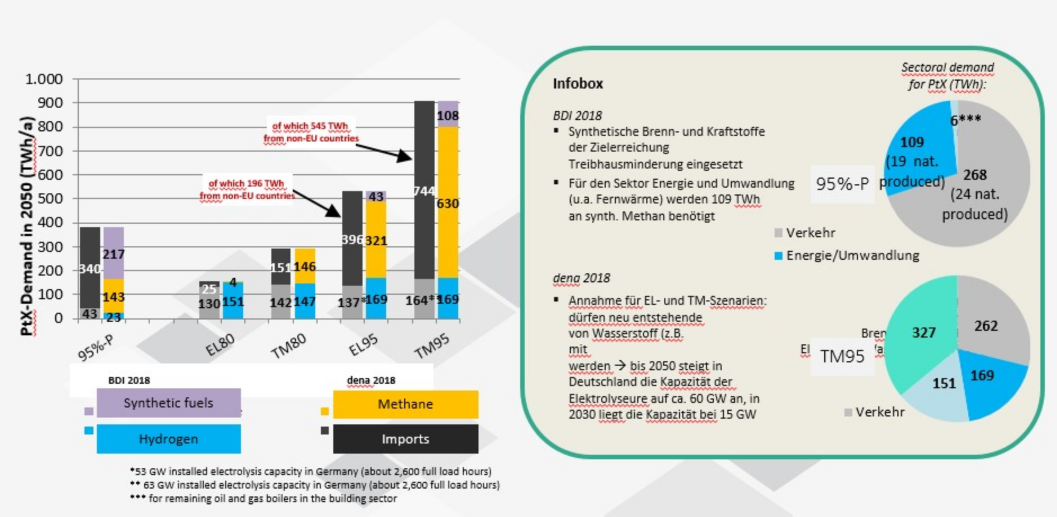
Other studies show a broad range of potential PtX demand in Germany (Figure 5):

- BDI (2018) comes along with a PtX demand of around 380 TWh in a 95% reduction scenario, similar to our estimate.
- dena (2018) determines PtX potentials for Germany of 533[1] to 900[2] TWh range in 95% reduction scenarios. The lower value is for a scenario which applies more strictly the hierarchical principle.

[1] Electrification scenario (EL): broad electrification (direct) in all sectors, GHG reduction of 80 % (EL80) and 95 % (EL95)

[2] Technology mix scenario (TM): wide variation in technologies used (including indirect use of electricity), GHG reduction by 80 % (TM80) and 95 % (TM95)

Figure 5: PtX requirements are valuated quite differently in Germany in 95% reduction scenarios



Source: Wietschel et al. 2018 based on the evaluation of the studies BDI (2018) and dena (2018)

Based on such in-depth studies of a country like Germany with the requirement to reduce GHG emissions by 95% and the application of the hierarchical principle of Hypothesis 9 allows estimates of the world potential for PtX, applying similar analysis to other developed countries with similar reduction requirements.

With the hierarchical principle of Hypothesis 9 (see there) we estimate PtX potentials in the range of 320 - 726 TWh for 2030 and 972 - 6180 TWh by 2050. This corresponds to a market size of 45 – 102 Billion Euro annually in 2030 and 107 – 680 Billion Euro annually in 2050 (for comparison: the size of oil markets at present prices is around 2000 Billion Euro annually).

The lower values are for 80% GHG reduction and minimum uses of PtX; the upper values for 95% GHG reduction and maximum uses of PtX under such a hierarchical principle. Compared to the potential estimate of 10000 - 40000 TWh by Frontier Economics at the beginning of this section, this appears somewhat below the lower estimate of this source.

Table 6: Estimate of worldwide demand for PtX (in TWh)

Potential demand PtX worldwide (TWh)	2030	2050
Installed electrolyser capacity	55 - 126 GW	260 - 2865 GW
Volume H2 produced	267 - 605 TWh	810 - 5150 TWh
Potential amount of synthetic fuels/methane (assuming full conversion of H2, 80% efficiency)	320 - 726 TWh	972 - 6180 TWh
Market size (annual; only fuel sales, not equipment market)	45 – 102 Billion Euro	107 – 680 Billion Euro
For comparison: size of oil market at present prices is 2000 billion Euro annually		

Source: own estimate; Wuppertal Institute/Fraunhofer ISI/IZES (2018)

In conclusion, the estimated world-wide market potential for PtX is smaller than some of the more generous potential estimates come up, which do not apply the hierarchical principle from Hypothesis 9. However, it still presents a considerable market opportunity for potential PtX producers such as Morocco.

5.1.2 Hypothesis 2: If the requirement would only be 80% reduction in GHG (which is possibly compatible with a 2°C scenario) there would be very limited need in developed countries for PtX

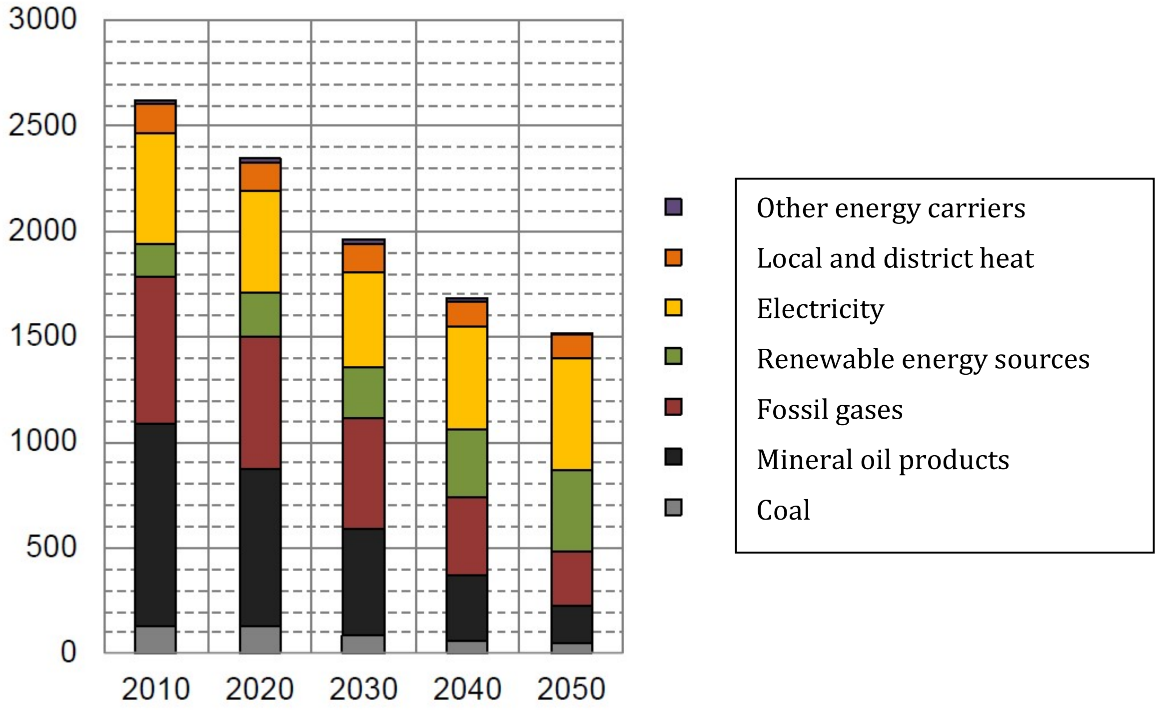
Main messages

- 80% GHG reduction does not imply substantial shares of PtX in developed countries. The 80% reduction is not in line with the Paris Agreement "to stay well below global 2°C temperature rise". This hypothesis must be envisaged as present energy and climate policies are not on track for the Paris Agreement. Adaptation measures will then have to take the place of mitigation measures.
- This is mainly due to the fact that energy efficiency plays an important role in reducing electricity demand across all applications.
- Further, the difficult end-uses which have led to the need in the 95% scenarios to use PtX, still can rely on a certain amount of fossil fuels (notably natural gas and remaining amounts of mineral oil, e.g. for air transport).

The Long-term Climate Scenarios for Germany show that 80% GHG reduction does not imply substantial shares of PtX (see the composition of final energy demand in Figure 6). This is also the reason why the electricity demand is not substantially higher in 2050 compared to today, despite the fact that a large part of the transport sector is electrified and that heat pumps play an important role for example in the building sector. This is mainly due to the fact that energy efficiency plays an important role in reducing electricity demand across all applications. Further, the difficult end-uses which have led to the need in the 95% scenarios to use PtX, still can rely on a certain amount of fossil fuels (notably natural gas and remaining amounts of mineral oil, e.g. for air transport.

Also, the 80% GHG reduction scenarios developed by dena (2018), see Figure 5, especially the EL80 scenario which relies strongly on direct electricity uses, shows similarly a comparatively small potential for PtX in a 80% GHG reduction world.

Figure 6: Projected composition of final energy demand in Germany by 2050 with an 80% GHG reduction requirement



Source: Fraunhofer ISI (2018a)

In conclusion, energy and climate policies which aim only at 80% GHG reduction in developed countries do not imply substantial shares of PtX in developed countries. It must be emphasised, however, that such policies are not in line with the Paris Agreement and the requirement to reduce emissions from developed countries in such a manner that global temperature rise stays well below 1.5°C. However, we live at present with energy and climate policies that are not compatible with the Paris Agreement and we have to recognise in this hypothesis that the Paris agreement could be missed. This has strong impacts then on the PtX demand. In that case, temperature rise will have to be encountered by adaptation measures.

5.1.3 Hypothesis 3: Developing countries have lower GHG reduction requirements by 2050, hence less pressure to introduce PtX for own purposes

Main messages

- While developed countries have to achieve at least a 95% reduction in GHG by 2050, developing countries may require less reduction.
- Typical estimates for countries at the development stage of Morocco, would be a rough stabilisation of emissions at present levels, implying a 60-70% reduction from the baseline development.
- At such a level of reduction, PtX is not required to a large degree by developing countries.
- Nevertheless, Morocco wants to take a leading role on climate in the developing world and even worldwide, and has set itself targets for 2030 which are close to the EU targets. Provided international finance comes in support, Morocco could therefore envisage PtX for GHG reduction purposes in the own country on a very ambitious GHG reduction pathway to 2050

Developing countries would have lower requirements on GHG reduction. So, they will probably not have to reduce their carbon emissions to a degree which requires 95% reduction in those countries. This implies in particular that GHG emissions in Morocco and other countries will not have to be reduced by 95% in 2050. Hence there is no pressure to introduce PtX in those countries for own decarbonisation needs and the PtX potential in those countries will contribute to a smaller degree than for developed countries.

It is not easy to allocate a "fair share" of the world-wide emission reduction, as required by the Paris Agreement to individual countries. A number of approaches are discussed in literature (Robiou du Pont et al., 2017). The Climate Action Tracker (2018) develops a practical approach for different countries to gauge national mitigation efforts with the needs of the Paris Agreement (Figure 7).

Overall, Morocco gets an excellent mark for its present emission path to 2030. In order to be compatible with the 2050 requirements, the tracker estimates that Morocco should roughly keep its emissions at the present level of around 100 Mt CO2 equivalents (upper range of the light green field in 2050), despite an increase at the 2030 time frame to around 150 Mt CO2. Compared to the extrapolation of the dashed baseline to 2050, this requires an estimated reduction of 60-70% in GHG emissions. This provides ground for the hypothesis that a country like Morocco should roughly reduce GHG emissions by 60-70% compared to a baseline development, which may be exemplary for other countries at a similar development stage.

At this reduction level, PtX is not an absolute need for the countries, as there is still enough fossil fuels in the energy system to cope with the sectors which are more difficult to decarbonise.

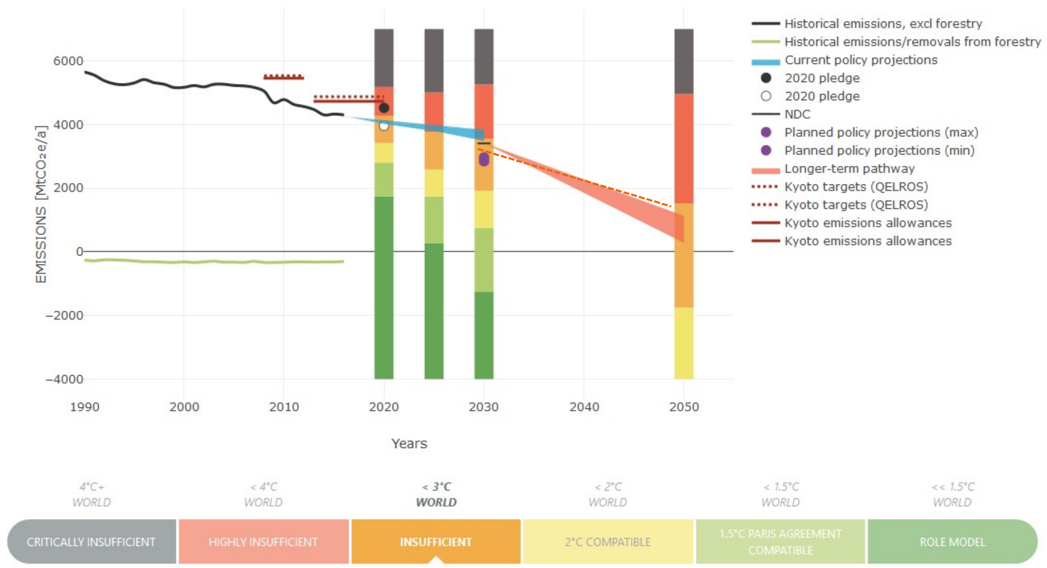
For comparison: the EU should achieve negative emissions beyond 2030 to contribute in a fair share to the Paris Agreement (Figure 8).

Nevertheless, Morocco wants to take a leading role on climate in the developing world and even worldwide, and has set itself targets for 2030 which are close to the EU targets. Provided international finance comes in support, Morocco could therefore envisage PtX for GHG reduction purposes in the own country on a very ambitious GHG reduction pathway to 2050. A second rational is that such an ambitious GHG reduction strategy for the own country would create opportunities for a PtX market in the country which would come in support of a possible export strategy. The example of Morocco may also inspire other ambitious developing countries to go ahead with similar strategies. Recent activities in Morocco which provide signs for the hypothesis that Morocco could develop an ambitious climate and energy strategies are the recent enormous expansion of renewables in the power sector and the introduction of a pilot CO_2 market in the phosphor sector.

Figure 7: Climate Action Tracker for Morocco

Source: Climate Action Tracker (2018)

Figure 8: Climate Action Tracker for the EU



Source: Climate Action Tracker (2018)

5.1.4 Hypothesis 4: There is no need for PtX from the pure requirement of a 100% RES share in the power sector. This concerns both Morocco and for example, European countries, as long as the power systems are optimised (grid expansions, market arrangements ...)

Main messages

- An optimised power system in Morocco will have limited amounts of excess electricity from RES (1 TWh in 2030, 5 TWh in 2050)
- In addition, the full load hours where excess electricity is available are well below the full load hours required by capital-intensive H_2 electrolyses.
- In case of a non-optimised power system, the figures are higher. This is also supported by findings from the German electricity system. However, the strategy should be to remove bottlenecks to an optimised system and to increase integration with the European electricity systems, rather than using a non-optimised power system for PtX.
- Remaining amounts of surplus electricity system could be used for smaller PtX applications but full load hours are generally too short for capital intensive PtX plants.
- PtX production plants must therefore be built on top of RES plants covering electricity demand and should not be expanded at the expense of such plants.

Countries with high RES shares are supposed to produce surplus electricity in times with high RES generation. In order to investigate the amount of surplus electricity generation in countries like Morocco that could be used for PtX production, Fraunhofer ISI carried out modelling on a combined EU-MENA electricity system for 2030 and 2050 with the ENERTILE model (see www.enertile.eu), reaching RES shares of 89% and 100% respectively (see Table 7).

This implies annual growth rates for the period of 2010 to 2030 in installed RES of:

- 2010-2030 for wind: 19%/a and for solar: 27%/a
- 2010-2050 for wind: 11%/a and for solar: 18%/a

These growth rates are compatible with RES growth achieved to 2020.

Hydro storage capacities remain constant, given the country's limited hydro resources.

It must be emphasised that the scenario is a „low restriction scenario“, i.e. no major barriers exist for grid expansion, permitting, market integration of RES, etc.).

Table 7: Modelling of the Moroccan power system 2030/2050 with RES shares of 89% and 100% respectively

Power mix (MW)	2030	2050
Total installed capacity [MW]	22,376	43,978
Total installed RES capacity (incl. hydro) [MW]	19,834	43,978
RES share in installed capacity [%]	89%	100%
Wind onshore	9,714	16,908
Wind offshore	-	-
PV	4,468	13,412
CSP	4,335	12,340
Hydro	1,318	1,318
Gas CCGT	171	0
Gas OCGT	0	0
Hard Coal	2,370	0
Storage (pumped hydro)	466	466

Source: Own modelling based on ENERTILE runs (www.enertile.eu)

Table 8 shows that under such assumptions the curtailment in Morocco is about 1 TWh in 2030 (for an electricity demand of 75 TWh) and 5 TWh in 2050 (for an electricity demand of 130 TWh).

