Deliverable 4.3 | Jan. 2020

Infrastructure needs of an EU industrial transformation towards deep decarbonisation

Workshop report for the region of Southern-Poland

Summary of the relevant background information, infrastructure storylines and their discussion at the workshop held on 7 Nov. 2019 in Katowice

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With support of Simon Heck and Philipp Hammelmann

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Climate-KIC

Climate-KIC is supported by the EIT, a body of the European Union

European Climate Foundation

Wuppertal Institut

This report is a result of the research project „Infrastructure needs of an EU industrial transformation towards deep decarbonisation“ and is funded by EIT Climate-KIC.
Task ID: TC_2.11.1_190229_P259-1B

The responsibility for the content of this publication lies with the authors.

Please quote the report as follows:
Wuppertal Institut / ECF (2020): „Workshop report for the region of Southern-Poland (Deliverable 4.3) – Infrastructure needs of an EU industrial transformation towards deep decarbonisation, research project funded by EIT Climate-KIC. Task ID: TC_2.11.1_190229_P259-1B, January 2020

Project duration: Jan– Dec 2019

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Imprint

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Date of report: January 2020

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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-Poland 2050, as presented and discussed at the regional workshop held on 7 Nov 2019 in Katowice (see Appendix).

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 (ENTSO-E, 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/

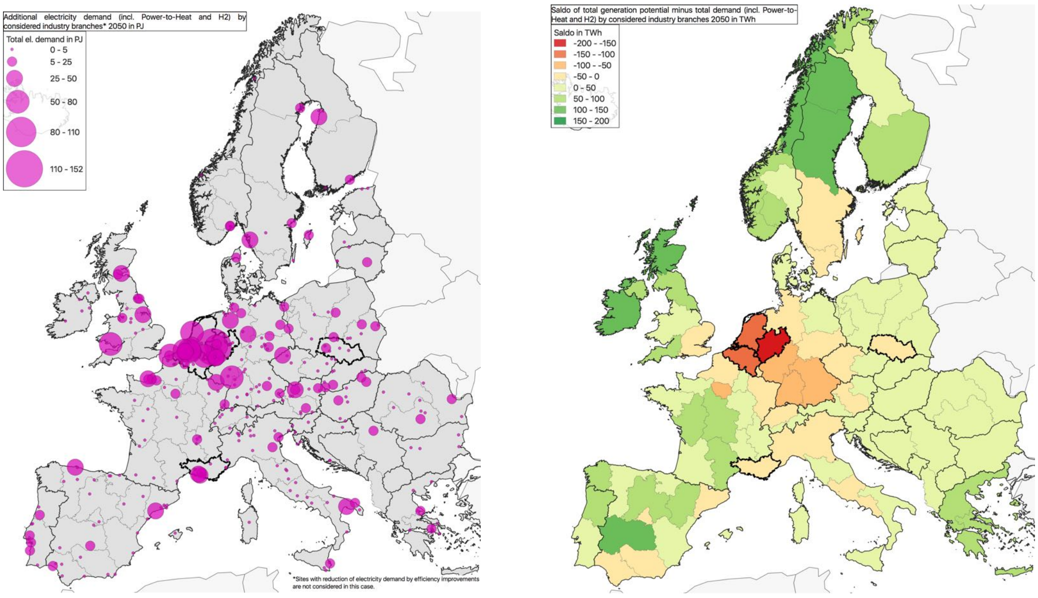

Figure 1: Regional distribution of electricity demand 2050 of three decarbonised core industries (left) and resulting electricity balances by considering electrifiation of other sectors

Soruce: own graphs based on own calculations and on (Material Economics, 2019), (ENTSO-E, 2014)

According to the scenarios developed in the study “Industrial Transformation 2050” (ENTSO-E, 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 3). 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.

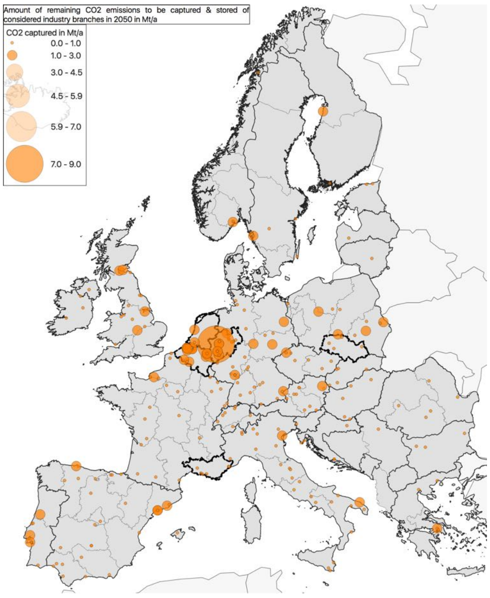

Figure 2: Remaining CO2 emissions from considered industry branches that need to be adressed by CCS in Mt/a from 2050 onwards

Source: own graph 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 4 (Wuppertal Institut & ECF, 2020c))
- Southern France - as a proxy for the Mediterranean Region (see deliverable WS 2 (Wuppertal Institut & ECF, 2020b))
- Southern Poland - as a proxy for central European industrial regions (focus of this deliverable)

The region Southern Poland (Silesia) covers the most industrialised and urbanised region in Poland, where the Upper Silesia region is the last remaining coal and steel region within the EU, where coking coal is mined and processed at several sites through the blast furnace steel route. Achieving climate neutrality in steel production is therefore a major challenge for the region.

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 3 below. Chapter 2 and 5 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

[2] North Rhine-Westphalia

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 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.

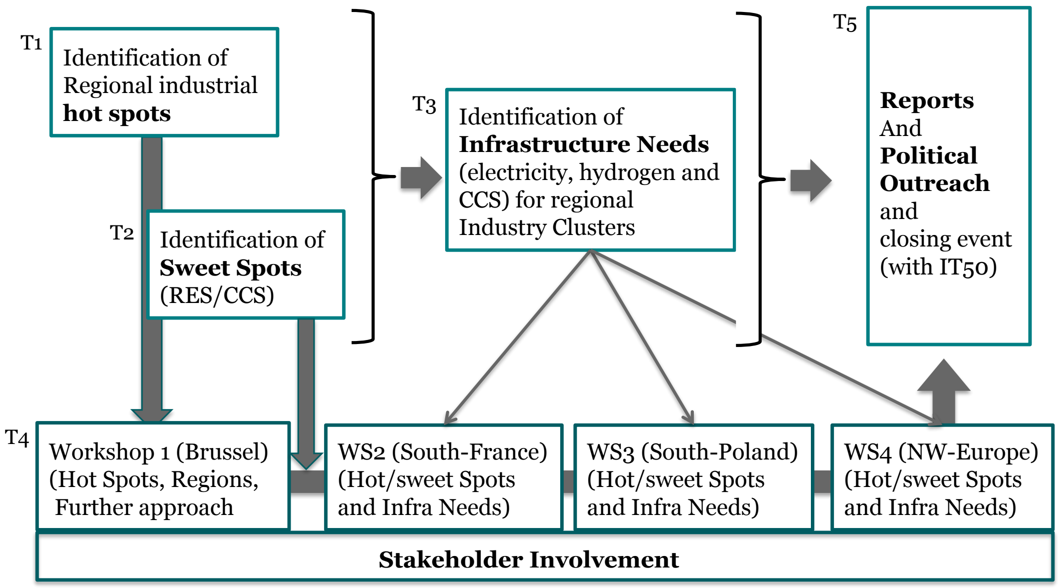

Figure 3: Structure of the study Infrastructure Needs

Source: own graph

The own analyses are mainly built on the following two studies and their data (cf. chapter 2.1 and 2.2), 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" (ENTSO-E, 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.

