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

STORE&GO

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

D8.9

Report on an EU-wide potential analysis of power-to-gas locations coupled to local CO_2 and renewable energy sources

Due Date	2020-02-29
Deliverable Number	D8.9
WP Number	WP8, Task 8.3
Responsible	Johannes Schaffert, Gas- und Wärme-Institut Essen e.V. (GWI)
Author(s)	Schaffert, Johannes; Cigarida, Hristina; Coquette, Dominik; Leukefeld, Jan; Lange, Manfred; Levedag, Dario; Albus, Rolf; Burmeister, Frank; Görner, Klaus
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	Authors	Description
0.1	2019-10-14	HC, DC	Drafting
0.5	2019-11-26	HC, DC, JL	Drafting
1.0	2020-01-08	HC, JL	Drafting
1.5	2020-01-20	HC	Drafting, first version for partners
2.0	2020-01-27	JS	Internal Review
2.1	2020-02-07	HC, JS	Amendments
2.2	2020-02-14	HC, JS	Internal Review
3.0	2020-02-20	JS	Internal Review
3.6	2020-03-02	JS	Internal Review
3.7	2020-03-10	JS, HC, JL	Internal Review and amendments
7.3	2020-04-08	JS, HC, ML, JL	Finalising consolidated version
7.5	2020-04-09	JS	Final Version

Contents

List of Figures

List of Tables

Abbreviations

BLG	Black-Liquor Gasification
CAPEX	Capital Expenditure
CC	Carbon Capture
CH_4	Methane
CLC	CORINE Land Cover
CO_2	Carbon dioxide
DAC	Direct Air Capture (of CO_2)
EEA	European Environment Agency
E-PRTR	European Pollutant Release and Transfer Register
EU	European Union
GHG	Green House Gas
GIS	Geographical Information System
GPPD	Global Power Plant Database
GWI	Gas- und Wärme-Institut Essen e.V.
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
OPEX	Operational Expenditure
OSM	OpenStreetMap
PtG	Power-to-gas
PtM	Power-to-methane
PV	Photovoltaics
QGIS	Geographic-Information-System used for geographic analyses
RES	Renewable Energy Sources
SEM	Solar Energy Map
SNG	Synthetic Natural Gas (= technically produced methane)

Executive Summary

The **objectives of this work** were to identify suitable locations for power-to-methane (PtM) in Europe and to estimate the methane production potential for 2050.

The **PtM location identification** is based on the concept of coupling existing CO_2 sources (biogas and industrial plants) with locally available renewable energy (RE) sources, i.e. wind turbines and utility-scale PV systems. The **data acquisition** was performed by researching publicly available data on renewable energy generation and biogas production sites, as well as by manual research to confirm or extend the available data. For the industrial CO_2 emissions, the European Pollutant Release and Transfer database was exploited.

A highly resolved **geo-information data model** was used to calculate the local correlations of CO_2 availability and renewable energy production throughout Europe. CO_2 sources exhibiting large-scale renewable energy generation within a radius of 10 km were identified as potential PtM energy conversion sites, enabling local energy sector coupling and the production of methane.

Additional information such as the locations and distances between potential energy conversion sites and substations from the electricity system or other infrastructures can be visualised and included in the assessments. The local land use e.g. in terms of the exact polygons of agricultural land may be utilised for example to model future erections of photovoltaic plants, as presented in the **case studies** of chapter 8.

The **projections of the 2050 methane production potentials** were carried out on national level. Since the design of this study centres the development of power-to-methane plants around existing CO_2 sources, the production potentials were assessed on the basis of two scenarios for the future availability of CO_2: a *limited CO_2 availability scenario* and a *balanced CO_2 availability scenario*, respectively.

The resulting **power-to-methane maps** provide insights into the possibilities of developing a methanation technology rollout starting from the status quo of renewable energy infrastructure in Europe.

As an outcome of this work, the following **key results** can be summarized:

- **PtM potentials exist all across Europe**, as most of the CO_2 point sources exhibit RE generation in their proximity (10 km) already today. 15 789 out of 17 868 (88 %) analysed CO_2 point sources were identified for potential local energy coupling. Of the large countries with respect to area, Denmark and Germany exhibit the highest shares (98 % of the located points) due to the high numbers of wind turbines and CO_2 sources.

- Already today, **50 % of all CO_2 sources** included in the study show potential for energy coupling based on the local availability of <u>both</u> considered RE sources. The **combined supply with wind power and utility-scale PV** plants leads to synergies beneficial for the operation of the conversion technologies due to complementing load profiles that lead to enhanced full-load hours based on local RE production. These conditions were found for 316 industrial and 8 648 biogas plants. As of today, most of the identified potential sites are located in Germany. However, with an anticipated deeper penetration of RE generation in Europe, all nations are expected to show an increase in PtM potentials, reaching the same high level of geographical correlation and even exceeding it.