Table 8: Results on curtailment in RES Scenarios with high RES shares in Morocco

	2030	2050
Electricity demand, domestic [TWh]	75	130
Curtailment / Surplus generation [TWh]	- 1	- 5

Source: Own modelling based on ENERTILE runs (www.enertile.eu)

The main findings on curtailment for Morocco are as follows:

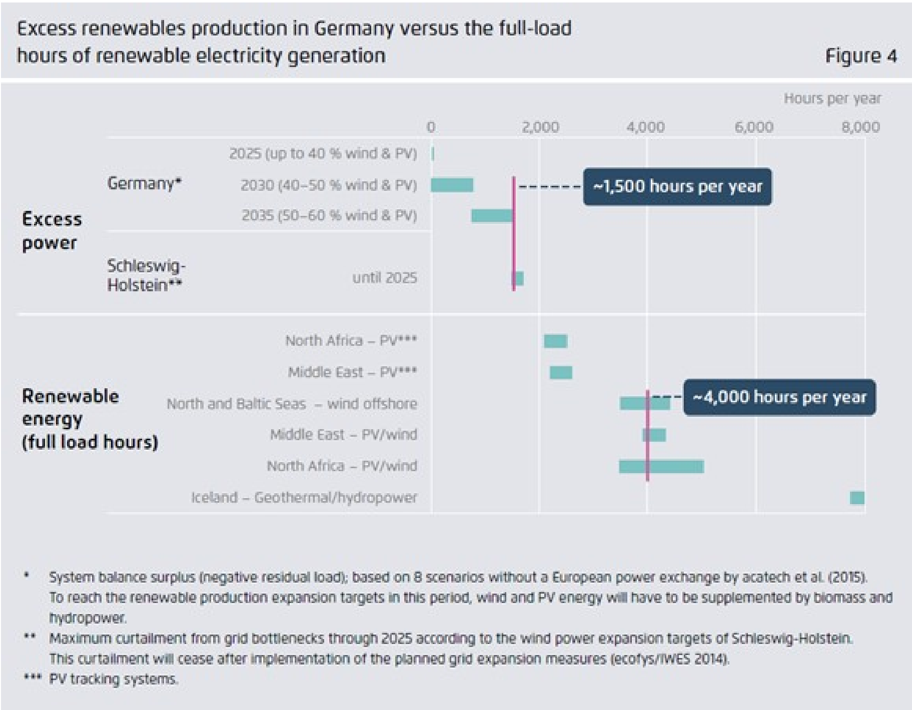
- the optimized RES scenario has low curtailment / low surplus generation even in scenarios with very high RES shares
- Limited amounts of curtailed electricity are also observed on other scenarios for Morocco, e.g. SET Roadmap (EY/Artelys, Castalia, Fraunhofer ISI, 2018) and the scenarios calculated by DLR for Morocco (DLR, 2016).

- This leaves limited room for curtailed electricity to be used for PtX production from surplus electricity.
- PtX production plants must therefore be built on top of RES plants covering electricity demand and should not be expanded at the expense of such plants.

Similar findings are noted by Agora/Frontier Economics (2018) for Germany:

- PtG and PtL facilities are capital intensive and have high fixed costs. Therefore, they need to achieve 3-4,000 full load hours annually.
- Inexpensive renewable power is essential for the economically viable operation of power-to-gas and power-to-liquid production facilities and must be available during 3-4000 full load hours.
- The use of excess renewable energy, which is typically only available for 1500h/year (Figure 9), therefore, does not suffice as a decarbonisation strategy.
- Renewable power plants must be built explicitly for the purpose of producing synthetic fuels, either in Germany as offshore wind parks or, for example, in North Africa or the Middle East as onshore wind turbines and/or PV installations.

Figure 9: Availability of Excess RES Production Germany



Source: Agora/Frontier Economics (2018)

Other studies on Germany confirm these findings on limited surplus electricity in well-integrated electricity grids and well-managed electricity markets , for example:

- Core statements BDI (2018):
  - More flexibility in the energy system: The increase in volatile generation can still be well absorbed by more "direct" flexibility (intercon-

nectors, storage, flexible consumers, etc.) - prerequisite: grid expansion.
    - Hardly any surplus electricity: Despite the very high share of renewables, the flexibility measures will result in only 6 TWh of "surplus electricity" in 2050 - the potential of RES surplus for national PtX applications is therefore limited.

- Core statements dena 2018:
    - No explicit information on surplus electricity
- Core statements of the 2030 Electricity Grid Development Plan (Version 2017, second draft of the transmission system operators):
    - Surplus electricity without grid expansion 2030: 43.9 TWh
    - Surplus electricity with timely implementation of all projects contained in the federal requirements plan 2030: 8.2 TWh

The statements from the 2030 Grid Development Plan in Germany show that without an optimised grid expansion, the surplus generation in 2030 may reach 5 times the value in case of an optimised grid expansion. **It is important therefore, to underline, that the above observations of limited curtailment are valid for an optimised Moroccan power system which profits from interconnections to Spain, not for the case of non-optimised systems**. However, rather than working with a highly restricted and imperfect electricity markets and market integration in the case of high RES shares - implying high surpluses that could possibly be used for PtX generation - efforts should be made to remove restrictions such as barriers to grid expansion, permitting barriers etc.

The current development of the Moroccan power systems envisages scenarios with a very long life-time for coal-fired power plants up to 2040 and beyond. These plants are comparatively inflexible and will not be compatible with the requirement of a highly flexible electricity system based on large shares of renewables. In such a configuration, more surplus electricity could be generated as the system is non-optimised, however at the expense of higher costs and a more inefficient electricity system. Such a development path should be avoided.

5.2 Morocco’s potential share of world-wide demand for PtX

5.2.1 Hypothesis 5: Morocco can capture a non-negligible share in the world-wide demand for PtX

Main messages

- Estimated RES potentials in Morocco are high and sufficient to cover both domestic electricity demand and PtX production
- Limiting factor is the capability to sustain a long-term growth in RES capacities (grid expansion, planning procedures, and availability of construction capacities...):

  - 2010-2017, growth in wind was 20% annually, growth in solar 27% annually

  - Achieving a 2030 target of 59% of RES capacity requires growth 2010-2030 in wind of 16% annually, in solar of 26%.

- Achieving in 2030 a 65% RES target requires growth 2010-2030 in wind of 16% annually, in solar of 29%.

- Doubling of the RES capacities in 2030 required for decarbonizing the power sector to 59% would allow capturing around 2-4% of the worldwide potential for PtX in 2030, and implies adding about **9 GW additional RES in Morocco**, on top of the RES expansion for covering the electricity demand and the RES targets. Such an expansion is compatible with the expansion rates achieved by Morocco in the past, while offering market opportunities for PtX through first mover advantages.
- Financing capabilities may be another limiting factor for the Moroccan economy.

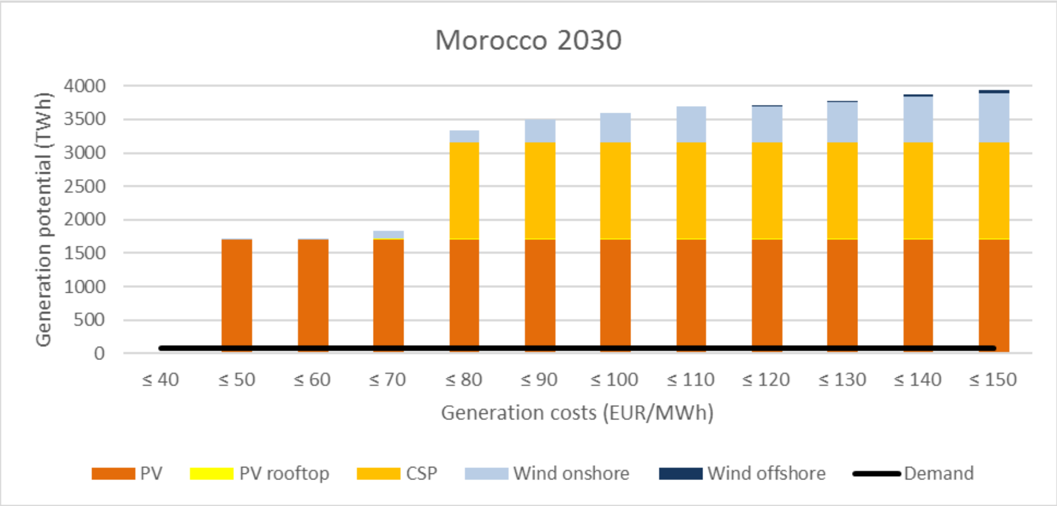
How much of the world market demand for PtX could be captured by Morocco? Relevant factors to answer this question are:

- The size of the world-wide PtX demand (see Hypothesis 1)
- The RES potentials in a country at low cost
- The ability to sustain a reasonable RES growth IN ADDITION to the decarbonisation of the own power sector (and possible exports of electricity)
- Appropriate financing capability
- Sustainability criteria for PtX

We already showed for hypothesis 1 that the demand for PtX world-wide could be substantial despite the cautious approach chosen here t estimate those potentials. Also, estimated **RES potentials** in Morocco are high and sufficient to cover both domestic electricity demand and PtX production (Figure 10):

- There are abundant low-cost RES potentials available in 2030 and 2050 for PtX markets (up to 4000 TWh).
- RES Potentials in Morocco are sufficient for covering 25% of the estimated maximum RES requirements in 2050 for PtX demand (see Hypothesis 1).

Figure 10: Estimated RES Potentials in 2030 in Morocco compared the electricity demand



Source: Fraunhofer ISI (2018)

A next possible limiting factor could be **limitations in the growth rate for the expansion of RES**, both for covering the domestic electricity demand (in fulfilment of national targets).Table 9 shows possible RES capacity expansions for the power sector in Morocco and for PtX production (MW):

- **Case 1** implies reaching the 59% RES capacity target in 2030 (9.5 GW installed RES capacity), plus 9 GW for PtX in 2030. The latter captures 1.9-4.2% of the worldwide demand for PtX in 2030. Annual growth rates in RES installations are 19% annually for wind and 32% annually for solar. These growth rates are compatible with historic trends and trends expected up to 2020 (see Chapter 2). **Higher annual growth rates may be possible but appear as quite ambitious.**
- **Case 2** implies a more ambitious RES target for the power sector of 65% RES capacities in the power mix in 2030 (11.5 GW). This target is presently under discussion. In order to maintain a similar growth rate as in case 1, only 7 GW are available, in addition to Power Sector RES, for PtX. This captures 1.4-3.3% of the worldwide demand for PtX in 2030.
- **Case 3** implies reaching a 89% RES share in 2030 (18.5 GW). This is the ambitious RES target modelled for Hypothesis 4 with the ENERTILE model. In that case, no reasonable capability seems left to cover, in addition to the electricity demand, also PtX potentials.
- **Case 4** implies reaching a 100% RES target by 2050 (42.7 GW). In addition, 40 GW of RES for PtX are installed. This captures 1-6.2% of the worldwide demand for PtX in 2050. Annual growth rates in RES installations are 12.7% annually for wind and 20% annually for solar.

Table 9: Possible RES Capacities for the Power Sector and PtX production in Morocco (MW)

	2030 RES for Power Sector	2030 RES for PtX	Share in worldwide PtX demand	CAGR RES 2010 – 2030 (Power sector + PtX)
Case 1	9.5 GW (59% RES target)	9.0 GW	1.9 - 4.2%	19% CAGR wind 32% CAGR solar
Case 2	11.5 GW (65% RES target)	7 GW	1.4 – 3.3%	
Case 3	18.5 GW (89% RES target)	-	-	
	2050 RES for Power Sector	2050 RES for PtX	Share in worldwide PtX demand	CAGR RES 2010 – 2050 (Power sector + PtX)
Case 4	42.7 GW (100% target)	40 GW	1.0 - 6.2%	12.7% CAGR wind 20% CAGR solar

CAGR: compound annual growth rate

Source: own calculations

These considerations show that a major limiting factor for Morocco for capturing the world-wide PtX potentials is the capability to sustain a long-term growth in RES capacities beyond the RES for satisfying general electricity needs (grid expansion, planning procedures, availability of construction capacities...):

- In the period 2010-2017, growth in wind was 20% annually, growth in solar 27% annually
- Achieving a 2030 target of 59% of RES capacity requires growth rates in the period 2010-2030 for wind of 15% annually, for solar of 27%.
- Achieving in 2030 a 65% RES target requires growth 2010-2030 in wind of 16% annually, in solar of 29%.
- Doubling of the RES capacities in 2030 required for decarbonizing the power sector to 59% would allow capturing around 2-4% of the worldwide potential demand for PtX in 2030, and implies adding about 9 GW additional RES to the 9.5 GW required for decarbonising the power sector. In terms of absorptive capacities, the growth rate for wind including RES for PtX is in the range of the present capacity extension path. For solar it is higher and would require additional efforts for integration.
- By 2050, an additional 40 GW RES would be available for PtX at reasonable annual growth rates (capturing around 1-6.2% of the worldwide potential demand for PtX in 2050), beyond the 42.7 GW required to decarbonise the power sector totally.

A third limiting factor may be financing capabilities, which in turn depends on the trust of financial markets in the stability of the Moroccan economy:

- Weighted cost of capital: exporting countries are subject to country-specific risk premiums on account of political or regulatory instability, and these premiums could increase the costs of production plants for synthetic fuels.
- For example, cost of capital rates of 12% (instead of 6%) would raise the 2050 reference cost of PtG produced in North Africa from combined PV/wind facilities from 11 to 15 cEuro/kWh (Agora/Frontier Economics, 2018).
- This would imply that the production of PtX in Morocco could be more costly than the production of synthetic fuels in Europe using offshore wind power with a cost of capital rate of 6%. Therefore, the potential advantage of Morocco would vanish under such circumstances, and countries with more favourable financial risk premiums and similar spatial options to generate additional RES electricity could benefit from that better context for exports (e.g. Australia, USA).
- State guarantees (e.g. Hermes in Germany) can lower cost of capital for such investments.

5.2.2 Hypothesis 6: Power exports to Europe is not a strong competitor for PtX exports

Main messages

- Compared to studies 10 years ago, investment cost in RES have strongly dropped both in Europe and MENA. Transport cost for long distance transport of electricity have seen less cost degression.
- Hence, the competitive advantage of Morocco with higher RES potentials as an electricity exporter have eroded.
- An optimised power system in Morocco will have limited amounts of exports of electricity from RES (8 TWh in 2030, 15 TWh in 2050). This is confirmed also by other scenario runs, e.g. SET Roadmap (EY/Artelys/Castalia/Fraunhofer ISI, 2018); DLR (2016).
- In case of a non-optimised EU-MENA power system, the figures may be higher. However, the strategy should be to remove bottlenecks to an optimised systems and to increase integration with the European electricity systems, rather than using a non-optimised power system for exports of power.
- Exporting electricity is not (anymore) an important competitor for PtX exports.

Direct electricity exports from Morocco to Europe have for number of years been considered as an interesting strategy for Morocco, taking advantage of the largely superior potentials for solar and wind as compared to Europe. Therefore, in principle, direct electricity exports to Europe could in principle be an option for Morocco, instead of producing PtX products. If RES capacities for such exports would be erected, this would limit the capability of Morocco of producing RES electricity for PtX, in addition to RES for the domestic power sector and for power exports (see the discussion under Hypothesis 5 for the annual RES growth rates as the limiting factor).

Table 10 shows that for the electricity sector modelling for Morocco described in the Hypothesis 4 the Import-Export balance in Morocco is about 8 TWh in 2030 (for an electricity demand of 75 TWh) and 15 TWh in 2050 (for an electricity demand of 130 TWh), in favour of exports.

Table 10: Results on import/export balance in RES Scenarios with high RES shares in Morocco

	2030	2050
Electricity demand, domestic [TWh]	75	130
Import-Export balance [TWh]	- 8	- 15

Source: Own modelling based on ENERTILE runs (www.enertile.eu)

This result shows that the optimized scenario, assuming an optimized, connected EU-MENA electricity market, has only moderate exports of electricity even with very high RES share. **Hence, direct electricity exports to Europe do not constitute a**

major economic competitor to PtX exports, given the lower differential RES generation cost compared to the transmission cost from Morocco to Europe.

Similar findings are observed in other studies:

- DLR (2016):
  - Electricity demand 90- 110 TWh in 2050; originally 160 TWh (130 TWh in BMU Long-term Scenarios)
  - RES shares 80-90%
  - No electricity exports
- SET Roadmap (EY/Artelys/Castalia/Fraunhofer ISI, 2018):
  - Electricity demand 115 TWh
  - Electricity imports or exports, depending on scenario (net exports 5 TWh in 2050 in deep decarbonisation scenario
  - RES share around 80% (around 40 GW RES in 2050)

5.2.3 Hypothesis 7: Renewable-based PtX products may under favourable conditions become economic compared to fossil competitors beyond 2030

Main messages

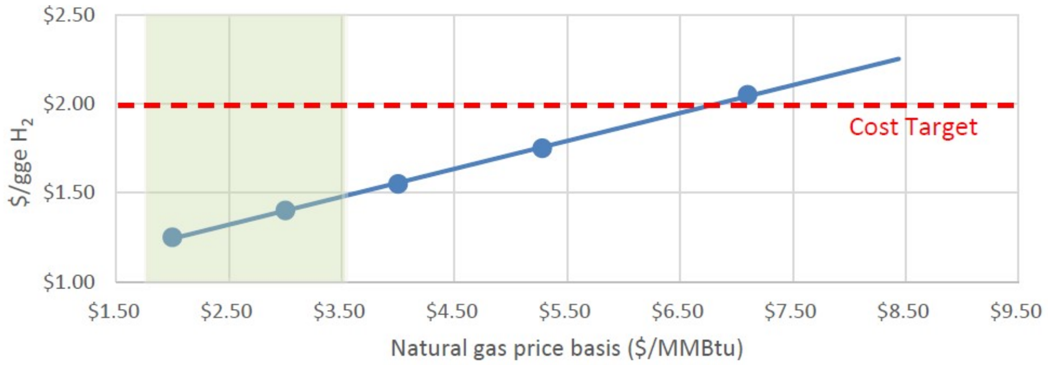
- With 4000 full load hours, hydrogen production based on RES in 2030 is still more expensive than fossil-based hydrogen (whose costs are rising nevertheless due to rising CO_2 and fuel cost), while it would be comparable with 8000 full load hours.
- A combination of wind and PV would only reach around 4000h, if not connected to the grid. With Concentrating Solar Power (CSP) higher full load hours could be reached, given the storage characteristics of this technologies, however, at higher RES cost, at present, as the technology is still early in the learning curve compared to PV and wind.
- **By 2050 with 4000 full load hours and optimistic RES cost, including connection cost, renewable hydrogen would be considerably cheaper than fossil hydrogen**, in particular, if the latter sees the full carbon price of 90 €/t CO_2, projected presently for the European Emission Trading Scheme by 2050 (implying full auctioning of allowances, including for industrial processes, i.e. removal of free allocation to industry).
- Morocco, under these conditions could become an exporter for hydrogen after 2030, considering, however, that the demand for hydrogen will depend on other countries/regions building up own hydrogen infrastructures and an own hydrogen economy.
- Also for the production of synthetic methane and methanol, given the lower RES cost in Morocco and the perspective of further drop in generation cost, there will be lower cost per tonne of product after 2030, though differences will remain long after 2030 with the fossil-based competitors (despite their rising cost due to rising CO2 and fuel cost). However, these synthetic energy carriers require true recycling of CO_2, e.g. from air capture, which limits strongly their expansion (see hypothesis 10).

