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Infrastructure needs of an EU industrial transformation towards deep decarbonisation

Workshop report for the region of Southern-France

Summary of the relevant background information, infrastructure storylines and their discussion at the workshop held on 29 Oct. 2019 in Marseille

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With support of Simon Heck and Philipp Hammelmann

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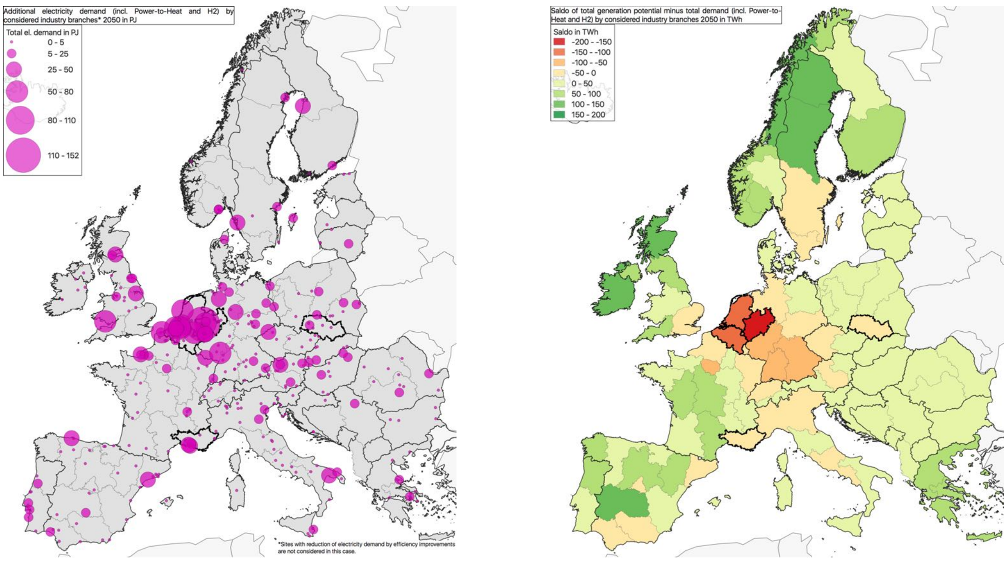
1 Introduction

This workshop report has been developed in the course of the study[1] „Infrastructure Needs of an EU Industrial Transformation towards deep decarbonisation“ (Infra Needs). It summarises the main methodological steps as well as the main findings for decarbonised industrial clusters and related infrastructures in Southern-France 2050, as presented and discussed at the regional workshop held on 29 Oct 2019 in Marseille (see Appendix for agenda).

The background is that the decarbonisation of core energy intensive industries in Europe, such as steel making, basic chemicals or cement, to a net-zero level of greenhouse gas emissions will need considerable additional amounts of renewable based electricity, gases and feedstocks. However, there will still remain significant process-related CO_2 emissions, e.g. from cement making, that need to be captured and stored or used (CCS/CCU). Therefore, achieving climate neutrality in basic industries will require massive transport and storage infrastructures for renewable energy and CO_2 as a prerequisite for a green industrial transformation.

This study aims to geographically localise industrial demands for power, gas and CCS in Europe 2050, which result from existing decarbonisation scenarios, and to explore which infrastructure solutions for electricity, hydrogen (H_2) and CO_2 would be necessary to cover these demands for three selected industrial regions. Figure 1 shows exemplarily the emerging huge and concentrated electricity demand regions in Europe 2050 for decarbonising steel, basic chemicals and cement making (left) based on (Material Economics, 2019) and the resulting electricity balances (right), if in addition the demands from the electrification of the other sectors from (e-Highway 2050, 2014) are considered.



[1] The study is gratefully funded by EIT Climate KIC (Task ID: TC_2.11.1_190229_P259-1B). Further information and deliverables of the study can be found here: https://wupperinst.org/en/p/wi/p/s/pd/818/

Figure 1: Regional distribution of electricity demand 2050 of three decarbonised core industries (left) and resulting electricity balances by considering electrifiation of other sectors

Soruce: own graphs based on own calculations and on (Material Economics, 2019), (e-Highway 2050, 2014)

According to the scenarios developed in the study “Industrial Transformation 2050” (e-Highway 2050, 2014), the additional industrial electricity demand compared to 2015 could sum up to about 450 to 750 billions of kWh_{el} in 2050. These values “only” apply to the three branches of basic chemicals, steel and cement and depend on the pathways and in particular the amount of hydrogen production via electrolysis (cf. chapter 2 and 2). This new industrial demand alone equals to an increase of up to 26% compared to the total electricity demand of appr. 2,900 billions of kWh_{el} in the EU 2015 (eurostat, 2019), which in itself requires a significant enhancement of the existing European power grid.

Within this "new processes" scenario, CCS plays only a relatively minor role, but nevertheless, annual emissions of 45 Mt remain from 2050 onwards, which must be captured and stored for full decarbonisation. If, however, an alternative, more CCS-intensive strategy was to be pursued (“carbon capture” pathway in (Material Economics, 2019)), this number drastically increases to 235 Mt CO_2/a from 2050 onwards. The latter demand for CCS and it’s spatial distribution across Europe is depicted in Figure 2.

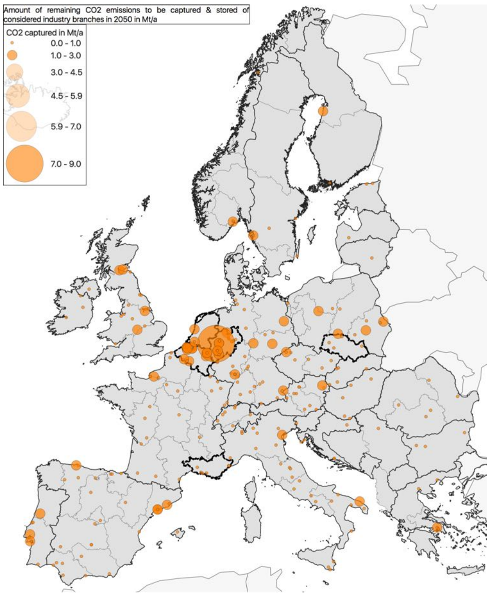


Figure 2: Remaining CO2 emissions from considered industry branches that need to be adressed by CCS in Mt/a from 2050 onwards

Source: own graphs based on own calculations and on (Material Economics, 2019)

Furthermore, Figure 1 shows that due to the existing spatial distribution of basic industries in the EU, the future demand will be largely concentrated in just a few regions with important industrial clusters. These are in particular the region of

North-West Europe (BENELUX+NRW[2]), Mid-East England, Southern France, Southern Italy, Eastern Spain and Southern Poland. Thereof, the following three regions have been selected for an in-depth analysis based on their relevance and geographical distribution (cf. chapter 2):

- North-West Europe - as by far the largest industrial cluster in the EU (see deliverable WS 2 (Wuppertal Institut & ECF, 2020c))
- Southern France - as a proxy for the Mediterranean Region (focus of this deliverable)
- Southern Poland - as a proxy for central European industrial regions (see deliverable WS 3(Wuppertal Institut & ECF, 2020b))

The Southern France region is highly-industrialised and home of different heavy industries like steel, chemicals, refineries and cement production. It is well connected to further hinterland sites in the Rhône-Alpes and Lyon region via existing product and energy infrastructures and has a large port for industry and trade in Marseille. This allows good transport relations to the countries bordering the Mediterranean Sea, especially to the renewable-rich countries of North Africa.

The relevant qualitative and quantitative characteristics of this hot spot region, the decarbonisation strategies considered and the resulting new demand patterns are described more in detail in chapter 2 below. Chapter 4 to 6 then look also on the existing infrastructure and mainly discuss potential infrastructure solutions (depicted as storylines) for electricity, hydrogen and CCS, which have been discussed and individually evaluated by the regional experts during the interactive workshop part. The findings, which reflect the workshop results, are presented at the end of the respective chapters.

[2] North Rhine-Westphalia

2 Methodological remarks

This chapter explains the study structure, the main reference studies used, the main methodological steps and the concept for the interactive WS part.

The study is structured into five different tasks illustrated in Figure 3, whereof the first four tasks are described below in more detail. The first two tasks T1 (industrial hot spots) and T2 (supply/storage sweet spots) lay down the basis for the analyses in core task T3 (infrastructure needs) and they altogether are the basis for the four different regional workshops (T4) and the dissemination of the results (T5).

It should be noted that the analyses about the hot and sweet spots are undertaken for both the European-wide level as well as for the regional level, while the exploration of infrastructure needs (and solutions) is performed only for the three selected hot spot regions as semi-quantitative case studies.

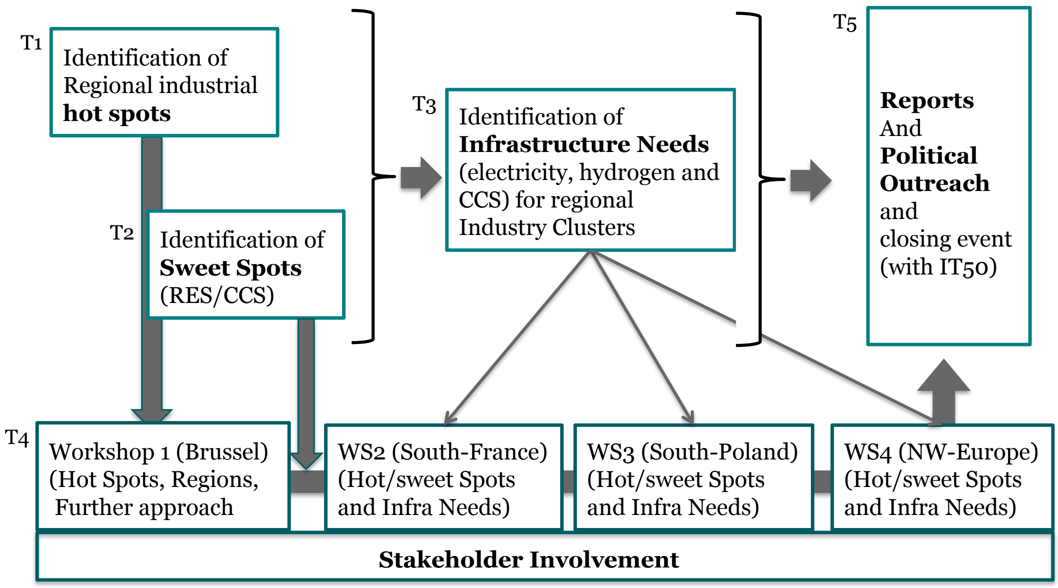


Figure 3: Structure of the study Infrastructure Needs [own graph]

The own analyses are mainly built on the following two studies and their data (cf. chapter 2.1 and 0), being used as references (see Figure 4):

1 | The study “Industry Transformation 2050” (Material Economics, 2019), which determines three different scenario strategies for the decarbonisation of three industry branches (chemicals, steel and cement) on EU-level and

2 | The study “e-HIHGWAY 2050” (e-Highway 2050, 2015), which assesses future transmission system structures for five different ambitious scenarios, in order to reach European climate targets (minus 80-95% of CO_2-emissions in 2050 vs. 1990). Of the five scenarios we choose the scenario X7, which represents an electricity supply system based to 100% on renewable energies, because it is the most ambitious one for the future power grid.

For the CCS analyses we have used a couple of different basic studies, described in chapter 2.3.

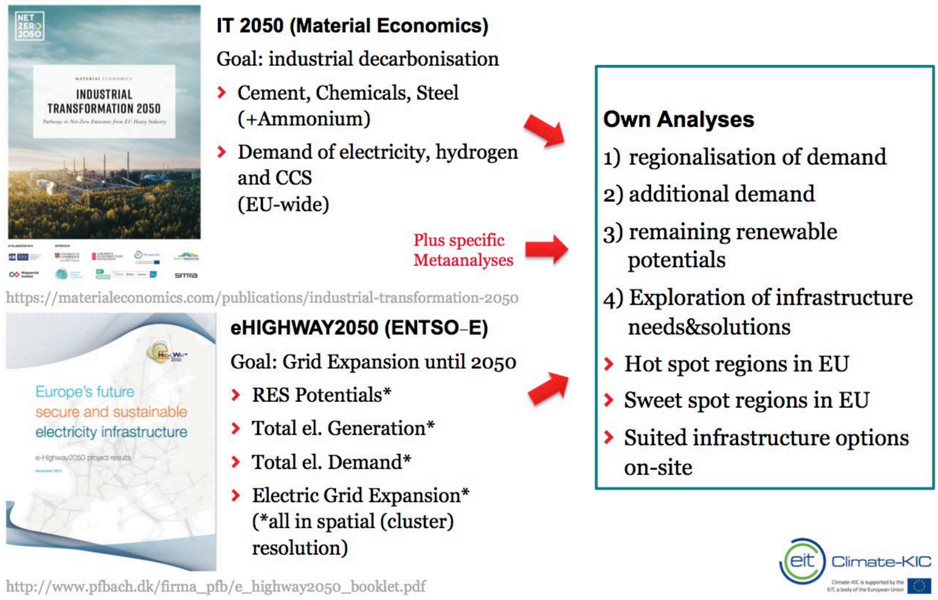


Figure 4: Reference scenarios used for own analyses

Source: own graph with front pages from (Material Economics, 2019; e-Highway 2050, 2015)

The first study (Industrial Transformation 2050 by Material Economics) gives us the aggregated demand data for the decarbonised industry branches differentiated by processes and decarbonisation strategies. These together with our own industry database and industry model (cf. Schneider et al., 2014) are used to determine both the total demand (electricity, hydrogen) as well as the additional demand (compared to 2015) in 2050 by the three considered branches on their production sites. The same is valid for the remaining GHG emissions.

