Co-funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 691797

Innovative large-scale energy storage technologies and Power-to-gas concepts after optimisation

D8.7

Report on data and methods used for the potential analysis of power-to-methane in Europe

Due Date	30 April 2019
Deliverable Number	D8.7
WP Number	WP8
Responsible	Johannes Schaffert, Gas- und Wärme-Institut Essen e.V. (GWI)
Author(s)	Schaffert, Johannes; Cigarida, Hristina; Lange, Manfred; Levedag, Dario; Coquette, Dominik
Reviewer	Hüttenrauch, Jens (DBI)
Status	Started / Draft / Consolidated / Review / Approved / Submitted **/ Accepted by the EC** / Rework

Dissemination level

✘	**PU**	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the Commission Services)
	CO	Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Author	Description
0.1	2018-09-26	JS, HC	Formatting, Editing Title (contact Coord.)
0.5	2019-01-11	JS, HC	Drafting
0.6	2019-02-07	JS, HC	Drafting
0.7	2019-02-19	HC, DC	Drafting
1.0	2019-02-21	JS	Internal Review
1.1	2019-02-28	HC, DC	Amendments
1.2	2019-03-05	JS, HC	Internal Review
1.4	2019-03-08	HC	Internal Review
1.5	2019-03-12	JS	Internal Review
1.6	2019-03-14	HC, DC	Amendments
1.7	2019-03-15	JS	Finalising consolidated version
2.0	2019-04-09	HC, JS	Final Version

Table of Contents

List of Figures

List of Tables

Abbreviations

BLG	Black-Liquor Gasification
CC	Carbon Capture
CH_4	Methane
CO_2	Carbon dioxide
EEA	European Environment Agency
E-PRTR	European Pollutant Release and Transfer Register
EU	European Union
GIS	Geographical Information System
H_2	Hydrogen
ISIC	International Standard Industrial Classification
LEILAC	Low Emissions Intensity Lime and Cement
NACE	Nomenclature des Activités Économiques dans la Communauté Européenne
NUTS	Nomenclature of territorial units for statistics
OSM	Open Street Map
PtG	Power-to-gas
PtM	Power-to-methane
PV	Photovoltaic
QGIS	Geographic-Information-System used for geographic analyses

Executive Summary

The energy conversion concept studied in STORE&GO [1] can be summarized in the following way. In a first conversion step, renewable electrical energy is used to produce hydrogen. This is done by dissociating water molecules within electrolyser stacks. The subsequent synthesis of methane is the second conversion step. It consumes carbon dioxide (CO_2) captured from flue gas streams or ambient air during a methanation process that delivers methane (CH_4) which serves as a green substitute for the natural gas demand in Europe. In the following, we will refer to the full process chain as power-to-gas (PtG) or power-to-methane (PtM).

The target of this report is to present the input data and the methods used for calculating the potential CO_2 that can be captured from the relevant industry sectors and biogas plants in Europe for large-scale PtG energy storage as well as the methods for locating the most suitable potential PtG locations[1]. The number of the industry plants within the considered industry sectors, their total emitted CO_2 amounts and their geographical distribution are also demonstrated. The potential locations for the PtG energy conversion plants are identified based on the geographical availability of wind energy and substation distribution, combined with the industrial and biological CO_2 sources. In this Deliverable D8.7 of the STORE&GO project [1], the focus is on the potential of coupling wind energy generation with CO_2 sources for the production of renewable gas along the PtG route. The corresponding potential using renewable electricity from photovoltaic plants (PV) will be analysed in a next step and published in the upcoming Deliverable D8.9. The geo-informational analysis and the preliminary results presented here show that almost 58 % of the analysed industrial plants as well as the same share of the biogas plants exhibit renewable electricity generation within their proximity (10 km radius) already today, unveiling the high potential for PtG across Europe. With an expected growth of bio-based energy generation, all states are presumed to show increasing potentials of biogas-based PtM energy conversion. This report step by step presents the methods for calculating the PtM potentials resulting from the conversion of captured CO_2. With an assumption of an average of 90 % CO_2 capturing rate implemented in the largest plants of five focused industry sectors, a total methane production potential in the order of up to 2 500 TWh/a is expected.

Minor modifications in the methods and the results as well as the corrections of datasets are reserved for the following Deliverable D8.9, which will include a PV potential analysis and the corresponding PtM potentials using biological CO_2 sources, the corresponding electricity demands for renewable gas production, an outlook on the future portfolio of CO_2 sources and a final assessment of results.

[1] Despite a high electricity demand, direct air capture of CO_2 is a promising technology that can be applied everywhere allowing the design of PtM-plants that do not rely on industrial or biomass infrastructures. Due to its location-independency, direct air capture is not within the scope of the GIS-study presented here.

1 Introduction

To ensure the success of an ecological transformation of the economy there must be substantial reductions in CO_2 emissions. However, certain industries will continue to produce CO_2 as inevitable by-products from their production processes (e.g. cement, glass) in addition to remaining energy related emissions. Therefore, CO_2 capture and reuse may be of great importance for the future. The energy intensive industries that are considered here will play a key role for a successful energy transition. Besides demand side management concepts and other flexibility options, Power-to-gas provides a large-scale solution building upon already existing infrastructures and taking advantages of possible synergy effects within the system [2]. Whenever there is a surplus energy production from a renewable energy sources, hydrogen may be produced as a clean gaseous energy carrier. Hydrogen may either be used directly on-site or be admixed into the natural gas grids or potential specific hydrogen infrastructures. Alternatively, using CO_2 as a second feedstock the renewable hydrogen may be converted into other versatile products such as methane, which is the main component of natural gas, or other hydrocarbons. The focus of the STORE&GO project is to study and demonstrate the production of synthetic methane. The potential of Power-to-methane is constrained by the availability of renewable electricity as well as the quality and quantity of available CO_2. [1]

1.1 Objective of this Deliverable

This Deliverable is part of work package 8, task 3 of the STORE&GO project and has the objective to describe the methods used to identify potentials of large scale renewable energy storage via PtG and methanation plants in Europe, including suitable locations.

By correlating reported European datasets on carbon dioxide emissions with geospatial data on renewable energy generation sites (in this case wind power) the theoretical regional potentials for methane production are evaluated. The potential available carbon dioxide for each country is calculated by industry sector, and subsequently the potential methane quantities are derived.

In a second step, potential storage and conversion sites for Power-to-methane plants using biological CO_2 sources are being tackled. For this part of the study, an extensive research of existing biogas plants across Europe has been conducted by literature and online research, as well as addressing associations, institutes and public authorities. The resulting data was included into a geo-information database that allows for correlation analyses with local wind energy production sites and substations of the electricity grids with the aim to investigate the suitability of local coupling of biogas and electricity infrastructures.
The overall theoretical potentials of converting CO_2 from biological sources into methane via the Power-to-gas approach are illustrated on a national level based on potentials from literature. Here, biogas as well as gasification were included in the work since both technology classes may lead to the availability of a notable green CO_2 feedstock in the future.

2 Input Data

2.1 CO_2 from industrial point sources

2.1.1 European Pollutant Release and Transfer Register (E-PRTR)

The European Pollutant Release and Transfer Register (E-PRTR, [3]) provides key environmental data from industrial facilities from 28 EU member states plus Liechtenstein, Norway, Switzerland, Iceland and Serbia (EU28+5), starting from the year 2007. The register contains annual data of more than 30 000 industrial facilities from 9 industrial sectors (subdivided in 65 economic activities):

- Energy (and refinery)
- Chemical industry
- Production and processing of metals
- Mineral industry
- Paper and wood production
- Waste and waste water management
- Animal and vegetable products from the food and beverage sector
- Intensive livestock production and aquaculture
- Other activities (added to the chemical industry for this analysis)

The database contains 91 pollutants, including pesticides, heavy metals, greenhouse gases and dioxins that are released to air, water and land as well as off-site waste transfer and wastewater.

Some criteria have to be met in order for a facility operator to face reporting obligation under E-PRTR:

-The facility falls under at least one of the 65 economic activities and exceeds at least one of the E-PRTR capacity thresholds

-The facility transfers waste off-site which exceed specific threshold

-The facility releases pollutants which exceed specific threshold specified for each media air, water and land

If the facility carries out several activities under the same *Annex I* activity, the reported data is a sum of all the activities. The data includes all releases that are coming from deliberate, accidental, routine and non-routine activities at the specific reporting site.

The facilities report the data annually to the relevant authorities, who are responsible for assuring data quality and transferring the data to the European Commission and the European Environment Agency (EEA) for compilation and dissemination. The data is published on the public E-PRTR website. [3]

For the analysis, five energy-intensive industries are focused: Production and processing of metals, paper and wood production, waste and waste water management, chemical industry and mineral industry. For the calculations in this report, the three facilities identified from the "Other activities" sector were added to the "Chemical industry" sector. This is justified by researching the three production sites online and validating the main economic activities.

The input criteria resulted in a total number of 956 industrial plants releasing 511 987 kt of CO_2 per year. The energy sector was not analysed because the coal-fired industry, for the 2050 projections, is considered to be irrelevant. Individual fossil power plants are not regarded in this work as integrating them risks lock-in effects of fossil infrastructure, does not prevent carbon emissions and instead just delays them. In addition, carbon capture from fossil power plants leads to an immense need for CO_2 storage and extra CO_2 penalties for the capture step due to temporal mismatch of fossil plant operation and surplus renewable electricity generation. Also, the industry sector will face drastic changes concerning fuel switches e.g. from coal-firing to firing of natural gas (which can be gradually decarbonised by implementing PtG-processes). To some extend solid biomass can be used. In general, a trend to electrification of processes may be expected where appropriate. All three measures help decision-makers in industry to reduce emissions and thus the corresponding demand for carbon dioxide emission certificates. In addition, continuous energy efficiency measures will be witnessed leading to further (slight) reduction of energy demand. Nevertheless, the energy intensive industries studied here (>100 000 tons of CO_2 per year) will remain the largest available point emitters and may in the future be regarded as carbon sources that deliver the feedstock for carbon-based products that will be produced along the power-to-X process routes. Unlike the energy sector, that is expected to be most radically transformed, this work assumes the producing industry sectors to persist and thus focusses on the CO_2 these plants offer as the basis for a PtM production potential calculation.

In order for the PtG to be considered as a viable solution for large-scale energy storage, notable quantities of CO_2 are required. Therefore, in this work energy-intensive industrial sources are considered that emit more than 100 000 tons of CO_2 per year.

2.1.2 NACE codes

The five chosen industries contain subcategories defined by the so-called NACE codes. NACE (Nomenclature des Activités Économiques dans la Communauté Européenne) is the European statistical classification of economic activities. [4] Facilities are grouped according to their business activities. Statistics produced on the basis of NACE are comparable at European level and, in general, at world level in line with the United Nations' International Standard Industrial Classification (ISIC) [5].

The categories included in each of the industries analysed here are listed below. The list contains a description of the NACE codes (two by two digit numbers), as well as the corresponding E-PRTR codes (single digit followed by a letter), that gives a detailed illustration of the categories within each industry sector.

In brackets, the proportions of the respective industry sectors with respect of the total industrial CO_2 amounts taken into account in this work are given.

1. *Production and processing of metals* (28 %)

NACE codes: 24.10, 24.20, 27.10, 27.22, 27.30, 27.34, 27.35, 24.41, 24.42, 24.43, 24.44, 24.45,27.40, 27.42, 27.43, 27.44, 27.45

24.10 (27.10) - Manufacture of basic iron and steel and of ferro-alloys

24.20 - Manufacture of tubes, pipes, hollow profiles and related fittings, of steel

27.22 - Manufacture of steel tubes

27.30 - Other first processing of iron and steel and production of non-ECSC ferro-alloys

27.34 - Wire drawing

27.35 - Other first processing of iron and steel n.e.c.; production of non-ECSC ferro-alloys

24.41 - Precious metals production

24.42 (27.42) - Aluminium production

24.43 (27.43) - Lead, zinc and tin production

24.44 (27.44) - Copper production

24.45 (27.45) - Other non-ferrous metal production

27.40 - Manufacture of basic precious and non-ferrous metals

Or,

2.(a) Metal ore (including sulphide ore) roasting or sintering installations

2.(b) Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting

2.(c) Installations for the processing of ferrous metals

2.(d) Ferrous metal foundries

2.(e) Installations for: the production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes; For the smelting, including the alloying, of non-ferrous metals, including recovered products (refining, foundry casting, etc.)