- Case studies for the proximities of the three STORE&GO demonstration sites located in Germany, Switzerland and Italy yield **detailed local insights** into the developed dataset. Potentials for future PV plant expansion are taken into account as well. The case studies show that despite the very different prerequisites all focussed areas exhibit potentials for methane production using local RE and CO_2 sources.

- Finally, this report presents **European Power-to-Methane Potential Maps** showing projections for the potential methane production in 2050. Calculations are based on two scenarios:

  The Limited CO_2 Availability Scenario is based on an extremely deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 95 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, a conservative estimation is made by further reducing the minimal biomass potentials for residues and forestry to 1/3 of literature values. The energy crop potentials are even reduced to 1/6 in order to consider lacking social acceptance and ecologic drawbacks of energy crop cultivation. By these steps, an ecologic rather than maximal exploitation of European biomass potentials as well as evolving usage competitions are considered. The total 2050 PtM potential based on the *limited CO_2 availability scenario* is 1 320 TWh/a. The methane share produced from industrial CO_2 is 130 TWh/a, while the methane from the green CO_2 sources amounts to 1 190 TWh/a, demonstrating the dominating role of biogenic carbon sources in a deeply defossilised future.

  The Balanced CO_2 Availability Scenario is based on a deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 90 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, a balanced estimation was made based on the same assumptions for residues and forestry but a loosened restriction for the exploitation of energy crop potentials (1/3 of literature values). The PtM potential for 2050 amounts to 1 650 TWh/a. The share of the potential methane from industrial CO_2 sources is 260 TWh/a, and the methane from green sources 1 390 TWh/a.

- The outcomes of the study may be evaluated by means of their potential to cover the European gas demand 2050 by comparing to literature. The results of this assessment correspond to approximately 38 – 176 % of the 2050 methane demand for the chosen scenarios. Methane production using CO_2 from biomass and remaining industrial sources may therefore play a crucial role in the energy system of the future.

1 Introduction

Energy storage emerges as a key enabling technology for addressing the flexibility requirements for integrating variable renewable electricity into the energy system and thus to provide green energy for transport, industry, commerce and households temporally decoupled from electricity production. Large amounts of variable renewable electricity can be stored in the form of hydrogen and derived e-fuels such as methane, providing significant flexibility and even seasonal balancing to the electricity system and enabling the decarbonisation of all energy-consuming sectors.

Within the European research and demonstration project STORE&GO [Hori00], the methanation option is broadly studied. The results range from technical developments, engineering, system integration, various plant designs and operation to economic analyses, business models, legal framework, life cycle assessments, potential analysis, a power-to-gas roadmap and policy recommendations.

1.1 Objective of this Deliverable

This report presents the results of a potential analysis conducted in STORE&GO Work Package 8, task 3. The objective of the work was to analyse and map the potentials for power-to-methane technologies across Europe by taking into account the geographical implications of the availability of the local feedstocks, renewable electricity and carbon dioxide as boundary conditions. This is achieved by researching location data to locally match CO_2 sources with wind power and PV production, and thus to gain insight into the regional potentials for local sector coupling by power-to-gas across Europe.

Biogenic and industrial point sources as well as carbon capture technologies are presented, and potentials are discussed and compared to the European demand for (decarbonized) gases. Where possible, future outlooks are given e.g. concerning future technology costs or gas demand. In the field of PV potentials agro-photovoltaics are taken into account. The geographical analysis leads to a set of power-to-gas potential maps that yield insight to the distribution of suited technologies and feedstocks to be coupled for the production of synthetic methane across Europe. Finally, exemplary case studies conducted for the three STORE&GO demo sites highlight the lateral resolution of the resulting data sets, and zoom into the specific local opportunities. A summary briefly recapitulates the key findings. The results contribute to the final Deliverables D8.10 and D8.11, which contain a roadmap for power-to-gas in Europe as well as policy recommendations, and will be published via the STORE&GO project homepage[1].

[1] www.storeandgo.info

2 CO_2 and hydrogen as feedstocks for methanation

Each power-to-methane installation depends on two input gas streams, CO_2 and hydrogen, to be converted into synthetic methane in the methanation step.