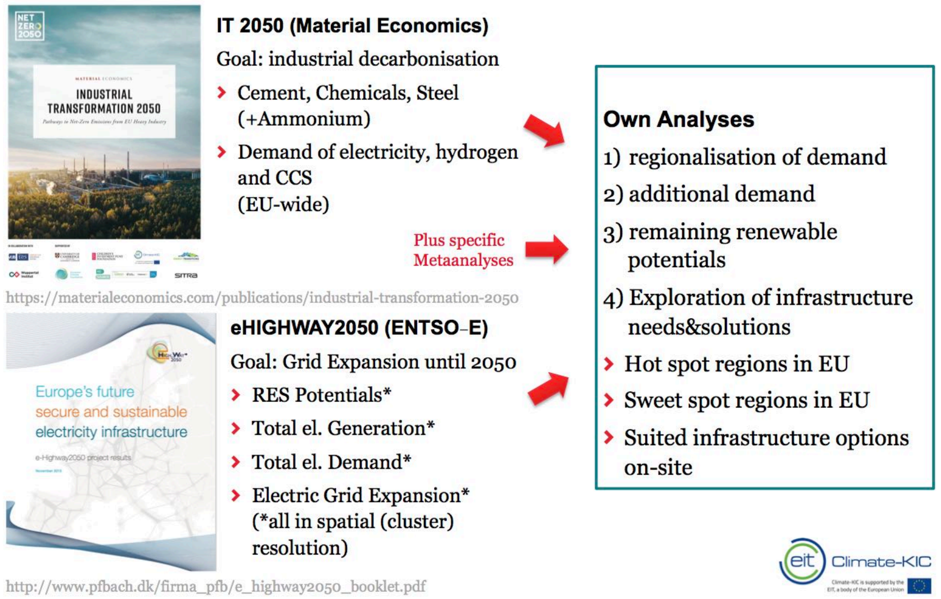

Figure 4: Reference scenarios used for own analyses

Source: own graph with front pages from (Material Economics, 2019; ENTSO-E, 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.

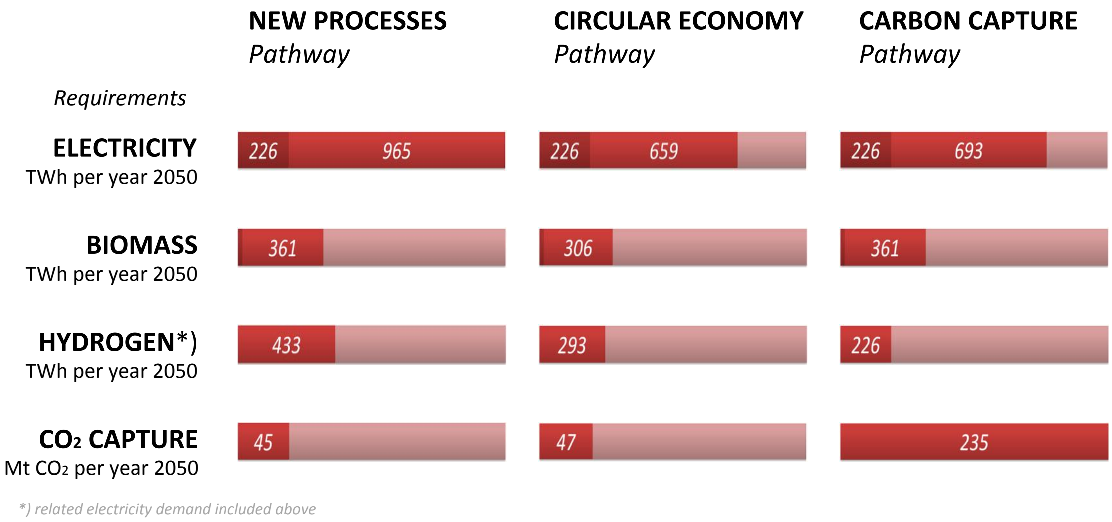

Figure 5: Energy Requirements in the three scenarios by Material Economics

Source: own illustration 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).

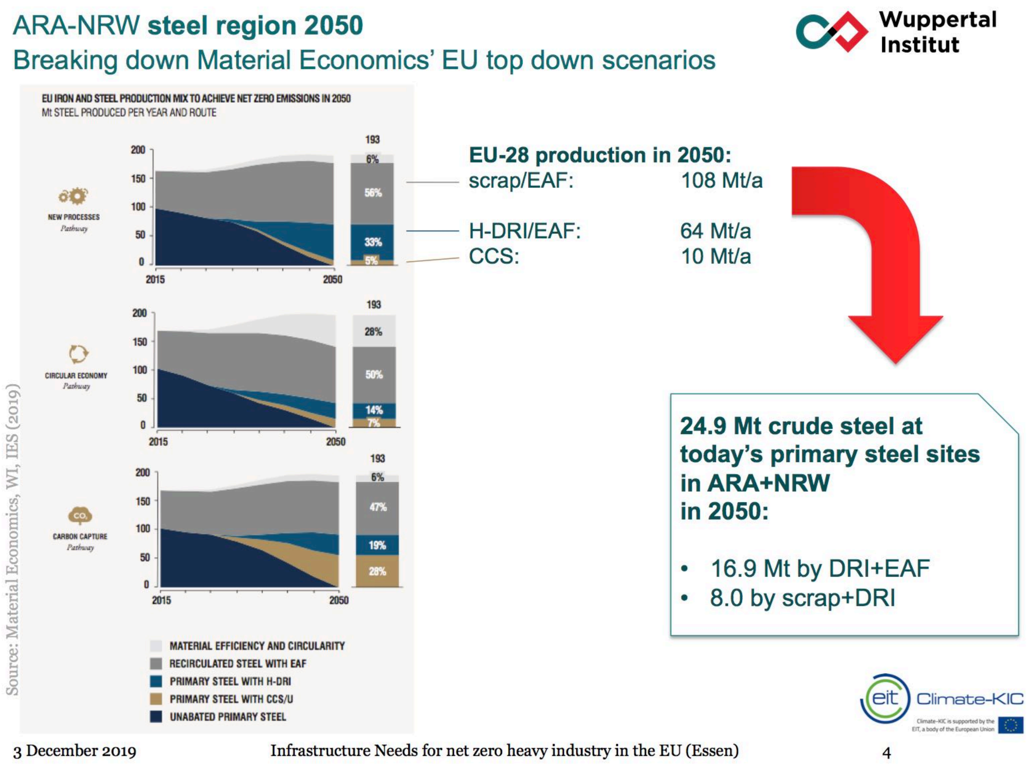

Figure 6: (Exemplary) scheme for breaking down the aggregated consumption values to industrial values according to strategies after (Material Economics, 2019)

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 (ENTSO-E, 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 (ENTSO-E, 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.

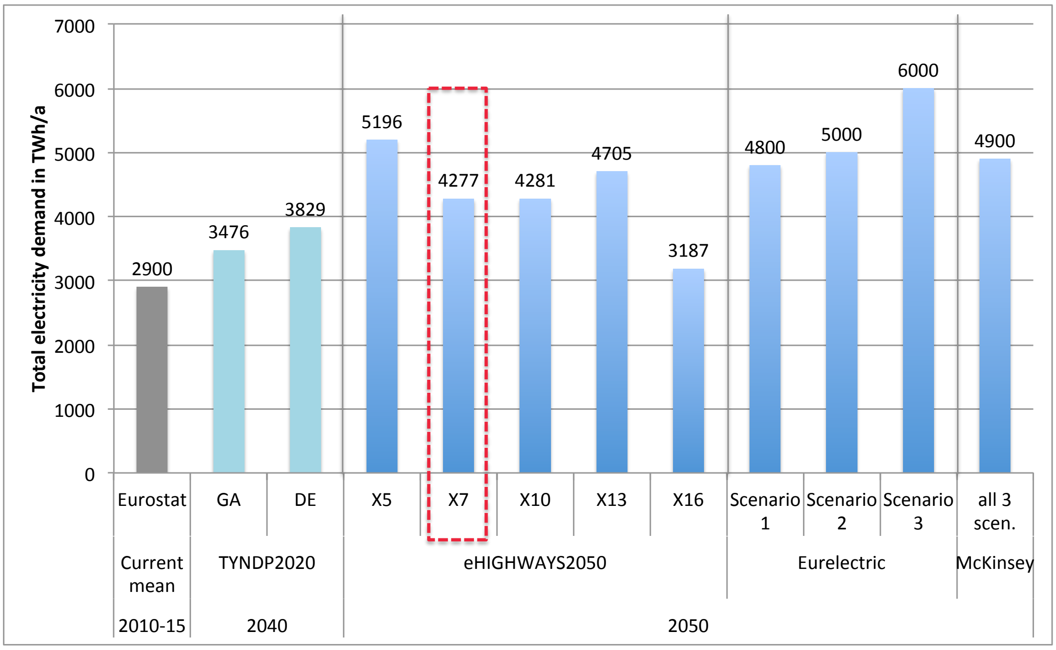

Figure 7: Total electricity demand of scenario X7 (red dotted rectangle) compared to today and to other scenarios

Source: own graph based on (ENTSO-E, 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 (ENTSO-E, 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} (ENTSO-E, 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.