The second study (eHIGHWAY2050 by ENTSOE-E) supports us with spatially resolved data of renewable energy generation and potentials, “conventional”[3] electric demand and NTC-expansion for the reference scenario X7 by clustering. These cluster data are geographically assigned with the on-site industrial demand data from above. This allows us first, to determine the additional electric demand caused by industry decarbonisation compared to the total conventional demand. Together with the known electricity generation of the reference scenario, we then calculate the resulting new electricity balance and the remaining potential for renewable electricity production in the cluster that belongs to the hot spot region.

These results build the main basis for the infrastructure and workshop analyses.

[3] In the sense, that it does not contain electric demand by the sophisticated decarbonisation strategies assumed in the first reference study of Material Economics.

2.1 Task 1: Localisation of relevant industrial cluster and their total as well as additional demands (industrial hot spots)

Task 1 (industrial hot spots) concentrate on the localisation and selection of industrial demand cluster by breaking down aggregated industrial demands on EU-level to the existing industrial production sites.

The future "hot spots" highlighted in the project have been derived by a thorough analysis of today's production locations. Wuppertal Institute's WISEE edm database includes all known production sites in Europe for primary steel making, steam cracking and cement clinker production with their geographical (GIS) coordinates and production capacities and was thus suited to locate possible future energy demands.

Another dimension is the technology routes used. The portfolio of technology routes used in the study by Material Economics (2019) is the same across all scenarios and includes:

- electrifying high-temperature heat supply in ovens
- electrifying steam supply
- higher shares of secondary production
- Carbon Capture and Storage (CCS)
- electrification of primary steel production by using H_2 as a reducing agent (DRI process)
- chemical recycling of plastic waste
- using biogenic feedstock for polymer production
- water electrolysis to supply hydrogen

However, the three scenarios differ in regard to the shares they attribute to certain strategies.

The "New Processes" scenario focuses on converting the production stock to electrified processes and electricity-derived chemical feedstock. As a result electricity demand in this scenario is the highest of all three amounting to 965 TWh in 2050. The major part is used for the production of hydrogen, only 226 TWh are direct electricity use (e.g. for mechanical energy or to produce heat).

The "Circular Economy" scenario tries to evaluate the contribution of ambitious circular measures in order to reduce energy requirements and costs as well as CCS. It thus ends up with the lowest electricity demand and low CO_2 volumes to be stored.

The Carbon Capture pathway shows a "world" where CCS is applied at a large scale - and not only for process-related emissions like CO_2 from cement or "CCS sweet spots", like sites at a sea port close to potential storage sites.

In all following analyses we focus on the "New Processes" scenario to give an indication for future infrastructure requirements in an "Electrification" scenario and on the "Carbon Capture" scenario to indicate CO_2 infrastructure requirements.

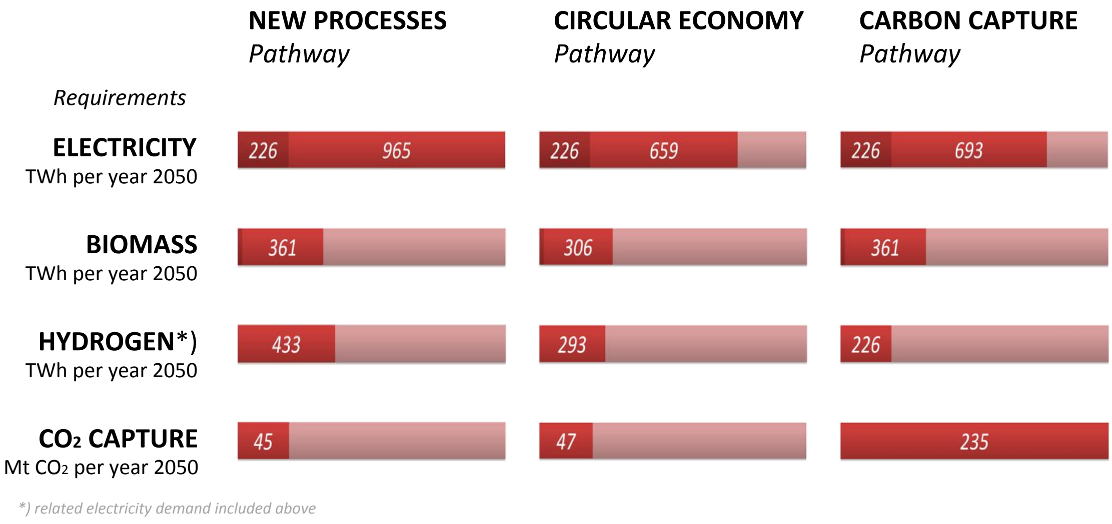


Figure 5: Energy Requirements in the three scenarios by Material Economics

Source: own graph based on (Material Economics, 2019)

The scenario results calculated by Material Economics for the EU as a whole were broken down to a production site level. We therefore also used the results of the Material Economics study and applied the technology mix for 2050 evenly for all production sites identified (see the following exemplary graph for steel industry).

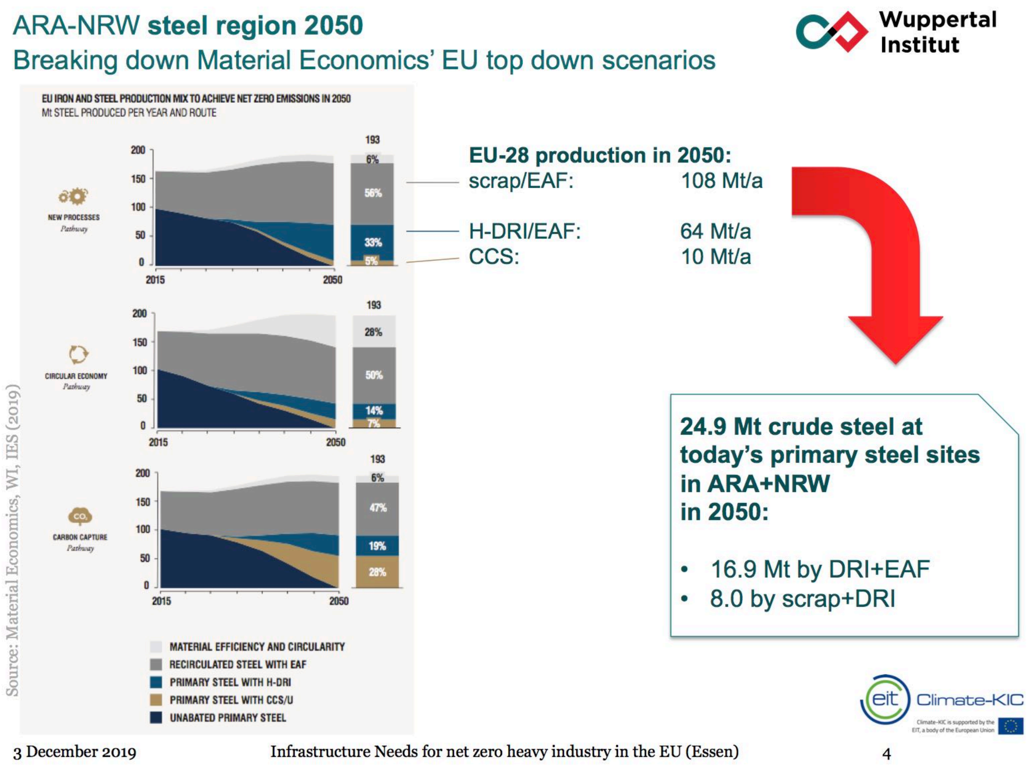


Figure 6: (Exemplary) scheme for breaking down the aggregated consumption values to industrial values according to strategies (Material Economics, 2019)

Source: Slide from presentation held on 3rd of Dec. 2019 in Essen

The study "eHIGHWAYS2050" (see above) is used to estimate how large the additional electricity consumption of the decarbonized industries according to (e-Highway 2050, 2014) will be compared to the future total electricity consumption in 2050. It is suitable as a reference study for the entire electricity system because the focus for decarbonization is more on the other sectors. For the industrial sector, efficiency improvements as well as a moderate electrification of industrial process heat demand by power-to-heat and with renewable electricity are assumed. It is therefore supposed that the associated additional industrial electricity demand in scenario X7 will be negligible compared to that for the strategies of (e-Highway 2050, 2014) considered above. They therefore overlap little and are added to the total electricity consumption in 2050 for our analyses. Taking into account the three decarbonised industries, this is between 4750 and 5050 TWh_{el}/a.

For a better classification of this value, Figure 7 shows the total power consumption of X7 compared to "today" (average value over the years 2010-2015) and to other scenarios for the years 2040 and 2050. It is almost 50 % higher than today's total power consumption, which represents an average annual increase of almost 1 %/a. This corresponds relatively well with the assumption for electricity consumption in the DE scenario (0.9 %/a) for the year 2040 (ENTSO-E & ENTSO-G, 2019, 19f). Otherwise, the reference value of X7 is rather in the lower range of the other scenarios considered for the year 2050[4], so both this and our total electricity consumption derived from it, including the decarbonized industrial sectors, can therefore be regarded as conservative.

4 While Eurelectric's three scenarios place increasing emphasis on industrial electrification (≤60%), McKinsey's scenarios for industry rely heavily on CCS. Both studies pursue less ambitious decarbonization strategies compared to our reference study.

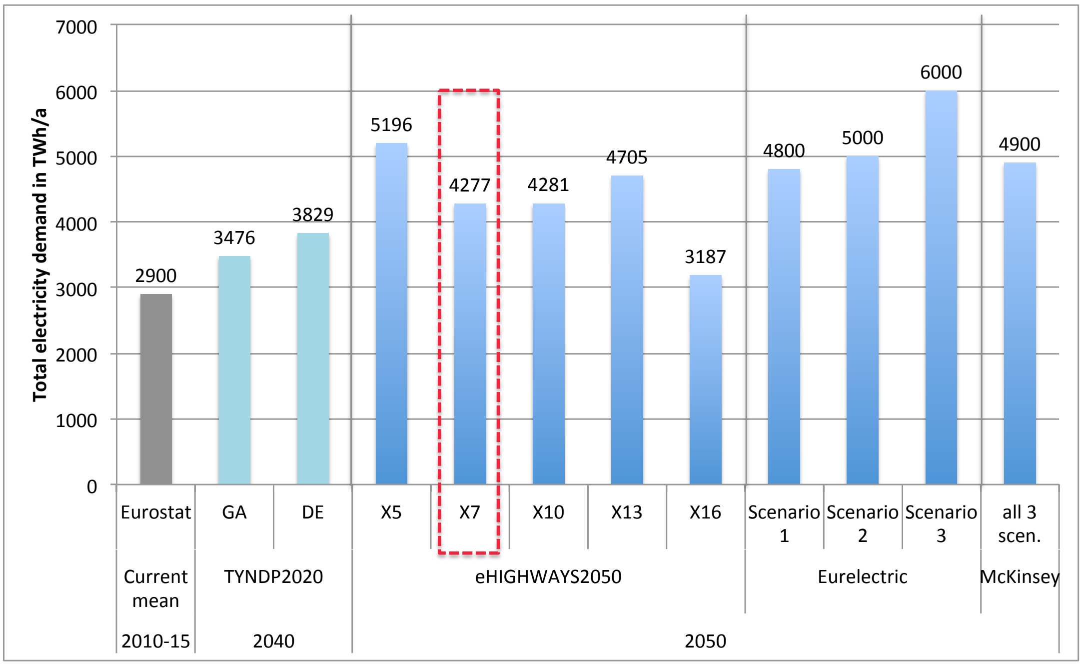


Figure 7: Total electricity demand of scenario X7 (red dotted rectangle) compared to today and to other scenarios

Source: own graph based on (e-Highway 2050, 2014; eurostat, 2019; Material Economics, 2019)

2.2 Task 2: Localisation of high-yield renewable energy potentials (sweet spots)

The goal of this task is to determine and localise spatial resolved technical potentials for renewable electricity production both in Europe and in the hot spot regions as well as to identify areas with high-yield renewable energy potentials (sweet spots).

First of all, we analysed whether the technical potential for renewable electricity production in Europe is (arithmetically) sufficient to cover the expected conventional electricity demand as well as the additional industrial demand due to decarbonisation in 2050. We have achieved this by a meta-analysis of relevant studies from which we have selected the following two studies (e-Highway 2050, 2015) and (LBST, 2017) as references.) and shown at the first workshop in June (cf. (Wuppertal Institut & ECF, 2020a)). The results indicate a broad range of generation potentials (from 4,500 TWh_{el} (e-Highway 2050, 2014) up to 14,000 TWh_{el} (LBST, 2017). This will be sufficient for the considered demand sizes, if the better assumptions about the permitted land use rates as well as the allowed water depths and coast distances for wind offshore power plants, which mainly influence the potential size, are taken into account.

In the next step, we used the technical generation potential data of the reference scenario X7 from (e-Highway 2050, 2014) to determine the renewable electricity production 2050 in the different European cluster regions needed for the supply of the conventional electricity demand. The result is shown on the left side of Figure 8.

This gives the remaining solar and wind potential in the clusters after deducting the conventional power demand of X7 (see right side of Figure 8).

These spatially derived figures of the potential renewable electricity production in 2050 build the basis for the further assessment of electricity balances and remaining regional potentials when considering the additional industrial demands by decarbonisation. This helps to identify the infrastructural challenge and solution options in the hot spot regions and to prepare the interactive workshop parts by concrete background information.