2.1 Green and grey CO_2 sources

One of the key questions for a future large-scale implementation of methanation technologies in the EU is the quantity of CO_2 available for a substitution of the fossil natural gas distributed today. The large-scale production of SNG via methanation requires high CO_2 availability and volume flow as well as preferably high purity. In this report, CO_2 sources are divided into the two categories 'green' and 'grey'. The green CO_2 sources consist of biomass and direct air capture while grey sources refer to industrial emitters.

The annual availability of **biomass** is reliable but limited as a matter of principle. A study done by the University of Groningen in the course of STORE&GO shows that the European quantities of biomass in 2050 will be in the range of 6 to 30 EJ [Faai18]. Another study by Thrän *et al*. reports that the biomass availability in Europe will be between 3.6 and 8.6 EJ (1 000 TWh and 2 390 TWh) [ThMü11]. In this work, the latter study will be used for reference, with the aim to not overestimate the potentials for CO_2 from biomass sources for power-to-methane processes.

Direct air capture technologies are an additional promising solution for green CO_2 provision in the future, since they separate the CO_2 molecules from ambient air and provide the gas feed to methanation reactors independently of any industrial flue gas or biogas stream and related infrastructural boundary conditions. It is in principle only limited by the availability of renewable electricity. Due to the low CO_2 content of ambient air the direct air capture technology requires high energy inputs for separating the molecules.

Industrial facilities as sources of grey CO_2 will remain the largest point sources of concentrated CO_2 for sequestration and utilisation in methanation and other Power-to-X processes, although in order to reach the Paris agreement goals drastic CO_2 reductions in the industrial sector need to be achieved.

All three classes of potential CO_2 sources for power-to-gas and related technologies will be discussed in chapters 3 and 4.

2.2 Hydrogen

The world currently consumes more than 55 Mt/a hydrogen (million tons per annum), as reported by the Hydrogen Council, of which some 95 % stem from fossil fuels. 55 % of the total hydrogen amount is used for ammonia production, 25 % in petroleum refining, and about 10 % for methanol production [AaEH18].

Hydrogen can be blended with natural gas and used in the residential and commercial sector as well as industry or transportation, or be used for fuel synthesis (combined with CO_2) e.g. to produce synthetic methane that can serve as a substitute for natural gas. **The blending option** may serve as a proportional decarbonisation measure which is available today from the technology perspective. However, due to technical reasons the admixing potentials are principally limited and maximum hydrogen tolerances are currently studied, e.g. in the EU-project THyGA [EDGG20].

Hydrogen and **derived power-to-gas products** such as methane can be effective decarbonisation fuels if produced with a low carbon footprint. Limiting factors concerning their large-scale implementation into the energy system include the learning rates for the costs of technologies like electrolysers and fuel cells, the further development of suitable infrastructure as well as European and national standards, technical rules and policies.

The Energy transition outlook [Dnvg18] projects that the global hydrogen demand in the industry will reach a value of 69 - 114 Mt in 2050 and that the iron and steel industry might be among the first movers in beginning to use hydrogen in the direct iron reduction steelmaking process in the range of 4 – 11 Mt of hydrogen by 2050 [AaEH18].

Application	Low-uptake scenario	Reference scenario	High-uptake scenario
Ammonia	35	41	54
Petroleum refining	11	13	15
Methanol	13	19	24
Other feedstock industry	6	8	10
DRI steelmaking	4	7	11
Total	**69**	**88**	**114**

Figure 2-1 Estimated demand for hydrogen as a feedstock in 2050 (Mtpa), DNV GL [AaEH18]

Hydrogen may enable greater fractions of renewables in the electricity mix (greater market penetration of renewables) as the surplus electricity from renewables can be valorised by converting renewable electricity into green fuels and thus paving a way for a deep integration of renewables in the fossil dominated sectors industry, mobility and heat. The production of green hydrogen via electrolysis from renewable energy causes almost zero GHG emissions. Hydrogen can also serve as seasonal storage of electricity (e.g. using salt caverns or depleted oil or gas fields as storages) over long periods [AaEH18]. Power-to-gas as the enabling large-scale energy conversion technology class may develop a strong momentum as a global key technology for decarbonisation measures across all energy-intensive sectors.

3 Carbon Capture / Carbon Capture and Use

One important option that could play a substantial role in decarbonisation is **carbon capture** (CC) as it is considered an important contributor for reaching the climate protection goals. This technology is technically feasible for the large CO_2 point sources such as the energy intensive industries studied in this report. Unlike carbon capture and storage (CCS), which has raised a lot of questions about acceptance and risks, **carbon capture and usage** (CCU) has the potential of converting CO_2 into high-value products, and enables the development of closed carbon circles. There are several pilot CCU projects (some of which described in 3.1) that are in different stages of technical maturity. Nevertheless, capturing rates of 90 % and above may be achieved throughout the fields of application. The captured CO_2 can be valorised as a raw material for carbon-based products or for production of power-to-gas products such as SNG (methane), which may contribute to a sustainable transition of the industry, mobility and heating sector.