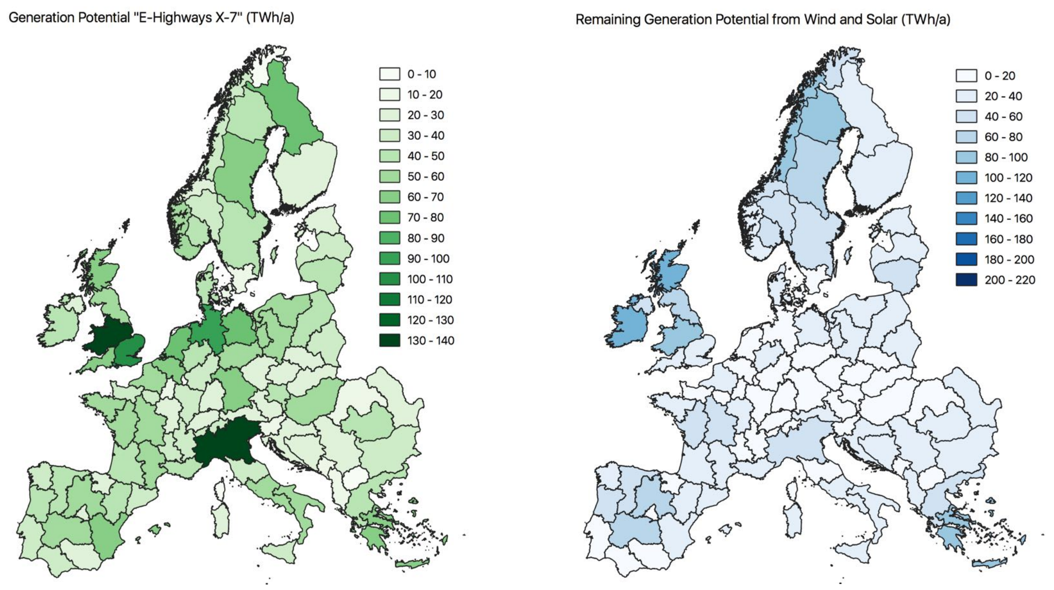

Figure 8: Yearly renewable generation potential in reference scenario X7 (left side); remaining technical wind and solar potentials after supply of conventional electricity demand 2050 (right side)

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.

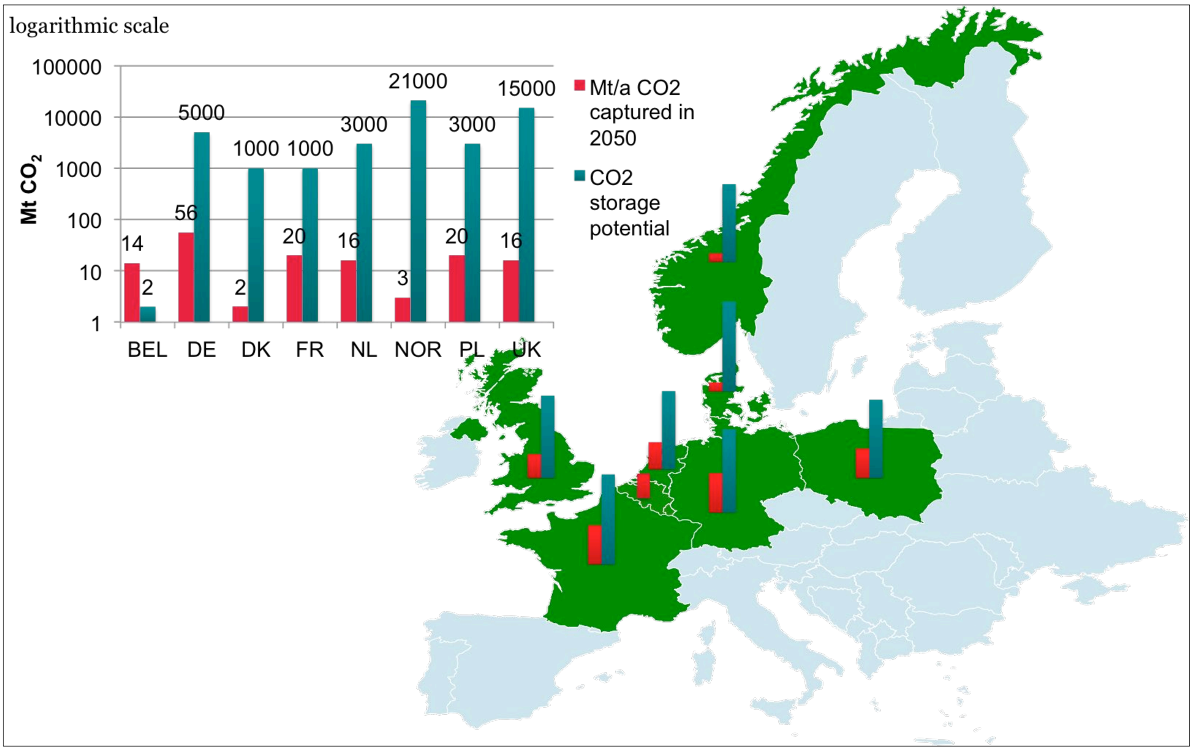

Figure 9: Storage demands and aggregated effective potentials according to Carbon Capture scenario

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.

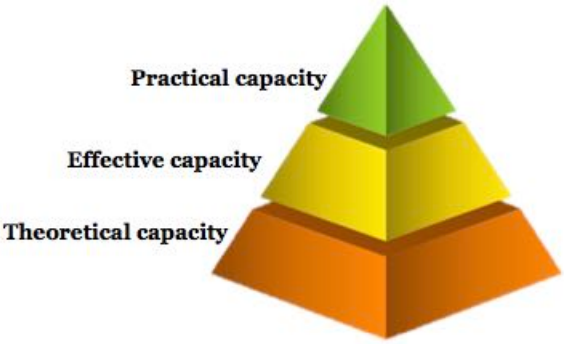

Figure 10: Capacity definitions for CO_2 storage in the literature, of which only effective storage capacities are used in this analysis in order to ensure realistic assumptions

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 4-5) 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.

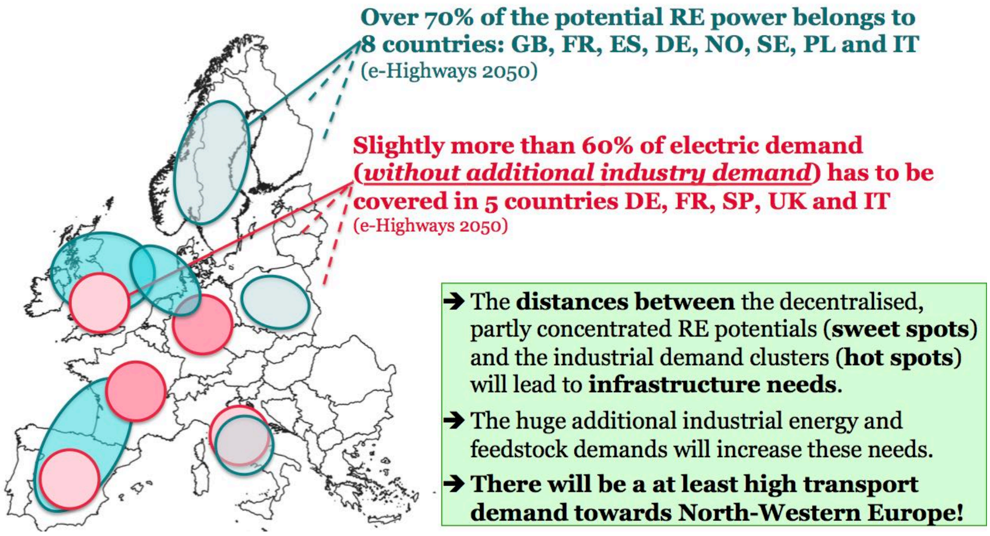

Figure 11: Overview of the major locations of renewable electricity potentials and electricity demand by European countries

Source: own graph based on information 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 4-5).

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 21 and Figure 25).

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 21).

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. Figure 25).