2.(f) Installations for surface treatment of metals and plastic materials using an electrolytic or chemical process

2. *Mineral industry* (27 %)

NACE: 23.20, 23.51, 23.52, 23.64, 23.99, 26.00, 26.26, 26.50, 26.51, 26.52, 26.64, 26.80, 23.11, 23.12, 23.13, 23.14, 23.19, 26.10, 26.11, 26.12, 26.13, 26.14, 26.15

23.20 (26.26) - Manufacture of refractory products

23.51 (26.51) - Manufacture of cement

23.52 (26.52) - Manufacture of lime and plaster

23.64 (26.64) - Manufacture of mortars

23.99 - Manufacture of other non-metallic mineral products n.e.c

23.11 (26.11) - Manufacture of flat glass

23.12 (26.12) - Shaping and processing of flat glass

23.13 (26.13) - Manufacture of hollow glass

23.14 (26.14) - Manufacture of glass fibres

23.19 (26.15) - Manufacture and processing of other glass, including technical glassware

26.10 - Manufacture of glass and glass products

Or,

3.(c) Installations for the production of: lime in rotary kilns, Cement clinker or lime in other furnaces

3.(e) Installations for the manufacture of glass, including glass fibre

3.(f) Installations for melting mineral substances, including the production of mineral fibres

3.(g) Installations for the manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain

3. *Paper and wood production* (14 %)

NACE: 16.10, 16.21, 17.11, 17.12, 17.29, 21.11, 21.12

16.10 - Sawmilling and planning of wood

16.21 - Manufacture of veneer sheets and wood-based panels

17.11 (21.11) - Manufacture of pulp

17.12 (21.12) - Manufacture of paper and paperboard

17.29 - Manufacture of other articles of paper and paperboard

Or,

6.(a) Industrial plants for the production of pulp from timber or similar fibrous materials

6.(b) Industrial plants for the production of paper and board and other primary wood products

4. *Chemical industry* (19 %)

NACE: 08.93, 10.41, 10.81, 10.89, 20.13, 20.14, 20.15, 20.16, 20.17, 20.41, 20.52, 20.59, 20.60, 24.10, 24.11, 24.13, 24.14, 24.15, 24.16, 24.17, 24.20, 24.51, 24.62, 24.66, 24.70

08.93 - Extraction of salt

10.41 - Manufacture of oils and fats

10.81 - Manufacture of sugar

10.89 - Manufacture of other food products n.e.c.

20.13 (24.13) - Manufacture of other inorganic basic chemicals

20.14 (24.14) - Manufacture of other organic basic chemicals

20.15 (24.15) - Manufacture of fertilisers and nitrogen compounds

20.16 (24.16) - Manufacture of plastics in primary forms

20.17 (24.17) - Manufacture of synthetic rubber in primary forms

20.41 (24.51) - Manufacture of soap and detergents, cleaning and polishing preparations

20.52 - Manufacture of glues

20.59 (24.66) - Manufacture of other chemical products n.e.c.

20.60 (24.70) - Manufacture of man-made fibres

24.10 v.1– Manufacture of basic chemicals

24.11 - Manufacture of industrial gases

24.20 v.1 - Manufacture of pesticides and other agro-chemical products

24.62 - Manufacture of glues and gelatines

Or,

4.(a) Chemical installations for the production on an industrial scale of basic organic chemicals: Simple hydrocarbons (linear or cyclic, saturated or unsaturated), Oxygen-containing hydrocarbons, Basic plastic materials (polymers, synthetic fibres and cellulose-based fibres), Dyes and pigments

4.(b) Chemical installations for the production on an industrial scale of basic inorganic chemicals, such as: Salts, Gases, Non-metals, metal oxides or other inorganic compounds, Bases, Acids

4.(c) Chemical installations for the production on an industrial scale of phosphorous-, nitrogen- or potassium-based fertilisers (simple or compound fertilisers)

4.(d) Chemical installations for the production on an industrial scale of basic plant health products and of biocides

4.(e) Installations using a chemical or biological process for the production on an industrial scale of basic pharmaceutical products

9.(c) Installations for the surface treatment of substances, objects or products using organic solvents,

9.(d) Installations for the production of carbon (hard-burnt coal) or electro-graphite by means of incineration or graphitisation

5. *Waste incineration (waste and waste water management)* (12 %)

NACE: 38.11, 38.21

38.11 - Collection of non-hazardous waste

38.21 - Treatment and disposal of non-hazardous waste

Or,

5.(a) Installations for the recovery or disposal of hazardous waste

5.(b) Installations for the incineration of non-hazardous waste in the scope of Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste

5.(c) Installations for the disposal of non-hazardous waste

5.(f) Urban waste-water treatment plants

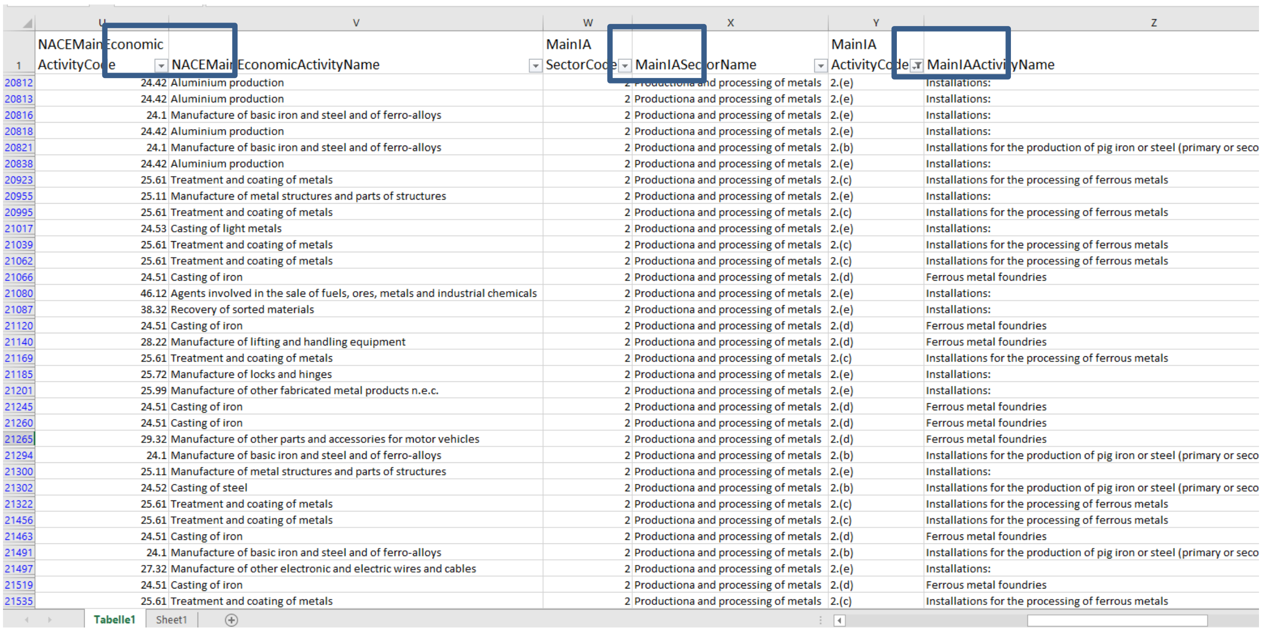
5.(g) Independently operated industrial waste-water treatment plants which serve one or more activities of this annex [4].[6]

Implementation of the NACE codes in the E-PRTR database

For a comprehensive categorization, the large variety of data coming with the NACE codes (more than 1 000 codes) are simplified for use in the E-PRTR database. The distribution of the industry activities described with the NACE codes is concentrated in a smaller set of 9 industrial sectors (see above). Each of the 9 industrial sectors contains sub-sectors, labelled with a number and a letter, as an example 9.(a).

For example: one plant with a NACE code “24,1” that has been reported as “Manufacture of basic iron and steel and of ferro-alloys” is given a number “2” in the E-PRTR data-base as a Main industry sector “Production and processing of metals” and is given a sub-sector “2.(b)” as a Main activity code, by which the further analysis is done, as can be seen in Figure 2-1.

In this way the NACE codes are integrated in the E-PRTR data base in a simplified manner. For further analysis in QGIS and the presentation of the results, only the E-PRTR codes are referred to.



	NACEMainEconomicActivityCode	NACEMainEconomicActivityName	MainIASectorCode	MainIASectorName	MainIAActivityCode	MainIAActivityName
20812	24.42	Aluminium production	2	Productiona and processing of metals	2.(e)	Installations:
20813	24.42	Aluminium production	2	Productiona and processing of metals	2.(e)	Installations:
20816	24.1	Manufacture of basic iron and steel and of ferro-alloys	2	Productiona and processing of metals	2.(e)	Installations:
20818	24.42	Aluminium production	2	Productiona and processing of metals	2.(e)	Installations:
20821	24.1	Manufacture of basic iron and steel and of ferro-alloys	2	Productiona and processing of metals	2.(b)	Installations for the production of pig iron or steel (primary or seco
20838	24.42	Aluminium production	2	Productiona and processing of metals	2.(e)	Installations:
20923	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
20955	25.11	Manufacture of metal structures and parts of structures	2	Productiona and processing of metals	2.(e)	Installations:
20995	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21017	24.53	Casting of light metals	2	Productiona and processing of metals	2.(e)	Installations:
21039	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21062	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21066	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21080	46.12	Agents involved in the sale of fuels, ores, metals and industrial chemicals	2	Productiona and processing of metals	2.(e)	Installations:
21087	38.32	Recovery of sorted materials	2	Productiona and processing of metals	2.(e)	Installations:
21120	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21140	28.22	Manufacture of lifting and handling equipment	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21169	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21185	25.72	Manufacture of locks and hinges	2	Productiona and processing of metals	2.(e)	Installations:
21201	25.99	Manufacture of other fabricated metal products n.e.c.	2	Productiona and processing of metals	2.(e)	Installations:
21245	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21260	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21265	29.32	Manufacture of other parts and accessories for motor vehicles	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21294	24.1	Manufacture of basic iron and steel and of ferro-alloys	2	Productiona and processing of metals	2.(b)	Installations for the production of pig iron or steel (primary or seco
21300	25.11	Manufacture of metal structures and parts of structures	2	Productiona and processing of metals	2.(e)	Installations:
21302	24.52	Casting of steel	2	Productiona and processing of metals	2.(b)	Installations for the production of pig iron or steel (primary or seco
21322	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21456	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals
21463	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21491	24.1	Manufacture of basic iron and steel and of ferro-alloys	2	Productiona and processing of metals	2.(b)	Installations for the production of pig iron or steel (primary or seco
21497	27.32	Manufacture of other electronic and electric wires and cables	2	Productiona and processing of metals	2.(e)	Installations:
21519	24.51	Casting of iron	2	Productiona and processing of metals	2.(d)	Ferrous metal foundries
21535	25.61	Treatment and coating of metals	2	Productiona and processing of metals	2.(c)	Installations for the processing of ferrous metals

Figure 2-1: An example (preview) of the data from the E-PRTR database incorporating the NACE codes