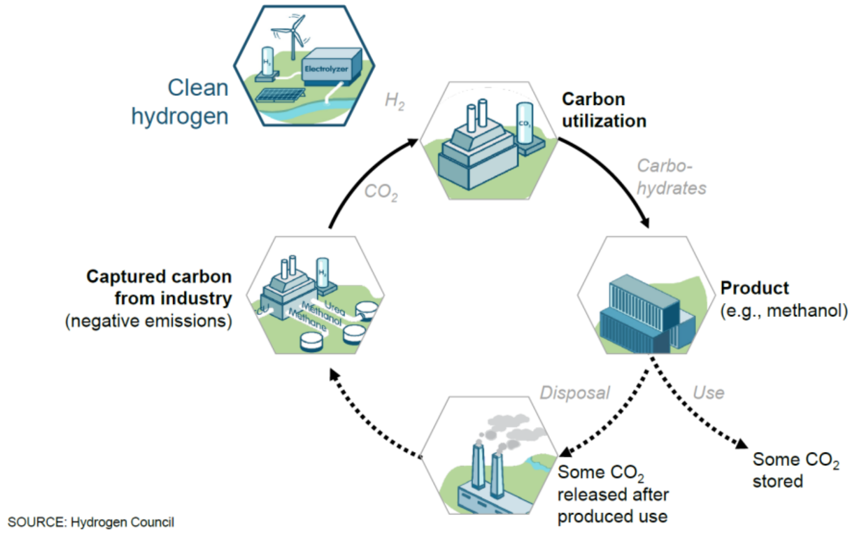


Figure 3-1 Carbon capture cycle (Source: Hydrogen council [Hydr17])

Facing the 2 °C target and the need for a substantial reduction of GHG emissions by 2050, first industries recognised their crucial role and recognize the necessity of a sustainable industry transition. Indeed, a swift development of innovative technologies is needed to meet the challenge of up to 95 % industrial CO_2 emission reduction targets while maintaining productivity.

Where CC or CCU technologies are applied in industrial processes today, they are implemented into the overall process design to meet certain requirements of the individual process such as lowering the emissions of the plant or treatment/upgrading of the product gases for further process steps [BZGT18]. Due to the high level of industrial plant integration in the energy-intensive industry sectors, CO_2 separation technologies typically cannot straight-forwardly be added in terms of retrofit installations. Suitable access to flue gases at certain temperature levels needs to be chosen to not interfere with the demands of the production processes itself. For large and complex plant designs, individual solutions must be developed based on local boundary conditions and feasibility.

Currently, even the most advanced CO_2 capturing technologies have certain drawbacks, mostly due to the large amounts of energy that are needed to capture the CO_2, resulting in either extra energy demands or efficiency losses. Potential advances might be offered by innovative capturing technologies using high-temperature fuel cells that allow power to be generated while capturing CO_2. A number of studies regarding this technology focus on SOFC and MCFC types of fuel cells in combination with cryogenic CO_2 separation and oxy-combustion with condensation [Grol09, Iea19].

Leading industrial enterprises report on new technological advances on how to significantly reduce greenhouse emissions. Some of these were already presented in the previous Deliverable D8.7 [SCLL19]. The following subsections present a brief overview and the latest projects on industrial carbon capture technologies.

3.1 Carbon capture and use options in industry

The CO_2 capturing potential for the most energy-intensive industrial sectors in this analysis is based on publications and latest projects in the field. As literature generally suggests, a CO_2 separation ratio of about 90 % is achievable at a number of predominant processes in the most energy-intensive industries selected for investigation.

Metal industry

The metal industry is characterised as the most energy-intensive manufacturing sector. The demand for iron and steel demand is expected to continue to rise in the future, so carbon mitigation is essential for this sector, given its importance [VMPE12]. Applying different carbon capture technologies in steel plants, like the Sorption Enhanced Water Gas Shift (SEWGS) process, may result in 85 – 90 % carbon capture potentials, according to Gazzani *et al.* [GaRM13].

Gradual decarbonisation strategies by **co-firing of biogas or hydrogen** exist already today with the status quo of plant setups. However, they are not expected to fulfil the 2050 demand for a deep decarbonisation of the sector.