Hydrogen production

Hydrogen is produced today mainly from fossil sources, about half from natural gas (by steam reforming of methane, SMR), the remainder from oil and coal. It is used as an additive in oil refineries and as a raw material for making ammonia and fertilizers (see Figure 4). In future, it may also be used to produce synthetic fuels such as methane, methanol and synthetic Diesel or gasoline.

Figure 11 shows the dependency of the hydrogen price of SMR hydrogen on the gas price for typical US gas prices.

Figure 11: Cost of H_2-Production via Steam Methane Reforming SMR as a Function of Natural Gas Prices



Source: U.S. DRIVE Partnership (2017)[1]

Hydrogen production cost are in the range 1.5 USD/kg SMR hydrogen (1.3 €/ kg SMR hydrogen). At European level, hydrogen cost are in the range of 2-3 USD/kg hydrogen, (1.8-2.7 €/kg hydrogen) with the upper value observed for higher gas prices in the range of 50 €/MWh of natural gas.

A second factor which as strong impact of fossil hydrogen production, is the cost of carbon. According to the Benchmarking Decision of the European Commission (2011), the hydrogen benchmark is set to 8.85 allowances per tonne of product. If hydrogen would see the full carbon price (which would be the case if auctioning is the main allocation mechanism), the additional cost at a carbon price of 20 Euro/t CO2 would be 0.18 €/kg SMR hydrogen. European Commission (2016) projects carbon prices of about 35 €/t CO_2 in 2030 and 90 €/t CO_2 in 2050. This leads to additional hydrogen costs of 0.31 and 0.80 €/kg SMR hydrogen in 2030, respectively 2050. Naturally, the full cost of carbon would only be seen by fossil-based hydrogen production, once free allocation is abolished and which could be the case after 2030 and with a world-wide harmonisation of carbon cost.

With this background, the production cost of hydrogen based on renewable energy sources and electrolysis can be appreciated (see Annex 2 and Table 11). Values are calculated for optimistic and pessimistic RES generation cost according Agora/Frontier Economics (2018).

Annex 2 provides more detailed calculations. For stand-alone plants, 4000 full load hours at the generation cost levels discussed, are most realistic. This also includes connection costs to the electrolysis of 10 €/MWh.

Under these conditions and with 4000 full load hours, hydrogen production based on RES in 2030 is still more expensive than fossil-based hydrogen, while it would be comparable with 8000 full load hours. A combination of wind and PV would only reach 4000h, if not connected to the grid. With Concentrating Solar Pow-

[1] H2 production cost ($/gge untaxed) at varying natural gas prices for current DNGR technology (assuming 1,500 gge/day plant size and economy of scale in plants deployment). Cost target for hydrogen (<$2.00/gge) can be met with a price of NG < $7.00 /MMBTU. The shaded area represents the range of natural gas spot prices for 2016. Note: 1 gasoline gallon equivalent (gge) of hydrogen is equivalent to 1 kg of hydrogen based on energy content.

er (CSP) higher full load hours could be reached, given the storage characteristics of this technologies, however, at higher RES cost, at present, as the technology is still early in the learning curve compared to PV and wind. Lowest generation cost for CSP are at present still at 60-70 €/MWh, hence would lead to higher RES cost in a mix with PV and wind. In the long-term further cost degression seems possible given that CSP is presently at a total of 5GW installed world-wide while PV and wind reach 400-500 GW cumulative installed power capacities.

Table 11: RES-based hydrogen cost for Morocco

€/kg hydrogen	2015	2030	2050
Fossil-based hydrogen (SMR)	Europe: 1.8 €/kg US: 1.3 €/kg	2.3 €/kg (incl. carbon price 35 €/t CO_2)	3.45 €/kg (incl. carbon price 90 €/t CO_2)
Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price **excluding** connection cost of around 10 €/MWh. **8000 full load hours.**	3.5 €/kg RES production cost: 38 €/MWh	2.0 €/kg RES production cost: 23 €/MWh	1.2 €/kg RES production cost: 11 €/MWh
Pessimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price **excluding** connection cost of around 10 €/MWh. **8000 full load hours.**	4.0 €/kg RES production cost: 47 €/MWh	2.5 €/kg RES production cost: 33 €/MWh	1.9 €/kg RES production cost: 27 €/MWh
Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price **including** connection cost of around 10 €/MWh. **4000 full load hours.**	5.4 €/kg RES production cost: 48 €/MWh	3.3 €/kg RES production cost: 33 €/MWh	2.3 €/kg RES production cost: 21 €/MWh

Source: Own calculations, see Annex 2

By 2050 with 4000 full load hours and optimistic RES cost, including connection cost, renewable hydrogen would be considerably cheaper than fossil hydrogen, in particular, if the latter sees the full carbon price of 90 €/t CO2, projected presently for the European Emission Trading Scheme by 2050 (implying full auctioning of allowances, including for industrial processes, i.e. removal of free allocation to industry).

In conclusion, give the uncertainties, the cost of RES-based hydrogen, under the conditions of Morocco will be comparable or lower than fossil-based hydrogen, some time after 2030, depending on the evolution of gas prices and the inclusion of (full) carbon cost.

Additional cost are to be considered for desalination plants and hydrogen transport, in case the hydrogen produced with be used elsewhere. Both cost elements contribute, however, only in a minor manner to the overall cost, in particular, if the electrolysis plants are large (see for example Agora/Frontier Economics, 2016).

Morocco, under these conditions could become an exporter for hydrogen, considering, however, that the demand for hydrogen will depend on other countries/regions building up own hydrogen infrastructures and an own hydrogen economy.

Synthetic methane and methanol production

Annex 2 provides cost information for the production of synthetic methane and methanol. Also for these fuels, given the lower RES cost in Morocco and the perspective of further drop in generation cost, there will be lower cost per tonne of product after 2030.

However, a major issue for discussion for synthetic methane, synthetic liquid fuels and methanol is the need for a CO_2 source. Considering sustainability criteria (see hypothesis 10), the source cannot be or fossil origin, at least not on a permanent basis. The CO_2 must be derived from Direct Air Capture (DAC), in order to allow for a true CO_2 recycling.

5.3 Production of synthetic ammonia as a promising economic opportunity for Morocco

5.3.1 Hypothesis 8: The production of synthetic ammonia offers - under favourable conditions - economic opportunities to Morocco as a producer of green ammonia for own purposes and for export.

Main messages

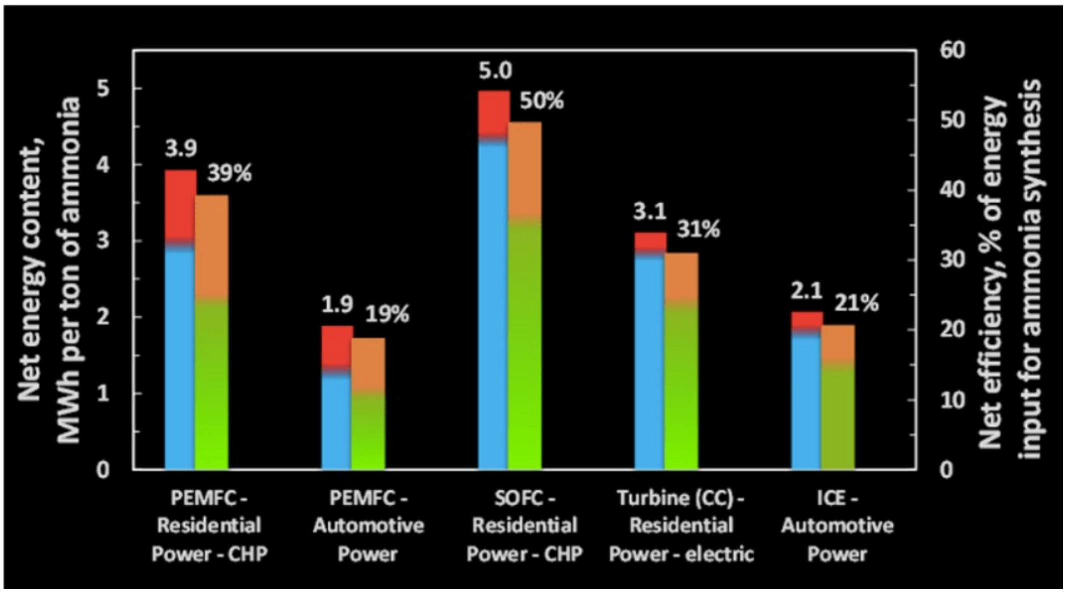
- Ammonia is at first an energy and carbon intensive process (mainly for the production of fertilizers). It may also become a media for energy storage.
- In both applications growth perspectives are identified, leading to a possible quadrupling of production by 2050.
- About half of the present world-wide ammonia production could be covered in 2030 by carbon pricing schemes, leading in combination with rising gas prices to a price increase for the fossil-fuel based ammonia process.
- The present context of Morocco is characterised by strong dependencies on imported ammonia as inputs to phosphor-based fertilizers.
- By 2030, or some time period later, green ammonia based on RES could compete with fossil ammonia under favourable conditions with respect to full load hours and capital cost, especially if fossil ammonia faces full carbon cost.

Introduction to the ammonia industry in Morocco

Ammonia is at first an energy and carbon intensive process. A typical modern ammonia-producing plant first converts natural gas (methane) or LPG (liquefied petroleum gases such as propane and butane) or petroleum naphtha into gaseous hydrogen. The method for producing hydrogen from hydrocarbons is known as steam reforming. The hydrogen is then combined with nitrogen (extracted from air) to produce ammonia via the Haber-Bosch process. The hydrogen entering the Haber-Bosch process may be produced from electrolysis based on renewable energy sources. Most of the ammonia is produced for fertilizer purposes.

Ammonia may also become a media for energy storage (Power Technology, 2018). The ammonia produced by renewables is stored in a tank and converted back into electricity when needed, either through traditional combustion methods or by cracking it into nitrogen and hydrogen. In the latter method, the hydrogen can then be used in hydrogen fuel cells to power devices such as electric vehicles. No carbon emissions are produced during the entire process. A drawbacks has been a low chain efficiency (Figure 12) though recent research claims up to 72% (Wang et al., 2018). Further, while gas-turbine combustion techniques fuelled with ammonia do not produce any carbon dioxide, the presence of nitrogen in the fuel carries the risk of nitrogen dioxide and nitric oxide emissions – classed together as nitrogen oxides (NOx).

Figure 12: Round-trip Efficiency of Ammonia as a Renewable Energy Transportation Media

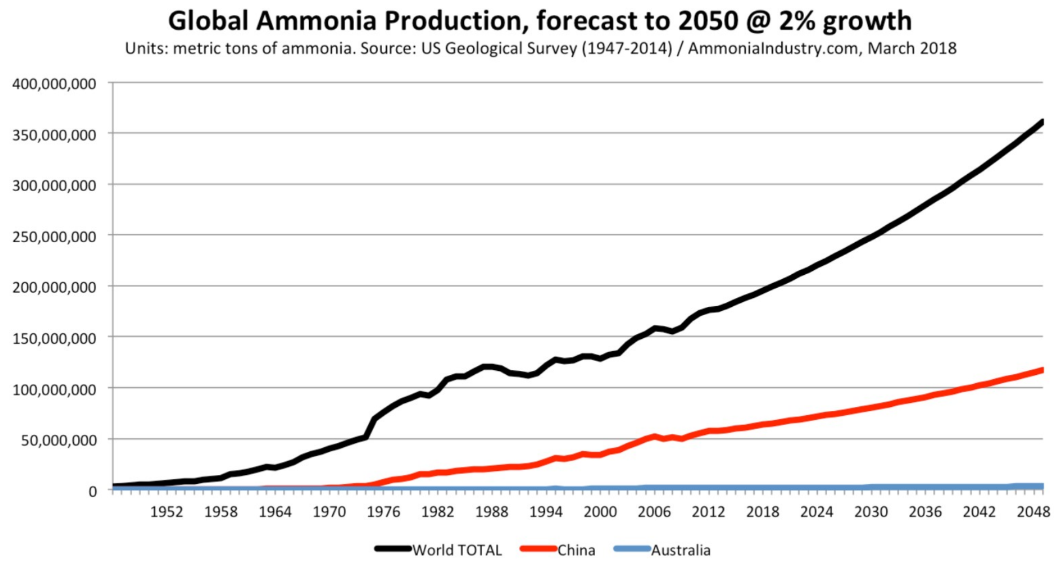


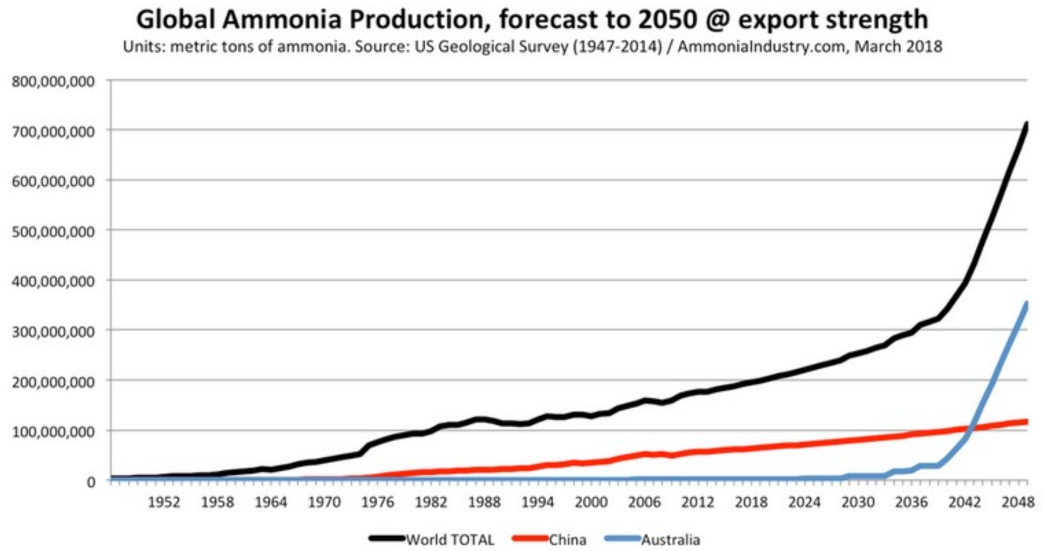
Source: Brown, T. (2017)

In both applications, Brown, T. (2018) identifies growth perspectives:

- Ammonia, mainly for fertilizer uses, has been growing at an annual rate of 2% annually (Figure 13, upper part). Extrapolating this growth to 2050, leads to a doubling of the present production of around 180 Mt annually. Though it can be questioned whether fertilizer uses ca be expanded at a similar path as previously, for environmental reasons, there is certainly an upward trend in ammonia uses to be expected.
- In case, ammonia could become a major energy storage media, another doubling of production might occur (Figure 13, lower part). Especially Australia, with large RES potentials, is investigating ammonia for energy in the frame of a larger hydrogen strategy for the country (Crolius S., 2018). As main advantages of Ammonia for Energy the Australian strategy identifies (Commonwealth of Australia, 2018):
    - It is a carbon-free fuel that can be directly burned to release energy or decomposed to liberate hydrogen and nitrogen.
    - It is a key component of existing industrial products such as fertilisers and explosives.
    - It can be transported as a liquid at ambient temperature and mild pressure. It is already shipped at large scale with well-established infrastructure and handling practices.
    - The amount of hydrogen that can be transported per ship is likely to be significantly higher with ammonia than with liquefied hydrogen, given ammonia's greater hydrogen density and simpler cooling and physical storage requirements.
    - Australia already produces and exports significant quantities.

Figure 13: Possible growth in ammonia production up to 2050 due to increasing fertilizer use (upper figure) and due to the possible use of ammonia as an energy storage means (lower figure).





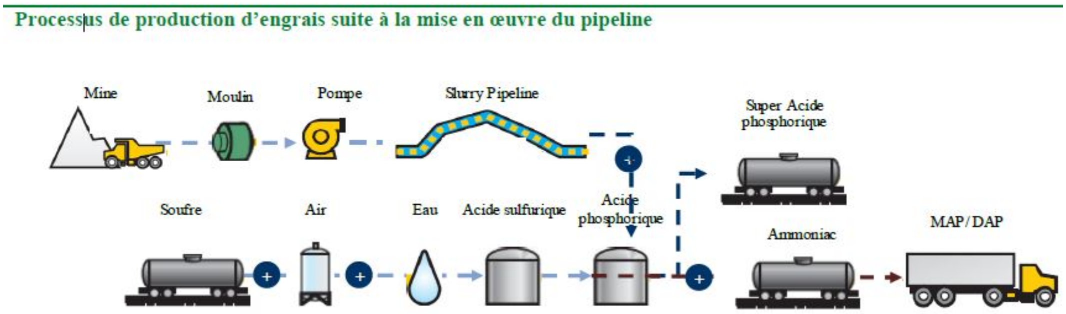
Source: Brown, T. (2018)

What are the possible stakes of Morocco in the growing markets of ammonia? Most of the world's phosphate reserves are in Morocco, with the country accounting for approximately 70% of the total reserves of 50 billion tons. It is also the second-largest producer with most of the production coming from Western Sahara. Morocco remains the largest exporter of phosphate. Ammonia, which is presently imported at more than one million tonnes per year is used to obtain three phosphate derivatives:

- Diammonium Phosphate Fertilizer - DAP : DAP is the most widely used phosphate fertilizer in the world. The manufacture of DAP is based on a neutralization reaction of phosphoric acid, the source of phosphorus, with ammonia, the source of nitrogen. N is 18% concentrated, P_2O_5 46%.