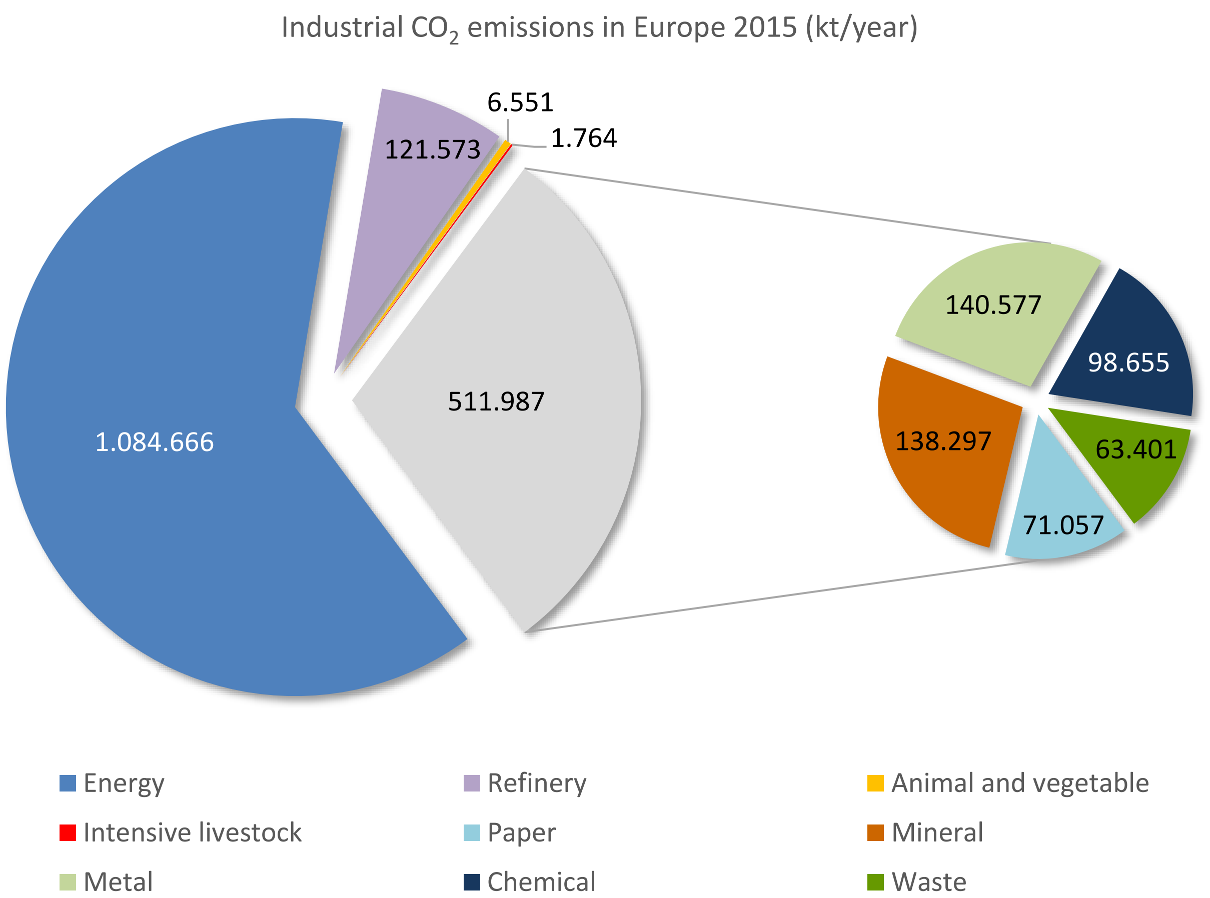


Figure 2-2: The role of the selected 5 industries in the CO_2 emissions within the 9 E-PRTR industry sectors[3]

The five focused industry sectors are responsible for 30 % of the total CO_2 emitted from all plants (from the 9 industrial sectors) included in the E-PRTR database. Their relative CO_2 emission shares are illustrated in Figure 2-2.

2.1.3 CO_2 capturing potential

The CO_2 capturing potential was estimated for each industry sector separately. The appropriate value was chosen according to literature research done on industrial carbon capture (CC). As literature suggests, a CO_2 separation ratio of around 90 % was applicable to some of the industries, like metal and cement industry. In contrary to that, limited literature was found for the carbon capture potential and technologies in paper and the chemical industry.

The **steel and iron industry** is characterised as the most energy-intensive manufacturing sector, thus resulting in large amounts of CO_2 emissions. The steel industry is responsible for approximately 7 % of the global CO_2 emissions. The steel demand is expected to continue to rise in the future, so carbon mitigation is essential for this sector, given its importance. [7] Applying different carbon capture technologies in the steel plants, like the Sorption Enhanced Water Gas Shift (SEWGS) process may result in 85–90 % carbon capture potentials, according to Gazzani *et al.* [8]
Further developments are also made for introducing hydrogen (H_2) as a fuel in the steel sector that may allow CO_2 emission free processes. A field trial is done at Voest in Linz, as part of the *H2Future* project, where Siemens will use a PEM electrolysis system (6 MW) to split water and produce “green” hydrogen, claiming 80 % of efficiency for the electrolysis process. [9] The produced “green” hydrogen can then be used as a green fuel for the steel making processes (direct reduction) substituting coal combustion. [10]

The CO_2 emissions from the **cement industry** account for 5 % of the global CO_2 emissions. [11] As the pre-combustion carbon capturing technologies would not affect the CO_2 emissions originating from the calcination process in the cement plants, where almost 65 % of emissions come from, the post-combustion carbon capture processes are seen as promising solution for CO_2 reduction. [11] According to Hilz, a carbon capture potential of more than 90 % is achievable with directly and indirectly heated *carbonate looping* (CaL), up to 95 % if applied to the cement industry and up to 92 % if applied to the steel industry. [12] The calcium looping technology, as well as *chilled ammonia* (CAP), *membrane-assisted CO_2 liquefaction* and *oxyfuel capture*, were also tested by the CEMCAP project. [13] CEMCAP, a Horizon 2020 project, aims at testing CO_2 capture technologies suitable for retrofitting to existing cement plants. The results showed capture rates higher than 90 % for all of the four technologies and demonstrated up to 98 % capture rate at a pilot plant at the IFK (Institute of Combustion and Power Plant Technology at University of Stuttgart). [14] Additionally, the project LEILAC (Low Emissions Intensity Lime and Cement) suggests implementing minimal changes to the calciner of the cement plant, by introducing a *direct separating reactor*, for capturing the CO_2 that is being released in the process of calcination. This technology allows up to 95 % capture potential of the CO_2 from the calcination process. [15]
Similar to the work by Kjärstad *et al.* [16] a carbon capture rate of 90 % for both steel and cement industry is implemented for the potential study.

The **pulp and paper industry** accounts for 2 % of the total global industrial emissions. [17] The Kraft mills, that are one of the two main production pathways of pulp and paper, have the largest potential of carbon capture, as they account for almost 73 % of the European pulp and paper emissions. [18] The recovery boiler in the Kraft plant, where black liquor is burned, is the main source of CO_2 emission, making it of a special interest for implementing capturing technologies. [19] According to Pettersson [20] ,the *black-liquor gasification* (BLG) is considered as one technology that can improve

the efficiency of the Kraft plants and positively affect the CO_2 emissions from the recovery boiler. The BLG, if combined with a carbon capture technology, holds a potential for large CO_2 reductions in this industry sector.
A post-combustion carbon capture process is usually considered in this industry, as it does not alter the construction of the boiler, in comparison to pre-combustion capture or oxy-fuel combustion. [18] McGrail *et al.*, considered around 62 % of emission capturing in one USA pulp and paper mill, by using a post-combustion amine capture unit to the recovery boiler. [17]

Ammonia, ethylene oxide production and hydrogen production, as part of the **chemical industry**, are considered as high purity CO_2 sources (streams with more than 90 % CO_2 purity), as highly concentrated CO_2 is already available as a by-product from these processes, in with lower costs for carbon capture compared to the other industries. [17] Few separation technologies are used in the chemical industry like: chemical solvents, solid looping and cryogenic technologies. [21] Selecting the appropriate process depends on a number of factors including gas inlet pressure, size and end use specification. [22]

Based on this literature review, for the calculations in this paper, the 90 % value was chosen as a carbon capture potential that can be applied to all of the 5 selected industries.

2.2 CO_2 from biological sources

Biogas plants are an available and reliable source of biogenic CO_2. Additionally, possibilities for coupling a biogas plant with a PtG plant already exist today and therefore biogas plants are considered to be the preferred “green” CO_2 source for the methanation process in this analysis.

One particularly advantageous option for implementing a PtG plant at a biogas plant is a so-called biomethane plant. In these, the raw biogas is purified by separating the CO_2 for the feed-in of the remaining biomethane into the gas grids. The captured carbon dioxide has a high purity and can be used for methanation processes without further treatment. Today, existing biomethane plants let the high-quality CO_2 into the ambient air. Next to the availability of CO_2 another advantage of biomethane plants as potential sites for PtM units is that they already possess a feed-in point to the natural gas network. Thus, the potential erection of an additional PtM plant leads to limited investment. At present (as of 2017), 540 biomethane plants with a capacity of 1.94 billion m³ are installed in Europe.[23]

Here, not only biomethane plants but all biogas plants shall be taken into account for integration into the study. The vision is to substitute the typical combustion of biogas for electricity production by more sophisticated plant designs that include CO_2 separation and additional green gas production via the Power-to-Methane route. The green gas can be transported using the existing natural gas infrastructure and substitute fossil gases at the end-user applications for greenhouse gas emission reduction.

In order to determine the potential and to identify the possible sites for biogenic PtG plants, a distinctive knowledge of existing green CO_2 sources and renewable energy sources is necessary. This includes, among others, the positions of the considered renewable energy sources, the substations and both locations of and production data on biogenic CO_2 sources. The approaches for obtaining the data, as well as the methods used in the process are presented in the following chapters.

2.2.1 Obtaining data for country-level (top-down approach)

There are two different bases for calculating the countrywide potentials for bio PtG plants: primary production of biogas in the year 2016 published by Eurostat [24], and the report "Sustainable strategies for biomass use in the European context" [25] about future potentials of biomass in Europe.

Eurostat is the European statistical office and collects various data concerning the economy of all EU-member states and other European states. For the calculation of the emitted CO_2 the primary production of biogas is important. Eurostat obtains these numbers from national agencies and publishes them on a regular base, lastly in 2016. Based on the fact that the biogas consists of 30 – 50 vol.-% of CO_2, the amount of emitted CO_2 is calculated from the amount of biogas that is produced by the biogas plants. [26]

In a report by Thrän [25], the maximum methane potential from biomass is calculated. Different assumptions concerning the development of forest wood, residuals and energy crops are made, so that the total production of methane from biological sources is presented. Methane is on the one hand produced by anaerobic digestion and on the other hand by thermo-chemical processes. Taking into account that both methods produce CO_2 as a side product, the total emission of CO_2 from biomass can be estimated.

2.2.2 Obtaining data for the local-level (bottom-up approach)

For identification of the potential PtG sites, it is necessary to take into account the locations of all biogas plants in the considered countries with precise coordinates. Therefore, location data of the biogas plants is needed. The data is collected from different sources, e.g. national biogas associations, the European biogas association, local economical and national agencies. Mostly the data consists of coordinates, addresses or maps where the plants are marked. To work with addresses, the data has to be converted appropriately to represent each address by coordinates. This process is called *geocoding* and is done using the *OpenStreetMap (OSM)* database. For using locations marked on maps, a similar process is done.

OpenStreetMap (OSM) is an open source project, created by volunteers, to create free editable geographical data that is usable worldwide. The data is gathered by using GPS or by analysing aerial photographs. [27]

During the process of *geo-referencing*, the map is imported into the QGIS software, fitted to a suitable coordinate system by projecting and subsequently linking all marked plants to coordinates manually. *Quantum-GIS* (QGIS) is open-source Geo-Information System (GIS) to present, edit and capture spatial data. It supports different vector and raster data formats. As it is being developed under the GNU General Public License (GPL), the software allows modifying of the source code. It is possible to perform spatial data analyses on spatial databases and other OGR-supported formats. Also, it offers vector analyses, sampling, geo-processing, geometry and database management tools. The results can be visualized with different integrated composing tools. [28]

After implementing the location data into QGIS, the results are visualized like in Figure 2-3 and may be used for geoinformational calculations. The highest density of biogas plants can be found in Central Europe. Germany, northern Italy, the Czech Republic and Denmark have large concentrations of biogas plants in several regions. Fewer plants are found in southern Europe, especially in the south of Italy and Spain, which can be linked to incompleteness of the data sets (e.g. Spain → only data for agricultural biogas plants because of privacy policies). The distribution of the identified biogas plants is presented in level NUTS-2 on Figure 2-3.

NUTS (NUTS - Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for different purposes, like socio-economic analyses or collecting regional statistics. There are three NUTS levels that build on each other. Thus, the spectrum ranges from 104 regions in NUTS-1, to 281 in NUTS-2, and 1 348 levels in NUTS-3.[29] NUTS-2, are the basic regions for the application of regional development policy. All the analysis in this report are done and presented based on the NUTS-2 level.