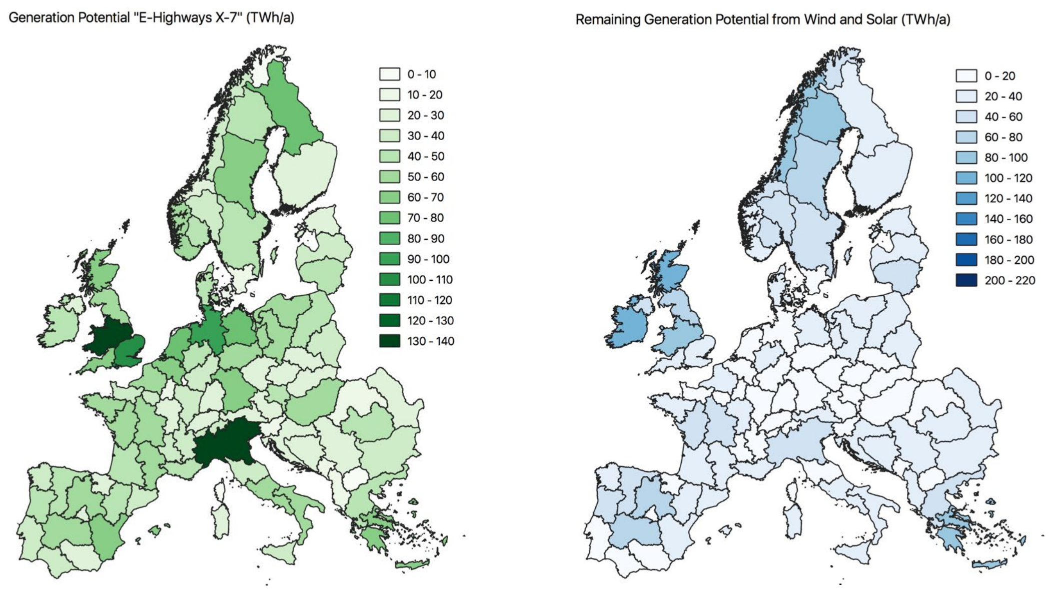


Figure 8: Yearly renewable generation potential in reference scenario X7 (left side); remaining technical wind and solar potentials after supply of conventional electricity demand 2050 (right side)

Source: own maps based on (Material Economics, 2019; e-Highway 2050, 2014)

2.3 Task 3: Localization of well suited carbon storage potentials

The main objective regarding the Carbon Capture and Storage (CCS) analysis is to roughly determine and localize the sweet spot regions for CCS in the EU by matching storage potentials, CO_2 sources and infrastructural considerations. Investigations are carried out both on the aggregated European level as well as more in detail for the respective focus regions. Primarily, meta-analyses of relevant scenario and potential studies for the EU and the selected regions are used while missing or inconsistent data are supplemented by expert judgements and own assumptions. However, neither model calculation/optimization nor complex infrastructure planning is conducted regarding CCS. Data at the European level are based mainly on the linkage of the comprehensive publications (Viebahn et al., 2010), (Neele, 2010) and (Christensen, 2009), from which the effective storage potentials are contrasted with the own determined storage requirements in Figure 9. As can be seen, the aggregated storage potentials seem to be sufficient for most countries on an aggregated level, but a closer examination will exclude many facilities due to their location, spread and geological characteristics. In order to conduct more specific regional analyses (especially as part of the storylines), a larger range of recent national level studies is used in addition, particularly (Norwegian Petroleum Directorate, 2019), (Pale Blue Dot Energy, 2016), (MEDDE, 2015), (Ministerstwo Srodowiska, 2014), (Neele et al., 2013), (TNO, 2012) and further.

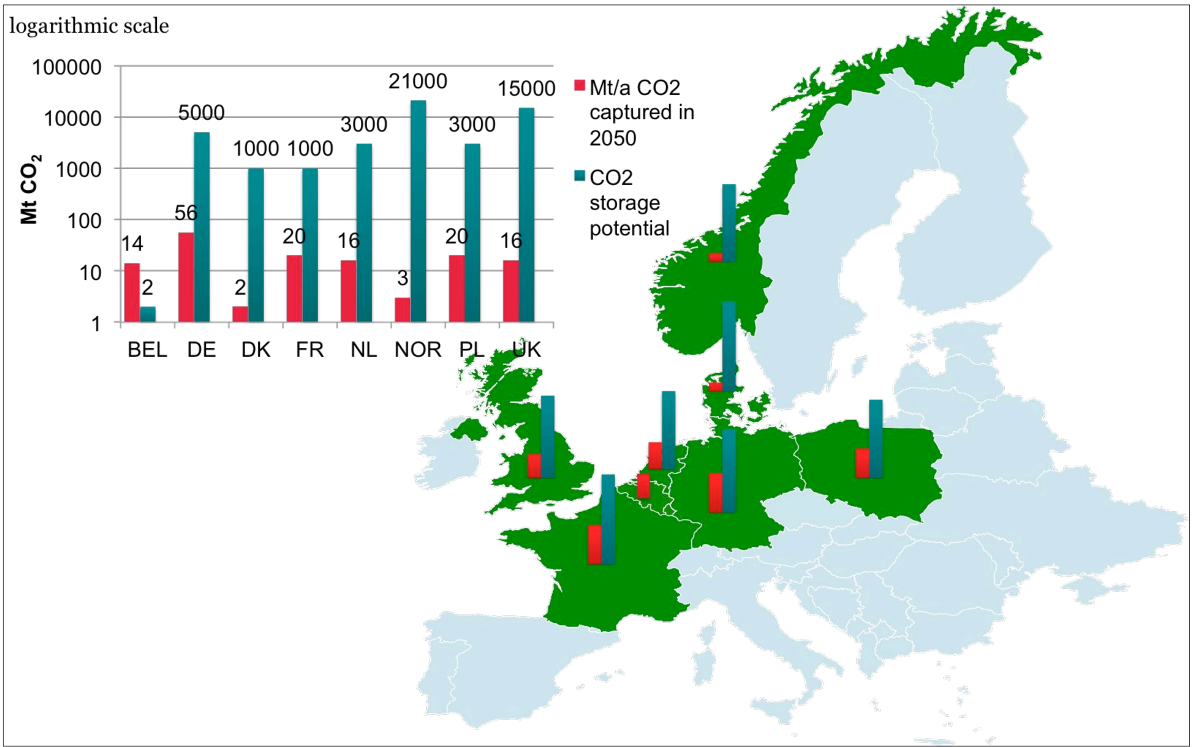


Figure 9: Storage demands and aggregated effective potentials according to Carbon Capture scenario

Source: own graph based on (Viebahn et al., 2010) and (Strategy Compass GmbH, 2020)

Regarding storage potentials, only effective storage capacities are used in this analysis in order to ensure realistic assumptions (see Figure 10). Furthermore, the focus lies on depleted oil and gas fields, as their capacity assessments refer to known hydrocarbon output volumes and are therefore assumed to be quite realistic. Coal seams are excluded from the analyses due to safety reasons. Regarding aquifers, only deep closed saline aquifers are considered and, as far as possible, the analysis is always based on the lower effective capacity limits mentioned in the literature.

For further insights into the general methodology, please see also Wuppertal Institut / ECF (2019): „Workshop evaluation report 01 (Deliverable 4.1) – Infrastructure needs of an EU industrial transformation towards deep decarbonisation, research project funded by EIT Climate-KIC.

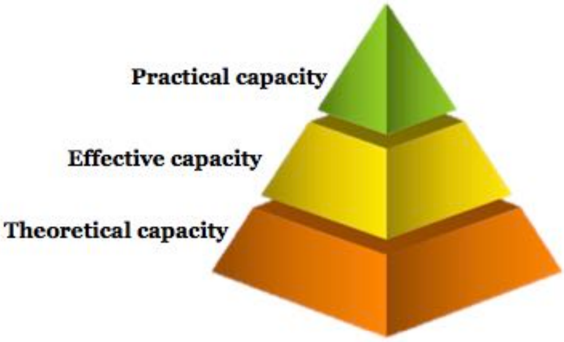


Figure 10: Capacity definitions for CO_2 storage in the literature, of which only effective storage capacities are used in this analysis in order to ensure realistic assumptions

Source: own graph

2.4 Task 3: Infrastructure analyses for selected hot spot regions

This task aims to indicate first the magnitude of the future infrastructural challenge for the selected regions and then to derive and describe possible suited solutions, which are used as input for the evaluations in the workshops (see Task 4).

The main idea behind the exploration of infrastructure needs and solutions is first to determine the size and regional pattern of the additional demands for electricity, hydrogen and CCS, in order to get a better understanding of the future challenge in the region. The next step is to determine the supply and storage capacities required in each case, assuming that the demand is for base loads with very high capacity utilization (8000 h/a). These capacities represent approximately the minimum challenge for adaptation and expansion of the infrastructures. They are then first compared with the corresponding potentials in the immediate vicinity of the region in order to assess the possibilities of decentralised solutions. In addition, it will be investigated in which more distant regions suitable potentials for the supply of demand can be found. For this purpose, imports from non-European countries, especially from North Africa, are also taken into account.

Based on these analyses and considerations, different semi-quantitative storylines for infrastructure solutions (see chapter 4-6) are developed for each region and the corresponding workshops. These are differentiated according to regional, national and European or international solutions, depending on the requirements and suitability. It is assumed that the infrastructure solutions are preferably spatially oriented between hot and sweet spots.

Figure 11 illustrates these relationships using electricity as an example. The majority of renewable electricity generation potentials are concentrated in a few countries, mainly in regions away from the demand centres. This applies in particular to the very large potentials in the North Sea, Great Britain, Spain and Scandinavia. In comparison, the majority of electricity demand is concentrated mainly in five countries and metropolitan areas.

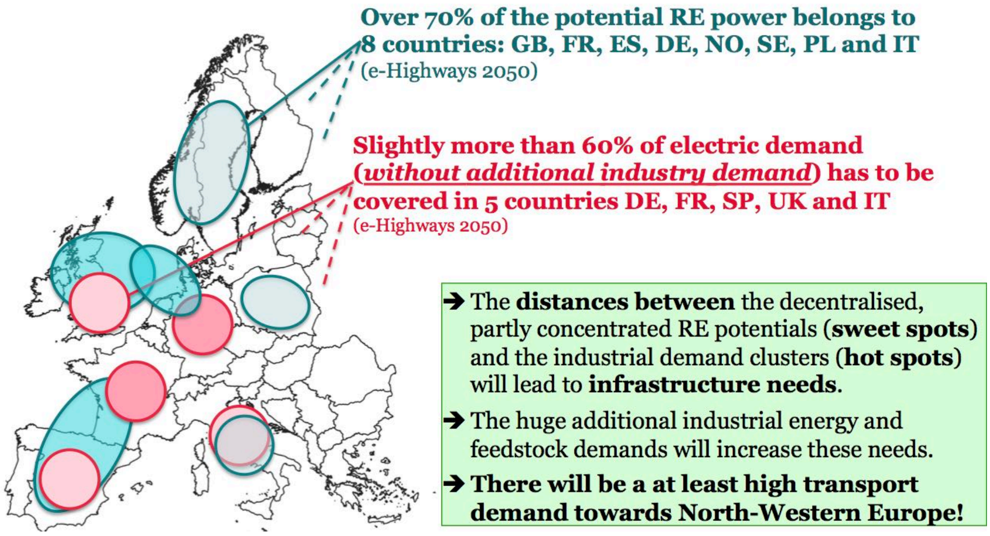


Figure 11: Overview of the major locations of renewable electricity potentials and electricity demand by European countries

Source: own graph based on informations in (Material Economics, 2019; e-Highway 2050, 2014)

For the quantitative part of the analyses, new electricity balances for all clusters are calculated from the previously determined cluster data on conventional electricity demand and corresponding electricity generation as well as on the additional industrial electricity demand, and are presented as maps. These show very clearly where and to what extent the supply requirements are changing and in particular where they are becoming more acute. The new electricity balances are compared with the remaining, not yet fully exploited renewable generation potential on site and in Europe. The results are in turn corresponding maps which serve as a basis for the WS analyses (see chapter 4-6).

In addition, the selected hot spot regions tend to already have relatively powerful electricity and gas pipelines, which in principle offer good conditions for future challenges. For this reason, additional essential data is collected in order to be able to better assess the importance of the existing infrastructures, at least qualitatively.

Finally, it has to be noted that the infrastructure analyses have been done on the above mentioned semi-quantitative level, but not by modelling or economic optimisation.

2.5 Task 4: Interactive workshop parts for exploration and evaluation of infrastructure solutions

Only desktop research as outlined before cannot adequately adress and solve the infrastructure challenges of decarbonised industries in the regions. That is why we performed a total of four different workshops in order to involve relevant experts from practice with respect to the topics and the hot spot regions. This is intended to increase the awareness of the infrastructure needs of a future decarbonised industry and to critically and constructively review the results and possible solutions in order to improve them as far as possible.

The first workshop on 13 June 2019 in Brussels served initially to publicise the study and subsequent regional workshops and to present and reflect on the basic assumptions and approaches with regard to their suitability. There is a separate workshop report about the contents and findings (see (Wuppertal Institut & ECF, 2020a).

The three regional workshops, on the other hand, each focus on the selected regions in the context of their surroundings and Europe and follow the same concept and procedure to a large extent. This is exemplified in the agenda for the workshop on which this report is based in Figure 12.

First, the background, objectives, reference studies and basic assumptions are presented relatively briefly, followed by a detailed presentation of decarbonization strategies and resulting demands for the hot spot region. Since a good understanding of these strategies and results is particularly important for the following interactive parts, the participants are given the necessary time for further questions and initial discussions.

Depending on the number of participants, the main interactive parts of the workshop will then preferably take place separately for electricity, hydrogen and CCS. Each part starts with a short presentation of the background (i.e. additional industrial electricity demand by industry and location, resulting electricity balances for the clusters and existing infrastructures) and then leads to the required supply capacities and the derivation and description of possible infrastructure solutions as a storyline.

These storylines then form the basis for further joint discussion of the infrastructures. First of all, the participants collect topics and arguments to be seen as (essential) strengths and weaknesses for each storyline, by writing or sticking them on a large poster. The contributions are presented to each other and in some cases already discussed (more intensively). The result is an overview of individual strengths and weaknesses for each infrastructure option (cf. Figure 18 and Figure 32).