- Monoammonium Phosphate Fertilizer - MAP : The process is identical to that of the DAP. Only the dosages change as follows: N is concentrated at 11%, P_2O_5 at 52%.
- NPK fertilizer : The principle of the production process is the same as for DAP and MAP, only the dosages change. Potash is also introduced at the end of the process.

Figure 14: Phosphate/Ammonia-based Fertilizers



Source: OCP Group Annual Report

Hence **the present context of Morocco is characterised by strong dependencies on imported ammonia for the three processes** (see Annex 1, the International Trade of Morocco, with a particular focus on Ammonia). The Group OCP, which is Morocco's public phosphate producer and largest company, needs ammonia to produce three phosphate derivatives DAP, MAP and NPK mentioned above. These are used as fertilizer for the agriculture industry. The group OCP stated in its annual reports that the fluctuations of the price of Ammonia affect heavily the Group's profitability. Beyond cost, any interruption in the supply of raw materials, such as a supplier shutdown or a contract renegotiation problem, would have a negative impact on the OCP business and results. Therefore, OCP is looking for an alternative to importing ammonia especially that an international rating agency has stated the following: "*OCP does not have cheap access to its two main raw materials, sulphur and ammonia, which can have significant price variations. OCP also remains exposed to country risk with a high concentration of assets in Morocco, and to the risk associated with a cyclical industry with highly volatile phosphate prices and structural overcapacity*."

In this context of growing or, possibly growing, markets for demand for ammonia, the question arises, what are the driving forces for green ammonia over the coming decades. We focus here on ammonia as an energy-intensive industrial process. When considering ammonia as an energy storage chemical, it is clear that this can only develop when ammonia is produced with green processes and not with the classical Haber-Bosch based on natural gas.

When looking at the world-wide production of ammonia today, it appears that while only around 6.7% of the production is subject to a carbon price today, up to an additional 44% are phasing likely (China) or possible carbon pricing (USA, Australia, Canada) in some foreseeable future (

Table 12). In total, this concerns around half of the world production.

Table 12: Worldwide production of ammonia (in kt)

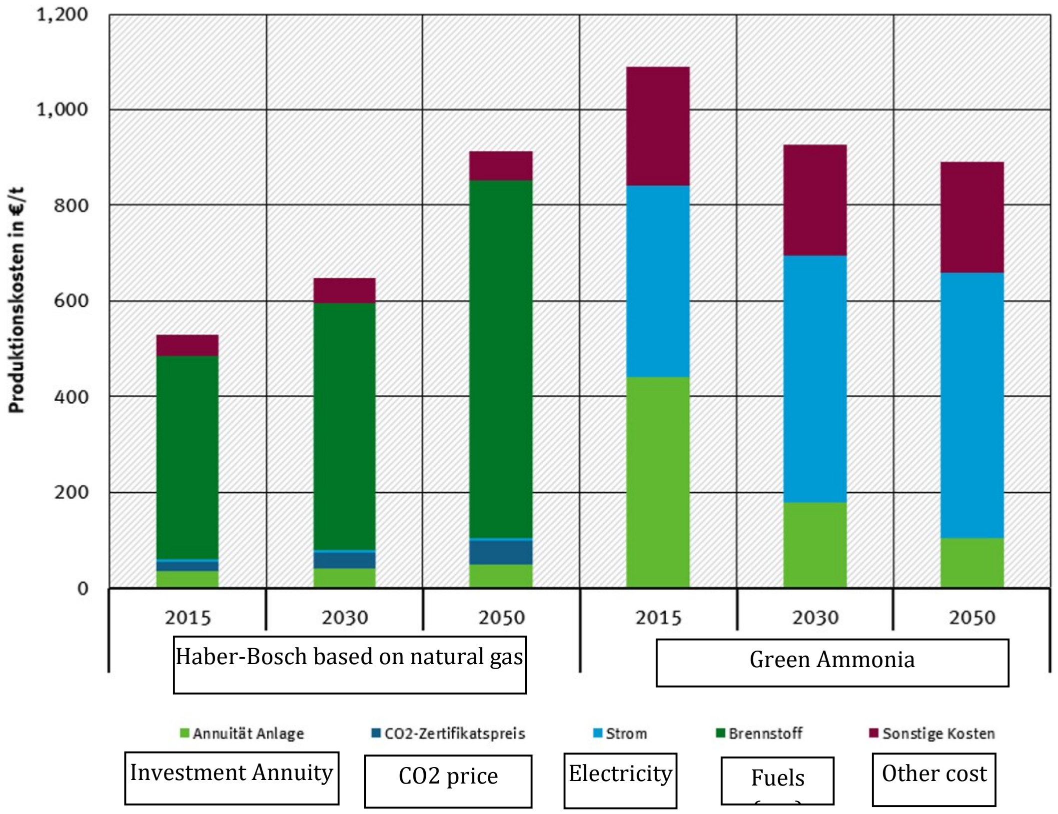
kt of ammonia	2016	2017e
Algeria	1,130	1,200
Australia	1,300	1,300
Belarus	1,060	1,100
Brazil	1,000	1,000
Canada	4,140	4,100
China	46,000	46,000
Egypt	1,800	2,000
France	2,600	2,600
Germany	2,500	2,500
India	10,800	11,000
Indonesia	5,000	5,000
Iran	2,640	2,700
Malaysia	1,460	1,500
Mexico	1,100	1,100
Netherlands	2,300	2,300
Oman	1,700	1,700
Pakistan	2,600	2,600
Poland	2,200	2,200
Qatar	3,050	3,000
Russia	12,500	13,000
Saudi Arabia	4,100	4,100
Trinidad and Tobago	4,910	4,900
Ukraine	1,800	1,800
United States	10,200	10,500
Uzbekistan	1,200	1,200
Venezuela	1,000	1,000
Vietnam	1,100	1,100
Other countries	13,100	13,100
World total (rounded)	144,000	150,000
Share of production submitted to Carbon Price today	6.7%	6.6%
Share of production in phase of being submitted to Carbon Price or possibly submitted to carbon price by 2030	44.0%	43.8%

Source: USGS (2018)

For those countries, the pressure will be high to develop clean ammonia processes or to import clean ammonia. Though carbon leakage (i.e. shift of ammonia production based on the classical Haber-Bosch with natural gas) can be an issue for a certain period of time (which countries subject to emission trading will deal with free allowances up to a benchmark, which will be tightened over time), it is unlikely that this pressure to introduce low carbon ammonia will not generate opportunities to develop clean ammonia processes. In the EU such developments may be supported by an Innovation Fund[1] which shall support low carbon processes with auction revenues from the EU ETS, as well as loan guarantees and other financial instruments.

The cost for green ammonia in "95%-reduction" countries like Germany will most likely be considerably higher as for the classical Haber-Bosch (Figure 15) today. Nevertheless, by 2050 the cost for the classical process will be increased, notably under the pressure of the rising price for natural gas and the rising CO_2 price. By 2040, the cost of the two ways to produce ammonia could be comparable under certain conditions in Germany. When this will occur will depend on how the policy level handles carbon leakage while developing innovative processes. Overall this shows that the cost of the fossil-based ammonia production will be on the rise, mainly due to rising gas prices and partly due to rising CO_2 prices.

Figure 15: Comparison of the specific production cost for ammonia production in Germany up to 2050 (95% GHG reduction requirement)



Source: Fraunhofer ISI (2018)

While there is limited pressure on developing countries (including Morocco) to decarbonise their own economy to the same high degree as developed countries (see Hypothesis 3), there could be economic drivers as well as issues of corporate responsibility and company image, why ammonia producing or consuming countries could opt for green ammonia.

[1] https://ec.europa.eu/clima/events/articles/0115_en

Opportunities for local Green Ammonia production

For Morocco in particular, the following options are possible:

- Morocco may continue to import ammonia from the classical Haber-Bosch. From the above described developments it is likely that the price of ammonia will increase in the whole ammonia market and, possibly, fluctuate as well. Ammonia imports will affect heavily Morocco’s trade balance, especially with the flexibility of the currency of Morocco (MAD vs Euro). If the price of ammonia increases further in the next thirty years (in case exporting countries are subject to high carbon prices), this will affect further the trade balance. This can be the case of the Ukraine notably, from which Morocco at present is importing a major part of its ammonia at present (see Annex 1). The Ukraine seeks to adapt to European legislation and is on the path to introduce emission trading. Other importers such as Russia, Algeria and Trinidad and Tobago may not be subject to carbon pricing but Figure 15 shows that the major driver for cost will be gas prices which will concern most countries equally as the gas markets are linked.
- Morocco may start an own production based on the classical Haber-Bosch process. However, this would be a very uncertain strategy, given the likely rising cost for that process as well as the question whether this would lead to questions on Morocco's industrial strategy ("Why attract carbon-intensive industries in a country without own gas resources and with the ambition to be a country contributing to protect the climate and to contribute to the Paris Agreement, as evidenced by the country's renewable strategy for power generation?"
- Finally, Morocco - based on the local strong potentials for wind and solar - could start own clean ammonia production with a triple perspective:

Replace the imported ammonia with green ammonia to strengthen the local manufacturing of fertilizers. This process will mainly be driven by economic considerations. Figure 16 and

Scenario 2: Medium full load hours - 4500h

Figure 17 shows the possible evolution of production cost for green ammonia in Morocco under the assumption of medium full load hours for electrolysis. This assumption can be realised with wind/PV combinations, in particular in Southern remote areas without strong grid connection.

- Figure 17, as well as Annex 3) show that under favourable conditions (high load hours, low interest rates and moderate to optimistic development of RES cost), green ammonia production cost could be comparable or lower than the rising production cost for fossil-based ammonia before or at 2020, otherwise some time period after 2030. There will be a transition period with fossil-based ammonia and green ammonia in parallel. This will raise challenges for green ammonia plants, especially when competing against fossil-based plants in countries which are not subject to carbon pricing, at least not in a foreseeable time frame. In order to produce 1 Mt of green ammonia (which corresponds to the presently imported amount of ammonia), Morocco would have to install about 3 GW RES by 2030 (assuming a mix of solar and wind with 4000 full load hours per year). This fits well within the amount of 9 GW assumed in Hypothesis 5.

- ***Export clean ammonia to "95%-countries" in replacement of ammonia consuming processes in those countries.*** As discussed more generally in Hypothesis 1, this will mainly be the case for countries with limited resources and space to generated sufficiently RES electricity on their own. Other countries such as the US have sufficient own RES potentials and space to generate clean ammonia at similar cost as in Morocco (or lower, if they have lower capital cost compared to Morocco). Each additional million tonne of clean ammonia for requires about 3 GW RES generation. If all of the PtX potentials which Morocco can reasonably realise by 2030 are used for ammonia production according to hypothesis 5, Morocco could produce 2-3 Mt ammonia by 2030.
- ***Export clean ammonia to "95%-countries" for covering energy needs***. This might happen under similar boundary conditions as for the previous bullet point. Such export potentials may realistically only be covered with RES capacities beyond 2030.

For the economics of the ammonia production we consider two scenarios:

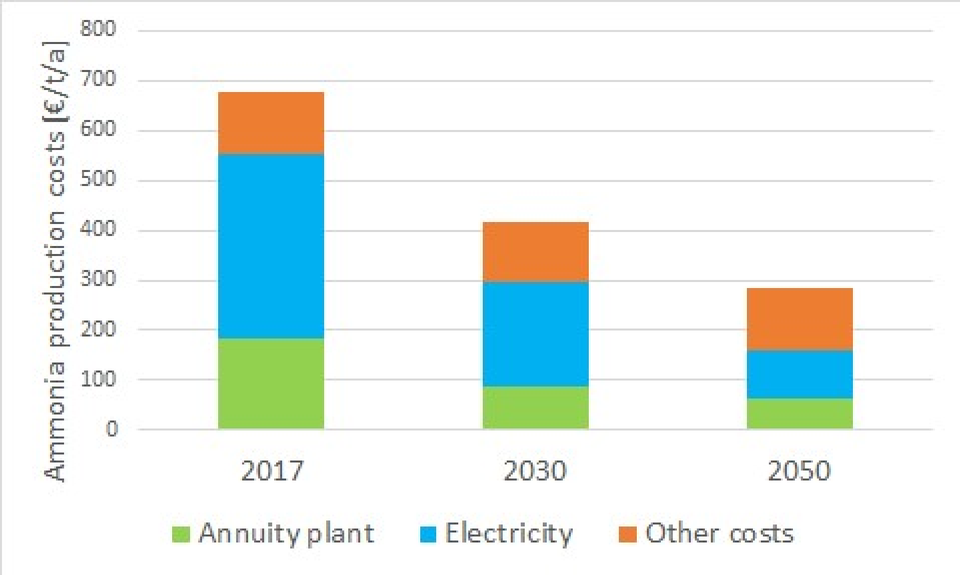
- Scenario 1: high full load hours - 8000h
- Scenario 2: medium full load hours - 4500h

Scenario 1: high full load hours - 8000h

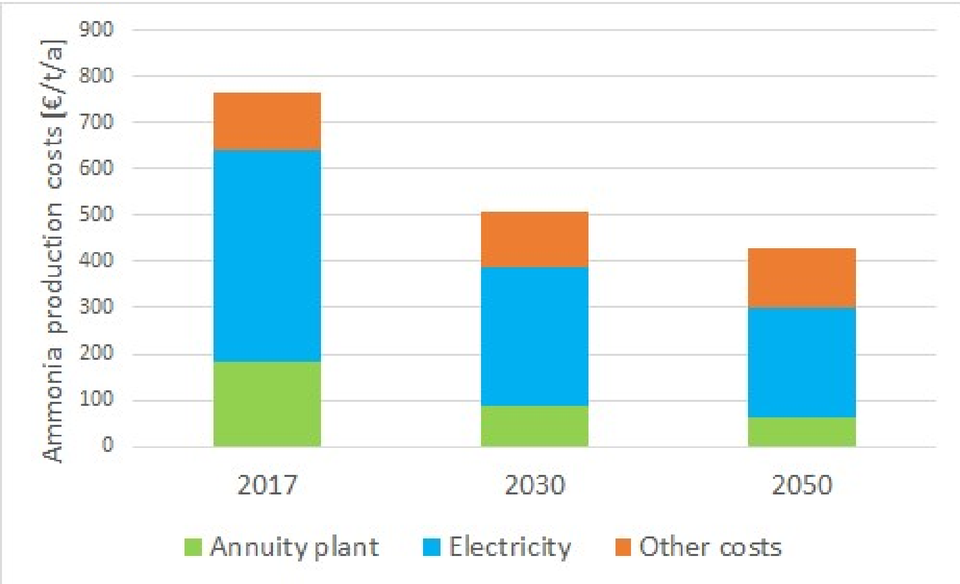
Figure 16 shows the possible evolution of production cost for green ammonia in Morocco under the assumption of very high full load hours for electrolysis. This assumption is only achievable when the electrolysis is connected to the general grid or when storability of electricity is possible at low cost, e.g. by including low-cost CSP in the power mix for the electrolysis. CSP is presently still at high cost compared to PV but has the advantage of offering storage for up to a day. Efforts in China to double world-wide CSP capacity could lead to a substantial cost decrease also. Grid connection cost, in case there is a general grid connection, may add another 10 Euro/MWh and are not taken into account in the calculation yet. However, this may not be economically possible for more remote regions in the South of Morocco. On the other hand, thus solution may offer reserve capabilities for the grid, which is relevant as the shares of fluctuating renewables are increasing.

Figure 16: Specific production cost for ammonia production in Morocco up to 2050 (under favorable conditions: high full load hours - 8000h, low interest rates for capital - 2%)

Optimistic development of RES cost (see Annex 3)



More moderate development of RES cost (see Annex 3)



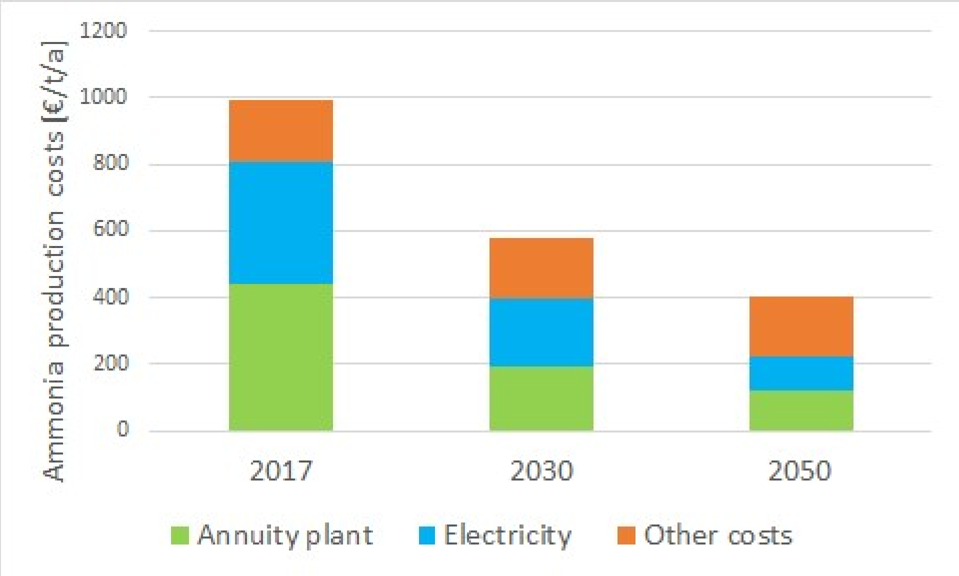
Source: own calculations

Scenario 2: Medium full load hours - 4500h

Figure 17 shows the possible evolution of production cost for green ammonia in Morocco under the assumption of medium full load hours for electrolysis. This assumption can be realised with wind/PV combinations, in particular in Southern remote areas without strong grid connection.