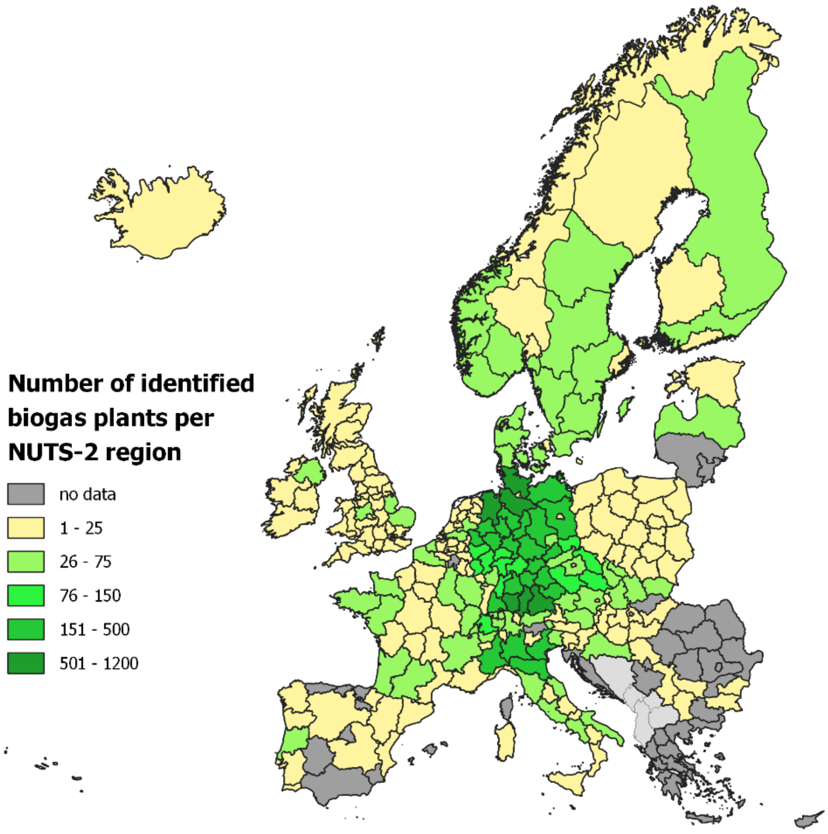


Figure 2-3: Number of identified biogas plants per NUTS-2 region (own illustration)

2.3 Renewable Energy Generation (wind turbines)

In order to develop a sustainable low-emission energy storage process, a renewable energy source is needed to operate the electrolysis process in the PtG plant. As a flexibility option, energy storage is particularly suitable if it can be operated with excess electricity and thus prevents the shutdown of renewable energy plants. For the electrical supply of a PtG plant with excess electricity, operation with various regenerative energy sources is possible (like wind, solar, hydro). Wind turbine energy is highly developed form of renewable energy in Europe and is present in almost all of the EU28+5 countries. In 2017, the installed wind capacity was approximately 169 GW, which corresponds to 11.6 % of the EU's electricity demand, and therefore they are considered as primarily suitable source of electricity [30]. In comparison to the photovoltaic energy, the PtG system coupled with wind power plants can be operated also at night, leading to higher expectable number of full load hours of the systems, thus resulting in a positive effect on methane production costs. Consequently, wind turbines are defined as the preferred source of electricity for the considered PtG plants. For the analysis of the wind turbine locations, high-resolution geographical data of all wind turbines in the respected countries was necessary. The data for the wind turbines is obtained via the online map service *OpenStreetMap*.

This database identified 93 009 wind turbines (Jan 2019) in EU28+5 countries [31]. The information about installed capacities per wind turbine contained in the OSM database is very fragmentary and cannot be used for the purpose of this work. It can however be assumed that modern wind turbines exhibit installed electrical capacities of at least about 2 MW. Old turbines with lower capacities are expected to be exchanged during repowering projects in the future leading to installed capacities in the same range. Therefore, this work focusses on the exact locations of the wind turbines and their geometrical relationships with suitable CO_2 sources rather than the exact capacity per site. The number of wind turbines is particularly high in Denmark, Germany, France, Great Britain, Italy and Spain, but also significant instalments of turbines can be found in Greece, Poland, Ireland and Sweden. These areas can be identified as high-density wind turbine areas, between 1 000 to 4 000 wind turbines per NUTS-2 region. The density of the wind turbines by NUTS-2 regions is presented on Figure 2-4.

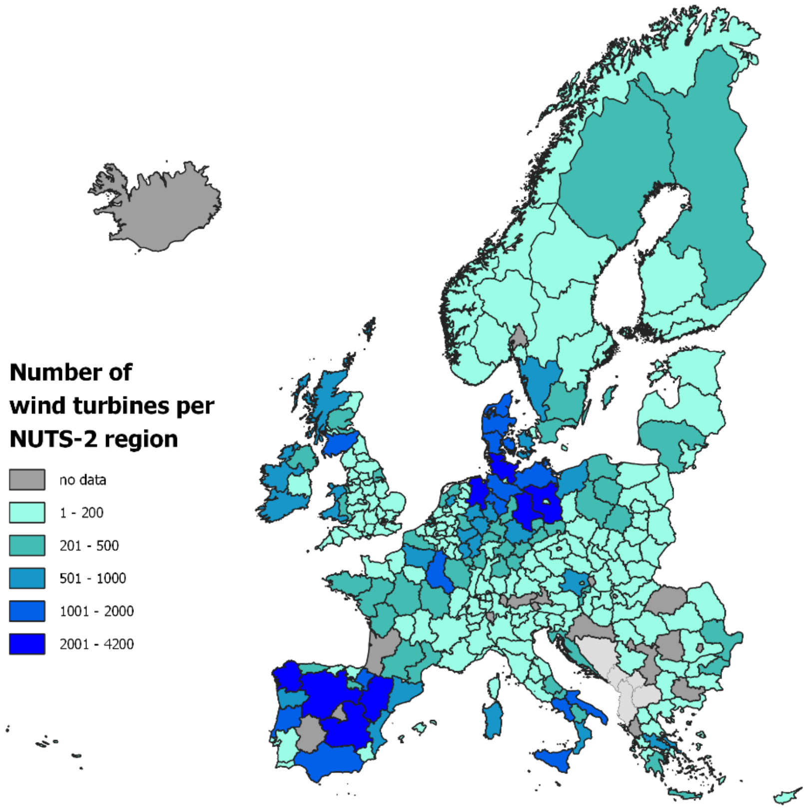


Figure 2-4: Number of wind turbines (Jan 2019) per NUTS-2 region [27]

2.4 Substations

The negative residual load formed by high wind power production affects the associated substations and may be utilized for power-to-X energy conversion or storage technologies in the proximity of these substations, interconnected via the grid or direct cabling to optimize the positive impact on the grid operation. Depending on the installed capacity, wind turbines and parks are connected to medium, high and extra-high voltage networks in the range of 10 kV to 380 kV.[32]

The location data for the substations stems from OSM. As a first step of the selection process only those substations (both points and polygons) that are tagged with power=substation and the attributes substation=*distribution* and/or substation=*transmission* (that operate in the range of about 10 kV to 380 kV) are selected, resulting in 17 317 substations for Europe. In the following step, substation polygons with areas smaller than 1 000 m^2 are neglected in order to exclude a notable number of small-scale power transformation units from the low voltage level from the dataset, that are subject to erroneous tags. This second filtering resulted in location data for 13 229 substations in the EU28+5 area.

Note: For the analyses of biogas and industry as CO_2 sources, different approaches need to be defined due to dissimilar scale and level of infrastructural integration. For the analysis of large-scale industrial CO_2 sources it is assumed, that all industrial locations possess an integration into the regional electricity infrastructure at the medium voltage level at minimum, i.e. the sites are assumed to exhibit own substations on-site. The industrial sites are therefore not assigned to distribution and/or transmission level substations in their surroundings.

Figure 2-5 shows the number of substations by NUTS-2 region integrated in the study.

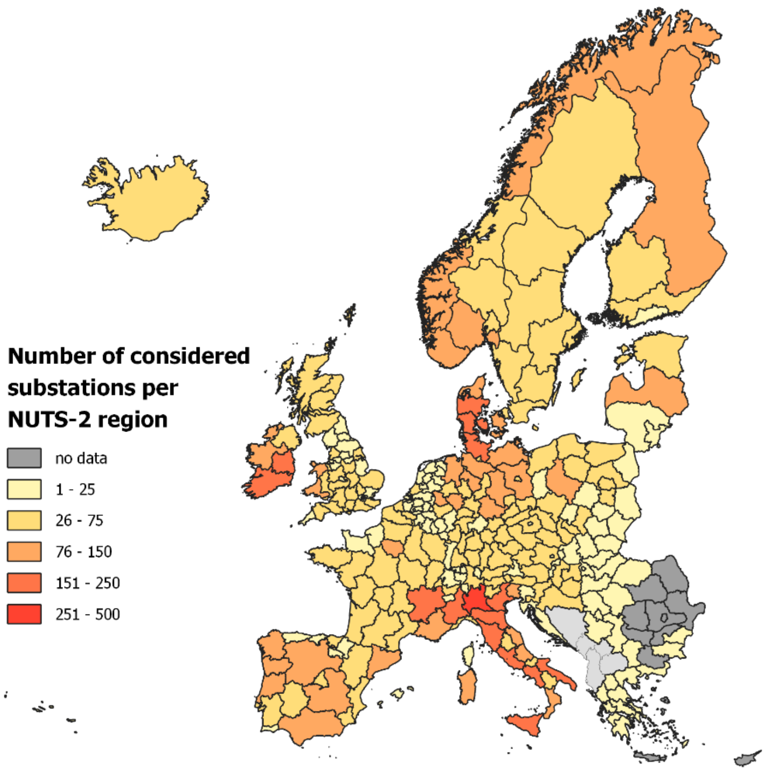


Figure 2-5: Number of considered substations per NUTS-2 region [27]

3 Geoinformation analysis

3.1 CO_2 data processing (for the industry sector)

The raw data files downloaded from the E-PRTR register contain information about each site (facility) that has reported any type of pollutant (of all 91 pollutants) that is released to air, water and land within the 9 industry sectors. The list contains detailed information about each site, like:

- location (latitude and longitude, and country)
- the main activity code (which is compatible with the NACE codes) and the sector, that makes it easy to choose the facilities that are included in the 5 industries,
- the reporting year (the file contains information for each site from 2007 till 2015),
- the type of pollutant they release and the total quantity of it.
- The list contains 480 581 sites. An example of the data is shown in Figure 3-1.