For more in-depth analyses, preferred solution options are selected next. This is done indirectly by identifying the overall least favoured storyline. For each storyline, the participants may assign resistance points between 0 (for no resistance) and 10 (for very high resistance), which express how strongly they themselves would reject this solution. The result is a set of (different) resistance points from which the average resistance is calculated for each option. The solution option with the highest resistance is then not considered further.

The in-depth analyses are then carried out differently for each workshop due to the different numbers of participants. For the underlying hot spot region North-West

Europe the following questions will be discussed for the remaining storylines together or divided into groups[5]:

- „Influencing factors on implementing necessary electricity infrastructure“ (group)
- „Important moments for the establishment of hydrogen infrastructure“ (group)
- „Which influencing factors do you see from today‘s situation for setting up a CCS infrastructure?“ (all)

As a result of the group work, the individual contributions of the participants to the questions are collected on a poster and clustered as far as possible (cf. Figure 24).

In the case of CCS, the group will also fill out a pre-fabricated diagram to show possible transformation paths for the CCS capacities required over the period until 2050 (cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**Figure 32).

At the end of the workshop, all participants come back together in the plenum and present to each other the results achieved and special features of the discussions.

Time	Duration	TOP		
09:30	00:30	Arrival, registration and welcome coffee		
10:00	00:15	**Welcome, short team introduction and overview of WS-schedule**		
10:15	00:10	Background Information (from general context to ME-scenarios and Infra Needs Project)		
10:30	00:20	Decarbonisation results for the hot spot region "Bouchon-du-Rhône" as common basis for WS sessions		
11:10	00:05	Distribution to 3 sessions		
11:15	00:15	Coffee break		
11:30		**Start Session P&H: Infra Needs for Power System and H2**		**Start Session C: Infra Needs for CCS**
11:30	00:15	Impulse lecture about Power and H2 demand…		Impulse lecture CCS…
11:45	00:15	Introduction into WS tasks		Introduction into WS tasks
12:00	01:00	WS-Part P&H1		WS-Part C1
13:00	01:00	**Lunch**		
14:00	00:10	short refresh and new distribution to 3 Sessions		
14:10	00:15	Introduction into WS-Part P2	Introduction into WS-Part H2	Introduction into WS-Part C2
14:25	01:00	WS-Part P2	WS-Part H2	WS-Part C2
15:25	00:20	P2-Resume	H2-Resume	C2-Resume
15:45	00:15	Coffee break		
16:00	00:30	Wrap-up of the day and outlook		
16:30		**Farewell**		

Figure 12: Agenda of the workshop for the hot spot region Southern-France

5 The two groups for electricity and hydrogen changed after half the time and then continued the group work based on the results of the previous group.

3 Regional demand characteristics in 2050

The region at the delta of the Rhône is one of the typical coastal industrial clusters in Europe that have been developed during the 1960s and 1970s. With Europe becoming more and more an importer of resources like crude oil, iron ore and coking coal the aim was to build up new conglomerates immediately at the sea with an easy and cheap access to the world markets. Other clusters of this type are Dunkerque in Northern France and Tarragona in Spain or Brindisi and Taranto in Italy. Although the Rhône delta region has a petrochemical "hinterland" it can be seen as a prototype, at least for the other Mediterranean port regions with a similar access to renewable energies or CO_2 storage options. Results for this region can thus be transferred to some extent to the other clusters of the same type.

In regard to petrochemicals the region has three major sites at Lavera, Berre l'Etang and Fos-sur-Mer. ArcelorMittal's primary steel plant is located at Fos as well.

The following figure shows the energy demands calculated for the year 2050 according to the "New Processes" scenario by Material Economics and according to the share of the region in European production capacities.

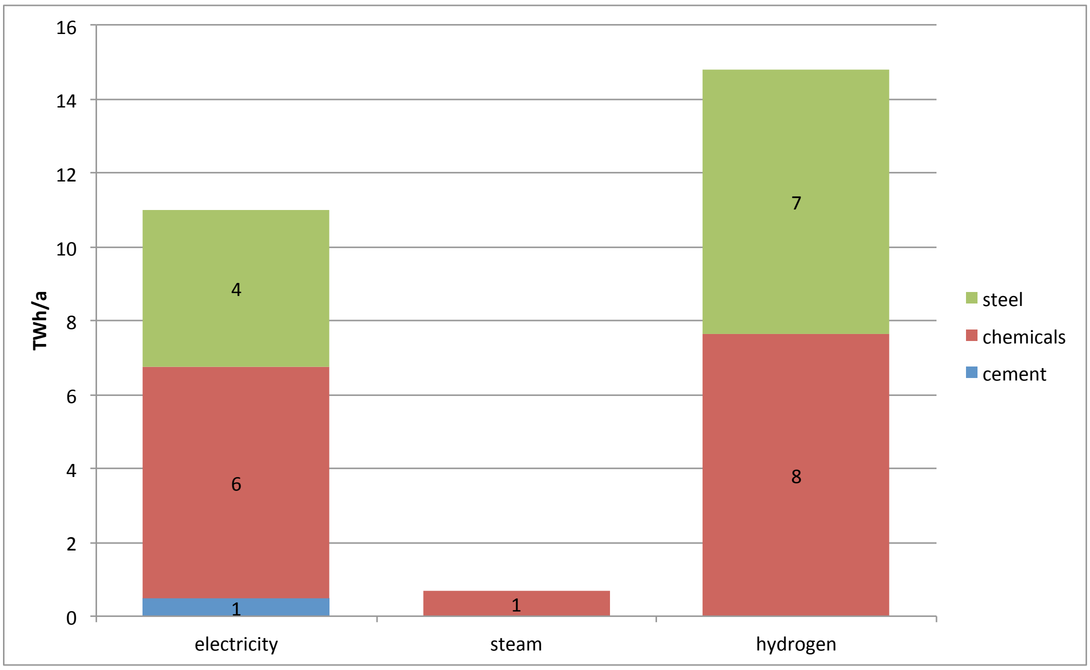


Figure 13: Electricity, steam and hydrogen demands in the hot spot region of the Rhône delta by industries (project analysis)

Source: own illustration

There is an electricity demand of 6 TWh in the chemical industry which is partly due to existing electricity-"captive" processes like chlorine electrolysis, partly due to new demands, e.g. for the supply of high-temperature heat in in the production chain for PVC, which is today delivered by natural gas. Electricity demand of the steel industry is due to the new established DRI-Electric arc furnace (EAF) route, where iron ore is reduced to direct reuced iron (DRI) by the means of hydrogen and smelted afterwards in an EAF. Electricity is required to operate the electric arc furnaces and also for the supply of heat in the production of DRI.

Electricity use in the cement industry is rather low in comparison to the other sectors. For the individual plants, however, which are rather small-scale, the amount is very relevant, and is due to the assumptions that rotary clinker kilns are operated with electricity to supply the required high-temperature heat.

Steam use is relevant in the petrochemical industry only. The major part is due to the operation of an ethylene oxide plant at Fos, which is however not part of a polymer production chain.

Finally *hydrogen* use is the most relevant energy carrier to get to a carbon neutral production according to the "New Processes" scenario. It is both relevant for the production of high-value chemicals like olefins and aromatics (the so called "platform chemicals" to produce polymers) and as a reducing agent in the DRI process as mentioned above.

4 Storylines for electricity infrastructure solutions

Southern France is a region of a high energy demand due to a strong industrial sector and will presumably remain so in the future. The decarbonisation of heavy industry sectors will lead to higher electricity demands, thereby intensify this load characteristic.

Figure 14 shows the industrial electricity demands in the considered sectors in 2015 and 2050, which rise from 4.2 TWh/a today to 13.4 TWh/a without additional hydrogen production and to 33.6 TWh/a if the hydrogen is also produced in the area. These numbers result from analyses based on the scenario "new processes" (Material Economics, 2019), which is the scenario with the highest additional electricity demand.

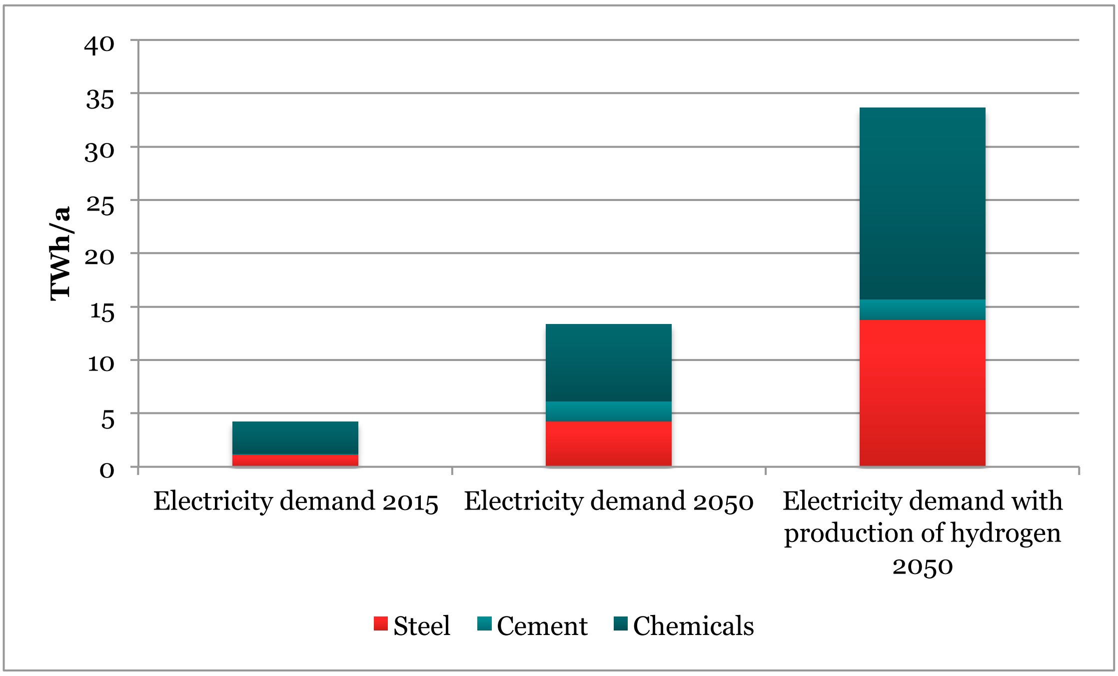
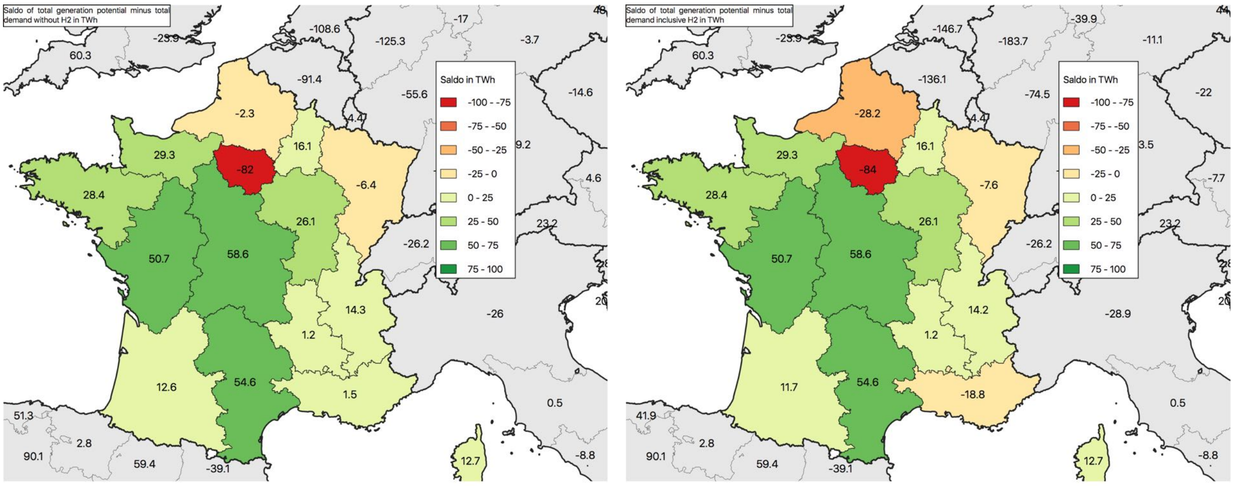


Figure 14: Industrial electricity demand in 2015 and 2050

Source: own illustration and calculations based on (Material Economics, 2019)

These industrial demands strengthen a characteristic of disadvantageous spatial distribution of loads. Figure 15 shows the balance of the potential for generating renewable electricity based on (e-Highway 2050, 2014) scenario "100% RES" and the electricity demand (sum of demand from "100% RES" and additional electricity demand for decarbonised industry). Offshore wind potentials are included in the adjacent regions' generation potentials. Regions coloured green are regions where the electricity generation potential is higher than the demand, red is indicating a higher demand than generation potentials. These maps show, that the renewable potential in the region is limited and will be exceeded fast, if the hydrogen needed is produced in Southern France.



(A) without electricity for H_2 (B) including electricity for H_2

Figure 15: Balance of generation potential and demand, (A): without electricity for hydrogen, (B): with electricity for hydrogen

Source: own illustration based on (Material Economics, 2019) and (e-Highway 2050, 2014)

It may be necessary to generate electricity in areas with higher generation potential and then import it into the region. There are three main different storylines for the electricity supply, that can be distinguished:

- Storyline Electricity 1: electricity generation in the region
- Storyline Electricity 2: import electricity via an enhancement of the national transmission grid
- Storyline Electricity 3: electricity import via DC-cable from North Africa

4.1 Storyline Electricity 1: electricity generation in the region

Figure 16 shows the balance between generation potential and additional demand without hydrogen. The self supply of energy in the region would only be possible, if the hydrogen needed is not produced in the region. It is therefore realistic to assume a slight increase in grid capacity, even if the focus of this storyline is to use renewable potentials as close to the locations of consumption as possible.