End-of-pipe carbon capture and usage technologies as demonstrated in the *Carbon2Chem* project in Duisburg, Germany, offer potentials for a partial decarbonisation and downstream use of the CO_2 for the synthesis of e.g. chemical (precursor) products [Bund18] (see chemical industry).

The one outstanding and most anticipated technology option for a deep decarbonisation of the steel sector however is the use of hydrogen as a reductant in the **direct reduction** steel production process. Developments that allow the CO_2 emission-free process were for example made in a field trial at Voest in Linz, Austria, as part of the *H2Futur*e project, where a PEM electrolyser system (6 MW) is used to split water and produce “green” hydrogen at 80 % efficiency of the electrolysis process [H2fu00]. The produced hydrogen is used as a fuel for the steel making processes (direct reduction), substituting coke as the reducing agent and its related CO_2 emissions by water vapour [Ref00]. Another project, *HYBRIT* [SsLV00] is a project under planning in Luleå, Sweden, to implement the use of hydrogen from electrolysis in a direct reduction steelmaking process, as a joint venture between SSAB, LKAB and Vattenfall. The aim of the project is to achieve fossil-free steel by 2035. If successful, it can reduce Sweden’s CO_2 emissions by 10 % and up to 7 % globally, according to the consortium [SsLV00]. *HYBRIT’s* proposed direct reduction process is shown in Figure 3-2. The concept design shows that a sufficient H_2 storage capacity to balance the H_2 demand for the steel making process needs to be available, and the hydrogen supply will be generated by wind, hydro power or photovoltaics.

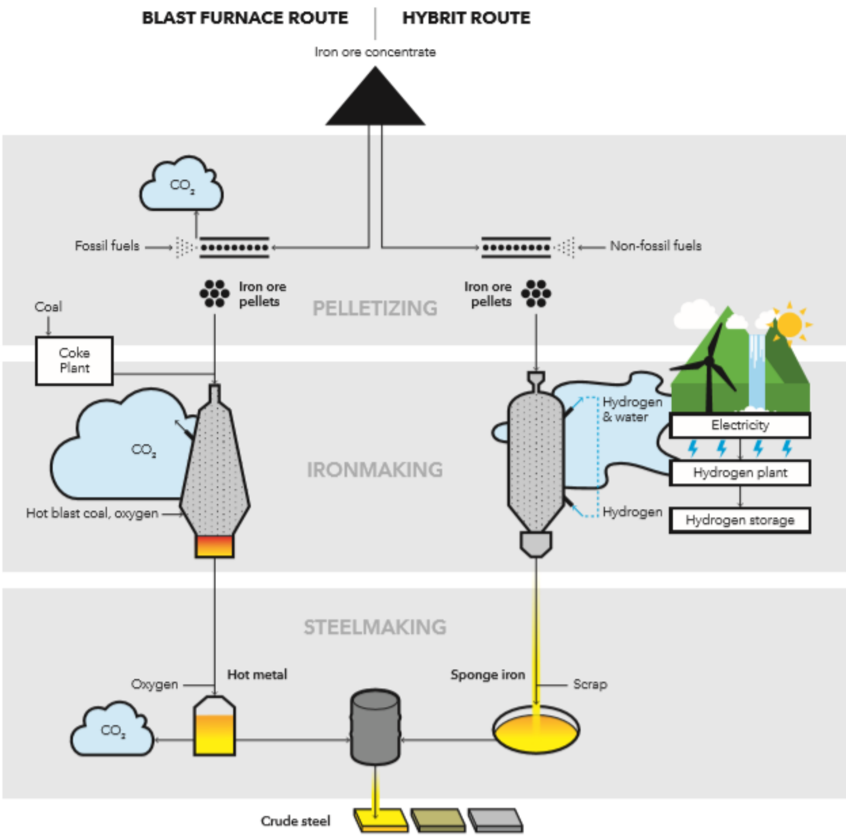


Figure 3-2 Direct reduction steelmaking process from the project HYBRIT (right-hand side) compared to classical coke plant based blast furnace route (left hand side) [AaEH18]

Cement industry

The CO_2 emissions from the cement industry, as part of the mineral sector, are the second largest right behind the metal industry. Most carbon capture technology options in the cement industry are post-combustion carbon capture processes [Ref09]. According to Hilz, a carbon capture potential of more than 90 % is achievable with directly and indirectly heated *carbonate looping* (CaL), even up to 95 % if applied to the cement industry and up to 92 % if applied to the steel industry [Hilz17, HoSS17]. The calcium looping technology, as well as *chilled ammonia* (CAP), *membrane-assisted CO_2 liquefaction* and oxy-fuel plus carbon capture, were also tested in the *CEMCAP* project [Cemc00]. The results showed CO_2 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 Stuttgart [JVSF17]. 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 [HSRF17]. A detailed description is given in Deliverable 8.7 [SCLL19].