Figure 17: Specific production cost for ammonia production in Morocco up to 2050 (under more unfavorable conditions: lower full load hours - 4500h, higher interest rates for capital - 6%)

Optimistic development of RES cost (see Annex 3)



More moderate development of RES cost (see Annex 3)

Source: own calculations

Strategy for a local Green Ammonia production

Morocco may follow three steps over time:

- Replace the imported ammonia with green ammonia to strengthen the local manufacturing of fertilizers. This approach appears economic under the conditions of high full load hours for the electrolysis, low interest rates and moderate to RES electricity cost. By 2030, approximately 3 GW of RES generation are necessary to produce 1 Mt of green ammonia, which corresponds to the present imports.
- Export clean ammonia to "95%-GHG reduction countries" in replacement of ammonia consuming processes in those countries. By 2030, Morocco may be able to produce a further 1-2 Mt green ammonia for export.

- Export clean ammonia to "95%-GHG reduction countries" for energy generation purposes. This may be a viable and economic strategy beyond 2030.

5.4 Guiding principles for the development of PtX in Morocco

5.4.1 Hypothesis 9: RES development should be accompanied by a hierarchy principle minimising necessary expansion, even with further falling cost, to minimise broader environmental impacts.

Main messages

- An "Energy Efficiency First" principle, as recently introduced into European policy making, must be a strong guiding principle for expanding the RES capacities in a country. This holds both for the PtX importing and exporting regions.
- A second important principle is "priority to renewables" in the further expansion of the power sector (or when replacement of fossil power capacities is necessary).
- When alternatives exist based on RES with similar type of services but less of the impacts mentioned above, they should be priorised. This includes in particular direct electric uses, as well as sustainable biomass/biofuels/biogas taking into account their limited availability.
- For PtX, which as a number of environmental impacts (notably use of area due to low chain efficiencies and water use) this implies a hierarchy of use: applications in which PtX is without alternatives at present, applications where chemical-based PtX competes with direct electrification processes and finally applications where PtX may only make sense in selected cases, due to the availability of more appropriate alternatives.

We recommend that Morocco takes up these guiding principles in the development of its 2050 energy strategy.

The electricity generation for PtX must be based on (variable or continuous) RES - though nuclear or, in principle, fossil power generation linked with Carbon Capture and Storage (CCS) could also be options. The more of such RES need to be installed in conjunction with PtX, the more the question of low chain efficiencies become important.

The massive installation of these variable renewable sources (solar, wind) can be a challenge for electricity networks and systems; it comes with environmental impacts such as land-use, noise, water-use and resource utilisation. Such arguments hold not only for densely populated regions such as in Europe but also for loosely populated regions in Morocco: "Even a desert has life". Further, these environmental impacts may raise acceptance problems. Although these impacts are not easily quantified and internalised into renewable electricity generation, they may provide **arguments for a hierarchy principle which minimises necessary RES capacities, even with further falling cost**. This implies two important consequences:

- an **"Energy Efficiency First" principle**, as recently introduced into European policy making, must be a strong guiding principle for expanding the RES capacities in a country. This holds both for the PtX importing and exporting regions. In the latter for the own PtX uses and the direct uses of RES electricity for own purposes, was well.

- A second important principle is **"priority to renewables"** in the further expansion of the power sector (or when replacement of fossil power capacities is necessary). As stated above, fossil fuels should be phased out as soon as possible, to provide room for opportunities for clean electricity generation or green PtX products.
- When alternatives exist based on RES with similar type of services but less of the impacts mentioned above, they should be priorised. This includes in particular direct electric uses, as well as sustainable biomass/biofuels/biogas taking into account their limited availability.

Naturally, it is not straightforward to define an optimum for RES expansion for PtX based on this principle, however, the following **hierarchy in applications for PtX** follows closely such a principle. We distinguish:

- Applications in which the use of material PtX technologies to the extent required is, according to the current state of knowledge, **without alternative**:
  - industrial process heat, chemicals, international air traffic, international shipping,...
- Applications in which the use of material PtX technologies **competes with direct electrification processes** and the respective use is subject to the evaluation of economic, infrastructural, environmental, social and other advantages and disadvantages of the respective technologies:
  - Rail transport, long-distance truck transport, low-temperature heat, industrial process heat,...
- Applications whose energy carriers can in principle be made available by PtX material technologies, but which, due to the corresponding alternatives, **only make sense in individual cases**:
  - Cars, local truck traffic, flexibility in the power grid, areas of low-temperature heat,...

More details of the possible use of PtX technologies in different application areas, according to the above mentioned hierarchical principle, as well as possible alternatives, are provided in Table 13.

For discussion purposes it should be reported that there are differing views on such a hierarchy principle as formulated here for PtX. The following citation illustrates such differences in view (Van Wijk, 2018): "*In a renewable energy system and in comparing renewable energy chains, the energy-efficiency is no longer important because the renewable energy resources are vast, there is enough space for renewable energy production and there are no emissions anymore in the system. It is all about cost!*". We recommend that Morocco takes up these guiding principles in the development of its 2050 energy strategy.

Table 13: Overview of PtX technologies in different application areas (I)

Field of application	Previous (fossil-based) technology	Direct electrification options	PtX-Technologies	Other renewable energy options
Transport				
Cars	Petrol and diesel engines Gas-powered vehicles	Battery-powered electric vehicles	Fuel cell vehicles Synthetic fuels	biofuels
Distribution by trucks (smaller size)	Petrol and diesel engines Gas-powered vehicles	Battery-powered electric vehicles	Fuel cell vehicles Synthetic fuels	Biodiesel, purified biogas
Heavy trucks	Diesel engines Gas-powered vehicles	Overhead contact lines on motorways	Fuel cell vehicles Synthetic fuels	Biodiesel, purified biogas
Rail transport	Electric drive Diesel engines	Electrification of non-electrified lines	Fuel cell vehicles Synthetic fuels	Biodiesel
Air transport	Turbines (kerosene)	No technologies foresee-able	Synthetic kerosene	Bio-based kerosene
Ship transport	Ship engines (heavy fuel oil, diesel), LNG in future	No technologies foresee-able	Fuel Cell Drive Synthetic Diesel Synthetic LNG	Biodiesel, purified biogas
Low-temperature heat for households, industry, trade, commerce and services				
Low temperature heat	oil, gas heating, district heating	Heat pumps, resistance heating	Synthetic gas	Biomass, -gas

Table 13: Overview of PtX technologies in different application areas (continued)

Field of application	Previous (fossil-based) technology	Direct electrification options	PtX-Technologies	Other renewable energy options
Industry				
Industrial process heat	Gas burners Steam	Electrode boiler, Induction heating, Plasma process, Resistance heating	Synthetic fuels	Biomass, -gas
Steel (primary route)	Coke	Not possible	Hydrogen	Biomass, -gas
Refinery	By-product hydrogen, fossil hydrogen (mainly natural gas)	Not possible	Hydrogen	Biomass, -gas
Chemicals	Petroleum- and natural gas-based basic chemicals	Not possible	Synthetic raw materials	Biomass, -gas
Power supply				
Short-term stabilisation of the electricity grid, provision of flexibility	Flexible use of power plants Demand Side Management (DSM)/ Demand Side Response (DSR) Flexibilization of demand grid extension	Electricity storage (pump storage, batteries, ...)	Flexible mode of operation for electrolysis	Flexible power generation from biomass
Stabilisation of the electricity grid due to structural lack of renewable electricity generation (dark doldrums)	Flexible use of power plants Demand Side Management (DSM)/ Demand Side Response (DSR)	No technologies foreseeable	Synthetic gas for reconversion to electricity in power plants or fuel cells	Flexible power generation from biomass

Own presentation in Adaptation of: Ausfelder, F.; Dura, H.E. (Ed.): Options for a sustainable energy system with Power-to-X technologies. Challenges - Potentials - Methods - Impacts. 1st roadmap of the Kopernikus project "Power-to-X": Flexible use of renewable resources (P2X). Frankfurt a.M.: DECHEMA Society for Chemical Engineering and Biotechnology e.V.

5.4.2 Hypothesis 10: Sustainability criteria play an important role for PtX in Morocco

Main messages

- Sustainability criteria for PtX are important parameters to be taken into account in building up a sustainable PtX production in Morocco, in particular when it comes to exports.
- Sustainability criteria concern in particular:

  - origin of carbon in case of synthetic energy carriers

  - consumption of land

  - consumption of water

  - no overlap with the countries' own RES expansion

Sustainability criteria for PtX are important parameters to be taken into account in building up a sustainable PtX production in Morocco, in particular when it comes to exports of PtX. They reduce the risk of stranded investment by avoiding that Morocco embarks on a path which is considered - especially by the possible PtX markets in developed countries, as non-sustainable, which would lead that the demand for such type of PtX eould not materialise.

Sustainability criteria concern:

- the **origin of carbon** in case of synthetic energy carriers such as methane, syn-fuels, methanol.
  - The production of 1TWh of synthetic methane requires 198 kt CO2 (Agora/Frontier Economics, 2018).
  - The CO_2 supply is limited in the long-term. Using CO_2 from fossil processes is not sustainable. A true CO_2 recycling process is required.
  - The origin of the carbon will be the more an issue if Morocco becomes an exporter of PtX to countries with 95% reduction targets. It is difficult to envisage that those countries would import PtX based on non-sustainable CO_2 sources.
  - Direct Air Capture (DAC) appears as the main approach.
  - Carbon Engineering
- **Consumption of land** for RES generation
- **Consumption of water:** appropriate are Sea Water Desalination plants as they are not in competition with the provision for drinking water; however, even those may become necessary for drinking water
- No overlap with the countries' own RES expansion; prevent competition for RES sites

Direct Air Capture (DAC) consists in the following: Banks of fans blow air through a carbon dioxide–capturing solution in this rendering of a direct air capture plant (

Figure 18). So far, cost for DAC has been very high in the range up to 1000 US$ per tonne of CO_2, given the distributed nature of CO_2 in the atmosphere. However, recent cost estimates are much lower with the perspective of reaching cost levels at or below 100 Euro/tonne CO_2 (Table 14).

Figure 18: Direct air capture (DAC) of CO_2

Source: http://www.sciencemag.org/news/2018/06/cost-plunges-capturing-carbon-dioxide-air

Table 14: Cost assumptions for CO_2 production from DAC in Euro2017 per tonne of CO_2

	Today	2030	2050
Direct air capture for PtG*	145	102	100
German cement industry	33		
Iceland cement industry	17		

* PV, North Africa, reference

Frontier Economics (2018)

Source: Agora/Frontier Economics (2018)

6. Conclusions and Recommendations

In this report, we formulated for the analysis 10 hypotheses on PtX and its opportunities for Morocco. This approach was taken because there are still quite some uncertainties about the possible future role of PtX, both in Europe and countries like Morocco. The formulation of such hypotheses, supported by analysis of the present knowledge and uncertainties, helps to feed the necessary discussion processes to determine more precisely the possible future role of PtX technologies in the energy system. For each hypothesis we followed the same approach: after having formulated the hypothesis, we cumulated the evidence which we know so far and the hypothesis is formulated in such a manner that - from the current perspective - the hypothesis appears as verified, but given the uncertainties. The discussion of the 10 hypotheses provides the following main conclusions and implications for Morocco.

6.1 Main conclusions for Morocco from the discussion of the ten hypotheses

6.1.1 Conclusions for Morocco from the hypotheses on the world-wide demand for PtX

The first four hypotheses deal with question of the size of the possible future market for PtX and what are main drivers and risks.

***Hypothesis 1*:** The world-wide demand for PtX will be driven by the requirements on developed countries to reach a reduction of 95% in view of contributing to the 1.5°C target of the Paris Agreement.

Main results from the analysis:

- Quite a number of studies come up with fairly high worldwide potentials for PtX in the range 10-40000 TWh in 2050.
- By applying the hierarchical principle of Hypothesis 9 (see there), we estimate PtX potentials in the range of 320 - 726 TWh for 2030 and 972 - 6180 TWh by 2050.
- This corresponds to a market size of 45 - 102 Billion Euro annually in 2030 and 107 - 680 Billion Euro annually in 2050 (for comparison: the size of oil markets at present prices is around 2000 Billion Euro annually).
- A major determinant for the own estimates in this report is the realisation of an ambitious energy efficiency strategy which reduces primary energy demand by 2050 to half of the present value in developed countries. Detailed studies show that such a reduction is economically feasible.
- The estimated world-wide market potential for PtX is smaller than some of the more generous potential estimates come up with, and which do not apply the hierarchical principle from Hypothesis 9. However, it still presents a considerable market opportunity for potential PtX producers such as Morocco.

A main conclusion for Morocco is that the Paris Agreement and the requirement to limit global temperature rise to well below 2°C are the major driver for PtX. Markets. PtX is required for a number of applications such as air transport or industrial processes such as ammonia production where presently alternatives are not existing or limited (e.g. biofuel production). Demand for PtX products arises, at first, mainly in developed countries with requirements to reduce GHG emissions by 95% and more and that have limited space to produce cheap renewable electricity which is a major requirement for the production of PtX. Cautious estimates of the expected market size indicate markets that are smaller than current oil markets (in the range 100-700 billion Euro by 2050) but still in notable size, providing opportunities for potential producers of PtX.

***Hypothesis 2*:** If the requirement would only be 80% reduction in GHG (which is possibly compatible with a 2°C scenario) there would be very limited need in developed countries for PtX.

Main results from the analysis:

- 80% GHG reduction does not imply substantial shares of PtX in developed countries. The 80% reduction is not in line with the Paris Agreement "to stay well below global 2°C temperature rise". This hypothesis must be envisaged as present energy and climate policies are not on track for the Paris Agreement. Adaptation measures will then have to take the place of mitigation measures.
- This is mainly due to the fact that energy efficiency plays an important role in reducing electricity demand across all applications.
- Further, the difficult end-uses which have led to the need in the 95% scenarios to use PtX, still can rely on a certain amount of fossil fuels (notably natural gas and remaining amounts of mineral oil, e.g. for air transport).

A main conclusion for Morocco is that the major risk for emerging PtX markets is a lower than required ambition of climate policies in developed countries. Countries worldwide have then to combat climate change with adaptation measures which partly may be unable to avoid dramatic consequences of climate change, such as large scale migration, or which appear as considerably more costly than mitigation measures according to the IPCC reports. It is difficult to evaluate the risk of global non-compliance with the Paris Agreement from the current perspective: present underrated climate policies in many countries argue for a non-negligible risk; the dramatic consequences of uncontrolled temperature rise for vigorous action. In any case, if Morocco aims for PtX as an industrial strategy, it is in the country's interest to support strong climate actions, which is in line with the country's present climate policy.

***Hypothesis 3*:** Developing countries have lower GHG reduction requirements by 2050, hence less pressure to introduce PtX for own purposes.

Main results from the analysis:

- While developed countries have to achieve at least a 95% reduction in GHG by 2050, developing countries may require less reduction.
- Typical estimates for countries at the development stage of Morocco, would be a rough stabilisation of emissions at present levels, implying a 60-70% reduction from the baseline development.
- At such a level of reduction, PtX is not required to a large degree by developing countries.
- Nevertheless, Morocco wants to take a leading role on climate in the developing world and even worldwide, and has set itself targets for 2030 which are close to the EU targets. Provided international finance comes in support, Morocco could therefore envisage PtX for GHG reduction purposes in the own country on a very ambitious GHG reduction pathway to 2050

A main conclusion for Morocco is that if an industrial PtX strategy is envisaged, it should also evaluate carefully, in the frame of its 2050 energy and climate strategy, the coherence between its own long-term climate targets and such an industrial PtX strategy. Aiming for targets comparable to the 95% GHG reduction target of developed countries will generate an own PtX market and demand which could ease the establishment of a strategy for PtX exports.

Hypothesis 4**:** There is no need for PtX from the pure requirement of a 100% RES share in the power sector. This concerns both Morocco and for example European countries, as long as the power systems are optimised (grid expansions, market arrangements ...)

Main results from the analysis:

- An optimised power system in Morocco will have limited amounts of excess electricity from RES (1 TWh in 2030, 5 TWh in 2050)
- In addition, the full load hours where excess electricity is available are well below the full load hours required by capital-intensive H2 electrolyses.
- In case of a non-optimised power system, the figures are higher. This is also supported by findings from the German electricity system. However, the strategy should be to remove bottlenecks to an optimised system and to increase integration with the European electricity systems, rather than using a non-optimised power system for PtX.
- Remaining amounts of surplus electricity system could be used for smaller PtX applications but full load hours are generally too short for capital intensive PtX plants.
- PtX production plants must therefore be built on top of RES plants covering electricity demand and should not be expanded at the expense of such plants.

A main conclusion for Morocco is that its surplus electricity is not a major driver for the development of PtX. Marocco is aiming for very high shares of renewable electricity by 2050. A non-optimised electricity system, e.g. combining still relatively high shares of rather inflexible coal-based generation with high shares of volatile power generation, could lead to higher surpluses which might be used for PtX generation (though the full load hours will in all cases be rather low making PtX less competitive). However, it would not be appropriate to remain with such an non-optimised system which entails higher cost of electricity generation for the country. Further, PtX production plant should not expand at the expense of plants destined to cover own electricity demand, in case the expansion of renewables capacities is a limiting factor. Nevertheless, a strong Energy Efficiency First Principle may provide more opportunities if the domestic electricity demand grows less rapidly.