Figure 17 shows the grid that has been calculated in (e-Highway 2050, 2014) in grey colour. This depicted grid includes grid expansion to 2050 in order to fulfil the transmission needs foreseen in the eHighway scenario “100% RES” and does not include transmission for additional electricity for decarbonised industry.

The red lines indicate additional transmission needs for electricity imports to the region. The lines indicate an example of where these additional connections could be made: strengthening the connection to neighbouring regions.

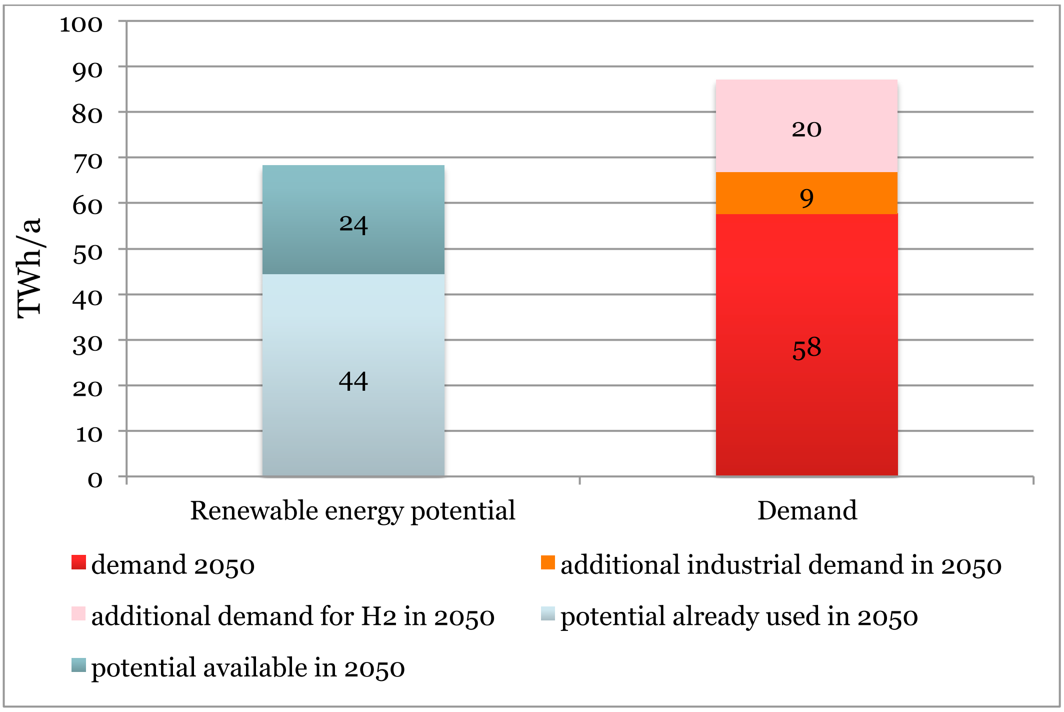


Figure 16: Renewable energy potential, electricity demand and additional industrial demand with and without hydrogen based on own calculations

Source: own illustration and calculations based on (Material Economics, 2019) and (e-Highway 2050, 2014)

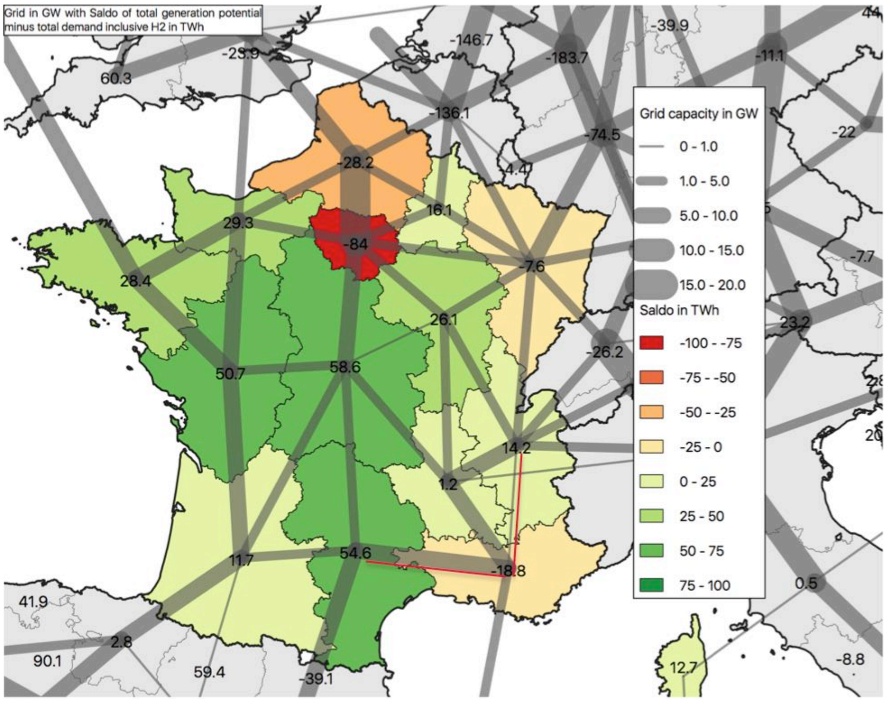


Figure 17: Electricity grid of storyline E.1 according to (e-Highway 2050, 2014) (grey), additional grid (red) and balance between generation potentials and electricity demand (with hydrogen)

Source: own illustration based on own calculations, (Material Economics, 2019) and (e-Highway 2050, 2014)

Evaluation of storyline E.1

Within the workshop, the storylines were evaluated in terms of their strengths and weaknesses (see Figure 18). For storyline E.1, the regional economic development, resulting in potential investments and job opportunities have been named as the major strength. According to the workshop participants, the weakness of this storyline is the limited renewable generation potential in the region which is hard to develop due to political resistance and acceptance challenges.

The overall rating of this storyline by the participants of the workshop was 7.33, where 0 can be regarded as full agreement and 10 as full rejection.

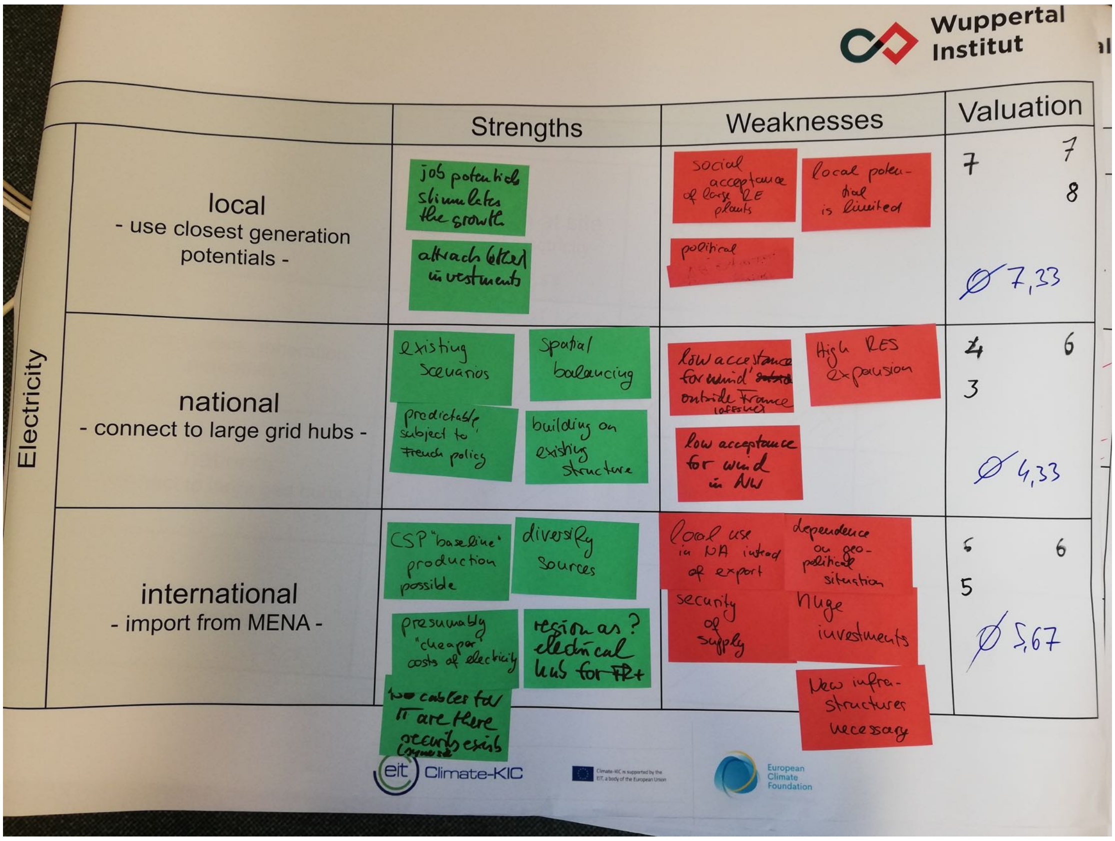


Figure 18: Workshop evaluations of the electricity storylines

Source: own photograph

4.2 Import electricity via an enhancement of the national transmission grid

Another possible supply of the energy needs in the region could be the strengthening of the national transmission grid. There are renewable potentials in France, which could be developed, especially the wind and solar resources of central and western France (see Figure 20). The capacity of the grid needed for these expansions is small, compared to the grid capacity already foreseen for 2050.

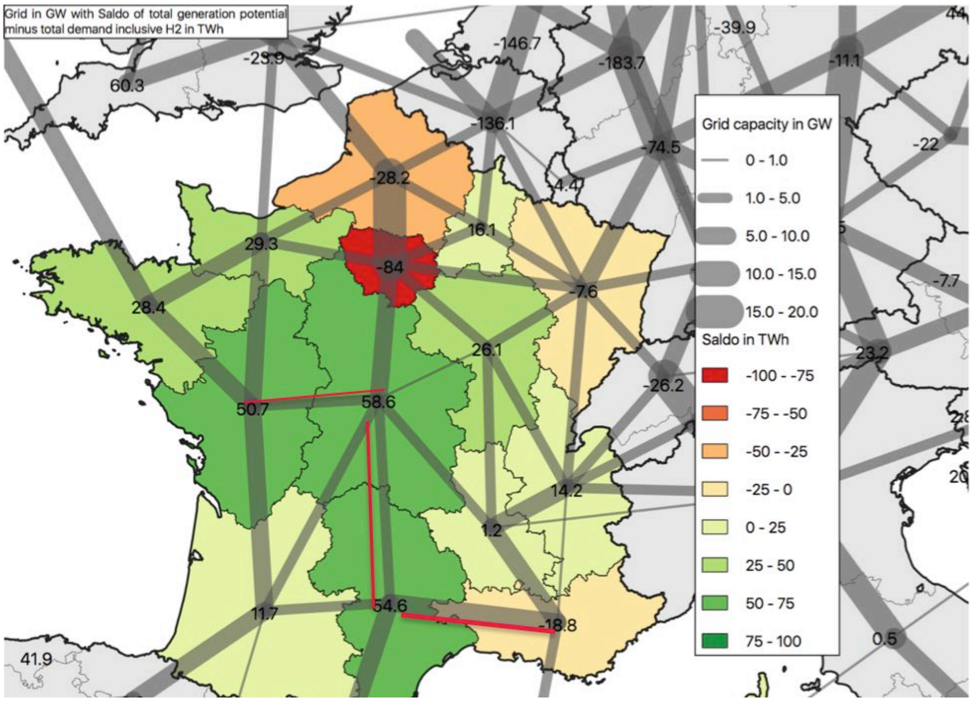


Figure 19 : Electricity grid of storyline E.2 according to (e-Highway 2050, 2014) (grey), additional grid (red) and balance between generation potentials and electricity demand (with hydrogen)

Source: own illustration based on own calculations, (Material Economics, 2019) and (e-Highway 2050, 2014)

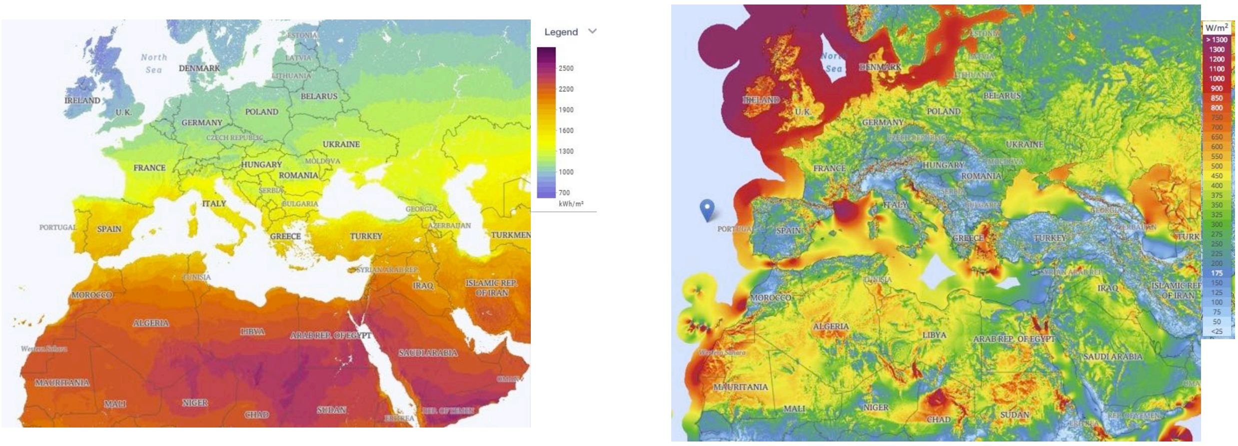
Evaluation of storyline E.2

The existing scenarios and infrastructure developments, which are in line with this storyline, have been mentioned as main strengths of storyline E.2. As this storyline focuses on the supply out of France, the regional and national policies are the key actors for the development. On the other hand, the low social acceptance of an expansion of wind energy in the north-western part of France is seen as a major weakness.