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	00:10	**Welcome, short introduction and overview of WS-schedule**	
10:10	00:10	Overview over the study "Industrial Transformation 2050"* and the on-going project "Infra Needs"**	
10:20	00:20	Industrial decarbonisation options for the **hot spot region "Silesia"**	
10:40	00:15	Transisition of the (regional) industry sector from the Polish perspective	
10:55	00:45	Discussion of decarbonisation options and impacts	
11:40	00:05	Distribution to 2 sessions	
11:45	00:15	Coffee break	
12:00		Session 1: Infra Needs for Power and H2/Gas Systems	Session 2: Infra Needs for CCS
12:00	00:15	Impulse lecture (overview over options and their characteristics)	Impulse lecture CCS
12:15	00:45	Discussion of the pro/strenghts and cons/weaknesses of Infrastrastructure solutions	Discussion of the pro/strenghts and cons/weaknesses of Infrastrastructure solutions
13:00			
13:00	01:00	**Lunch**	
14:00	00:30	Session 1: Follow-up Power and H2/Gas	Session 2: Follow-Up CCS
14:30	00:30	Resume of both Sessions	
15:00	00:15	Coffee break	
15:15	00:30	Wrap-up of the day and outlook	
15:45		**Farewell**	

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

[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 2050

The core of heavy industry in the region of Southern Poland is around the Upper Silesian coal basin. This is the EU's only remaining region where coking coal is mined. Coking coal is the crucial resource for the production of primary steel in the conventional blast furnace/basic oxygen furnace route. For this reason the original hypothesis for the region was that the conversion process to hydrogen based DRI and processing in an electric arc furnace could take more time here.

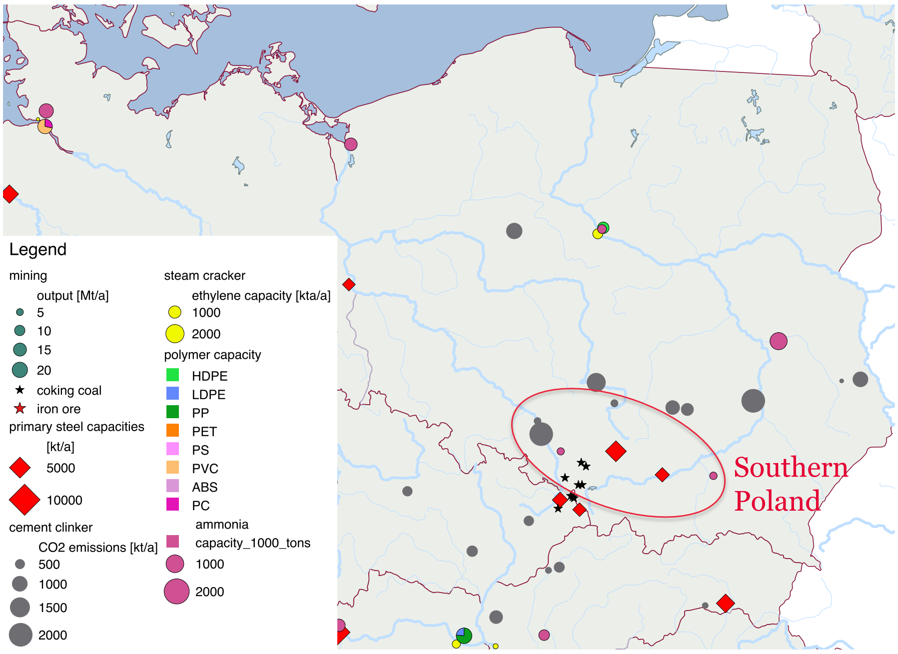

Figure 13: Map of heavy industry production capacities in Poland and the neighbouring regions

Source: own map

In order to achieve climate neutrality CCS has to be used instead. The "New Processes" scenario in the study of Material Economics (2019) is clearly focused on technologies other than CCS but still leaves space for some share of CCS to be used in 2050. Deviating from the methodology used for the other technologies and sectors where we assumed an equal technology mix at each site, we assumed for steel that CCS would be mainly used in Poland, the Czech Republic and Slovakia. This is due to the coking coal resources nearby and the scepticism towards natural gas imports in these countries, which would be required in a transition phase as reducing agent in the DRI plants.

The respective results are shown in the following figures.

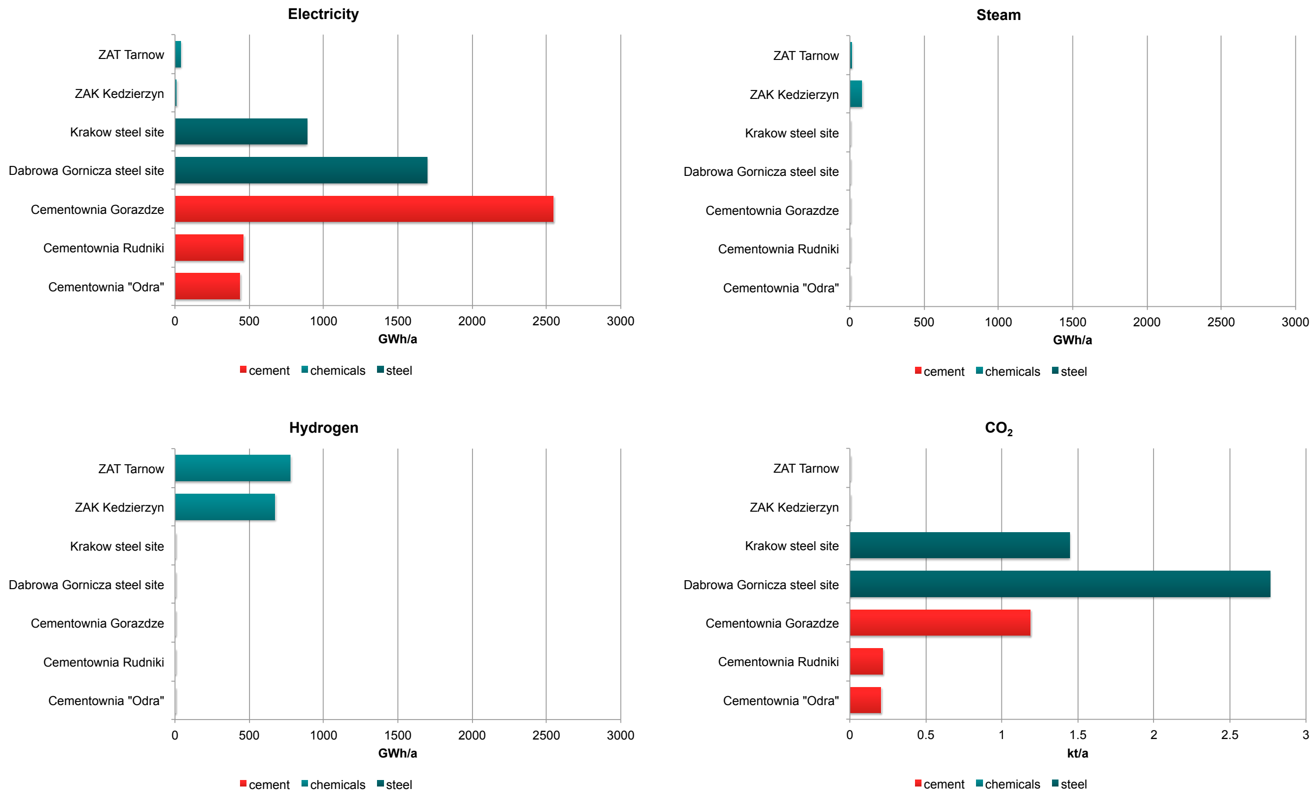

Figure 14: Electricity, steam, hydrogen and carbon capture requirements in the hot spot region of Southern Poland by sites

Source: own illustration

Total electricity demand by new applications amounts to 6 TWh in the region. Steam and hydrogen use are much smaller and are limited to the two ammonia plants in the region. The CO_2 volume to be collected from five different sites is 5.8 Mt/a, with two big sources in the steel industry, one big cement plant and two smaller ones. One of the two smaller cement plants is very close to the bigger one (Cementownia Gorazdze), the other smaller one is located further North and quite remote from the other sources.

The "CCS-first assumption" was challenged during the stakeholder workshop (see below). It has thus to be stated that hydrogen demands could be considerably higher in the region and CO_2 volumes to be stored could be lower respectively (1.6 Mt/a compared to 5.8 Mt/a).

4 Storylines for electricity and hydrogen infrastructure solutions

Preliminary note: In this analysis, it is necessary to use spatial clusters that have been derived in (e-Highway 2050, 2014). These clusters do not necessarily refer to administrative regions, so that it is not possible to conduct these analyses for Silesia. The cluster examined here is 43_PL (see Figure 15). This includes the voivodships Silesia, Opole and Lesser Poland. Therefore, in this section the term “Southern Poland” is used to describe the considered region.