6.1.2 Conclusions on Morocco's ability to capture a substantial share of world-wide demand for PtX

Hypotheses 5-7 deal with the question whether Morocco can capture a non-negligible share in the world-wide demand for PtX in order to establish an industrial strategy for PtX. These hypotheses also look at the alternative of direct electricity exports instead of PtX exports and at the economics of PtX production.

***Hypothesis 5*:** Morocco can capture a non-negligible share in the world-wide demand for PtX

Main results from the analysis:

- Estimated RES potentials in Morocco are high and sufficient to cover both domestic electricity demand and PtX production
- Limiting factor is the capability to sustain a long-term growth in RES capacities (grid expansion, planning procedures, and availability of construction capacities...):
  - 2010-2017, growth in wind was 20% annually, growth in solar 27% annually
  - Achieving a 2030 target of 59% of RES capacity requires growth 2010-2030 in wind of 16% annually, in solar of 26%.
  - Achieving in 2030 a 65% RES target requires growth 2010-2030 in wind of 16% annually, in solar of 29%.
- Doubling of the RES capacities in 2030 required for decarbonizing the power sector to 59% would allow capturing around 2-4% of the worldwide potential for PtX in 2030, and implies adding about 9 GW additional RES in Morocco , on top of the RES expansion for covering the electricity demand and the RES targets. Such an expansion is compatible with the expansion rates achieved by Morocco in the past, while offering market opportunities for PtX through first mover advantages.
- Financing capabilities may be another limiting factor for the Moroccan economy.

A main conclusion for Morocco is that the country can capture a share of 2-4% of the possible PtX demand in 2030 with a RES expansion that is double that to achieve a 59% renewables target. Such an expansion is ambitious but compatible with historic expansion rates in the period 2010-2017 as well as with the country's renewables ambition.

***Hypothesis 6*:** Power exports to Europe is not a strong competitor for PtX exports

Main results from the analysis:

- Compared to studies 10 years ago, investment cost in RES have strongly dropped both in Europe and MENA. Transport cost for long distance transport of electricity have seen less cost degression.
- Hence, the competitive advantage of Morocco with higher RES potentials as an electricity exporter have eroded.
- An optimised power system in Morocco will have limited amounts of exports of electricity from RES (8 TWh in 2030, 15 TWh in 2050). This is confirmed also by other scenario runs, e.g. SET Roadmap (EY/Artelys/Castalia/Fraunhofer ISI, 2018); DLR (2016).
- In case of a non-optimised EU-MENA power system, the figures may be higher. However, the strategy should be to remove bottlenecks to an optimised systems and to increase integration with the European electricity systems, rather than using a non-optimised power system for exports of power.
- Exporting electricity is not (anymore) an important competitor for PtX exports.

Conclusions and Recommendations

A main conclusion for Morocco is that the direct export of electricity is economically less attractive than a decade ago, given the strong drop of renewables generation cost compared to the cost of electricity transport. This does not imply that interconnecting Morocco with neighbouring countries, including Europe, is not interesting any more for the Moroccan power system. This increases the stability in the Moroccan system with high shares of renewables. PtX products are higher value products which keep the advantages of Morocco of lower cost of renewables electricity compared to Europe, as transport cost present a lower share in the case of PtX exports.

***Hypothesis 7*:** PtX products may under favourable conditions become economic compared to fossil competitors beyond 2030

Main results from the analysis:

- With 4000 full load hours, hydrogen production based on RES in 2030 is still more expensive than fossil-based hydrogen (whose costs are rising nevertheless due to rising CO_2 and fuel cost), while it would be comparable with 8000 full load hours.
- A combination of wind and PV would only reach around 4000h, if not connected to the grid. With Concentrating Solar Power (CSP) higher full load hours could be reached, given the storage characteristics of this technology, however, at higher RES cost, at present, as the technology is still early in the learning curve compared to PV and wind.
- By 2050 with 4000 full load hours and optimistic RES cost, including connection cost, renewable hydrogen would be considerably cheaper than fossil hydrogen, in particular, if the latter sees the full carbon price of 90 €/t CO_2, projected presently for the European Emission Trading Scheme by 2050 (implying full auctioning of allowances, including for industrial processes, i.e. removal of free allocation to industry).
- Morocco, under these conditions could become an exporter for hydrogen after 2030, considering, however, that the demand for hydrogen will depend on other countries/regions building up own hydrogen infrastructures and an own hydrogen economy.
- Also for the production of synthetic methane and methanol, given the lower RES cost in Morocco and the perspective of further drop in generation cost, there will be lower cost per tonne of product after 2030, though differences will remain long after 2030 with the fossil-based competitors (despite their rising cost due to rising CO_2 and fuel cost). However, these synthetic energy carriers require true recycling of CO_2, e.g. from air capture, which limits strongly their expansion (see hypothesis 10).

A main conclusion for Morocco is that the demand for PtX in developed countries would be sustained beyond 2030 and driven by the evolution of the cost differential between green PtX production and the cost of fossil competitors (rising cost of fossil production of "X" due to rising CO2 and fuel cost). This implies nevertheless policies which bring the CO_2 prices to levels of 90 €/t CO_2 in 2050 in developed countries. Economics further depend on the full load hours possible for the electrolysis and PtX production. By 2050 4000 full load hours may be sufficient which is compatible with non-grid connected combined solar/wind PtX production in the South of the country.

6.1.3 Conclusions on the production of synthetic ammonia as a promising economic opportunity for Morocco

Hypothesis 8 focuses on the most promising production of PtX, synthetic green ammonia. This may replace fossil ammonia imports for fertilizer production while paving the way for green ammonia exports for fertilizer production elsewhere of for energy generation purposes.

***Hypothesis 8*:** The production of synthetic ammonia offers - under favourable conditions - economic opportunities to Morocco as a producer of green ammonia for own purposes and for export.

Main results from the analysis:

- Ammonia is at first an energy and carbon intensive process (mainly for the production of fertilizers). It may also become a media for energy storage.
- In both applications growth perspectives are identified, leading to a possible quadrupling of production by 2050.
- About half of the world-wide fossil-based ammonia production could be covered in 2030 by carbon pricing schemes, leading in combination with rising gas prices to a price increase for the fossil-fuel based ammonia process.
- The present context of Morocco is characterised by strong dependencies on imported ammonia as inputs to phosphor-based fertilizers.
- By 2030, or some time period later, green ammonia based on RES could compete with fossil ammonia under favourable conditions with respect to full load hours and capital cost, especially if fossil ammonia faces full carbon cost.

A main conclusion of this most promising PtX option for Morocco is that the country may follow three steps over time:
- Replace the imported ammonia with green ammonia to strengthen the local manufacturing of fertilizers. This approach appears economic under the conditions of high full load hours for the electrolyis, low interest rates and moderate RES electricity cost. By 2030, approximately 3 GW of RES generation are necessary to produce 1 Mt of green ammonia, which corresponds to the present imports.
- Export clean ammonia to "95%-GHG reduction countries" in replacement of ammonia consuming processes in those countries. By 2030, Morocco may be able to produce a further 1-2 Mt green ammonia for export.
- Export clean ammonia to "95%-GHG reduction countries" for energy generation purposes. This may be a viable and economic strategy beyond 2030.

6.1.4 Guiding principles for the development of PtX in Morocco

Hypotheses 8 and 9 focuses on two guiding principles for the development of PtX world-wide and in Morocco: a hierarchy principle minimising necessary renewables expansion, even with further falling cost, to minimise broader environmental impacts and, connected to this, sustainability criteria for the development of PtX.

***Hypothesis 9*:** RES development should be accompanied by a hierarchy principle minimising necessary expansion, even with further falling cost, to minimise broader environmental impacts.

Main results from the analysis:

- An "Energy Efficiency First" principle, as recently introduced into European policy making, must be a strong guiding principle for expanding the RES capacities in a country. This holds both for the PtX importing and exporting regions.
- A second important principle is "priority to renewables" in the further expansion of the power sector (or when replacement of fossil power capacities is necessary).
- When alternatives exist based on RES with similar type of services but less of the impacts mentioned above, they should be priorised. This includes in particular direct electric uses, as well as sustainable biomass/biofuels/biogas taking into account their limited availability.
- For PtX, which as a number of environmental impacts (notably use of area due to low chain efficiencies and water use) this implies a hierarchy of use: applications in which PtX is without alternatives at present, applications where chemical-based PtX competes with direct electrification processes and finally applications where PtX may only make sense in selected cases, due to the availability of more appropriate alternatives.

We recommend that Morocco takes up these guiding principles in the development of its 2050 energy strategy, in particular if it embarks on a very ambitious GHG reduction strategy with own needs for PtX after 2030. Morocco cannot control whether such principles are followed elsewhere but should strongly support the development of such a principle for PtX at international level.

Hypothesis 10**:** Sustainability criteria play an important role for PtX in Morocco.

Main results from the analysis:

- Sustainability criteria for PtX are important parameters to be taken into account in building up a sustainable PtX production in Morocco, in particular when it comes to exports.
- Sustainability criteria concern in particular:
  - origin of carbon in case of synthetic energy carriers
  - consumption of land
  - consumption of water
  - no overlap with the countries' own RES expansion

Similar to the previous hypothesis, we recommend that Morocco takes up these sustainability criteria in the development of its 2050 energy strategy, in particular if it embarks on a very ambitious GHG reduction strategy with own needs for PtX after 2030. Morocco cannot control whether such criteria are followed elsewhere but should strongly support the development of such sustainability criteria for PtX at international level. It is in Morocco's interest to follow up such criteria, even if the international debate has not yet come to an end. There may be a risk of stranded investments if the debate later on moves to strong sustainability criteria (see the case of biofuels).

Though the study could not come up with an in-depth investigation of industrial and socio-economic impacts, a few elements are worth mentioning here:

- The PtX demand, conservatively estimated, represents a market size (annual; only fuel sales, not equipment market) of 45 – 102 billion Euro in 2030 and

107 – 680 billion Euro in 2050. Though this only one tenth to one third of present oil markets, it represents opportunities of new markets for first movers.

- Morocco may be able to capture on average 1.5% of the market by 2030 (up to 1.5 billion Euro) and 3% by 2050 (up to 20 billion Euro).
- At the same time, Morocco could replace imports of ammonia of a quarter billion Euro (with rising trends due to rising CO_2 and fuel)
- Morocco's strategic geographical proximity to Europe, along with its large potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with high added value.

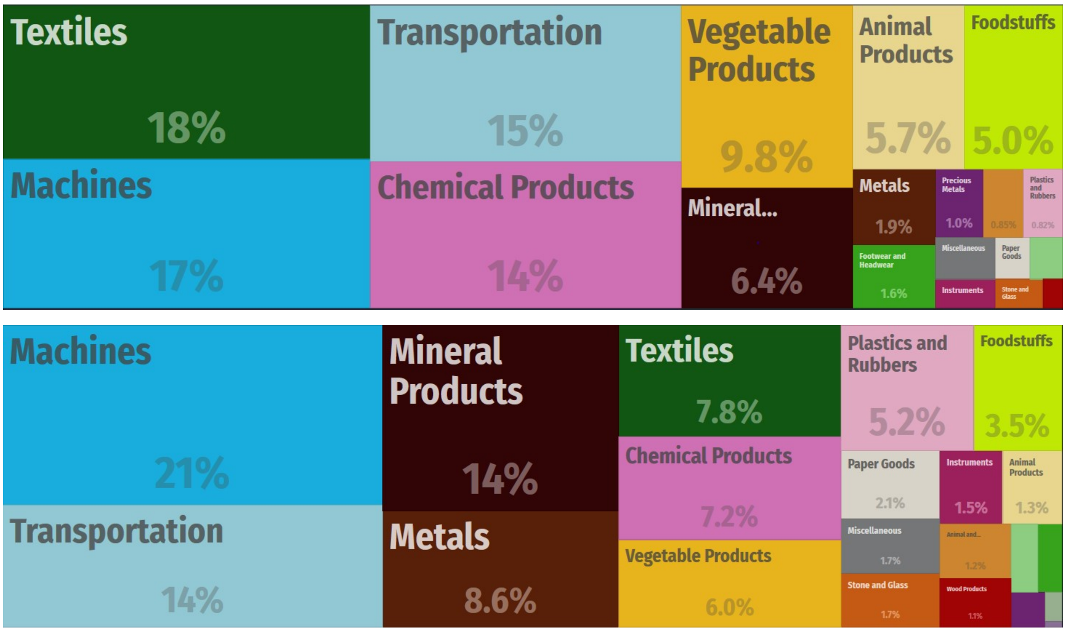
6.2 PtX - industrial opportunities for Morocco

Morocco is the 60th largest export economy in the world. In 2016, Morocco exported $27.5B and imported $41.5B, resulting in a negative trade balance of $14B (see Figure 19 and Annex 1):

- The top exports of Morocco are Cars ($3.3B), Insulated Wire ($2.73B), Mixed Mineral or Chemical Fertilizers a ($2.08B), Phosphoric Acid ($1.21B) and Non-Knit Women's Suits ($1.21B).
- Its top imports are Refined Petroleum ($3.13B), Cars ($1.97B), Wheat ($1.15B), Petroleum Gas ($1.08B) and Insulated Wire ($891M).

It is seen that chemical products belong to the strength of the Moroccan industry, as they contribute much more largely to the exports than to the imports of the country. Hence, the country can build on this export strength.

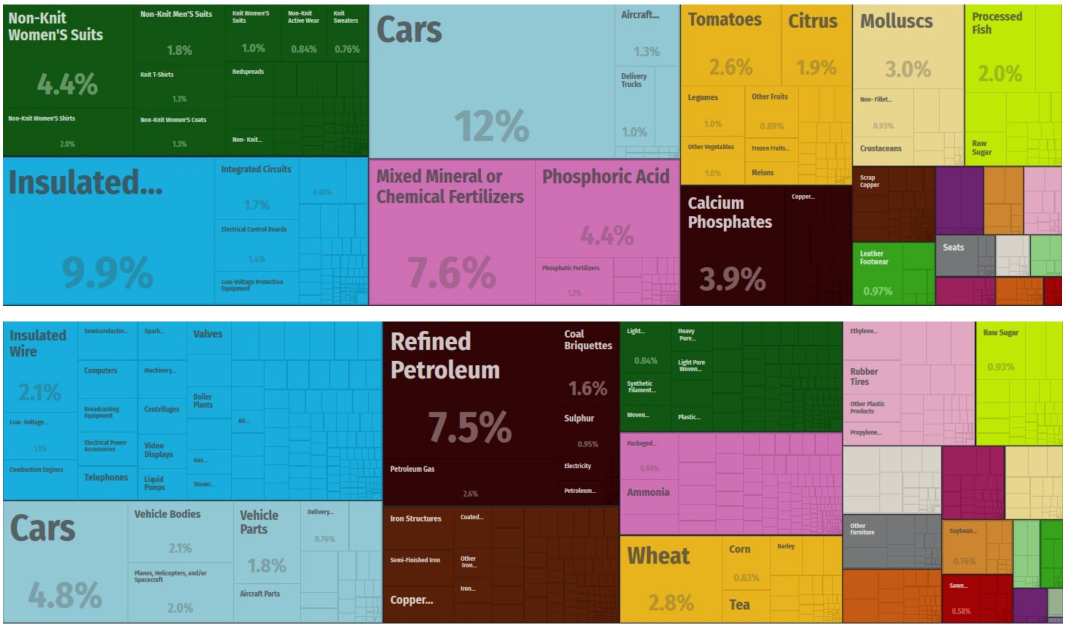
Figure 19: Morocco - International trade 2016 - Exports (upper graph) / Imports (lower graph)



Source: https://atlas.media.mit.edu/en/profile/country/mar/

A more detailed look to the exports (Figure 20) and imports shows, however, a more differentiated picture: while fertilizer products contribute largely to the positive export balance, chemicals such as ammonia contribute to the negative balance, given that 1-2 million tons of ammonia are imported. Mineral products, in particular, refined petroleum products, is another important contributor to the negative trade balance of Morocco.

Figure 20: Morocco - International trade 2016 - a more detailed look to Exports (upper graph) and Imports (lower graph)



This short analysis shows that a long-term opportunity for the Moroccan industry lies in the replacement of the imported refined petroleum products with:

(i) an ambitious energy efficiency strategy

(ii) domestically produced synthetic fuels

On the opposite, exporting synthetic energy carriers could contribute positively to the trade balance of Morocco. In 2016, just imported refined petroleum was in excess of 3 billion US$. Morocco's strategic geographical proximity to Europe, along with its exceptional potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with very high added value.

Replacing imported ammonia with domestically produced green ammonia, though it is a less important change in the trade balance than replacing refined petroleum products, is a first short-term step into the direction of developing an export strategy of PtX products.

6.3 Recommendations for short- and medium term R&D on the issue of PtX

On the basis of the analysis of the 10 hypotheses the following recommendations for short- and medium term R&D on the issue of PtX can be derived:

1. **Establishment of a detailed 2050 energy and climate strategy and of 2050 energy and climate targets for Morocco:**
    - The full role of PtX in Morocco need to be discussed in the frame of a detailed 2050 energy and climate strategy and by setting 2050 energy and climate targets for the country.
    - As it was shown in the analysis of this report, there is an interaction between a possible PtX Strategy and the strategies for renewables, fossil fuels, energy efficiency and climate, notably by the fact that limitations on PtX arise from the possible expansion rates of RES rather than by RES potentials.
    - Investigation of the contribution of PtX to the long-term stability of the power grid: flexible load benefits will accrue as soon as electrolysers are deployed at substantial scale. This is similar to aluminium electrolysis which is already used for that purpose: if it is connected to the grid it can contribute with load management. This does not take many full load hours away. However, there may be implication for choices of the location which should be investigated, possibly model-based.
    - Such an integrated strategy should be developed rapidly in order to investigate fix the frame for the countries' own needs of PtX, which depend notably on GHG reduction targets at 2050 levels and on RES targets for the power sector, as well as energy efficiency targets and the role of direct electric uses in the country (e.g. for electric vehicles and industrial process industries).