The overall rating of this storyline by the participants of the workshop was 4.33, where 0 can be regarded as full agreement and 10 as full rejection. This value is quite high, showing some resistance, but is still lower than the values of the other storylines.

4.3 Electricity import via DC-cable from North Africa

Another possible source of imports could be the MENA (Middle East North Africa) region. There are large renewable potentials, especially the resources of solar, but also of wind, are very high (see Figure 20).



global horizontal radiation (kWh/m²) wind power density at 100 m (W/m²)

Figure 20: Solar and wind resources according to Global Solar Atlas (World Bank Group, 2019) and Global Wind Atlas

Source: left: (World Bank Group, 2019), right: (World Bank Group & DTU Wind Energy, 2019)

If this potential is to be tapped for use in Europe, the local interests and needs of the MENA region must of course be taken into account. An exemplary import route is shown in Figure 21, where electricity generated in Algeria could be transported to North-West Europe via France. This import route could also be extended to supply not only Southern France, but to deliver electricity via this route to other regions with high energy demand in Europe as well.

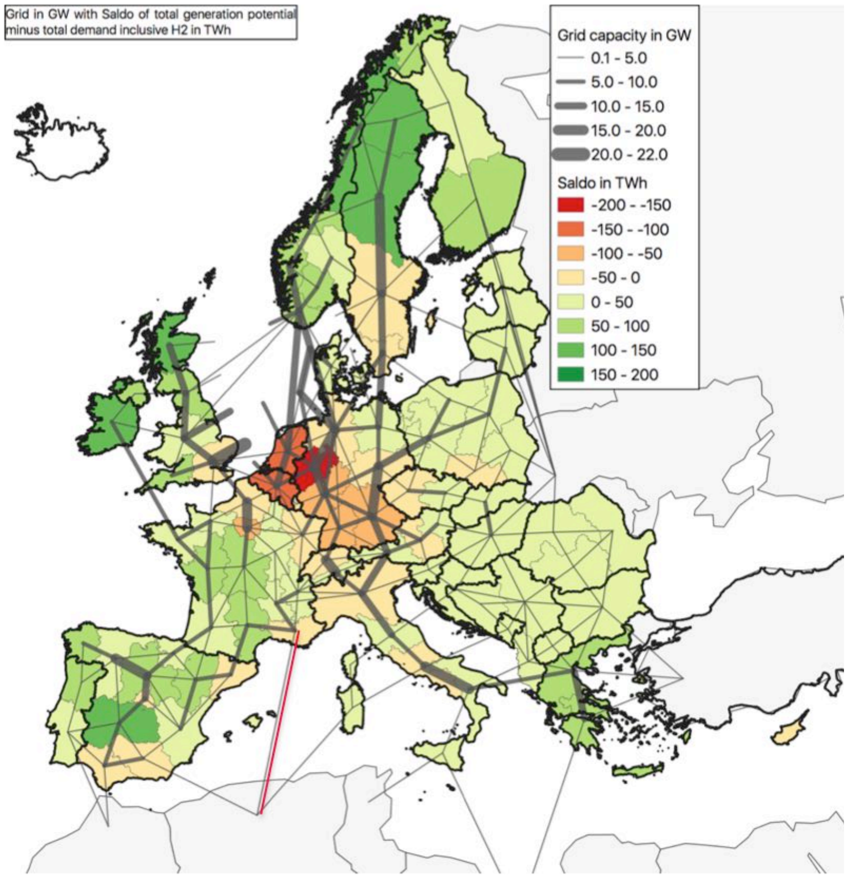


Figure 21: Electricity import route from MENA to Southern France in red

Source: own illustration based on own calculations after (Material Economics, 2019) and (e-Highway 2050, 2014)

Evaluation of storyline E.3

The diversification of energy sources and the possible cheaper production of electricity have been mentioned as the main advantages of this storyline. The storyline E.3 could also build on existing infrastructure, as there are currently 13 communication cables connecting the region and North Africa. But the dependency on the possible unstable geopolitical situation, the new infrastructure, which has to be build in Northern Africa and the possibility that the energy resources available will be preferably be used to fuel the domestic economic development and not always be available for the export have been mentioned as strong weaknesses.

The overall rating of this storyline by the participants of the workshop was 7.33, where 0 can be regarded as full agreement and 10 as full rejection.

5 Storylines for hydrogen infrastructure solutions

In addition to the industrial electricity demands described in the previous section, there is an expected hydrogen demand of 15.2 TWh/a in 2050 (based on (Material Economics, 2019) scenario "new processes"). To produce this hydrogen, 20.3 TWh electricity is necessary (at an assumed electrolysers' efficiency of 75 %); this nearly doubles the amount of additional electricity demand due to decarbonised industry. Figure 22 shows the distribution between the steel and the chemical sector of these hydrogen demands.

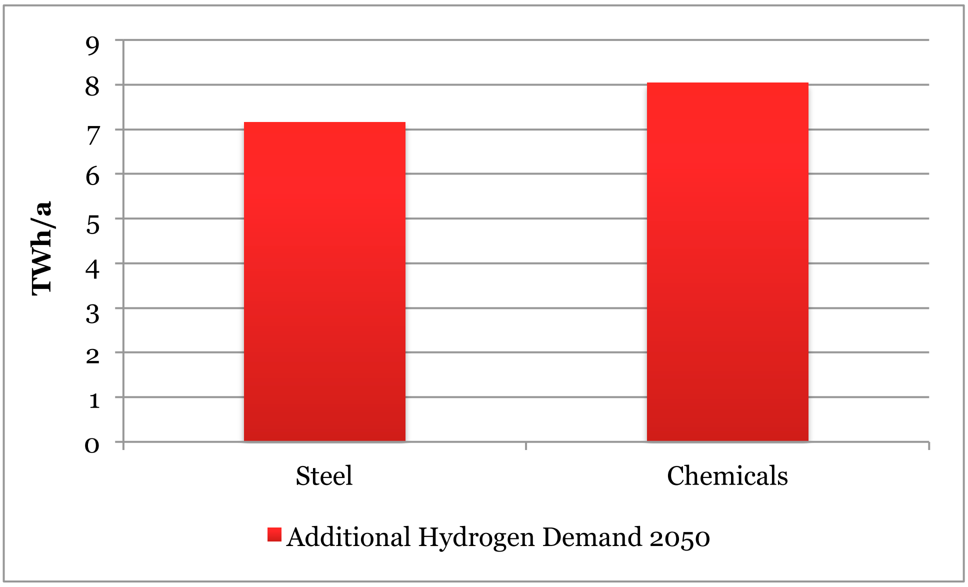


Figure 22: Hydrogen demand in 2050 per sector

Source: own illustration based on own calculations and (Material Economics, 2019)

Electrolysers to produce that hydrogen would need to have a capacity of about 2.5 GW at 8,000 full load hours, for a baseload generation of hydrogen. A more flexible generation which could be adapted to regional load or feed-in would result in even higher necessary capacities and according storage facilities.

There are different possibilities to generate and/or transport the needed hydrogen. Hydrogen can either be generated at each single site, it can be supplied via pipelines and a hydrogen grid or be directly imported via tanker from (e.g.) the MENA region. In the following, three distinguished storylines are described:

- Storyline Hydrogen 1: generate hydrogen at site and transport the electricity
- Storyline Hydrogen 2: transport hydrogen via pipelines from the north-western part of France
- Storyline Hydrogen 3: import hydrogen from the MENA region

5.1 Storyline Hydrogen 1: generate hydrogen at site

Within this storyline, the hydrogen demand is covered locally, with electrolysers located directly at the sites. In this case, electricity would need to be transported to the electrolysers. The overall hydrogen demand for the decarbonised industry in the region is estimated to be 15.2 TWh in 2050, which results in an overall electricity demand of 20.3 TWh. If the electrolysers are assumed to be operated close to baseload (8,000 full load hours), this results in an additional capacity of 2.5 GW. To cover this demand, an expansion of the national electricity transmission grid as shown in Figure 23 is very likely.

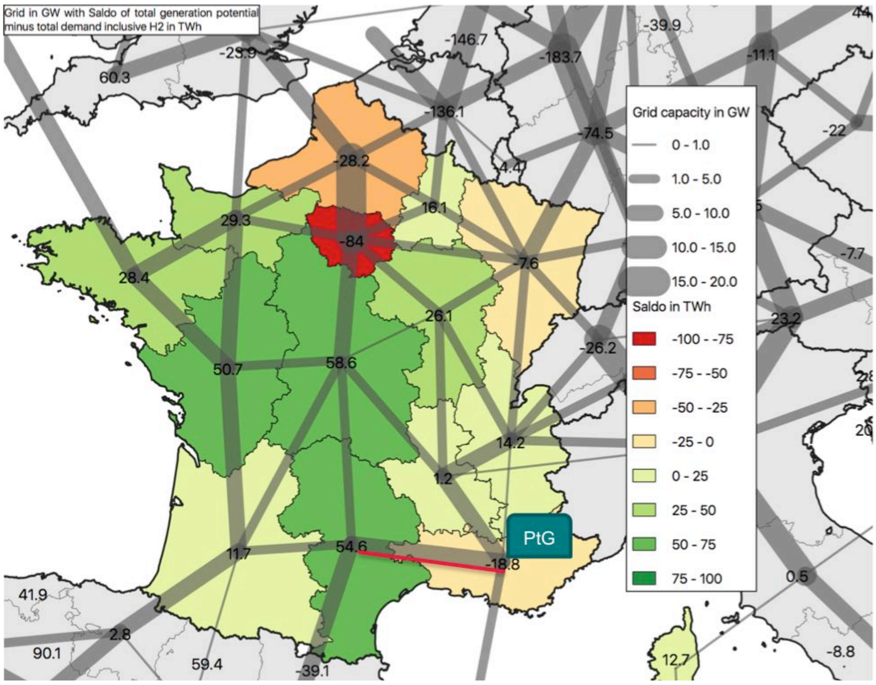


Figure 23: Electricity grid of storyline H.1 according to (e-Highway 2050, 2014) (grey), additional grid (red) and balance between generation potentials and electricity demand (with hydrogen)

Source: own illustration based on own calculations, (Material Economics, 2019) and (e-Highway 2050, 2014)

Evaluation of Storyline H.1

As Figure 24 shows, the main strength of storyline H.1 lies in it’s focus on one infrastructure. Since hydrogen can be produced where it is needed, there is no need to build up a separate hydrogen infrastructure with its own challenges and losses. As there is already hydrogen production in the region, such a storyline could build on existing experiences. The local added value has been mentioned as a further strength of this storyline. However, the local, regional and national acceptance of new renewable generation technologies is expected to be rather low. As this storyline depends on an extension of renewable generation capacities, this is seen as the major disadvantage.

The overall rating of this storyline by the participants of the workshop was 3.67, where 0 can be regarded as full agreement and 10 as full rejection.

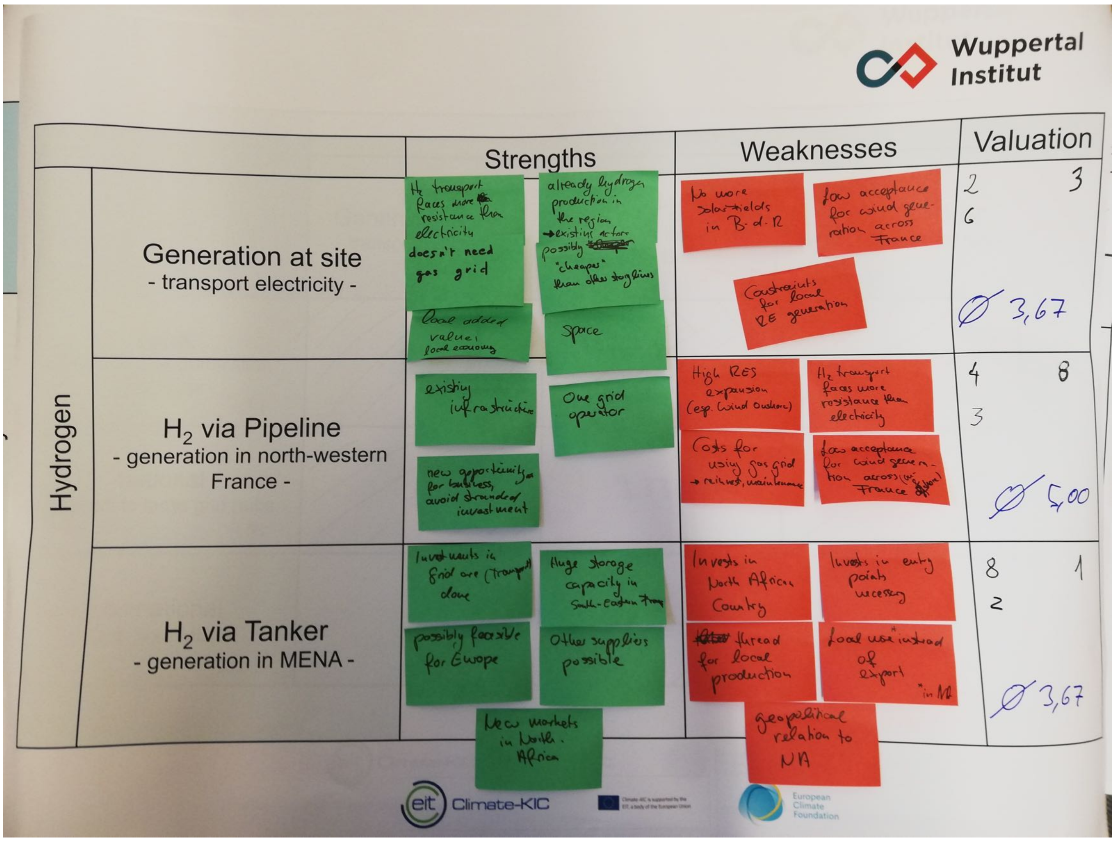


Figure 24: Workshop evaluations of the hydrogen storylines

Source: own photograph

5.2 Storyline Hydrogen 2: transport hydrogen via pipelines from the north-western part of France

Another possibility to supply the industrial sites with hydrogen is to use pipelines for hydrogen transport.