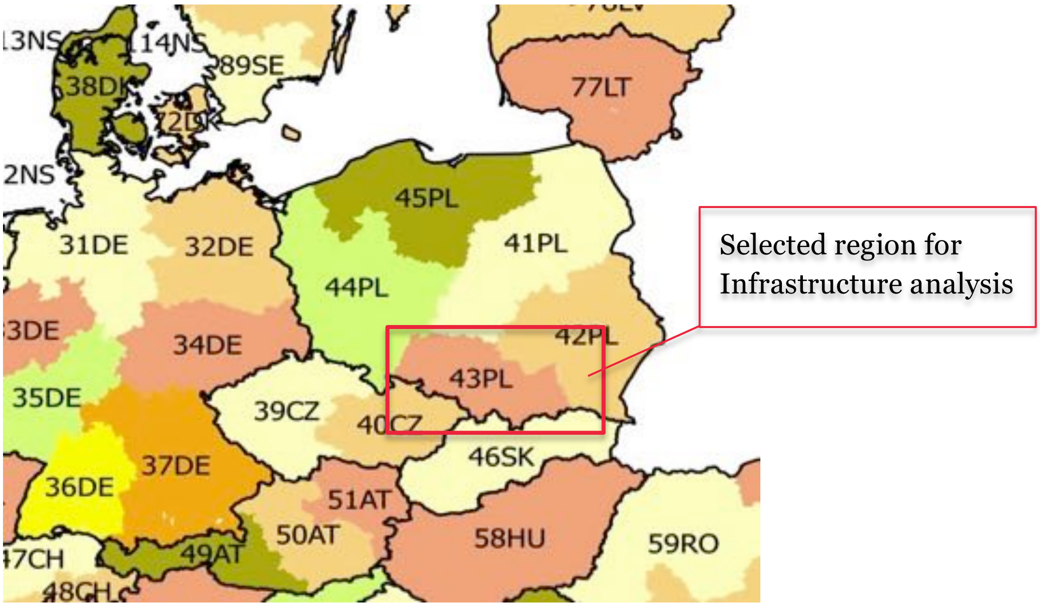

Figure 15: Cluster regions in (e-Highway 2050, 2014)

Source: (e-Highway 2050, 2014)

In Southern Poland, there is an expected additional electricity demand for decarbonised industry of about 4 TWh and a hydrogen demand of 1.4 TWh. These numbers result from analyses based on the scenario “new processes” (Material Economics, 2019), which is the scenario with the highest additional demands and therefore depicts the greatest challenge towards electricity and hydrogen infrastructures. The hydrogen demand results from ammonia industry, the additional electricity demands arise from cement (83 %), steel (13 %) and ammonia (5 %). Figure 16 shows the spatial distribution of the additional demands.

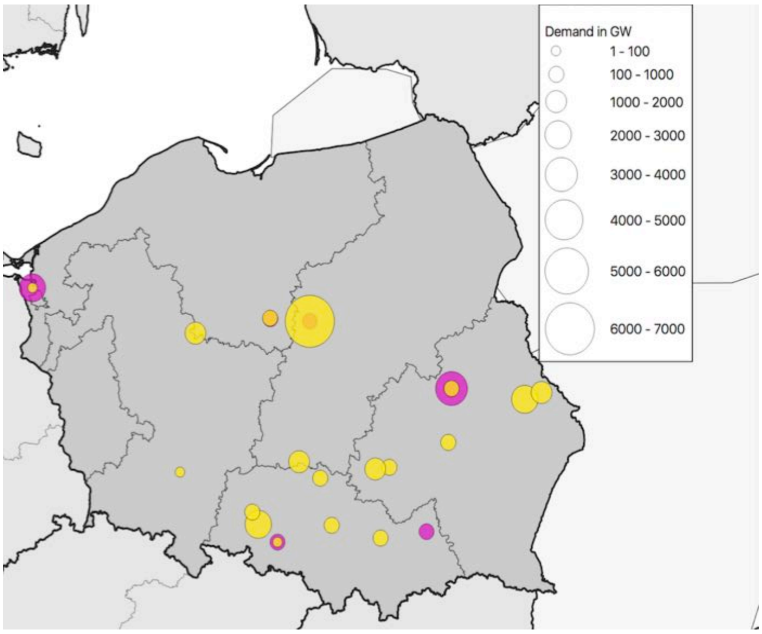

Figure 16: additional electricity and hydrogen demands for decarbonised industry in Poland in 2050

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

There are three main different storylines for the electricity and hydrogen infrastructures to supply the additional demands in Southern Poland that can be distinguished:

- Storyline A: local generation
- Storyline B: import electricity into the region
- Storyline C: import electricity and hydrogen into the region

4.1 Storyline A: local generation

One strategy could be to focus on local sources of energy. In the underlying scenario “100%RES” of (e-Highway 2050, 2014) which does not take into account the additional electricity demands for decarbonised industry, not all renewable generation potential in Southern Poland is exploited (see Figure 17): there is a remaining potential of about 11 TWh generation from wind and solar. That compares with additional generation demand of 6 TWh. 6 TWh is the sum of 4 TWh for direct electricity and steam appliances as well as 2 TWh electricity for hydrogen production at an efficiency of 75 %. So local potentials can suffice to cover the additional demands for decarbonised industry. An electrolysers’ capacity of 240 MW would be needed if the hydrogen is to be produced at nearly baseload (8,000 full load hours). The capacity would need to be higher, if that hydrogen is to be produced more flexibly.

When evaluating this infrastructure option, one needs to take into account that the region is a net consumer in the underlying scenario.

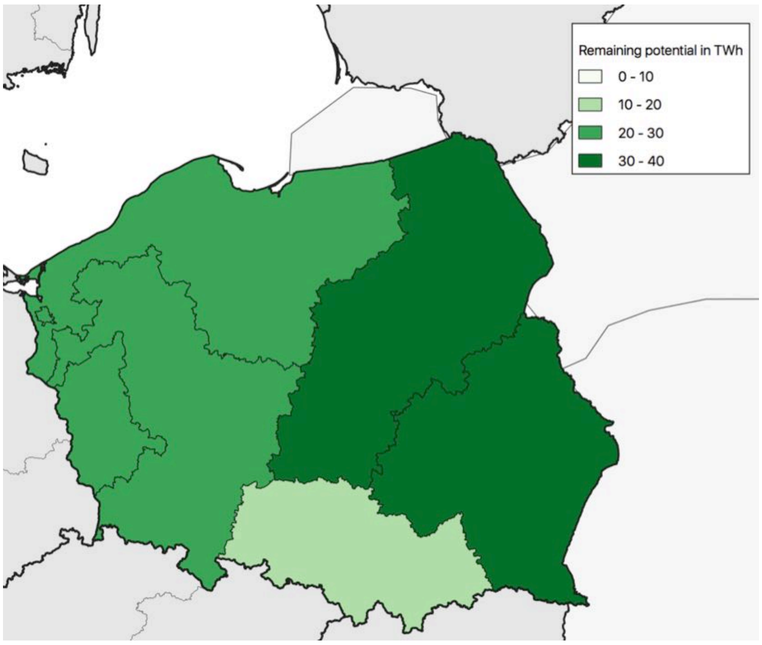

Figure 17: Remaining potential in Polish clusters according to (e-Highway 2050, 2014)

Source: own graph after (e-Highway 2050, 2014)

4.2 Storyline B: import electricity

Bearing in mind that the region of Southern Poland is expected to be a net importer in 2050 in (e-Highway 2050, 2014), another supply strategy is to import electricity from suited national sources to supply the electricity and hydrogen demand for decarbonised industry. Figure 18 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”, additional electricity demand and electricity for hydrogen). Regions coloured green are regions where the electricity generation potential is higher than the demand, red is indicating a higher demand than generation potentials.

This shows that the overall generation potentials in Southern Poland do not suffice to cover the overall demand in that region, but that the region is neighbouring areas which have a surplus of electricity production potential. From these regions, electricity could be transported to Southern Poland. To transport the necessary 6 TWh per year, a transmission capacity of 746 MW is required (at 8,000 full load hours). 2 TWh of that electricity can then be converted into 1.2 TWh hydrogen using electrolysers with an assumed efficiency of 75%.