	A	C	G	H	I	J	L	M	N	Q	R	T	U	
1	Facilit	FacilityNa	City	CountryI	Lat	Long	MainIAA	MainIASectorName	MainIAActivityName	ReportingYear	PollutantNan	TotalQuantity	ReleaseM	Me
168664	5784	Kunda Nord	Kunda linn	Estonia	59,49644	26,53109	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	398000000	Air	Me
168667	5784	Kunda Nord	Kunda linn	Estonia	59,49644	26,53109	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	398000000	Air	Me
187049	99969	AVAG KVA A	Thun	Switzerland	46,76206	7,60619	5.(b)	Waste and waste water mar	Installations for the incineration of r	2015	Carbon dioxide	114000000	Air	Ot
187595	85764	Juracime SA	Cornaux	Switzerland	47,03401	7,029617	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	195000000	Air	Ot
187598	85765	Vigier Ceme	Péry	Switzerland	47,1848	7,249311	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	521000000	Air	Ot
187602	85719	Cimo SA	Monthey	Switzerland	46,25294	6,965317	5.(a)	Waste and waste water mar	Installations for the recovery or disp	2015	Carbon dioxide	152000000	Air	Ot
187850	9891	VASSILIKO C	ZYGI	Cyprus	34,72167	33,31639	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	1370000000	Air	Gu
189616	85761	Holcim (Sch	Würenlinge	Switzerland	47,52172	8,239083	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	534000000	Air	Ot
190690	85760	Holcim (Suis	Eclépens	Switzerland	46,65566	6,546421	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	374000000	Air	Ot
190700	85763	Jura Cement	Wildegg	Switzerland	47,41466	8,156816	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	489000000	Air	Ot
191892	85762	Holcim (Sch	Untervaz	Switzerland	46,91547	9,552903	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	377000000	Air	Ot
193174	85905	Les Chenevi	Aire-la-Vill	Switzerland	46,19418	6,032203	5.(b)	Waste and waste water mar	Installations for the incineration of r	2015	Carbon dioxide	284000000	Air	Ot
193582	85715	KEBAG AG	Zuchwil	Switzerland	47,21528	7,570647	5.(b)	Waste and waste water mar	Installations for the incineration of r	2015	Carbon dioxide	287000000	Air	Ot
199361	6922	REPSOL QUI	Pobla de M	Spain	41,19359	1,226223	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	878000000	Air	Ma
199366	7059	DEPOSITO C	PINTO	Spain	40,25712	-3,63755	5.(d)	Waste and waste water mar	Landfills (see note in Guidance Docu	2015	Carbon dioxide	129000000	Air	Ot
199377	6788	ALCOA INES	AVILES	Spain	43,55547	-5,92199	2.(e)	Productiona and processing	Installations:	2015	Carbon dioxide	111000000	Air	Na
199551	8336	DOW CHEMI	Pobla de M	Spain	41,17795	1,220303	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	1050000000	Air	Ot
199557	24711	FINANCIERA	SANTIAGO	Spain	42,91355	-8,49879	6.(b)	Paper and wood production	Industrial plants for the production	2015	Carbon dioxide	125000000	Air	Ot
199576	8424	STORA ENSC	Castellbisb	Spain	41,50417	1,967815	6.(b)	Paper and wood production	Industrial plants for the production	2015	Carbon dioxide	190000000	Air	Na
199673	6922	REPSOL QUI	Pobla de M	Spain	41,19359	1,226223	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	878000000	Air	Ma
199685	6922	REPSOL QUI	Pobla de M	Spain	41,19359	1,226223	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	878000000	Air	Ma
199697	6922	REPSOL QUI	Pobla de M	Spain	41,19359	1,226223	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	878000000	Air	Ma
199752	6922	REPSOL QUI	Pobla de M	Spain	41,19359	1,226223	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	878000000	Air	Ma
199758	7180	CEMENTOS I	VENTA DE E	Spain	41,95689	-4,44778	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	267000000	Air	Na
199944	9171	LEMONA INI	ESTAZIÑOA	Spain	43,20688	-2,77142	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	453000000	Air	Eu
199989	6880	CEMENTOS (	MALAGA	Spain	36,7166	-4,32674	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	690000000	Air	Me
199990	7180	CEMENTOS I	VENTA DE E	Spain	41,95689	-4,44778	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	267000000	Air	Na
200235	8244	CEMEX ESPA	ALICANTE/	Spain	38,37861	-0,54185	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	874000000	Air	Ot
200243	23188	A.G. CEMEN	ALCONERA	Spain	38,37881	-6,48346	3.(c)	Mineral industry	Installations for the production of:	2015	Carbon dioxide	392000000	Air	Me
201136	7039	FÁBRICA DE	Palos de la	Spain	37,18396	-6,88957	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	191000000	Air	Me
201421	24539	SAICA 4	ZARAGOZA	Spain	41,54992	-0,67077	6.(b)	Paper and wood production	Industrial plants for the production	2015	Carbon dioxide	215000000	Air	Me
201539	6902	SEAT	Martorell	Spain	41,49635	1,903583	2.(f)	Productiona and processing	Installations for surface treatment o	2015	Carbon dioxide	101000000	Air	Ot
201639	8917	FERROATLAI	CAMARGO	Spain	43,41228	-3,83977	2.(e)	Productiona and processing	Installations:	2015	Carbon dioxide	158000000	Air	Ma
201837	6955	UBE CORPOI	Castellón d	Spain	39,95292	-0,00573	4.(a)	Chemical industry	Chemical installations for the produ	2015	Carbon dioxide	143000000	Air	Me

Figure 3-1: Example of the E-PRTR data on industrial CO_2 emissions

By filtering the dataset, three additional steps followed: The first step was crossing out every information that is before 2015 as reporting year, as 2015 is the final reporting year in the analysed E-PRTR database (that resulted in a number of 50 616 sites). The second step was filtering out all reported emissions other than CO_2. This reduces the number of sites drastically to 3 115 sites. The final step was filtering out the *energy sector* (mineral oil and gas refineries, thermal power stations and combustion installations, gasification and liquefaction, coke ovens) and *animal and livestock industries* from the 9 sectors, so only the sites within the five selected industry sectors were considered.

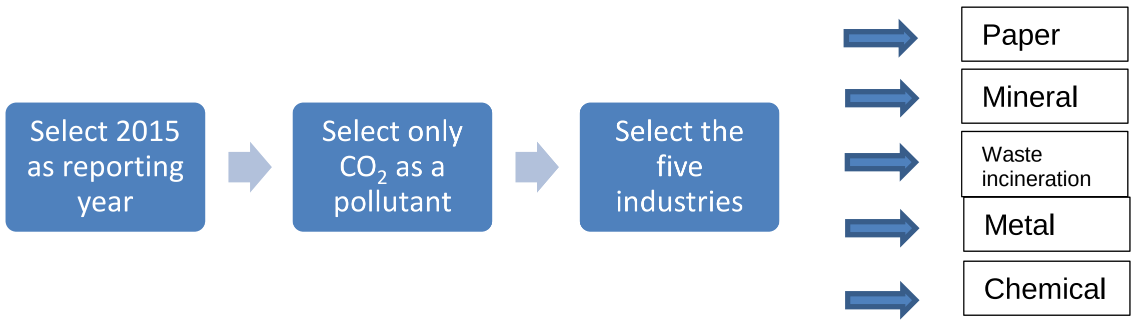


Figure 3-2: Overview of the selecting steps for generating separate data for each industry

The data selection resulted in the final number of 956 sites (for all five industries) and a total reported CO_2 emission of 511 976 kt of CO_2 per year.

	A	B	C	D
1		Industry	Activity	kt CO2
2	2.(a)	Productiona and processing of metals	Metal ore (including sulphide ore) roasting or sintering installations	15231
3	2.(b)	Productiona and processing of metals	Installations for the production of pig iron or steel (primary or secondary r	96034
4	2.(c)	Productiona and processing of metals	Installations for the processing of ferrous metals	13841
5	2.(d)	Productiona and processing of metals	Ferrous metal foundries	471
6	2.(e)	Productiona and processing of metals		14793
7	2.(f)	Productiona and processing of metals	Installations for surface treatment of metals and plastic materials using ar	207
8	3.(c)	Mineral industry	Installations for the production of:lime in rotary kilns	131418
9	3.(e)	Mineral industry	Installations for the manufacture of glass, including glass fibre	6457
10	3.(f)	Mineral industry	Installations for melting mineral substances, including the production of r	125
11	3.(g)	Mineral industry	Installations for the manufacture of ceramic products by firing, in particul	297
12	4.(a)	Chemical industry	Chemical installations for the production on an industrial scale of basic or	56829
13	4.(b)	Chemical industry	Chemical installations for the production on an industrial scale of basic in	25230
14	4.(c)	Chemical industry	Chemical installations for the production on an industrial scale of phosph	15669
15	4.(d)	Chemical industry	Chemical installations for the production on an industrial scale of basic pl	213
16	4.(e)	Chemical industry	Installations using a chemical or biological process for the production on a	103
17	5.(a)	Waste and waste water management	Installations for the recovery or disposal of hazardous waste	7070
18	5.(b)	Waste and waste water management	Installations for the incineration of non-hazardous waste in the scope of D	53512
19	5.(c)	Waste and waste water management	Installations for the disposal of non-hazardous waste	784
20	5.(f)	Waste and waste water management	Urban waste-water treatment plants	110
21	5.(g)	Waste and waste water management	Independently operated industrial waste-water treatment plants which s	1925
22	6.(a)	Paper and wood production processing	Industrial plants for the production of pulp from timber or similar fibrous	52281
23	6.(b)	Paper and wood production processing	Industrial plants for the production of paper and board and other primary	18776
24	9.(c)	Other activities-chemical	Installations for the surface treatment of substances, objects or products	457
25	9.(d)	Other activities-chemical	Installations for the production of carbon (hard-burnt coal) or electro-grap	154
26				
27		SUM		511987

Figure 3-3: An overview of the studied industry subsectors and their respective CO_2 emissions in kt for 2015 (reporting year)

For the further analyses, the geoinformation system software QGIS was being used. Importing the information into QGIS is done by firstly creating new layers for each industry, using an adding option for importing data from the Excel files that were generated in the previous step. A separate layer is created for each industry. A screenshot is shown in Figure 3-4.

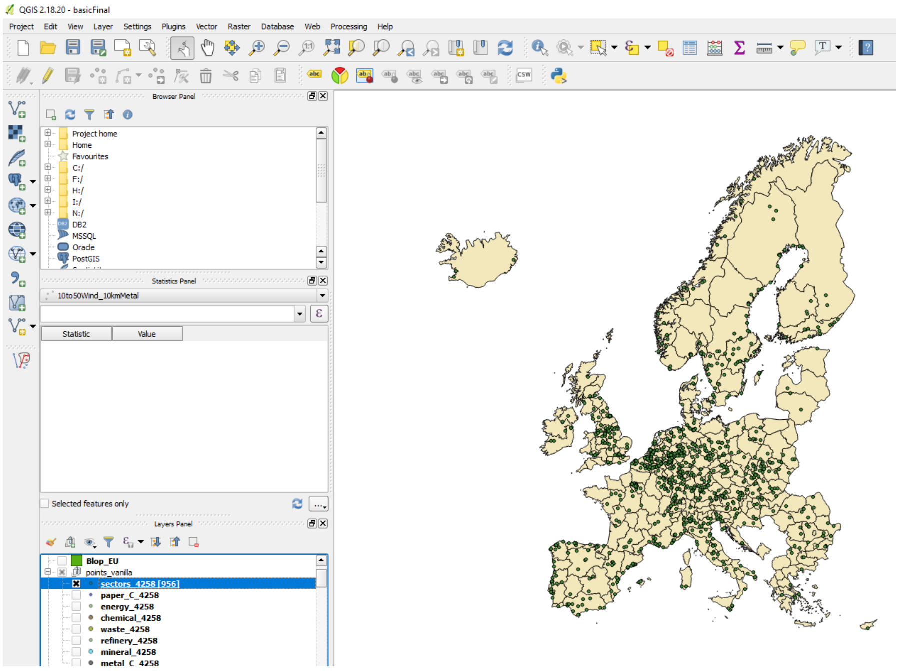


Figure 3-4: Screenshot of the created layers for each industry in QGIS

Each data point in the layers contains information about the geographical location of the respective plant, its industry sector and the released amount of CO_2 in kt in the reporting year.

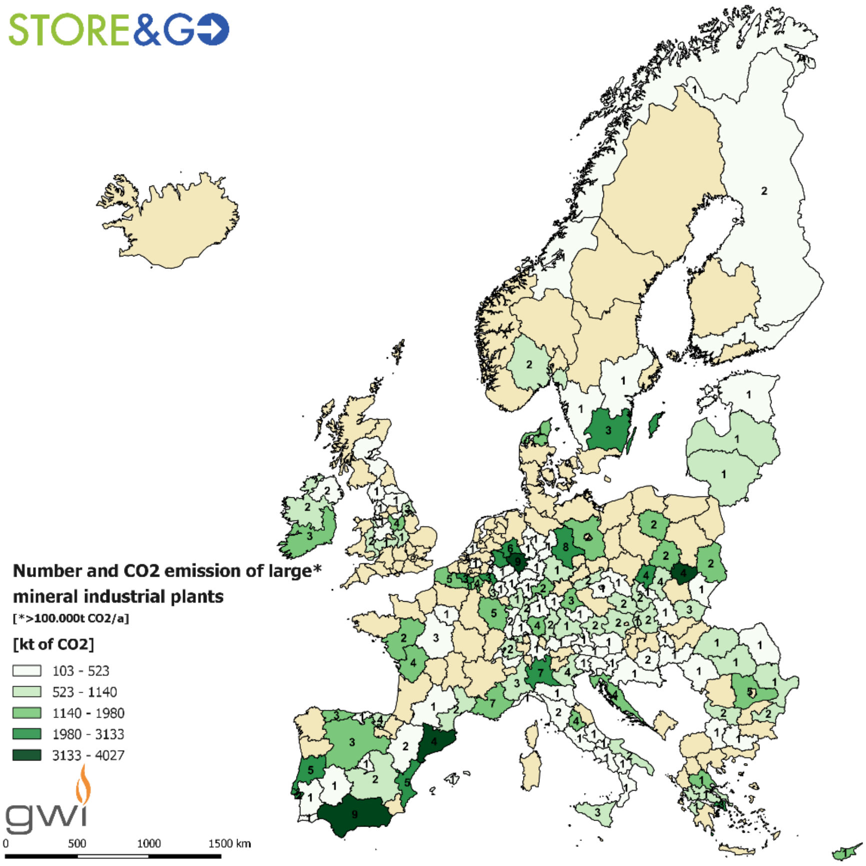


Figure 3-5: An example preview of results for the number and CO_2 emissions (in kt of CO_2/a) for the metal industrial plants [3]

3.2 Buffer analysis

3.2.1 Buffer analysis (industrial sector)

For the analyses and refining of site identification criteria, a buffer analysis was performed. This enables us to set local filtering conditions to the plants from the five selected industries.