By now, there are no hydrogen pipelines in the region, thus a new hydrogen grid would be necessary. This could either consist of newly built pipelines, parts of the natural gas grid could be repurposed, or a combination of both strategies. In Figure 25 it can be seen that hydrogen demands occur near to large natural gas transport capacities, which opens the possibility to a strategy build on repurpose of existing infrastructure.

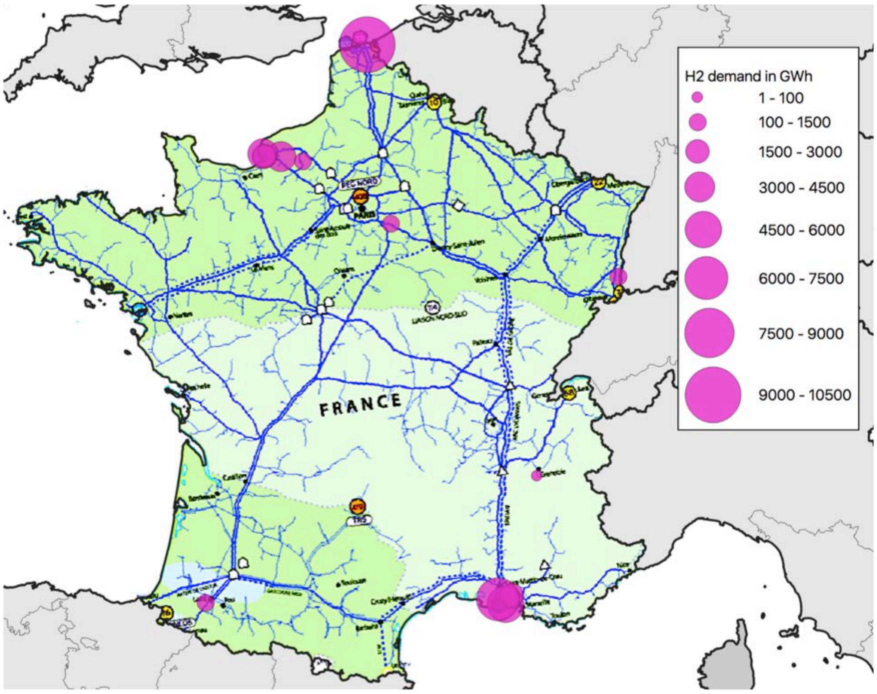


Figure 25: Hydrogen demand at sites and gas transport capacities

Source: own illustration based on own calculations, (ENTSOG, 2017) and (Material Economics, 2019)

Evaluation of storyline H.2

The reuse of existing natural gas pipelines and the new business opportunities have been mentioned as major strengths for the storyline H.2.

But the investments necessary to build-up or repurpose the existing natural gas infrastructure was seen as a weakness. Additional, the public acceptance for a hydrogen infrastructure has been rated lower than the acceptance of an electricity infrastructure.

The overall rating of this storyline by the participants of the workshop was 5.00, where 0 can be regarded as full agreement and 10 as full rejection.

5.3 Storyline Hydrogen 3: import hydrogen from the MENA region

The energy resources in northern Africa shown in Figure 20 could also be used to produce and export hydrogen to Southern France. The region under consideration here is a hydrogen load focus for France, but there are further hydrogen demands, especially in the northern part of France (see Figure 25).

In addition, there are other hydrogen demands that can be expected in a decarbonized energy future (e.g. for mobility). Therefore, hydrogen imports even over long distances could be worthwhile.

Evaluation of storyline H.3

According to the participants of the workshop, the main strength of this storyline is the diversification of the hydrogen supply. The import route could be part of a nationwide or even Europe-wide supply of imported hydrogen. If the import infrastructure is in place, a supply of hydrogen from other regions of the world should be possible as well. Additionally, there seem to be huge storage capacities for hydrogen in south-east of France. But the political insecurities and the potential threat to the existing regional production of hydrogen as well as the uncertainty whether the hydrogen could be imported or whether it would be used in the developing economies of northern Africa have been rated as disadvantages.

The overall rating of this storyline by the participants of the workshop was 3.67, where 0 can be regarded as full agreement and 10 as full rejection.

5.4 Compatibility of the preferred electricity and hydrogen storylines

If the ratings of the storylines are calculated together, the overall result can be seen in Figure 26. The combination of either hydrogen production on site or the import of hydrogen via tanker with the extension of the national electricity grid has been rated best.

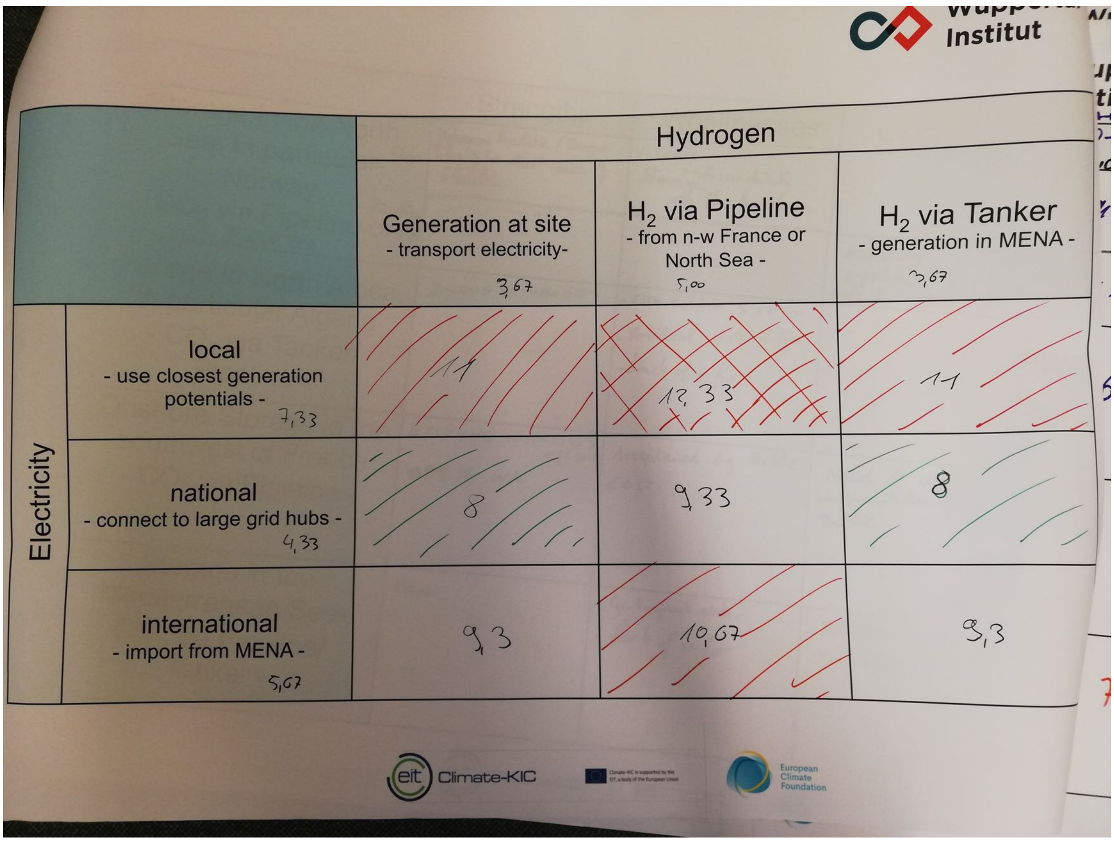


Figure 26: Important moments for the implementation of a centralised hydrogen production and a distribution via local and regional hydrogen grids

Source: own photograph

It seems, that the political and public debate in the region is not in favour of a certain storyline yet, as most ratings are relatively close together. As these results have been discussed with the whole workshop audience, different stakeholders disagreed with the rating, which further supports the conclusion, that there is not a favourable strategy to deal with the infrastructure challenges of a decarbonised industry yet.

6 Storylines for CCS infrastructure solutions

6.1 Transformation pathway for CCS capacity (interactive)

For the industries of southern France, the demand for Carbon Capture and Storage (CCS) is expected to be around 4 Mt CO_2/a from 2050 onwards. These value results from analyses based on the scenario “carbon capture” (Material Economics, 2019), which is the scenario with the highest share on CCS.

Between the first input lecture (see section 0) and the presentation of concrete storylines, the participants were asked to develop possible transformation pathways on how CCS capacity could evolve within Southern France towards the target value. The exercise served both as a common introduction to the CCS scenario and its target parameters, but was nevertheless intended to sensitize participants to the challenge on the time scale. First of all, the attendees had the opportunity to consider possible curve progressions in small-format versions by themselves. Afterwards, they were asked to transfer their considerations to a joint poster, present it to the plenum and justify their assessment (yellow stickers in Figure 27). Central arguments were a rising ETS resp. CO_2 price and (re-)investment cycles of existing plants. The quite different pathways offered much room for discussion, yet with the exception of one participant's vision they always reached the target value.

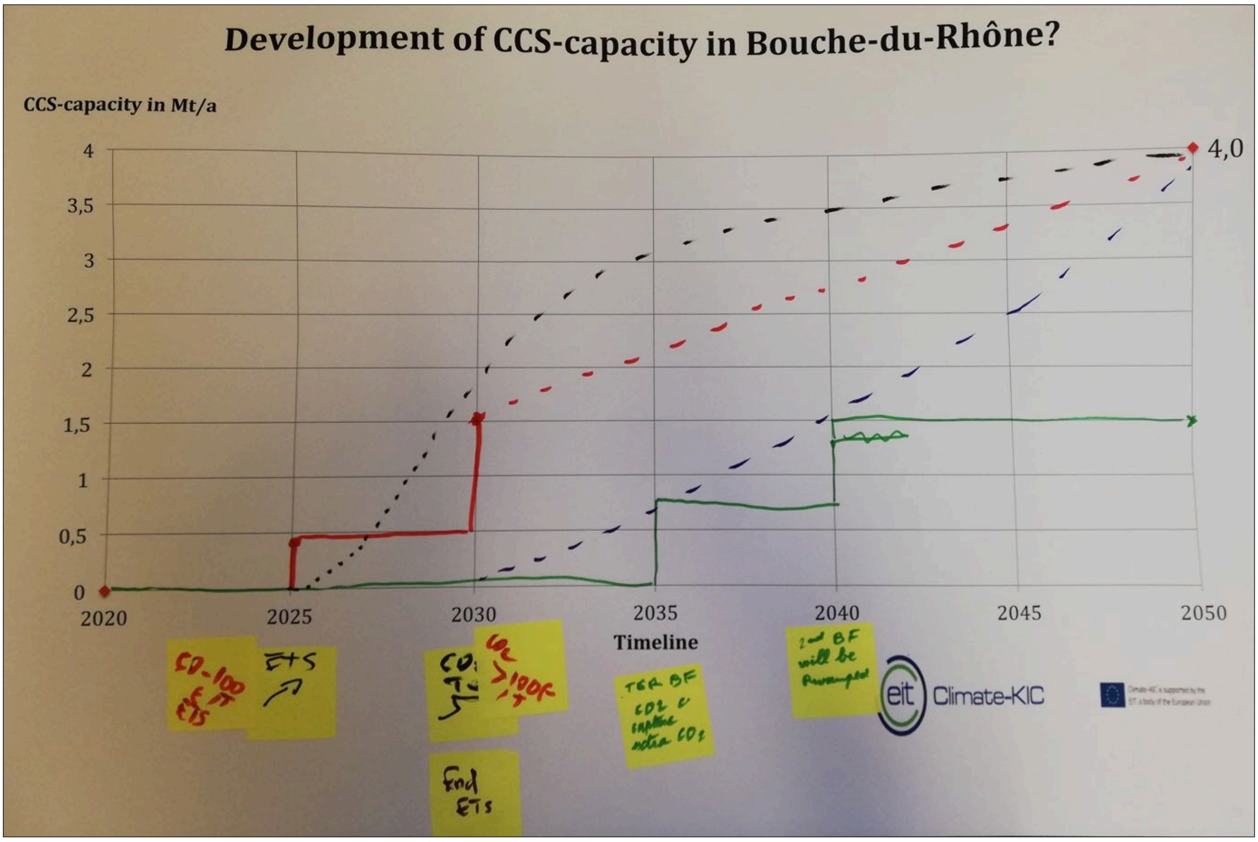


Figure 27: Possible transformation pathways for CCS in Bouche-du-Rhône (results)

Source: own photograph

6.2 Storylines

After this interactive introduction, the second input presentation focused on the derivation of possible infrastructure storylines. The particular challenge for Southern France is to find suitable storage facilities at all. Despite relatively poor data availability, it is highly probable that there are no local storage facilities in order of the required quantities (which are around 4 Mt per year). Also for neighbouring regions, there is no or only insufficient information on CO_2 storage potentials available. At the same time, the large European storage capacities are located far away in the North Sea. Hence, four different storylines have been developed, none of which is an optimal solution, highlighting the challenge of decarbonisation by CCS for this particular region:

- storage in the North Sea, particularly Norway,
- storage in North Africa, particularly Algeria,
- onshore storage in South-West France,
- storage in the Mediterranean Sea.