Implementing solar energy in the cement industry for the clinkering process is one of the latest innovative ideas towards lowering the CO_2 emissions released during the process. The so called *solarisation* of the calcination step uses a solar reactor in which heat is supplied by concentrated solar power. Research done by Moumin *et al*. shows that the effect of the solarisation of cement plants with solar irradiation levels of Spain can result in a CO_2 reduction of the total CO_2 emissions from the cement industry in Spain of 2 – 7 %, while the implementation of a controlled sequestration may even lead to a 8 – 28 % reduction of CO_2 emissions [MRZM20].

A study by Markewitz *et al.* reports on post-combustion carbon capture options for the cement industry and shows 70 – 90 % CO_2 avoidance rates at costs in the range of 77 – 115 €/t CO_2 [MZRM19], while studies included in STORE&GO Deliverable D7.5 report lower costs [BZGT18], see 3.4.

Today, cement producers use coal as fuel, petroleum coke (petcoke) as well as co-firing of biomass or waste, depending on prices and the availabilities of the fuels. Whereas a fuel-switch from coal to a (partial) biogas or biomass combustion would require a modest retrofit of the plant-design, the replacement of coal with hydrogen requires a complete redesign of the burners as well as all affected peripheries.

Pulp and paper industry

The pulp and paper industry accounts for 2 % of the total global industrial emissions [LMSP17]. The Kraft mills, which are one of the two main production pathways of pulp and paper, have the largest potential of carbon capture in Europe, as they account for almost 73 % of the European pulp and paper CO_2 emissions [Jöns00]. Since the recovery boiler in the Kraft plant, where black liquor is burned, is the main source of CO_2 emissions, it is of special interest for the implementation of carbon capture technologies [MeTo13]. According to Pettersson [Ref11], 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.
Like in other industry sectors, a post-combustion carbon capture approach is usually considered as a retrofit option in this industry, as it does not need modification of the production plant itself (end-of-pipe technologies), in comparison to pre-combustion capture or oxy-fuel combustion [Jöns00].

Chemical industry

Ammonia, ethylene oxide production and hydrogen production by steam reforming of natural gas, as part of the chemical industry, are considered as high-purity CO_2 sources. The highly concentrated CO_2 feeds available as by-products of these processes result in low costs for carbon capture compared to other processes and industries [LMSP17]. Separation technologies used in the chemical industry include the use of chemical solvents, solid looping and cryogenic technologies [Demo14]. Selecting the appropriate process depends on a number of factors including gas inlet pressure, sizing and end use specification [ZaCo10].

Throughout the industrial sectors, **end-of-pipe carbon capture technologies** offer potentials for decarbonisation and downstream use of the CO_2 for the synthesis of chemical (precursor) products. Thus, new basic chemical production sites are expected to arise in the future, which supply the chemical sector with basic chemicals feedstocks made from recycled carbon. In this way, a sector coupling among historically distinct sectors becomes reality while completely new process routes and raw material transport chains develop. The recycled material may stem from all remaining large-scale processes that rely on combustion of fossil fuels, bio-fuels or waste (all fuels that lead to CO_2 emissions). Hydrogen combustion however, as well as electrified processes, drop out of the spectrum of potential CO_2 producers for carbon capture and use applications.
The *Carbon2Chem* project [Bund18] in Duisburg, Germany, links the steel and the chemical sector by implementing an end-of-pipe carbon capture step with a choice of innovative carbon-based production processes, leading to chemical products such as methanol, alcohols, OME or polymers. The

newly erected laboratory offers an infrastructure for collaborative development of various CCU products [DeOS00].

Waste incineration

The CO_2 generated from waste incineration plants is generally released into the atmosphere. According to the UK Environmental Agency, between 0.7 and 1.7 tons of CO_2 per ton of combusted municipal waste is generated and released into the air [Envi20].
Finding a way of how to re-use the carbon dioxide from these plants can offer environmental benefits and financial sustainability to this industry sector. An innovative recycling technology was tested in a project at the Twence demo plant in the Netherlands, where sodium bicarbonate ($NaHCO_3$) is produced using carbon dioxide captured from the flue gasses of the waste incineration process. The project aimed at evaluating the concept of on-site production, storage and re-use of carbon dioxide [Twen00].
Twence is a waste incineration and energy generating plant in Hengelo, Netherlands, where waste is used for heat and power production in a process called Waste-to-Energy (WTE). In this plant, the CO_2 from the flue gas is scrubbed and used for mineralization. The captured CO_2 is used to convert sodium carbonate to sodium bicarbonate in an innovative reactor. Using this process, 1 ton of carbonate is converted to 1.6 tons of bicarbonate. This plant produces 8 000 tons of sodium bicarbonate annually. The production of $NaHCO_3$ usually uses CO_2 that is obtained by burning fossil fuels. Using the closed CO_2 cycle in this process yields a reduction in the CO_2 emissions of 2 000 tons annually for this plant [HuRV16]. The sodium bicarbonate is then used to remove the acidic components in the flue gas before it is emitted into the atmosphere. The sodium carbonate, as raw material, is cheaper than the bicarbonate, so this process results with overall cost savings as well as lower CO_2 emissions [HuRV16].