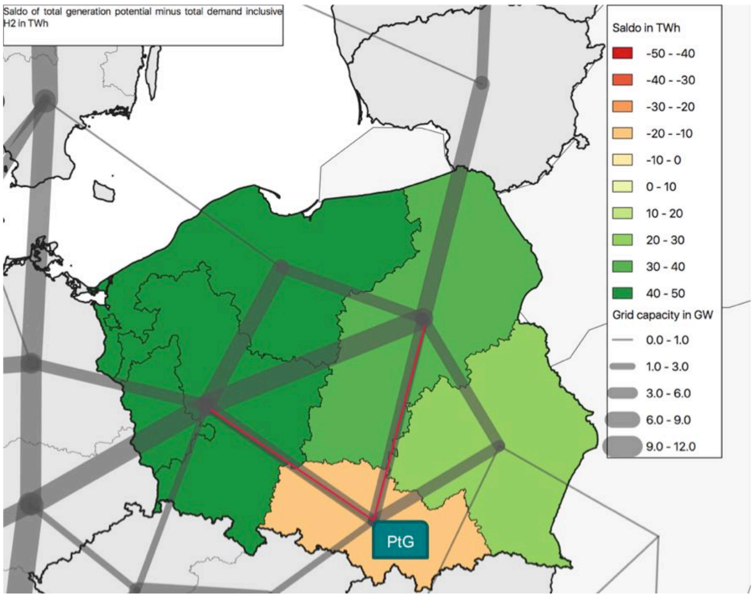

Figure 18: Balance of generation potential and demand including electricity for hydrogen

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

4.3 Storyline C: import electricity and hydrogen

Instead of converting electricity to hydrogen in the region, it could also be possible to import hydrogen directly. In that case, transmission capacity for additional electricity demands would be 460 MW (instead of 746 MW in storyline B).

For the transport of hydrogen into the region, there could either be new hydrogen pipelines, or the existing natural gas grid could be partly repurposed. In Figure 19 it can be observed that industrial hydrogen demands are located near large gas transport capacities and that there is a strong gas infrastructure from north-western to south-eastern Poland.

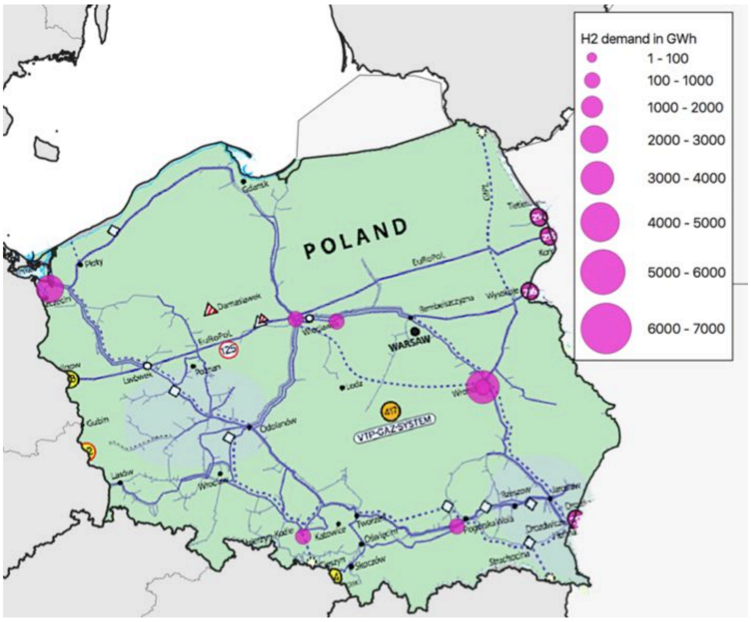

Figure 19: Hydrogen demand at sites 2050 and today's natural gas grid in Poland

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

To cover the hydrogen demand in Southern Poland, a transport capacity of 1.4 TWh/a (5 t/h) would be necessary. That translates to a pipeline diameter of 120 mm[6]. To additionally cover the hydrogen demand in Puławy, a pipeline of 220 mm would be necessary.

The hydrogen could either be produced in Poland's north east, which has the advantages of a high potential for renewable electricity generation (especially from wind), and a strong gas grid connection. A second possibility is to import hydrogen from international sources. As Figure 20 shows, there are possible excesses in Scandinavia, whereas most of central Europe is a deficit region that would need to rely on imports. The border region between Poland and Germany could be an access point of Scandinavian hydrogen (e.g. todays natural gas grid access point in Świnoujście), from where on the Polish hydrogen demands could be supplied. That would require an access and transport capacity of 8.2 TWh/a (28 t/h), which translates to a necessary pipeline diameter of 280 mm to fully supply the hydrogen demand for decarbonised industry in Poland.

[6] Assumptions: pipeline pressure 100 bar, velocity 10 m/s

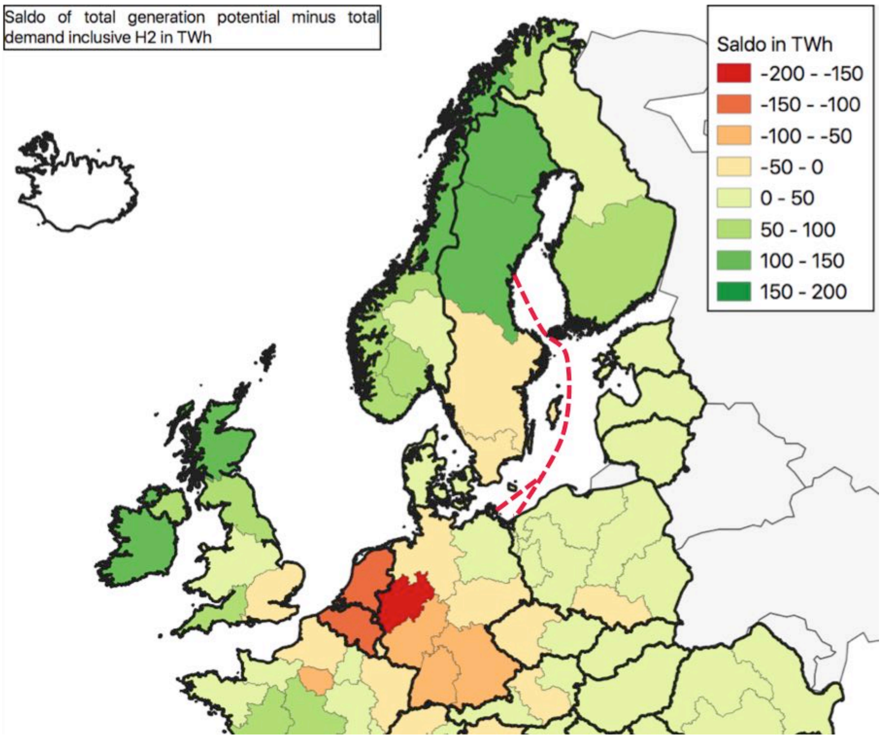

Figure 20: Balance of generation potential and demand including electricity for hydrogen and possible hydrogen transport infrastructure

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

4.4 Evaluation of storylines

In the workshop on hydrogen and electricity infrastructures, the strengths and weaknesses of the storylines have been discussed. Figure 21 shows the resulting matrix.

One very important point in the discussion was the challenge the Silesian region is currently facing. Therefore, local added value is of high relevance, which could help enabling a fair transition in the region. Also assets from coal mining, such as infrastructure for and knowledge about energy issues are seen as advantageous. Import dependencies are seen critically, regional potentials should be exploited instead. It was mentioned that wind energy is facing acceptance issues across Poland. There also were general remarks towards alternative sources of hydrogen (coal, nuclear electricity) which could be used during the transition to a renewable energy system.

The participants were asked to valuate the alternative infrastructure storylines. The preference for local solutions is mirrored in this evaluation: Storyline A (local) scores 1.7 resistance points, B (import electricity) scores 4 and both variants of storyline C (import electricity and H_2) score more than 7 resistance points, where 0 can be regarded as full agreement and 10 as full rejection.