For the case of data points (coordinates) the buffer polygons equal circles centred around the data points within a point layer. In the following analysis, a 10 km radius was considered. Within the resulting radii around the CO_2-sources the analysis algorithm identifies renewable energy sources.

For this step, the point layers of the wind turbines are imported. The data for the wind turbines is based on OSM data, as described in the previous chapter. Figure 3-6 shows a screenshot of the total number of 93 009 wind turbines included in the work.

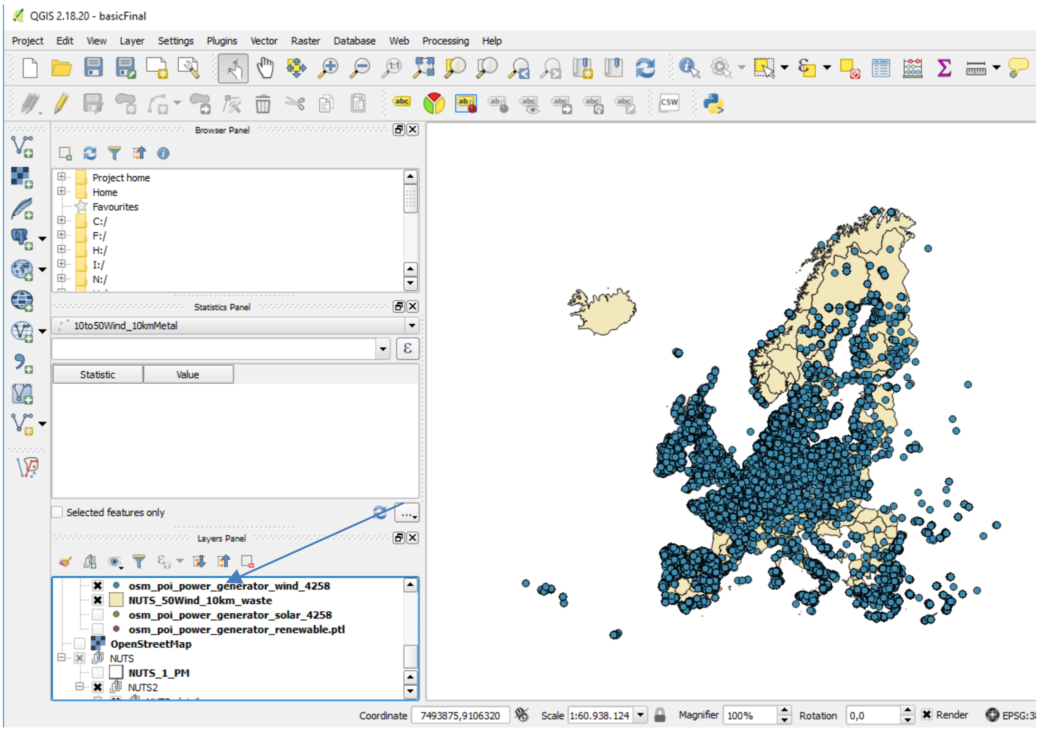


Figure 3-6: A preview of the “wind turbines” layer in QGIS

To illustrate the geographical distribution of the capacities, the regional density of installed wind turbines has been calculated. The background image on the map indicates the regions of Europe given by the statistical NUTS-2 regions [33].

As a next step, the data sets for the geographical distributions of the industrial sites and installed wind turbines were analyzed. A geo-processing tool was used for filtering those locations where at least one wind turbine is located within a 10 km radius around an industrial site. Following that, these data were filtered according to the 5 selected industry sectors, creating 5 new distinct data sets. Lastly, using a geographical vector tool, the actual number of wind turbines within the buffer areas were determined, for each of the five industries investigated. All wind turbine installations that were not within the 10 km buffer radius around an industrial site were neglected for the purpose of this analysis.

Three separate buffer analyses (criteria sets) were defined and implemented to each industry layer:

- at least 1 wind turbine in 10 km radius,
- 10 to 50 wind turbines in 10 km radius (high potential), and

- more than 50 wind turbines in 10 km radius (very high potential).

For each of the 3 buffer criteria, a separate layer was created. On Figure 3-7 the geographical distribution of large industrial CO_2 sources with at least 1 wind turbine in 10 km radius is shown as an example.

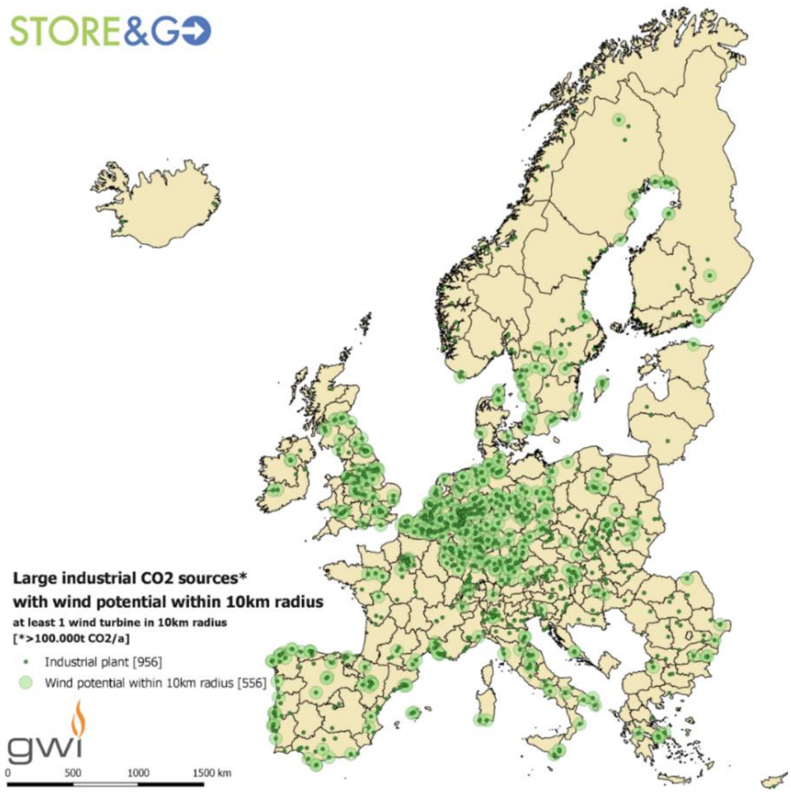


Figure 3-7: Geographical distribution of large industrial CO_2 sources, with at least 1 wind turbine in 10 km radius from all studied industry sectors.

In the first layer, the "*at least one wind turbine in 10 km radius*" layer, all the industrial plants, from all the five industries, that have at least one wind turbine in their 10 km radius were considered. From the total 956 sites, 556 sites have at least one wind turbine in 10 km radius. At the Norwegian coast, the analysis did not capture industrial plants due to typical distances larger than the buffer radius, especially for offshore wind power generation.

In the second layer, the "*10 to 50 wind turbines in 10 km radius*" or the "high potential" sites, sites with 10 to 50 wind turbines in their 10 km radius are presented. This reduces the number of potential plants to 221.

The final layer is the "*more than 50 wind turbines in 10 km radius*". These are the "very high potential" sites that have more than 50 wind turbines in the same radius. 100 sites, out of the total 965, meet this criterion. A preview of the last buffer analysis, "*more than 50 wind turbines in 10 km radius*" is shown in the Figure 3-8.

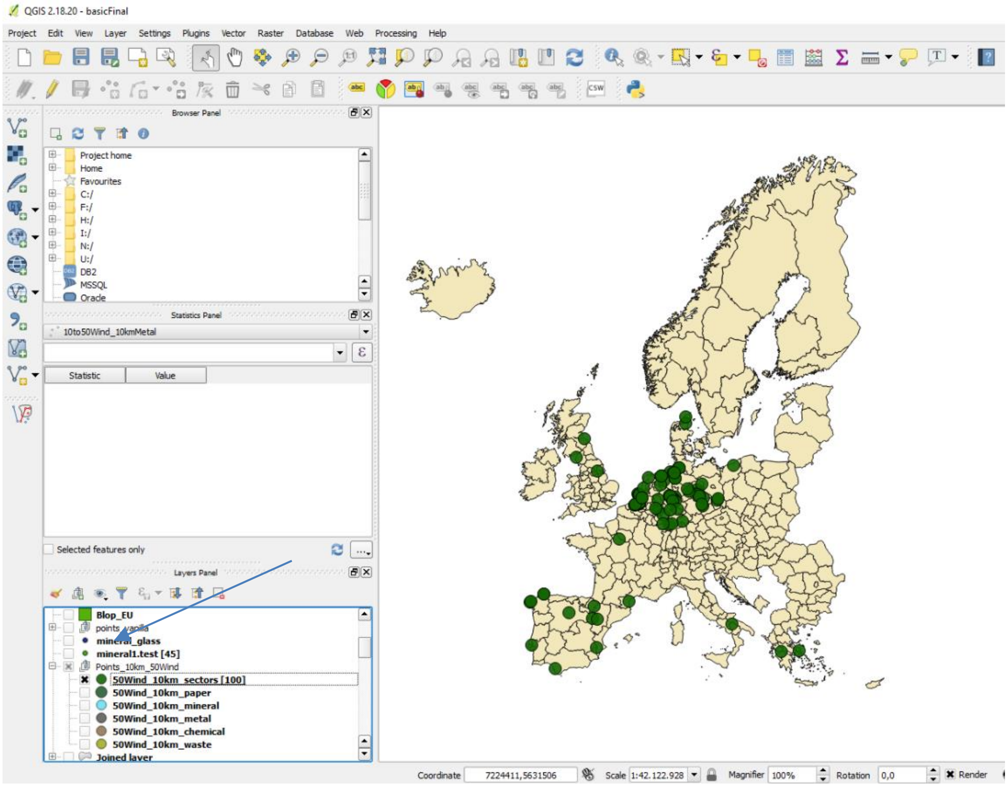


Figure 3-8: A preview of the buffer analysis “more than 50 wind turbines in 10 km radius”

An example of the buffer analysis is illustrated in Figure 3-9, where the buffer analysis “*10 to 50 wind turbines in 10 km radius*” is performed to a single metal plant that includes the wind turbines and the substations that are located in the 10 km buffer zone.