The synergy between the waste incineration and the chemical industry can offer mitigation of the CO_2 emissions that are associated with the process of waste incineration while providing new synthesis routes for raw materials for the industry and the transportation sector.
A consortium comprising of Air Liquide, AkzoNobel Specialty Chemicals, Enerkem and the Port of Rotterdam aims at developing a Waste-to-Chemicals plant at the Port of Rotterdam, where non-recyclable waste materials will be transformed into valuable chemicals, helping the Netherlands to achieve the goal of becoming carbon-neutral by 2050 [Eu00].This plant is Europe’s first facility providing a sustainable solution for non-recyclable waste (including waste plastics and other mixed wastes) by converting them into raw material, methanol. The facility aims at converting up to 360 000 tons of waste into 220 000 tons (270 million litres) of methanol. The quantity represents the total annual waste production of 700 000 households and will achieve CO_2 emission savings of up to 300 000 tons per year [Eu00]. The waste is converted into methanol through the processes of gasification, syngas conditioning and catalytic synthesis. In the gasifier, around 90 % of the carbon in the waste is converted into syngas. The syngas is then conditioned and purified before being fed to the catalytic reactor where it reacts with a catalyst to produce methanol [Doyl18].

Large-scale projects, like the previously described, demonstrate the feasibility of industrial CO_2 emission reduction, hydrogen use, potentials and high value of various carbon capture technologies as well as the potential role of PtG, which might allow a widespread adoption of power-to-gas technologies in industrial settings in the future.

Based on the literature review conducted in this work, a value of 90 % is chosen as a carbon capture potential throughout the processes and industrial sectors to be applied to all subsequent calculations of carbon capture and use potentials for methanation processes.

3.2 Carbon capture and use at bio-methane plants

In the fermentation process of biomass for biogas production, a notable amount of CO_2 is obtained within the raw biogas. When the raw biogas is upgraded for the production of biomethane, a high-quality gas that can be injected into the natural gas networks, these CO_2 amounts are separated, leading to a high-quality CO_2 stream as a by-product. The working assumption for this study is that in future scenarios towards 2050, these CO_2 streams are not exhausted into the ambient air any-more, but instead used for the production of green methane via the power-to-methane route. Next to the availability of $CO_{2,}$ another advantage of bio-methane plants as potential sites for PtG units is that they already possess a feed-in point to the natural gas network. Thus, the potential erection of an additional PtG plant leads to lower costs of investment. Biogas production and upgrading sites are therefore *low hanging fruits* for the integration with power-to-methane technologies.

As of 2017, 540 bio-methane plants with an annual capacity of 1.94 billion m^3 were installed in Eu-rope [Eba18]. One year later, 2018, already 660 plants producing 2.28 billion m^3 were reported [Eba19].

It is not mandatory to separate the biogas digestion from the methanation process. Rather, integrated reactor designs that combine the classical biogas production and a biogenic methanation are possi-ble, too, increasing the plant complexity but potentially harnessing synergies by avoiding costs for intermediate CO_2 sequestration and handling [THJS12].

Similar to the biogas plants, the waste water treatment plants that produce sewage gas can be used as a source for CO_2. The resulting gas mixture can also be directly fed into a methanation process or be converted into biomethane and synthetic methane when incorporating a CO_2 sequestration step and separated reactors [BZGT18].

Biogas plants are an available and reliable source of biogenic CO_2. Additionally, possibilities for coupling a biogas plant with a PtG plant already exists today (as for example shown in the *Audi e-gas project* [Audi13]). Therefore, biogas plants are considered to be the preferred “green” CO_2 source for the methanation process in the course of the present work.

In order to determine the potential and to identify the possible sites for biogenic PtG plants, a dis-tinctive 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, and both the locations and production data of biogenic CO_2 sources. The approaches for obtaining the data, as well as the methods used in the process, are presented in the following subchapters.