2. **Elaboration of a roadmap for hydrogen + derived PtX products for Morocco:**
    - According to the analysis in this report hydrogen and ammonia production appear as the most promising PtX strategies to be investigated.
    - For these two products, both production for the domestic market and for export markets should be investigated in detail
    - The hydrogen roadmap should include considerations on local manufacturing strategies for the relevant renewables, electrolysis and other conversion technologies for PtX, building on previous local manufacturing studies for CSP in Morocco.
    - The roadmap should also include a detailed analysis of Morocco's import and export balance, e.g. based on analysis of the Revealed Comparative Advantage (RCA) for different relevant products.
    - Green Ammonia appears as the most promising PtX product for Morocco, both for domestic uses to replace imports and for an export strategy. Ammonia is interesting (i) the economic perspective, (ii) from the attractive feature that no specific infrastructure is required

in the receiving countries, in difference from hydrogen, (iii) there is already experience with ammonia transport. This should also include technologies for the reconversion of ammonia to energy.

- The following steps are to be investigated in detail in the ammonia roadmap:
    i. Replacement of the imported ammonia with green ammonia to strengthen the local manufacturing of fertilizers. This approach appears economic under the conditions of high full load hours for the electrolysis, low interest rates and moderate to RES electricity cost. By 2030, approximately 3 GW of RES generation are necessary to produce 1 Mt of green ammonia, which corresponds to the present imports.
    ii. Export of clean ammonia to "95%-GHG reduction countries" in replacement of ammonia consuming processes in those countries. By 2030, Morocco may be able to produce a further 1-2 Mt green ammonia for export.
    iii. Export of clean ammonia to "95%-GHG reduction countries" for energy generation purposes. This may be a viable and economic strategy beyond 2030.
- Both for hydrogen and for ammonia (i) the export strategies of possible competitors, e.g. Australia (Hydrogen Roadmap), other MENA, USA,....AND possible PtX production in European countries (financing of investments/discount rates) and (ii) the infrastructure policy for possible importing countries are to be analysed.
- Development of sector coupling strategies for use of hydrogen/ammonia in the sectors industry, housing and transport.
- The road map should also include synthetic methane, synfuels and methanol though they appear as more problematic due to the need of carbon. Focus should be on synthetic fuels for air and ship transport; however, international measures for decarbonisation of these sectors are necessary.

3. **Elaboration of an infrastructure roadmap for hydrogen + derived PtX products for Morocco:**
    - The general PtX roadmap should also include infrastructure requirements (electricity, transport of inputs and outputs). In the present report, it was not possibly to investigate required infrastructures in detail. It is mentioned here separately because infrastructure are important components, which may require own methodologies (e.g. modelling of electricity infrastructures).
    - This should include including questions such as (i) whether production sites should be close to the seaside (for reasons of transport and requirements of water), or inside the country, in particular in the south of the country (for reasons of maximum RES potentials) (ii) whether PtX should be established stand-alone (for cost purposes) or in conjunction with grid connection (for providing ancillary services to the grid or for providing longer full load hours to the electrolyser - but considering possible impacts on power sector capacity development). (iii) Southern locations (for cost purposes) versus norther locations (for proximity to the consumption centers in Morocco).

4. **Development of sustainability criteria in the frame of the hydrogen/PtX roadmap:**
    - The general PtX roadmap should also include the development of sustainability criteria. It is mentioned here separately because sustainability criteria development requires own methodologies including stakeholder processes to settle on the criteria.
    - Sustainability considerations are important to avoid stranded investments (take lessons from the biofuels discussion in Europe)
    - Important sustainability criteria to be defined in detail are:
        - origin of carbon in case of synthetic energy carriers
        - consumption of land
        - consumption of water
        - no overlap with the countries' own RES expansion (link to the 2050 energy and climate strategy)

5. **Investigate governance structures for a Moroccan hydrogen and ammonia industry:**
    - A national roadmap for PtX could investigate governance structures for a Moroccan hydrogen and ammonia industry.
    - As hydrogen has multiple uses in multiple sectors, and can be consumed domestically as well as exported, governance is likely to involve multiple agencies at multiple levels of government.
    - Governance could focus on achieving end-to-end oversight of the hydrogen supply chain, carried out co-operatively and transparently between business, industry, technical experts, community representatives and all levels of government.

6. **Investigate electricity market design to support a Moroccan hydrogen and ammonia industry:**
    - PtX draws largely on renewable electricity. It therefore intervenes with the general organisation of electricity markets, there more, should it be interconnected with the general electricity grid and participate in balancing markets.
    - Specific issue may concern:
        - Is there a need for specific market regulation for PtX versus the general general electricity market regulation
        - Should there be a control of capacity growth in conjunction with the expansion of renewables for the general electricity demand?
        - What is the role of Independent Power Producers IPPs in RES generation for PtX versus the role of incumbents (ONEE)?. Examples are for example the RES producers for the cement sector.

7. **Technological R&D and demonstration plants of a reasonable size of several MWs which can enhance experience with technologies. Development of a market introduction scheme.:**
    - For any policy goals around hydrogen and ammonia to be achieved, further technology improvements as well as mass-market volumes are needed to drive cost-competitiveness in the broader energy system.

- If hydrogen is to become an internationally traded commodity, similar to LNG, supply chains will need to be demonstrated. R&D will be required across production, storage and transport to reduce the delivered cost.
- Develop R&D and demonstration plants of a reasonable size of several MWs which can enhance experience with technologies, may in particular be required for:
  - Hydrogen electrolysis plants
  - Green Ammonia production technology and the links to fertilizer industry
  - Combustion technology for ammonia or reconversion to hydrogen for use in fuel cells
  - Direct air capture of CO_2 (DAC)
  - Combination of PtX with sea water desalination
  - Demonstration projects to supply hydrogen and ammonia to European countries
  - Research on linking electrolysis plants at the megawatt level with the power sector.
  - coupling of electrolysers with variable electricity supply (wind power plants, PV plants), because electrolysers are able to operate at very favourable partial loads.
- Development of a market introduction scheme which could achieve already a certain market penetration of PtX products.

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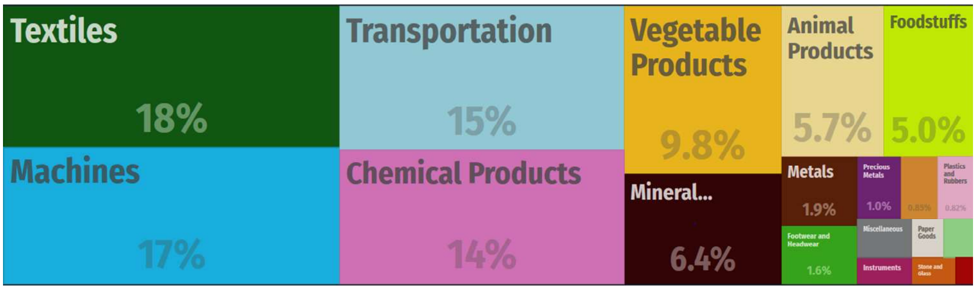
Annex 1: Morocco - International Trade

- 60th largest export economy in the world.
- In 2016, Morocco exported $27.5B and imported $41.5B, resulting in a **negative trade balance of $14B**.
- The **top exports** of Morocco are Cars ($3.3B), Insulated Wire ($2.73B), Mixed Mineral or Chemical Fertilizers [a] ($2.08B), Phosphoric Acid ($1.21B) and Non-Knit Women's Suits ($1.21B).
- Its **top imports** are Refined Petroleum ($3.13B), Cars ($1.97B), Wheat ($1.15B), Petroleum Gas ($1.08B) and Insulated Wire ($891M).
- The **top export destinations** of Morocco are Spain ($6.16B), France ($4.72B), Turkey ($1.11B), Germany ($1.03B) and the United States ($1.02B).
- The **top import origins** are Spain ($6.76B), France ($5.18B), China ($3.77B), the United States ($2.55B) and Germany ($2.4B).

Morocco - International trade- Exports

- 2016 data
- Export categories HS2



Findings:
- Chemical products are an important export commodity
- Export RCA 3.8

source: https://atlas.media.mit.edu/en/profile/country/mar/

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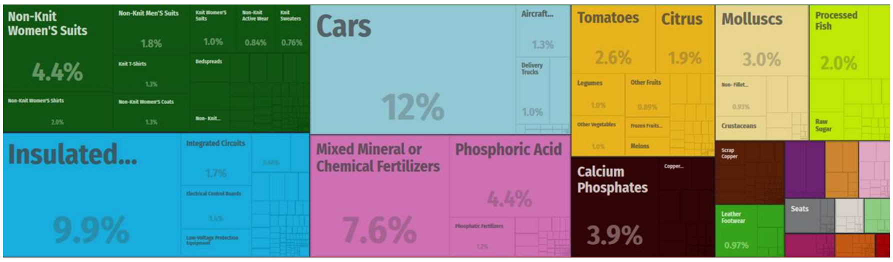
Morocco - International trade- Exports

- 2016 data
- Export categories, HS4



Findings:
- Fertilizers are most important chemical export product

source: https://atlas.media.mit.edu/en/profile/country/mar/

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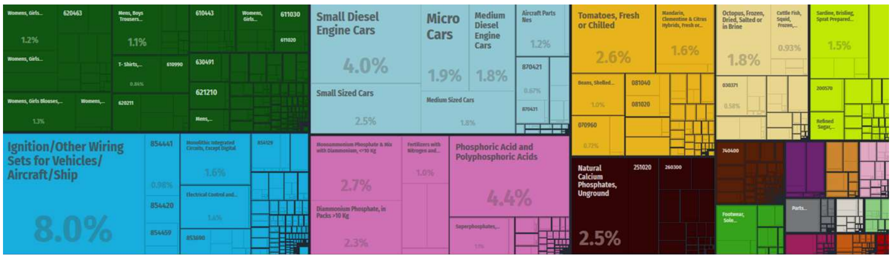
Morocco - International trade- Exports

- 2016 data
- Export categories, HS6



source: https://atlas.media.mit.edu/en/profile/country/mar/

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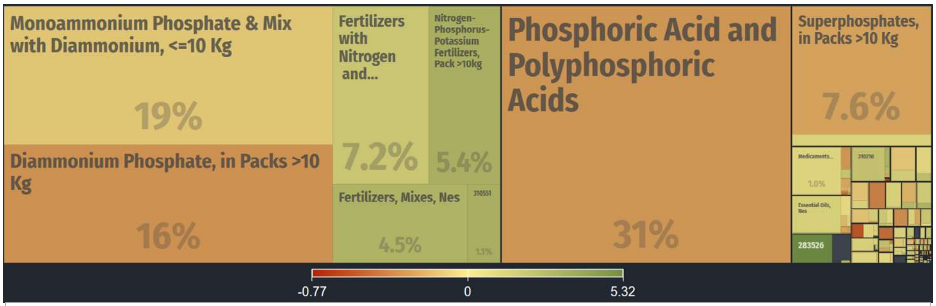
Morocco - Export of chemical products

- 2016 data
- colour code: 5 year growth rate



Findings:
- Phosphate is major resource (75 percent of global reserves, leading exporter)
- Ammonium-Phosphate products show declining exports
- Fertilizers are a moderately growing export market

source: https://atlas.media.mit.edu/en/profile/country/mar/

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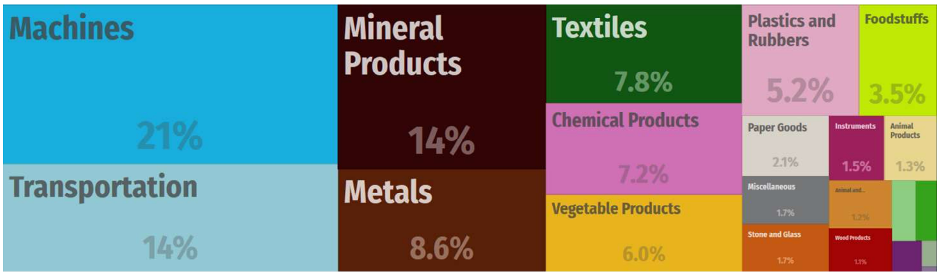
Morocco - International trade- Imports

- 2016 data
- Import categories HS2



Findings:
- Mineral products are an important import commodity

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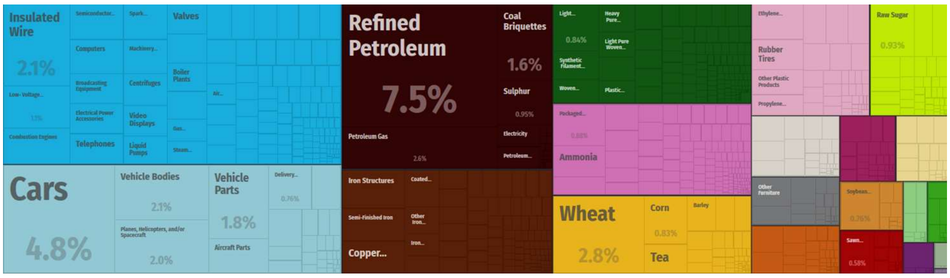
Morocco - International trade- Imports

- 2016 data
- Import categories HS4



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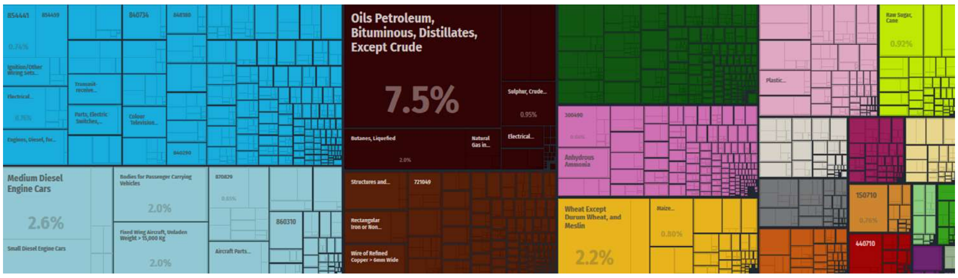
Morocco - International trade- Imports

- 2016 data
- Import categories HS6



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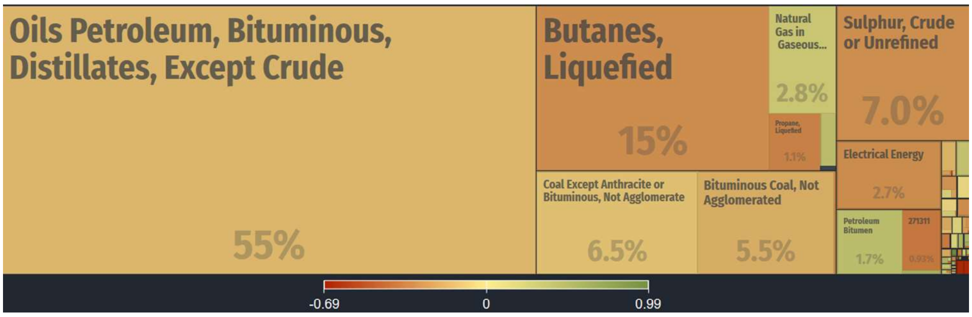
Morocco – Import of mineral products (2016)

- Colour code: 5 year growth rate



Findings:
- Country is major importer of petroleum products
- Synthetic fuels could be used to substitute imports

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Morocco – Import of chemical products (2016)

- Colour code: 5 year growth rate

Findings:
- Import of ammonia (HS92 ID 2814) value of $267M (2016), import RCA 13.7, Annual Growth Rate of imports (5 year) 0.0055
- Main import countries: Ukraine (42%), Russia (15%), US (7.5%), Trinidad & Tobago (6.8%), ...
- Domestic production of ammonia could substitute imports

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Imports of Ammonia to Morocco (Source: UNCOMTRADE, H02, Ammonia, anhydrous or in aqueous solutions)

Period	Trade Flow	Reporter	Partner	Commodity Code	Trade Value (US$)	Netweight (kg)	Qty Unit	Qty
2016	Import	Morocco	World	2814	$286,800,853	1,041,414,567	Weight in kilograms	1,041,414,567
2016	Import	Morocco	Algeria	2814	$19,619,096	79,290,691	Weight in kilograms	79,290,691
2016	Import	Morocco	Belgium	2814	$11,547	6,765	Weight in kilograms	6,765
2016	Import	Morocco	Canada	2814	$7,483,622	28,002,830	Weight in kilograms	28,002,830
2016	Import	Morocco	Estonia	2814	$8,758,828	36,289,050	Weight in kilograms	36,289,050
2016	Import	Morocco	France	2814	$3,004,560	11,001,070	Weight in kilograms	11,001,070
2016	Import	Morocco	Germany	2814	$4,595	608	Weight in kilograms	608
2016	Import	Morocco	Latvia	2814	$18,678,057	60,874,833	Weight in kilograms	60,874,833
2016	Import	Morocco	Netherlands	2814	$52,783	149,396	Weight in kilograms	149,396
2016	Import	Morocco	Nigeria	2814	$2,501,138	12,381,806	Weight in kilograms	12,381,806
2016	Import	Morocco	Poland	2814	$4,477,554	15,006,439	Weight in kilograms	15,006,439
2016	Import	Morocco	Russian Federation	2814	$44,360,828	142,894,667	Weight in kilograms	142,894,667
2016	Import	Morocco	Saudi Arabia	2814	$11,060,736	46,557,816	Weight in kilograms	46,557,816
2016	Import	Morocco	India	2814	$1,304	126	Weight in kilograms	126
2016	Import	Morocco	Spain	2814	$43,498	54,069	Weight in kilograms	54,069
2016	Import	Morocco	Trinidad and Tobago	2814	$20,177,194	86,141,609	Weight in kilograms	86,141,609
2016	Import	Morocco	Turkey	2814	$3,687,002	11,401,844	Weight in kilograms	11,401,844
2016	Import	Morocco	Ukraine	2814	$123,793,920	439,644,519	Weight in kilograms	439,644,519
2016	Import	Morocco	USA	2814	$19,084,589	71,716,429	Weight in kilograms	71,716,429