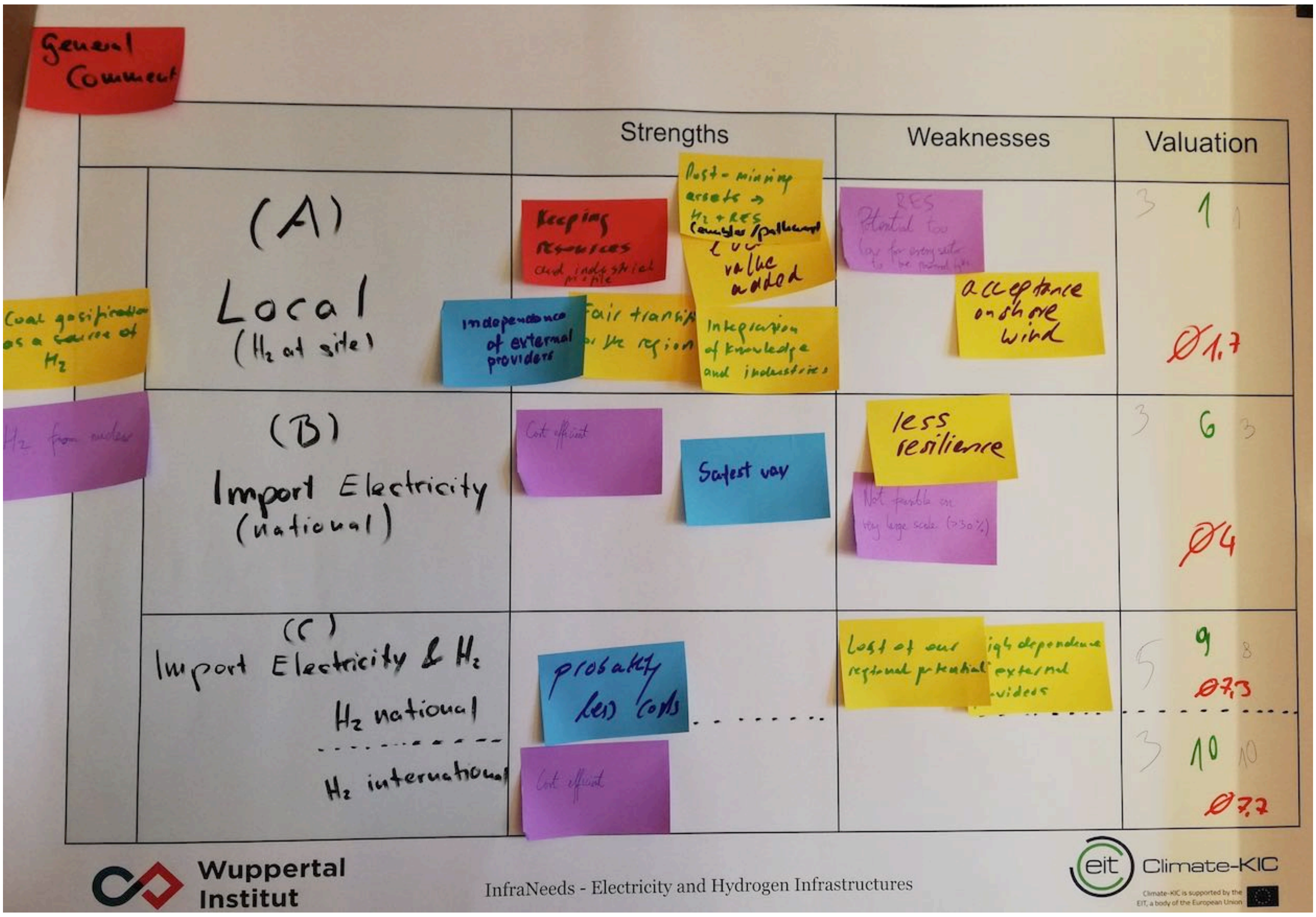

Figure 21: Workshop results – strengths and weaknesses of electricity and hydrogen storylines

5 Source: own photographStorylines for CCS infrastructure solutions and results

The CCS section is based on the “carbon capture” scenario (Material Economics, 2019), as this is where, in comparison to the other two scenarios, the largest installed carbon capture capacity is found and thus best illustrates the challenges in terms of capacities and CO_2 transport infrastructure. In this scenario, European heavy industry avoids 235 Mt of its total 545 Mt in the target year 2050 by CCS. Of this, southern Poland’s industries (steel, cement, basic chemicals) account for 9.2 Mt CO_2 captured annually from 2050 onwards.

The storage situation in the region around southern Poland is significantly better than in the previous focus region (Marseille), although it is far from optimal. Poland has exhausted gas fields and aquifers both on land and at sea, while the deep-sea ports of Szczecin and Gdansk offer the possibility of national CO_2 hubs in order to reach international storage sites. However, each of these options involves considerable transport costs and places specific demands on the associated infrastructure. Therefore, three different storylines were derived, which serve as a basis for the subsequent discussion:

- international strategy – offshore storage in the North Sea, particularly Norway,
- national strategy – offshore storage in the Baltic Sea,
- national strategy – onshore storage in Poland.

All three options are briefly introduced below. Afterwards, the interactive workshop part is presented.

5.1 Storyline 1: international strategy – offshore storage in the North Sea, particularly Norway

The first storyline consists of the intention to store the captured CO_2 in the North Sea (mainly in Norway), as there are large and relatively well known storage potentials. The Utsira Formation alone has an effective potential of 1000 Mt, enough to store today’s industrial emissions from southern Poland for 100 years (if only these emissions were stored). In total, Norway has about 21 000 Mt effective storage potential. Furthermore, Norway pursues an active pull strategy with regard to CCS.

In this scenario, the captured CO_2 from southern Poland is fed into a pipeline which will run for about 500 km to Szczecin. Szczecin with its overseas port acts as a national CCS hub, where the CO_2 is buffered and pumped onto ships. From there it would take about 1500 km (oneway) to the Norwegian offshore reservoirs (see Figure 22).

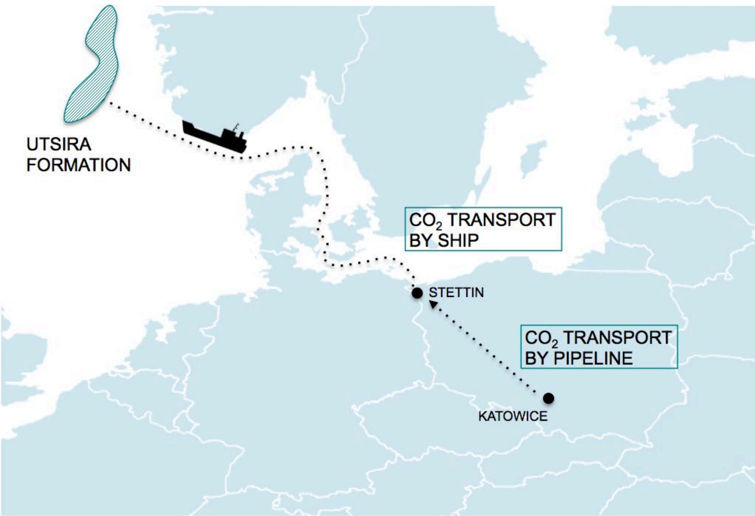

Figure 22: international strategy – offshore storage in the North Sea, particularly in Norway (e.g. Utsira)

Source: own graph

5.2 Storyline 2: national strategy – offshore storage in the Baltic Sea

The second storyline only includes Polish offshore storage facilities, as this allows greater independence and shorter transport routes. However, the Polish offshore storage facilities in the Baltic Sea are not as well researched and documented as the Norwegian storage formations. As in the international strategy, a pipeline about 500 km long would lead from southern Poland to the Baltic Sea. However in this case, Gdansk would serve as the target and CO_2 hub and not Szczecin (see Figure 23). From Gdansk, it is only 200 - 300 km to the Polish aquifer, which, according to current knowledge, has an effective storage potential of about 860 Mt. Under these conditions, industrial emissions from southern Poland could be stored for up to 90 years. Nevertheless, further research efforts would first have to be undertaken.

Figure 23: national strategy – offshore storage in the Polish Baltic Sea

Source: own graph

5.3 Storyline 3: national strategy – onshore storage in Poland

The last storyline is the onshore storage of CO_2 in Poland, which would mean significantly less infrastructure or transport effort and thus lower costs. Starting from Katowice, there are various storage options. On the one hand there are several hydrocarbon fields in the southeast and southwest of Poland. Their cumulated effective storage capacity is between 700 and 1 000 Mt. Secondly, there are two large aquifers with good conditions in Poland. The larger of the two structures (650 Mt) is located near Poznan (about 350 km from Katowice). The second slightly smaller aquifer (about 230 Mt) is located near Belchatow about 150 km from Katowice. Other aquifers are distributed all over Poland, but capacity and suitability are very uncertain. In principle, hydrocarbon fields are preferable to aquifers for various reasons (e.g. more resilient storage capacity or lower leakage risk, see section 2.3).

However, for both types of storage facilities, the social acceptance in Poland, as in other countries (e.g. Germany), for injecting CO_2 on land is quite low.