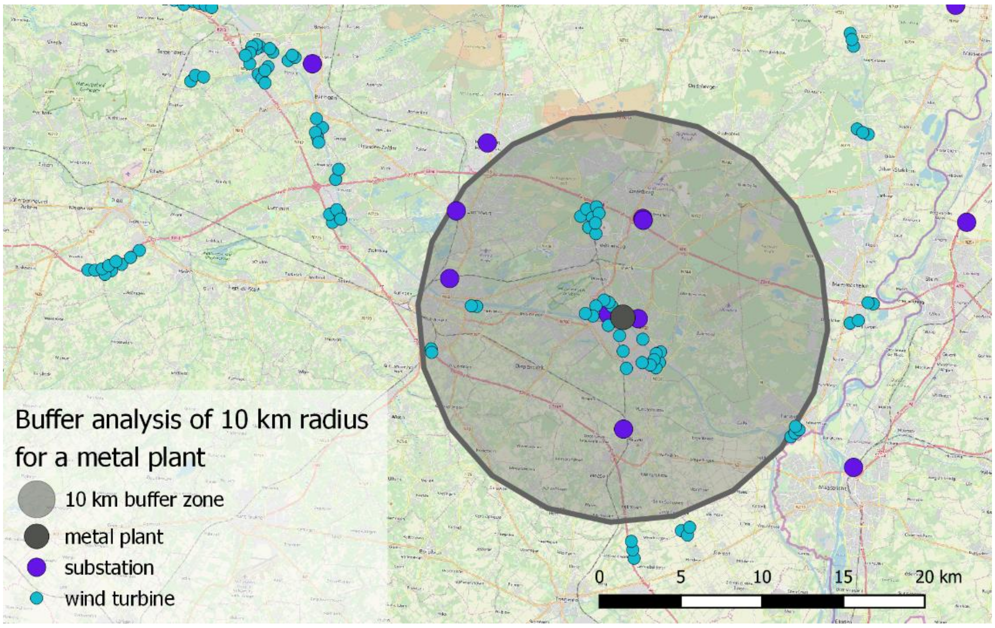


Figure 3-9: An example of a buffer analysis of 10km radius (gray area) around single metal plant, that includes the metal plant (gray), substations (purple) and wind turbines (blue)[27]

The three buffer analyses were implemented to each of the five industry layers separately resulting in 15 new layers, each containing data of the number of wind turbines around a single plant.

Finally, the created polygon layers were converted to .csv files and their data, containing information about the CO_2 emissions as well as the number of wind turbines, was fed into spreadsheets for further calculations. From these layers the final CO_2 emissions were generated, for each industry in each of the buffer criteria, as well as the number of wind turbines within the 10 km radius. An example of such excel spreadsheet with generated results is shown on Figure 3-10, where the buffer criteria "more than 50 wind turbines in 10 km radius" or "very high potential" was applied. The result shows that a total amount of 54 617 kt/year of CO_2 is emitted from the 100 sites that belong in this criteria. A total of 9 701 wind turbines are located within the 10 km radius of these 100 sites.

1	Lat	Long	Main Activity (and no.of plants)	CO_2 (kt/a)	Number of wind tubines
79	5.312.493	868.673	2.(c)	549	65
80	5.081.891	901.114	2.(d)	217	54
81	4.369.597	-747.375	2.(e)	412	116
82	4.294.820	-917.315	2.(e)	156	248
83	4.298.363	-908.549	2.(e)	182	289
84	5.261.934	687.345	5.(a)	160	58
85	4.960.350	717.141	5.(a)	105	96
86	5.070.242	807.318	5.(a)	123	92
87	5.312.475	872.721	5.(a)	269	60
88	4.836.000	176.000	5.(b)	108	82
89	5.189.704	427.639	5.(b)	1430	122
90	5.239.975	479.289	5.(b)	1170	50
91	5.702.436	1.001.641	5.(b)	182	51
92	5.168.326	458.162	5.(b)	913	52
93	5.354.789	861.801	5.(b)	285	100
94	5.151.888	657.641	5.(b)	220	51
95	5.083.799	630.958	5.(b)	364	80
96	5.118.156	1.201.945	5.(b)	299	147
97	5.158.196	1.397.745	5.(b)	221	123
98	5.330.972	698.764	5.(b)	381	141
99	5.319.045	542.910	5.(b)	240	90
100	5.745.307	1.003.202	5.(b)	102	94
101	5.168.962	458.016	5.(c)	161	53
102	**Total**		**100**	**54617**	**9701**

Figure 3-10: An example of the result for the buffer analysis "*more than 50 wind turbines in 10 km radius*" for all sectors, in an excel spreadsheet

3.2.2 Buffer analysis (biogas plants)

Additionally, a buffer analysis for the biogas plants was performed. Firstly, a buffer analysis to the substations was done. The geographical distribution of the considered substations is presented in Figure 2-5. The analysis was done using a geo-informational tool called *Voronoi diagram*, for selecting the substations with wind turbines in their closes area. A preview of the process is shown in Figure 3-11. With the *Voronoi diagram*, a region is formed around a single point (substation), where all points (in this case wind turbines) within the region are closer to the starting point than all other existing points. Each point in one of the polygons created in this way is therefore closer to the corresponding substation than to any other substation. If a wind turbine is located inside a polygon, it can be assumed with sufficient certainty that it is connected to the one substation defining the respective polygon since any other connection would have to bridge a longer air-line distance. In this way, it is possible to identify all substations that may potentially have direct access to electricity from wind energy. An additional geodata processing was performed to enhance data quality close to coastlines. Here, due to geometrical simplification of meandering coastlines some data points were erroneously located outside the land-polygons (in the water) and therefore disregarded by the analysis algorithms. We therefore added an additional buffer zone outside all shorelines to add a 2 km zone for ensuring that close-shoreline power generators as well as substations or industrial plants are not neglected. Both, coastal line extension and Voronoi polygon generation are depicted in Figure 3-11.

The process of the buffer analysis for the biogas plants was performed in the same way as for industrial CO_2 sources described above. The result from the buffer analysis is presented in Figure 5-3.

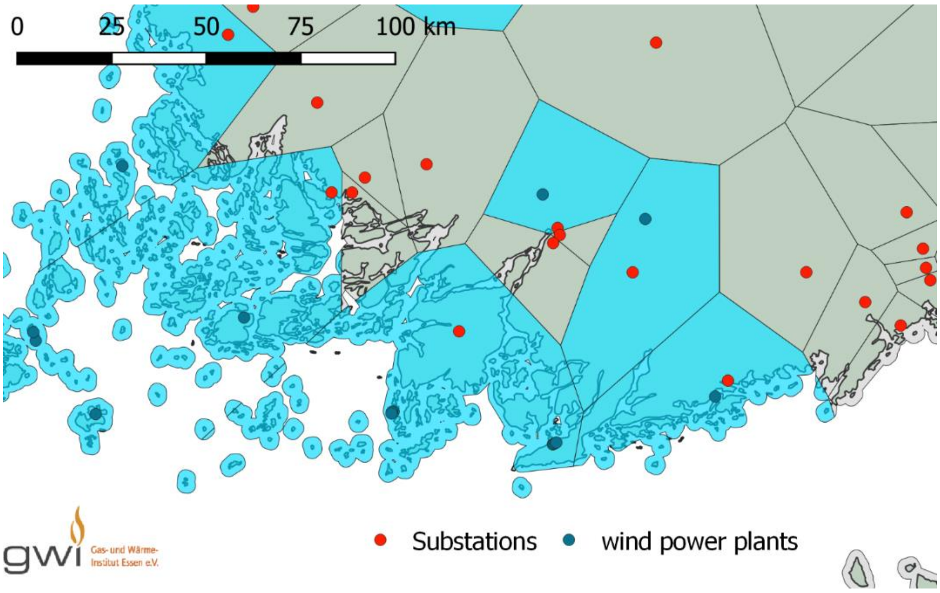


Figure 3-11: Voronoi polygons generated for assigning the wind turbines to the closest substation

4 Calculation of methanation potentials

Based on the literature review described in chapter 2.1.3, for the calculations in this paper the 90 % value was chosen as a carbon capture potential that can be applied to all of the 5 selected industries.

After implementing the 90 % capturing potential to the already defined CO_2 quantities of each industry, the potential CO_2 for methanation was defined and calculated.
Hydrogen is synthesised with CO_2 into methane through a catalytic Sabatier process:

$$4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O \qquad \Delta H = -167\,\frac{kJ}{mol}$$ **Equation 4-1**

Subsequently, the potential methane, in kt/a, was calculated by using the ratio of the molecular mass of methane and CO_2, resulting in the following figure:

$$\frac{CH_4}{CO_2} = \frac{M_{CH_4}}{M_{CO_2}} = 0.36$$ **Equation 4-2**

Where M_{CH4} = 16.04 g/mol and M_{CO2} = 44.01 g/mol.

Taking the aggregated usable CO_2 amount of 511 987 kt/a, from the total 956 industrial plants in the EU28+5, and applying the 90 % capturing potential, results to an amount of 460 788.3 kt/a of theoretical captured CO_2. Adding the conversion factor 0.36 (equation 4-2) to this potential CO_2 amount yields a theoretical amount of methane of 165 883.8 kt/a.
Assuming a complete conversion of the potential CO_2 to methane, with a gross calorific value of methane of $H_{s,CH4}$ = 15.4 kWh/kg (at 25 °C / 0 °C, 1 atm), this corresponds, via the following equation:

$$Q_{CH_4} = H_{s,CH_4} * \dot{m}_{CH_4}$$ **Equation 4-3**

to a potential energy of 2 586.27 TWh/a (where $\dot{m}_{CH4}$ is the amount (mass flow) of CH_4 in kg/a).

An example of such a calculation is shown in Table 4-1 for the waste incineration industry, where the captured CO_2 quantity of 63 401 kt/year results in a theoretical methane production potential of 320 TWh/year.

Waste incineration						
Number of countries	No. plants	Total emitted CO_2 (kt/year)	CO_2 capturing potential	Potential available CO_2 for methanation (kt/year)	Potential methane from CO_2 (kt/year)	Potential methane energy (UCV) (TWh/year)
20	213	63 401	90 %	57 061	20 796	320

Table 4-1: An example of the potential annual methane production for the waste incineration sector [3]

After implementing the same calculations on each industry separately and summing up, a total potential is reached. With an assumption of an average of 90 % CO_2 capturing rate implemented in the five focused industries, a total methane production potential in the order of magnitude of 1 000 up to 2 500 TWh/a is expected for the final results that will be published together with the PtM potentials from biogas, the corresponding electricity demands, outlook on the future portfolio of CO_2 sources and assessment of results in the future report D8.9.

5 Summary

The objective of this Deliverable is to describe the methods and data used to identify the potential locations for large scale renewable energy storage via power-to-gas in Europe as well as the potential methane quantities that may result from the conversion of CO_2 from energy-intensive industry sectors as well as biogas plants.

As an outcome of the previous sections, the following key messages can be concluded:

- Acquiring data for the location of the large-scale industrial plants as well as their CO_2 emissions was done by accessing the database of the European Pollutant Release and Transfer Register.

- Obtaining the data (locations, size of plants, production quantities…) for the biogas plants is a complex task. Data from different sources (associations and national agencies) was summarized where the varying organizational structures of the countries in the field of biogas across Europe had to be taken into account.

- The geoinformational analysis (the buffer analysis of the industry sector) showed:

  - 58 % of the total industrial plants have at least 1 wind turbine within a 10 km radius buffer zone, without any substantial differences in the distribution among the industry sectors, as shown on Figure 5-1. The high share of industrial sites exhibiting renewable generation within their proximity already today demonstrates the high potential of PtG plants as sector coupling elements.