2015	Import	Morocco	World	2814	$360,867,278	824,437,950	Weight in kilograms	824,437,950
2015	Import	Morocco	Algeria	2814	$21,365,874	46,662,981	Weight in kilograms	46,662,981
2015	Import	Morocco	Belgium	2814	$494	58	Weight in kilograms	58
2015	Import	Morocco	Estonia	2814	$1,780,727	4,000,000	Weight in kilograms	4,000,000
2015	Import	Morocco	France	2814	$2,744	675	Weight in kilograms	675
2015	Import	Morocco	Germany	2814	$1,518	24	Weight in kilograms	24
2015	Import	Morocco	Latvia	2814	$9,498,944	20,188,017	Weight in kilograms	20,188,017
2015	Import	Morocco	Netherlands	2814	$26,202	57,426	Weight in kilograms	57,426
2015	Import	Morocco	India	2814	$1,519	590	Weight in kilograms	590
2015	Import	Morocco	Spain	2814	$9,056,306	21,966,916	Weight in kilograms	21,966,916
2015	Import	Morocco	Trinidad and Tobago	2814	$10,314,504	23,405,134	Weight in kilograms	23,405,134
2015	Import	Morocco	Ukraine	2814	$308,818,446	708,156,130	Weight in kilograms	708,156,130
2014	Import	Morocco	World	2814	$396,032,003	807,774,756	Weight in kilograms	807,774,756
2014	Import	Morocco	Algeria	2814	$26,771,431	53,282,154	Weight in kilograms	53,282,154
2014	Import	Morocco	Belgium	2814	$152	31	Weight in kilograms	31
2014	Import	Morocco	France	2814	$3,621	498	Weight in kilograms	498
2014	Import	Morocco	Germany	2814	$2,460	446	Weight in kilograms	446
2014	Import	Morocco	Latvia	2814	$23,384,347	46,748,316	Weight in kilograms	46,748,316
2014	Import	Morocco	Netherlands	2814	$18,818	33,912	Weight in kilograms	33,912
2014	Import	Morocco	Nigeria	2814	$3,267,780	6,532,712	Weight in kilograms	6,532,712
2014	Import	Morocco	India	2814	$16	5	Weight in kilograms	5
2014	Import	Morocco	Spain	2814	$19,875,825	39,344,023	Weight in kilograms	39,344,023
2014	Import	Morocco	Trinidad and Tobago	2814	$10,717,712	25,000,688	Weight in kilograms	25,000,688
2014	Import	Morocco	Ukraine	2814	$299,129,613	606,833,635	Weight in kilograms	606,833,635
2014	Import	Morocco	USA	2814	$12,860,228	29,998,336	Weight in kilograms	29,998,336

2013	Import	Morocco	World	2814	$358,099,891	647,345,219	Weight in kilograms	647,345,219
2013	Import	Morocco	Algeria	2814	$31,903,792	54,931,188	Weight in kilograms	54,931,188
2013	Import	Morocco	Belgium	2814	$616	92	Weight in kilograms	92
2013	Import	Morocco	France	2814	$795	150	Weight in kilograms	150
2013	Import	Morocco	Germany	2814	$3,697	294	Weight in kilograms	294
2013	Import	Morocco	Latvia	2814	$13,340,078	23,372,164	Weight in kilograms	23,372,164
2013	Import	Morocco	Netherlands	2814	$51,136	76,032	Weight in kilograms	76,032
2013	Import	Morocco	Nigeria	2814	$10,124,959	17,730,987	Weight in kilograms	17,730,987
2013	Import	Morocco	India	2814	$24	9	Weight in kilograms	9
2013	Import	Morocco	Spain	2814	$1,557,693	3,090,256	Weight in kilograms	3,090,256
2013	Import	Morocco	Trinidad and Tobago	2814	$9,494,819	19,236,831	Weight in kilograms	19,236,831
2013	Import	Morocco	Turkey	2814	$8,564,199	15,004,700	Weight in kilograms	15,004,700
2013	Import	Morocco	Ukraine	2814	$271,078,769	489,632,695	Weight in kilograms	489,632,695
2013	Import	Morocco	Egypt	2814	$1,015,699	2,057,841	Weight in kilograms	2,057,841
2013	Import	Morocco	United Kingdom	2814	$366	58	Weight in kilograms	58
2013	Import	Morocco	USA	2814	$10,963,250	22,211,922	Weight in kilograms	22,211,922

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Hydrogen	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	38	23	11
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	39,4	39,4	39,4
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	1,4	1,3	1,2
Electricity demand annually in MWh_el/t	54,6	50,6	49,4
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	918	348	177
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	477	443	432
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	2,0	1,9	1,9
Electricity costs annually in €/t	2073	1163	543
Total costs			
Depreciation investment in €/t	918	348	177
Electricity costs in €/t	2073	1163	543
CO2-supply costs in €/t	-		
Other costs in €/t	479	444	434
Total costs in €/t	**3471**	**1955**	**1154**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Hydrogen	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	47	33	27
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	39,4	39,4	39,4
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	1,4	1,3	1,2
Electricity demand annually in MWh_el/t	54,6	50,6	49,4
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	918	348	177
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	477	443	432
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	2,0	1,9	1,9
Electricity costs annually in €/t	2564	1669	1333
Total costs			
Depreciation investment in €/t	918	348	177
Electricity costs in €/t	2564	1669	1333
CO2-supply costs in €/t	-		
Other costs in €/t	479	444	434
Total costs in €/t	**3962**	**2461**	**1944**

Note: <u>Pessimistic</u> RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Hydrogen	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	48	33	21
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	39,4	39,4	39,4
Full-load hours in h/a	4500	4500	4500
Plant capacity in MW	1,4	1,3	1,2
Electricity demand annually in MWh_el/t	54,6	50,6	49,4
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	1.631	619	315
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	849	787	768
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	3,6	3,4	3,3
Electricity costs annually in €/t	2619	1669	1037
Total costs			
Depreciation investment in €/t	1631	619	315
Electricity costs in €/t	2619	1669	1037
CO2-supply costs in €/t	-		
Other costs in €/t	852	790	771
Total costs in €/t	**5103**	**3077**	**2123**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price including connection cost of around 10 €/MWh. 4500 full load hours instead of 8000.

Source: own calculations

Methane	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	38	23	11
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	19,8	19,8	19,8
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	2,7	2,5	2,4
Electricity demand annually in MWh_el/t	27,4	25,4	24,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	450	170	87
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	234,1	216,5	211,3
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	1,0	0,9	0,9
Electricity costs annually in €/t	1042	585	273
Methane plant			
Production volume in t/a	800	800	800
CO2-supply costs in €/t	156	143	137
Electricity demand in MWh/t	2,67	2,40	1,92
Other costs in €/t	1,5	1,5	1,5
Investment in M€	0,295	0,056	0,022
Depreciation investment in €/t/a	23	4	2
Electricity costs in €/t/a	102	55	21
Maintenance costs in €/t/a	11	11	11
Operating costs in €/t/a	10	10	10
Total costs			
Depreciation investment in €/t	473	175	88
Electricity costs in €/t	1144	640	294
CO2-supply costs in €/t	156	143	137
Other costs in €/t	258	240	235
Total costs in €/t	**2031**	**1197**	**755**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Methane	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	47	33	27
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	19,8	19,8	19,8
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	2,7	2,5	2,4
Electricity demand annually in MWh_el/t	27,4	25,4	24,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	450	170	87
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	234	217	211
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	1,0	0,9	0,9
Electricity costs annually in €/t	1289	839	670
Methane plant			
Production volume in t/a	800	800	800
CO2-supply costs in €/t	156	143	137
Electricity demand in MWh/t	2,67	2,40	1,92
Other costs in €/t	1,5	1,5	1,5
Investment in M€	0,295	0,056	0,022
Depreciation investment in €/t/a	23	4	2
Electricity costs in €/t/a	125,7	79,2	52,0
Maintenance costs in €/t/a	11	11	11
Operating costs in €/t/a	10	10	10
Total costs			
Depreciation investment in €/t	473	175	88
Electricity costs in €/t	1415	918	722
CO2-supply costs in €/t	156	143	137
Other costs in €/t	258	240	235
Total costs in €/t	**2302**	**1476**	**1183**

Note: Pessimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Methane	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	48	33	21
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	19,8	19,8	19,8
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	2,7	2,5	2,4
Electricity demand annually in MWh_el/t	27,4	25,4	24,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	450	170	87
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	234,1	216,5	211,3
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	1,0	0,9	0,9
Electricity costs annually in €/t	1317	839	521
Methane plant			
Production volume in t/a	800	800	800
CO2-supply costs in €/t	156	143	137
Electricity demand in MWh/t	2,67	2,40	1,92
Other costs in €/t	1,5	1,5	1,5
Investment in M€	0,295	0,056	0,022
Depreciation investment in €/t/a	23	4	2
Electricity costs in €/t/a	128	79	40
Maintenance costs in €/t/a	11	11	11
Operating costs in €/t/a	10	10	10
Total costs			
Depreciation investment in €/t	473	175	88
Electricity costs in €/t	1445	918	562
CO2-supply costs in €/t	156	143	137
Other costs in €/t	258	240	235
Total costs in €/t	**2332**	**1476**	**1022**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price including connection cost of around 10 €/MWh. 4500 full load hours instead of 8000.

Source: own calculations

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Methanol	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	38	23	11
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,4	7,4	7,4
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	1045	966	943
Electricity demand annually in MWh_el/t	10,3	9,5	9,3
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	169	64	33
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	87,9	81,3	79,3
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,4	0,3	0,3
Electricity costs annually in €/t	391	220	103
Methanol plant			
Production volume in t/a	831857	831857	831857
CO2-supply costs in €/t	78	71	69
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	1,5	1,5	1,5
Investment in M€	164	192	235
Depreciation investment in €/t/a	12	14	17
Electricity costs in €/t/a	3,7	1,9	0,8
Maintenance costs in €/t/a	6	7	8
Operating costs in €/t/a	13	15	18
Total costs			
Depreciation investment in €/t	181	78	50
Electricity costs in €/t	395	221	103
CO2-supply costs in €/t	78	71	69
Other costs in €/t	109	105	108
Total costs in €/t	**763**	**476**	**330**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Methanol	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	47	33	27
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,4	7,4	7,4
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	1045	966	943
Electricity demand annually in MWh_el/t	10,3	9,5	9,3
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	169	64	33
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	87,9	81,3	79,3
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,4	0,3	0,3
Electricity costs annually in €/t	484	315	252
Methanol plant			
Production volume in t/a	831857	831857	831857
CO2-supply costs in €/t	78	71	69
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	1,5	1,5	1,5
Investment in M€	164	192	235
Depreciation investment in €/t/a	12	14	17
Electricity costs in €/t/a	4,6	2,8	1,9
Maintenance costs in €/t/a	6	7	8
Operating costs in €/t/a	13	15	18
Total costs			
Depreciation investment in €/t	181	78	50
Electricity costs in €/t	489	318	253
CO2-supply costs in €/t	78	71	69
Other costs in €/t	109	105	108
Total costs in €/t	**856**	**572**	**480**

Note: Pessimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Annex 2: Production Cost for Hydrogen and Derived Products in Morocco

Methanol	2015	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	48	33	21
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,4	7,4	7,4
Full-load hours in h/a	4500	4500	4500
Plant capacity in MW	1857	1718	1676
Electricity demand annually in MWh_el/t	10,3	9,5	9,3
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	300	114	58
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	156,3	144,6	141,0
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,7	0,6	0,6
Electricity costs annually in €/t	494	315	196
Methanol plant			
Production volume in t/a	831857	831857	831857
CO2-supply costs in €/t	78	71	69
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	1,5	1,5	1,5
Investment in M€	164	192	235
Depreciation investment in €/t/a	12	14	17
Electricity costs in €/t/a	4,7	2,8	1,5
Maintenance costs in €/t/a	6	7	8
Operating costs in €/t/a	13	15	18
Total costs			
Depreciation investment in €/t	312	128	75
Electricity costs in €/t	499	318	197
CO2-supply costs in €/t	78	71	69
Other costs in €/t	177	169	170
Total costs in €/t	**1067**	**686**	**511**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price including connection cost of around 10 €/MWh. 4500 full load hours instead of 8000.

Source: own calculations

Annex 3: Sensitivity Analysis Production Cost Green Ammonia

Ammonia	2017	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	38	23	11
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,0	7,0	7,0
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	802	742	724
Electricity demand annually in MWh_el/t	9,7	9,0	8,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	159	60	31
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	82,7	76,5	74,6
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,4	0,3	0,3
Electricity costs annually in €/t	368	206	96
Ammonia plant			
Production volume in t/a	679365	679365	679365
CO2-supply costs in €/t	-	-	-
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	2	2	2
Investment in M€	265	301	353
Depreciation investment in €/t/a	24	27	32
Electricity costs in €/t/a	3,7	1,9	0,8
Maintenance costs in €/t/a	12	13	16
Operating costs in €/t/a	25	29	34
Total costs			
Depreciation investment in €/t	183	87	62
Electricity costs in €/t	372	208	97
CO2-supply costs in €/t	-	-	-
Other costs in €/t	122	121	126
Total costs in €/t	**676**	**416**	**286**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Annex 3: Sensitivity Analysis Production Cost Green Ammonia

	2017	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	47	33	27
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Elektrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,0	7,0	7,0
Full-load hours in h/a	8000	8000	8000
Plant capacity in MW	802	742	724
Electricity demand annually in MWh_el/t	9,7	9,0	8,8
Investment electrolyzer in €/kW_el	2200	900	470
Depreciation investment in €/t/a	159	60	31
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t/a	82,7	76,5	74,6
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t/a	0,4	0,3	0,3
Electricity costs annually in €/t/a	455	296	237
Ammonia plant			
Production volume in t/a	679365	679365	679365
CO2-supply costs in €/t	-	-	-
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	2	2	2
Investment in M€	265	301	353
Depreciation investment in €/t/a	24	27	32
Electricity costs in €/t/a	4,6	2,8	1,9
Maintenance costs in €/t/a	12	13	16
Operating costs in €/t/a	25	29	34
Total costs			
Depreciation investment in €/t/a	183	87	62
Electricity costs in €/t/a	460	299	238
CO2-supply costs in €/t/a	-	-	-
Other costs in €/t/a	122	121	126
Total costs in €/t/a	**764**	**507**	**427**

Note: Pessimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price excluding connection cost of around 10 €/MWh.

Source: own calculations

Ammonia	2017	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	48	33	21
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,02	0,02	0,02
Annuity factor	0,0612	0,0612	0,0612
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,0	7,0	7,0
Full-load hours in h/a	4500	4500	4500
Plant capacity in MW	1426	1319	1287
Electricity demand annually in MWh_el/t	9,7	9,0	8,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	282	107	54
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	146,9	135,9	132,6
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,6	0,6	0,6
Electricity costs annually in €/t	465	296	184
Ammonia plant			
Production volume in t/a	679365	679365	679365
CO2-supply costs in €/t	-	-	-
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	2	2	2
Investment in M€	265	301	353
Depreciation investment in €/t/a	24	27	32
Electricity costs in €/t/a	4,7	2,8	1,5
Maintenance costs in €/t/a	12	13	16
Operating costs in €/t/a	25	29	34
Total costs			
Depreciation investment in €/t	306	134	86
Electricity costs in €/t	469	299	185
CO2-supply costs in €/t	-	-	-
Other costs in €/t	187	181	185
Total costs in €/t	**962**	**613**	**456**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price including connection cost of around 10 €/MWh. 4500 full load hours instead of 8000.

Source: own calculations

Annex 3: Sensitivity Analysis Production Cost Green Ammonia

Ammonia	2017	2030	2050
General			
Gas price in €/MWh	27,36	33,84	50,04
Electricity price in €/MWh	48	33	21
CO2 costs in €/t_CO2	57	52	50
CO2 certificate costs in €/t CO2	15	30	50
Lifetime (a)	20	20	20
Interest rate	0,06	0,06	0,06
Annuity factor	0,0872	0,0872	0,0872
Electrolysis			
Efficiency	0,74	0,8	0,82
Energy demand in kWh/kg	7,0	7,0	7,0
Full-load hours in h/a	4500	4500	4500
Plant capacity in MW	1426	1319	1287
Electricity demand annually in MWh_el/t	9,7	9,0	8,8
Investment electrolyzer in €/kW_el,in	2200	900	470
Depreciation investment in €/t	403	152	78
Maintenance costs in €/kW_el,in/a	70,0	70,0	70,0
Maintenance costs annually in €/t	146,9	135,9	132,6
Operating costs in €/kW_el,in/a	0,3	0,3	0,3
Operating costs annually in €/t	0,6	0,6	0,6
Electricity costs annually in €/t	465	296	184
Ammonia plant			
Production volume in t/a	679365	679365	679365
CO2-supply costs in €/t	-	-	-
Electricity demand in MWh/t	0,10	0,08	0,07
Other costs in €/t	2	2	2
Investment in M€	265	301	353
Depreciation investment in €/t/a	34	39	45
Electricity costs in €/t/a	4,7	2,8	1,5
Maintenance costs in €/t/a	12	13	16
Operating costs in €/t/a	25	29	34
Total costs			
Depreciation investment in €/t	437	191	123
Electricity costs in €/t	469	299	185
CO2-supply costs in €/t	-	-	-
Other costs in €/t	187	181	185
Total costs in €/t	**1093**	**670**	**493**

Note: Optimistic RES electricity generation cost from Agora/Frontier Economics (2018) for Morocco. Electricity price including connection cost of around 10 €/MWh. 4500 full load hours instead of 8000. 6% capital cost

Source: own calculations