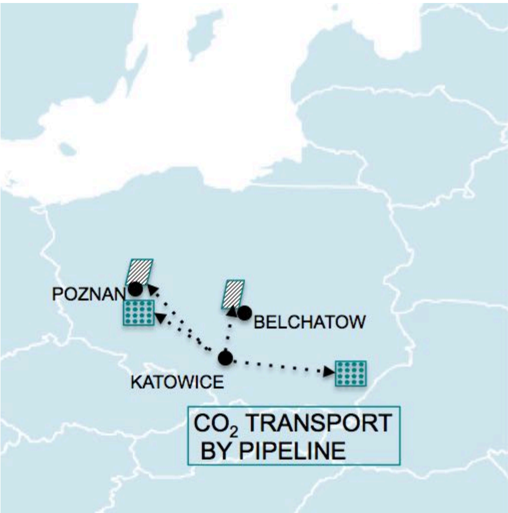

Figure 24: national strategy – onshore storage in Poland (hydrocarbon fields and Aquifers)

5.4 Source: own graphInteractive: strengths, weaknesses and evaluation

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 storylines and strategies from their point of view and to record them in a prepared matrix (see Figure 25). Furthermore it was possible to enter comments for each storyline in a third column. In addition, one participant suggested an „option D" as a fourth storage option (solid storage of CO_2 in Na_2CO_3), the strengths and weaknesses of which were also discussed (see Figure 25).

In general, the costs of CO_2 transport are seen as a dominating aspect. The international strategy (storyline 1) with the longest distance and the use of two transport systems (pipeline and maritime shipping) is seen as the most expensive option. In comparison to national offshore storage in the Polish Baltic Sea (storyline 2), the aspect of the depth of the sea is also mentioned. Thus, the storage development and implementation of the projects in the Baltic Sea is considered to be cheaper than in the North Sea. The national onshore storage strategy (storyline 3) would be the most appropriate from an economic point of view.

However, the participants see social acceptance as a strong barrier („Not-In-My-Backyard“ attitude), especially for onshore storage. They also see competition for use in the national offshore strategy, as the Baltic Sea in particular is also used for other activities/projects and might be utilized even more in the future (e.g. expansion of wind energy and tourism). However, in the case of an increased expansion of wind energy, possible synergies are seen with a view to CO_2 storage in the Baltic Sea.

With consideration to the international strategy (storage in the North Sea), there were no concerns regarding acceptance. On the contrary, the existing projects, the European dimension and the cooperation with the petrochemical industry were positively emphasised. Nevertheless, the participants repeatedly expressed their concern that the use of CCS in the industry could be seen as a "keep-coal-alive initiative" and possibly be taken up by energy suppliers for their CCS plans.

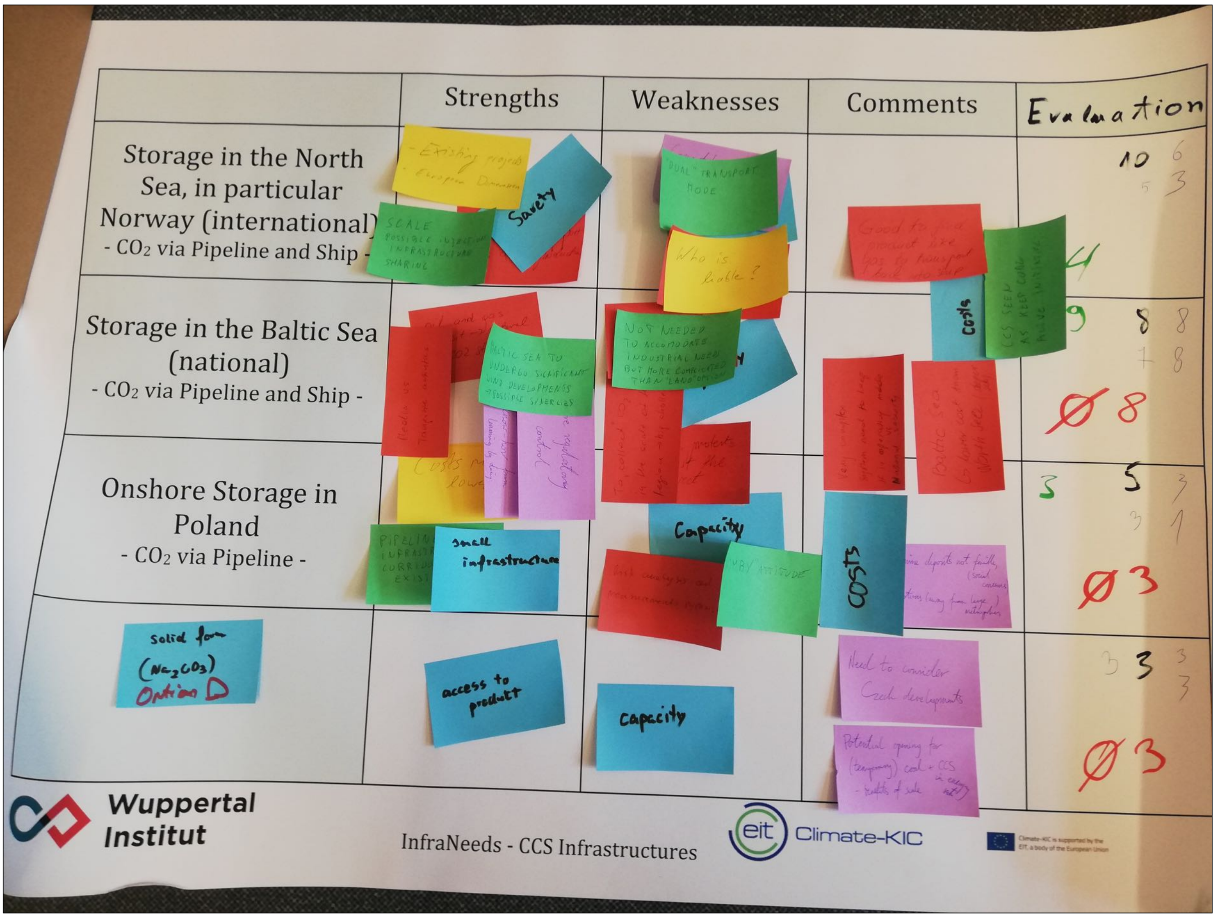

Figure 25: Strengths, weaknesses and evaluation of the three storylines + proposed “option D“ (solid storage in Na_2CO_3)

Source: own photograph

After discussing and noting down the strengths, weaknesses and comments, the participants were asked to evaluate the respective options. This was done in the form of rejection points on a scale of 0 - 10, i.e. a high score for a storyline is equivalent to a high level of disapproval. The aim of the task was to identify the storyline with the lowest rejection among the participants. Interestingly, the solid storage in Na_2CO_3 as well as the onshore storage in Poland have been evaluated with an average of 3.0 points, resulting in the lowest resistance among the participants. The highest resistance is found in national onshore storage in the Polish Baltic Sea (average 8.0 resistance points). The international storage strategy in Norway ranks in the middle of the survey with 5.6 resistance points.

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7 Appendix

7.1 Workshop agenda

Time	Duration	TOP	
09:30	00:30	Arrival, registration and welcome coffee	
10:00	00:10	**Welcome, short introduction and overview of WS-schedule**	
10:10	00:10	Overview over the study "Industrial Transformation 2050"* and the on-going project "Infra Needs"**	
10:20	00:20	Industrial decarbonisation options for the **hot spot region "Silesia"**	
10:40	00:15	Transisition of the (regional) industry sector from the Polish perspective	
10:55	00:45	Discussion of decarbonisation options and impacts	
11:40	00:05	Distribution to 2 sessions	
11:45	00:15	Coffee break	
12:00		Session 1: Infra Needs for Power and H2/Gas Systems	Session 2: Infra Needs for CCS
12:00	00:15	Impulse lecture (overview over options and their characteristics)	Impulse lecture CCS
12:15	00:45	Discussion of the pro/strenghts and cons/weaknesses of Infrastrastructure solutions	Discussion of the pro/strenghts and cons/weaknesses of Infrastrastructure solutions
13:00			
13:00	01:00	**Lunch**	
14:00	00:30	Session 1: Follow-up Power and H2/Gas	Session 2: Follow-Up CCS
14:30	00:30	Resume of both Sessions	
15:00	00:15	Coffee break	
15:15	00:30	Wrap-up of the day and outlook	
15:45		**Farewell**	