6.2.1 Storyline 1: storage in the North Sea, particularly Norway

In this storyline the large Norwegian offshore reservoirs, e.g. Utsira Formation, are used for storing the emissions of Southern France's industry. Two different transport routes were illustrated: either directly via ship from Marseille (~ 4000 km oneway) or via a combination of inland-pipeline from Marseille to Dunkerque (~ 1000 km) and subsequent ship transport to Norway (~ 2000 km oneway). Despite the long distance, the advantages lie in an existing resp. emerging CCS infrastructure in the North Sea, the willingness of the Norwegian government to store foreign emissions and the abundant storage potentials.

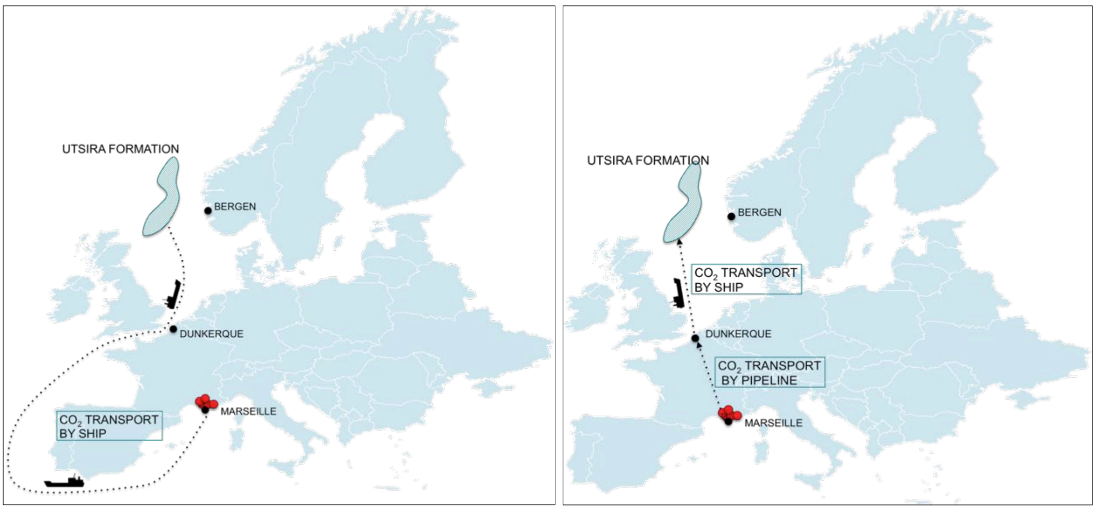


Figure 28: Storage in the North Sea via ship (left) or via combination of inland-pipeline/ship (right)

Source: own graph

6.2.2 Storyline 2: storage in North Africa, particularly Algeria

The second storyline is the possibility of storing CO_2 in North Africa. Algeria in particular has already gained some experience in this area, e.g. through the large-scale project *In Salah*. Although the data situation in this area is highly insufficient and further studies on the choice of location would be necessary, this region offers potentially abundant storage capacities and only little land competition. In any case, a ship transport from Marseille to North Africa/Algeria (~ 750 km) is necessary and would be supplemented by inland pipelines depending on the location (see Figure 29).

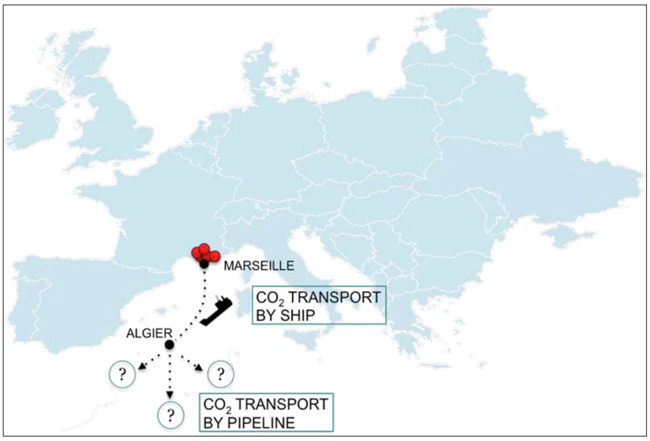


Figure 29: Storage in North Africa, in particular Algeria

Source: own graph

6.2.3 Storyline 3: onshore storage in southwest France

This third storyline opens up the debate on the politically and socially sensitive issue of onshore storage. Especially in southwest France, there are a number of depleted hydrocarbon fields potentially well suited for CCS, but their absolute capacity has not yet been conclusively assessed. As depicted in Figure 30, a pipeline system is particularly suitable for domestic CO_2 transport (~ 600 km).

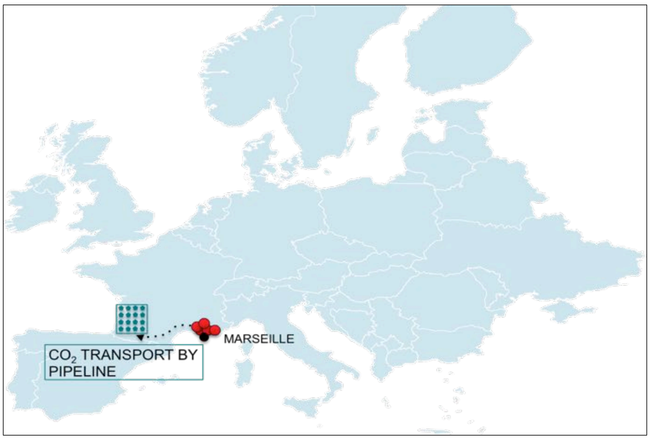


Figure 30: Local storage in southwest France (onshore)

Source: own graph

6.2.4 Storyline 4: storage in the Mediterranean Sea

With this fourth storyline, a similar terrain as in the North Africa option is being treaded. Potentially, larger storage facilities in form of deep saline aquifers could also be located here, and at a much shorter distance than the large European capacities in the North Sea. However, the data situation is highly insufficient and storage facilities would first have to be explored, with a corresponding risk of failure. In any case, the CO_2 would most likely be transported by ship (see Figure 31).

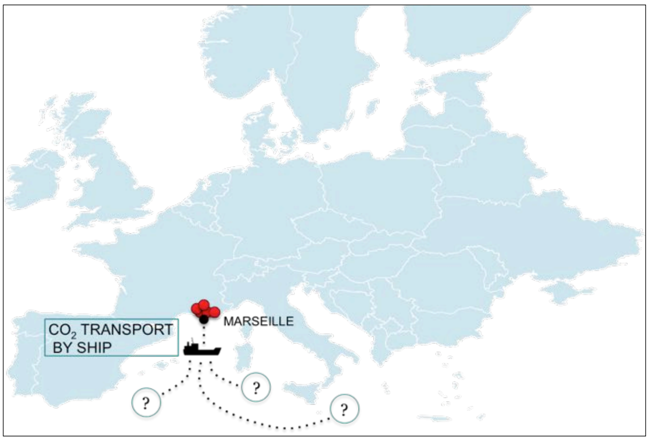


Figure 31: Storage in the Mediterranean Sea

Source: own graph

6.3 Strengths and weaknesses (interactive)

The subsequent discussion of the presented storylines was conducted interactively. The participants were asked to work out the core strengths and weaknesses of the respective strategies from their point of view and to record them in a prepared matrix (see Figure 32). The task opened up the debate in particular on non-economic aspects, which were not assigned a leading role at the beginning, and stimulated a lively discussion among the participants. The written results are presented in the appendix.

The participants emphasise the principal feasibility of the Norwegian option, as both the storage capacities are relatively well known and a common infrastructure could be used. In contrast, they see high costs (especially capital expenditures if pipelines are used) for relatively small amounts of CO_2. For the North African option, reference is made to the possibility of mutual transport (CO_2 export and hydrogen import), but this is offset by political risks and a lack of information regarding to the storage capacities. Advantages of onshore storage in France are low costs and existing infrastructure, but the social acceptance is low. The last option, storage in the Mediterranean Sea, can only score points with a small distance, but is otherwise associated with geological risks and lack of information.

In a second step the attendees were asked to evaluate the different storylines. This was done in the form of rejection points on a scale of 1 to 10, i.e. a high score for a storyline is equivalent to a high level of disapproval. The aim of this task was to identify the storyline with the lowest rejection among the participants. After the evaluation, it became clear that this was the strategy to transport CO_2 from Southern France via inland-pipeline first to Dunkerque, and then to Norway by ship (storyline 1). Due to political instability and an unclear storage situation, the most unpopular option was the transportation to North Africa (storyline 2).

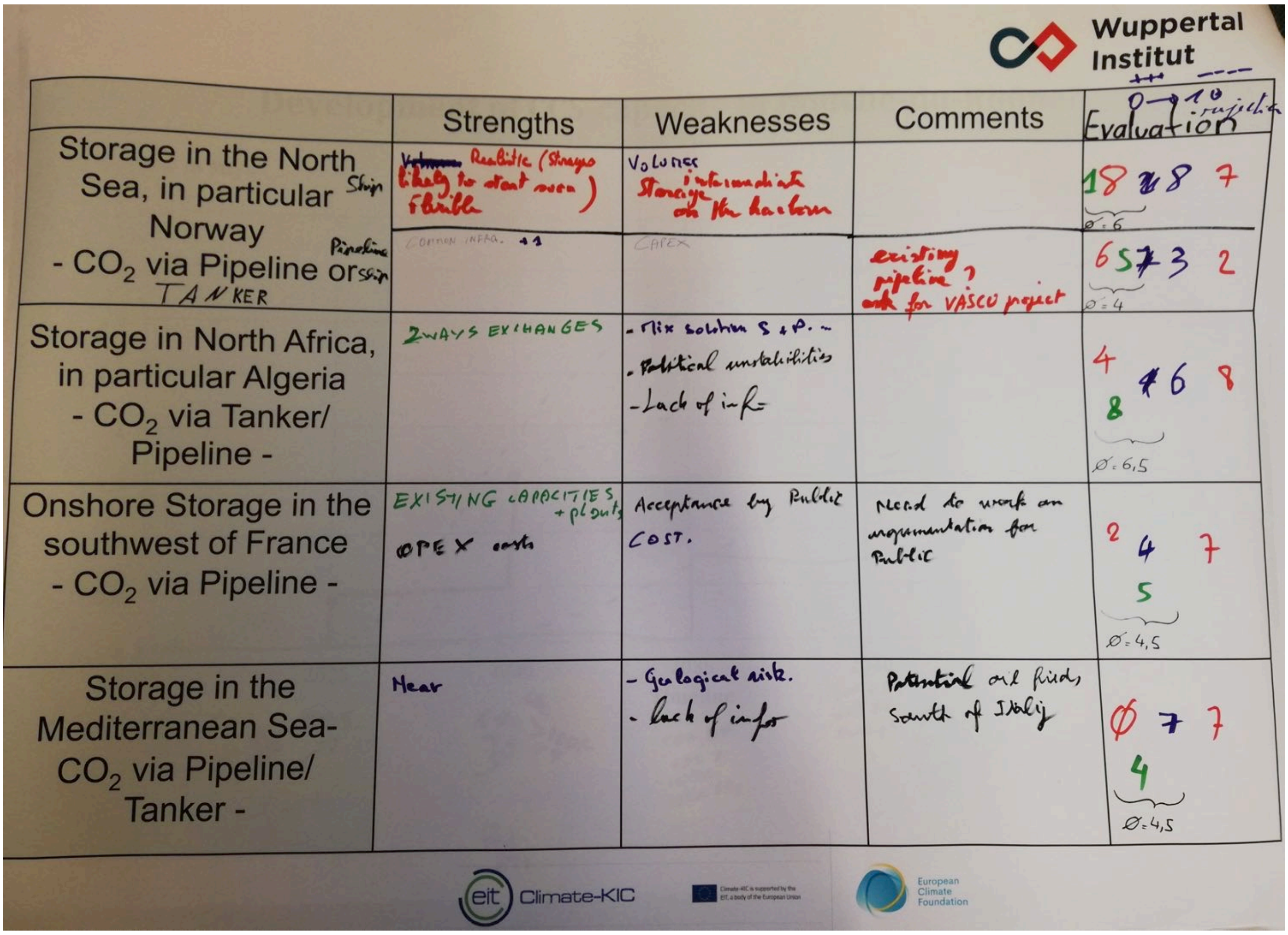


Figure 32: Strengths and weaknesses of the presented storylines (results)

Source: own photograph

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8 Appendix

8.1 Workshop agenda

Time	Duration	TOP		
09:30	00:30	Arrival, registration and welcome coffee		
10:00	00:15	**Welcome, short team introduction and overview of WS-schedule**		
10:15	00:10	Background Information (from general context to ME-scenarios and Infra Needs Project)		
10:30	00:20	Decarbonisation results for the hot spot region "Bouchon-du-Rhône" as common basis for WS sessions		
11:10	00:05	Distribution to 3 sessions		
11:15	00:15	Coffee break		
11:30		**Start Session P&H: Infra Needs for Power System and H2**		**Start Session C: Infra Needs for CCS**
11:30	00:15	Impulse lecture about Power and H2 demand…		Impulse lecture CCS…
11:45	00:15	Introduction into WS tasks		Introduction into WS tasks
12:00	01:00	WS-Part P&H1		WS-Part C1
13:00	01:00	**Lunch**		
14:00	00:10	short refresh and new distribution to 3 Sessions		
14:10	00:15	Introduction into WS-Part P2	Introduction into WS-Part H2	Introduction into WS-Part C2
14:25	01:00	WS-Part P2	WS-Part H2	WS-Part C2
15:25	00:20	P2-Resume	H2-Resume	C2-Resume
15:45	00:15	Coffee break		
16:00	00:30	Wrap-up of the day and outlook		
16:30		**Farewell**		