			Buffer analysis (in 10km radius)					
		CO_2	At least 1 wind turbine		10 to 50 wind turbines		> 50 wind turbines	
Industry	No.of facilities	emissions (kt/a)	Number of sites	Share of plants (%)	Number of sites	Share of plants (%)	Number of sites	Share of plants (%)
Metal	123	140577	67	54%	29	24%	9	7%
Chemical	171	98655	115	67%	40	23%	35	20%
Paper	137	71057	72	53%	26	19%	8	6%
Waste incineration	213	63401	147	69%	55	26%	18	8%
Mineral	312	138297	155	50%	71	23%	30	10%
Total	956	511987	556	58%	221	23%	100	10%

Figure 5-1: Buffer analysis (all 3 criteria) implemented to the 5 selected industries and their potential sites for PtG (in %) [3] (own illustration)

  - The wind energy availability among the five industry sectors shows almost equal distribution. Contrary to that, the wind energy availability among the countries exibits considerable differences. The highest potential for PtG plants is presented in Germany (because of the highest number of wind turbines installed today), followed by the United Kingdom, France and Belgium, as illustrated in Figure 5-2

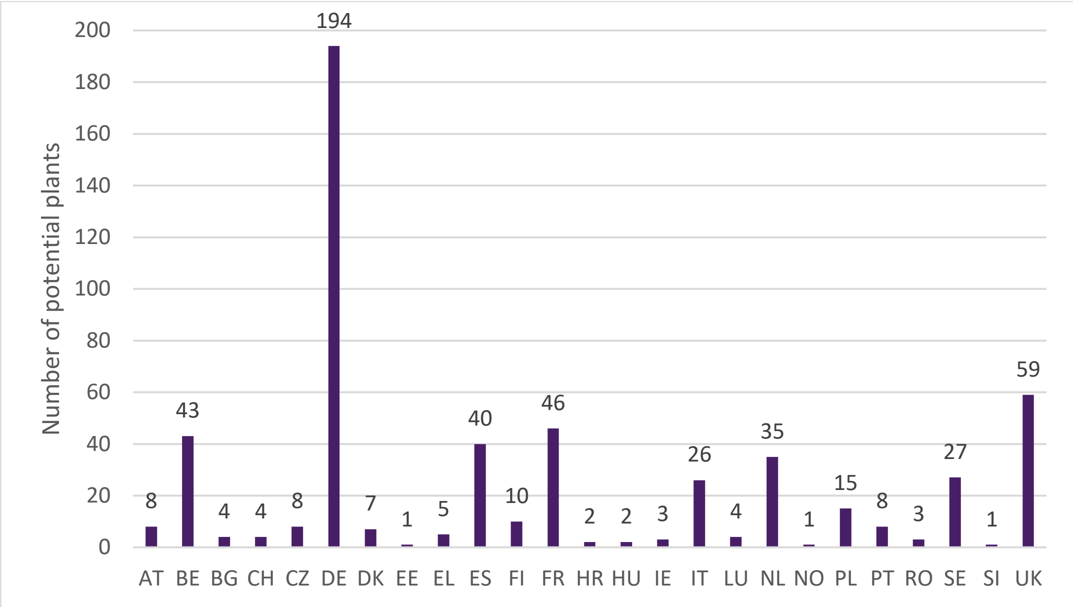


Figure 5-2: Number of potential power-to-methane plants in the five studied industry sectors (at least one wind turbine in 10 km buffer radius)

- The geoinformational analysis of the PtG plants located at biological CO_2 sources shows a wider distribution among the countries, with an exception of Germany that exhibits the highest potential for PtG plants (because of the high number of wind turbines and biogas plants installed today), followed by United Kingdom, as it is ilustrated in Figure 5-3. With an expectable deeper penetration of bio-based energy generation across Europe, all member states are expected to show increasing bioenergy production and consequently rising potentials for biogas-based power-to-methane energy conversion. The potential study will present quantitative results in the following Deliverable D8.9.

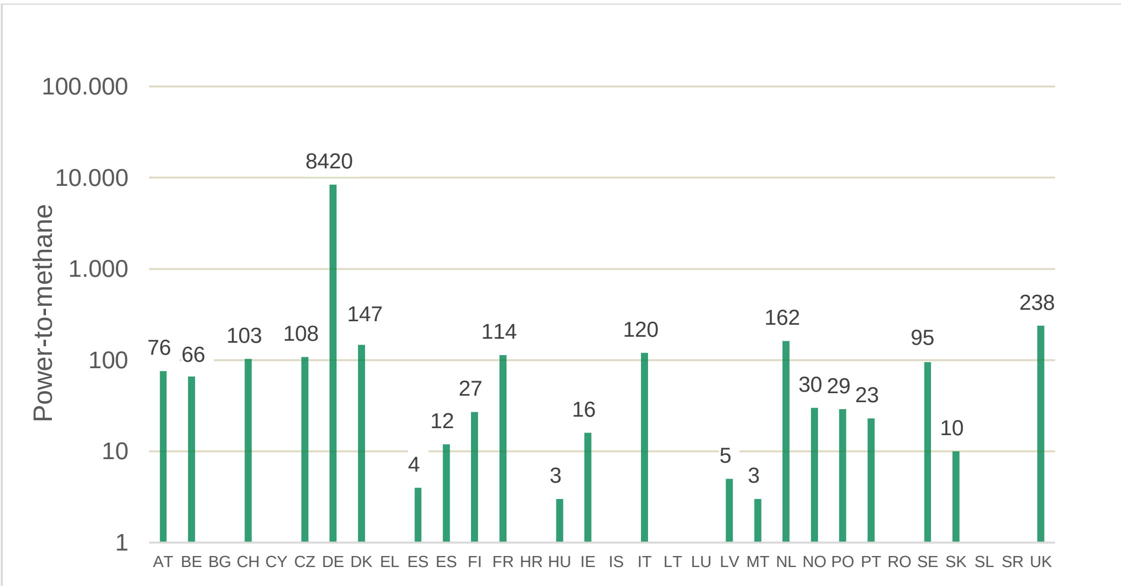


Figure 5-3: Number of potential power-to-methane plants to convert CO_2 from biogas plants

This Deliverable reports step by step the data acquisition approach as well as data handling and analysis methods developed in the course of the ongoing research within Task 8.3 of the STORE&GO project. The methane production potential from integrated biogas and power-to-methane plants as well as all deduced final results from industrial as well as from biological CO_2 sources as a feedstock for synthetic methane in Europe will be subject of the following Deliverable D8.9. That Deliverable will also include the PV potential analysis and the corresponding PtM potentials using biological CO_2 sources, the corresponding electricity demands for renewable gas production, with given outlook on the future portfolio of the CO_2 sources as well as an assessment of the final results. Minor modifications in the method and corrections of datasets are reserved until publication of the final Deliverable D8.9, planned for February 2020.

Bibliography

[1] Horizon 2020, 'Research and demonstration project STORE&GO, grant agreement No 691797'. [Online]. Available: http://www.storeandgo.info/. [Accessed: 15-Apr-2016]

[2] S. Schiebahn, T. Grube, M. Robinius, V. Tietze, B. Kumar, and D. Stolten, 'Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany', *International Journal of Hydrogen Energy*, vol. 40, pp. 4285–4294, Feb. 2015.

[3] European Environment Agency, 'European Pollutant Release and Transfer Register (E-PRTR)'. European Environment Agency.

[4] 'NACE codes'. [Online]. Available: http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

[5] 'UNSTATS - United Nations Department of Economic and Social Affairs - Statistics Division'. [Online]. Available: https://unstats.un.org/unsd/classifications/

[6] Statistical Office of the European Communities, *NACE Rev.2: statistical classification of economic activities in the European Community.* Luxembourg: Office for Official Publications of the European Communities, 2008.

[7] K. Vatopoulos, J. A. Moya, N. Pardo, European Commission, Joint Research Centre, and Institute for Energy and Transport, *Prospective scenarios on energy efficiency and CO2 emissions in the EU iron & steel industry*. Luxembourg: Publications Office, 2012.

[8] M. Gazzani, M. Romano, and G. Manzolini, 'Application of Sorption Enhanced Water Gas Shift for Carbon Capture in Integrated Steelworks', *Energy Procedia*, vol. 37, pp. 7125–7133, 2013.

[9] 'H2Future', *H2Future project*. [Online]. Available: https://www.h2future-project.eu/technology

[10] Brigitte Pechar, 'Linz bekommt die größte Wasserstoff-Pilotanlage der Welt' [Online]. Available: https://www.wienerzeitung.at/nachrichten/wirtschaft/oesterreich/959128_Linz-bekommt-die-groesste-Wasserstoff-Pilotanlage-der-Welt.html

[11] IEA, 'Cement Technology Roadmap 2009 Carbon emissions reductions up to 2050', 2009 [Online]. Available: file:///C:/Users/cig/Zotero/storage/RFQVX7UV/Cement.pdf

[12] M. Hornberger, R. Spörl, and G. Scheffknecht, 'Calcium Looping for CO2 Capture in Cement Plants – Pilot Scale Test', *Energy Procedia*, vol. 114, pp. 6171–6174, Jul. 2017.

[13] 'CEMCAP'. [Online]. Available: https://www.sintef.no/projectweb/cemcap/

[14] K. Jordal *et al.*, 'CEMCAP – Making CO2 Capture Retrofittable to Cement Plants', *Energy Procedia*, vol. 114, pp. 6175–6180, Jul. 2017.

[15] T. P. Hills, M. Sceats, D. Rennie, and P. Fennell, 'LEILAC: Low Cost CO2 Capture for the Cement and Lime Industries', *Energy Procedia*, vol. 114, pp. 6166–6170, Jul. 2017.

[16] J. Kjärstad, R. Ramdani, P. M. Gomes, J. Rootzén, and F. Johnsson, 'Establishing an integrated CCS transport infrastructure in northern Europe–Challenges and possibilities', *Energy Procedia*, vol. 4, pp. 2417–2424, 2011.

[17] D. Leeson, N. Mac Dowell, N. Shah, C. Petit, and P. S. Fennell, 'A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources', *International Journal of Greenhouse Gas Control*, vol. 61, pp. 71–84, Jun. 2017.

[18] J. Jönsson, 'Analysing different technology pathways for the pulp and paper industry in a European energy systems perspective', p. 124.

[19] S. Mesfun and A. Toffolo, 'Optimization of process integration in a Kraft pulp and paper mill – Evaporation train and CHP system', *Applied Energy*, vol. 107, pp. 98–110, Jul. 2013.

[20] KARIN PETTERSSON, 'Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO2 Emission Balance', CHALMERS UNIVERSITY OF TECHNOLOGY, Sweden, 2011 [Online]. Available: file:///C:/Users/cig/Zotero/storage/WXX83N4L/Gasification%20of%20black%20liquor-Pettersson.pdf

[21] 'Demonstrating CO2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study', Element Energy Ltd Carbon Counts Ltd PSE Ltd Imperial College University of Sheffield, Apr. 2014 [Online]. Available: file:///C:/Users/cig/Zotero/storage/UGXUF6T2/demonstrating-co2-capture-uk-cement-chemicals-iron-steel-oil-refining-sectors-2025-techno-economic-study-appendix.pdf

[22] P. Zakkour and G. Cook, 'CCS Roadmap for Industry: High-purity CO2 sources Sectoral Assessment – Final Report'. Unpublished, 2010 [Online]. Available: http://rgdoi.net/10.13140/RG.2.1.3717.8722. [Accessed: 10-Jan-2019]

[23] EBA, 'Statistical-report-of-the-European-Biogas-Association_excerpt-web_EBA_2017.pdf'. 05-Sep-2018 [Online]. Available: http://european-biogas.eu/wp-content/uploads/2017/12/Statistical-report-of-the-European-Biogas-Association_excerpt-web.pdf. [Accessed: 05-Sep-2018]

[24] 'EBA'. [Online]. Available: http://european-biogas.eu/

[25] D. Thrän *et al.*, 'Sustainable Strategies for Biomass Use in the European Context', IE, UHOH, BFH, ÖI, Leipzig, 2006.

[26] Frank Graf and Siegfried Bajohr, *Biogas - Erzeugung, Aufbereitung, Einspeisung*, 2. Auflage. Karlsruhe: Deutscher Industrie-Verlag, 2013.

[27] FOSSGIS e.V., 'OpenStreetMap', *openstreetmap.de*, Jul-2004. [Online]. Available: www.openstreetmap.de. [Accessed: 05-Mar-2015]

[28] 'QGIS'. [Online]. Available: http://www.qgis.org/de/site/. [Accessed: 22-Sep-2015]

[29] 'NUTS'. [Online]. Available: https://ec.europa.eu/eurostat/web/nuts/background

[30] M. Zapf, *Stromspeicher und Power-to-Gas im deutschen Energiesystem*, vol. 1. Springer Vieweg, 2017.

[31] 'Wind Europe'. [Online]. Available: https://windeurope.org/

[32] Dr. Thomas Benz, 'Energietechnische Gesellschaft im VDE'. [Online]. Available: http://www.fze.uni-saarland.de/AKE_Archiv/AKE2017F/Vortraege/AKE2017F_06_Benz_DC-imVerteilnetz.pdf

[33] eurostat, 'Regions in the European Union - Nomenclature of territorial units for statistics', European statistical system EES, Luxembourg, 2016 [Online]. Available: http://ec.europa.eu/eurostat

Acknowledgements

Funding by the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 691797 is gratefully acknowledged.

Hristina Cigarida gratefully acknowledges the funding by Deutsche Bundesstiftung Umwelt (DBU) as a part of the MOE-Austauschstipendienprogramm 2018.