3.3 Direct air capture

One of the technologies that has received increasing attention in the recent years is the direct cap-ture of CO_2 from the air. Unlike the high concentrations of CO_2 in the flue gases from the industrial plants or from the biogas production process, the concentration of CO_2 in the air is currently 0.041% (410ppm), so developing very efficient agents for capturing these small amounts is crucial. One of the biggest advantages of this technology compared to biomass-based CO_2 capture is its very small impact on land-use. It can for example be built un unused spaces such as roofs of commercial or industrial buildings. In addition, it can be vertically stacked. Besides the comparably high costs of direct air capture (see section 3.4), the second major drawback of this technology is the energy demand mostly coming from the process of thermally releasing the CO_2 from the sorbent (regener-ation phase). One the positive side, the production potential of direct air capture is solely limited by its energy demand. The specific technology implemented in STORE&GO demonstration in Troia, Italy, offers the opportunity to be provided by low-temperature heat to cover up to 90% of the required energy demand. This can be achieved through heat integration with electrolysis and methanation.

A general advantage of the DAC technology in contrast to industrial CO_2 sources is its geographically independent siting options, that do not need any technical, economical, contractual etc. coupling to industry plants or related infrastructure. Instead, coupling to renewable energy production or suitable grid connectivity suffices. Therefore, power-to-methane or other carbon usage options may be implemented close to the location where the product will be needed instead of prioritising a CO_2 point source (as in the present study). As a result, the transport task of the CO_2 or the CO_2-related product is omitted. Non-productive land and roof-tops may be chosen for the installations to avoid competition of land use. Due to the low environmental impact of this technology it has a potential to become one of the predominant technological options for capturing and removing CO_2 from the atmosphere in the future, e.g. at sites, where oversupplies of RE are available for a very significant part of the year

Depending on the scenarios of the European commission report *A Clean Planet for all – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*, a potential amount to be captured in 2050 could be in the range of 200 Mt CO_2, 'mainly coming from DACs' [Euro18]. Figure 3-3 shows CO_2 capture respectively storage and use scenarios from the EU primes model calculations described in [Euro18].

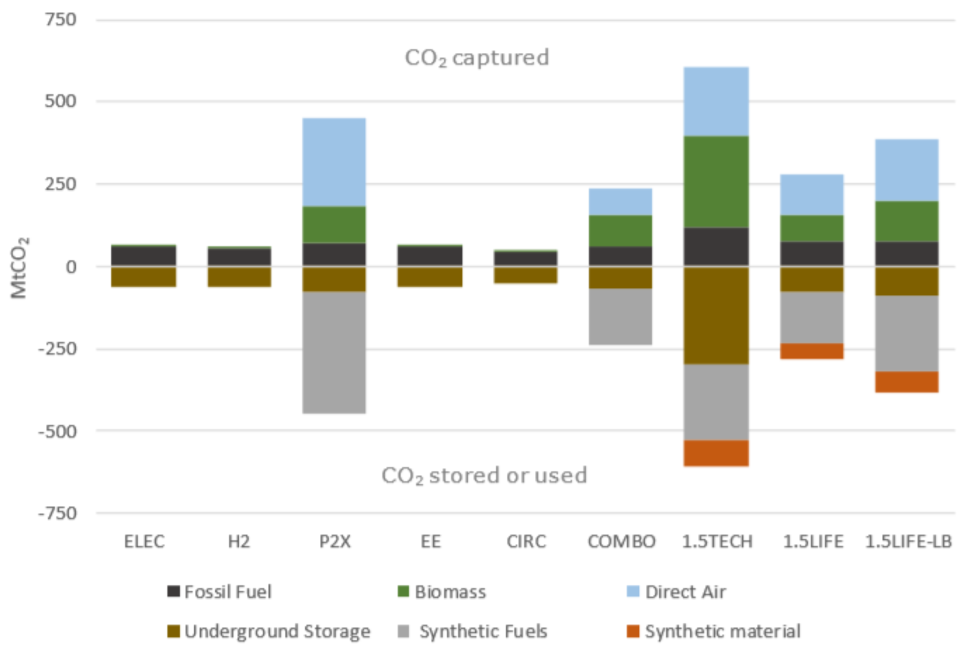


Figure 3-3 Different scenarios for CO_2 capture and storage or reuse for 2050 Source: PRIMES [Euro18]

Direct air capture is not accounted for in the potential study presented here, which focusses completely on CO_2 point sources. The latter offer high concentrations of CO_2 available for sequestration with comparably low efforts, and it is therefore expected that these CO_2 sources will be exploited first, where available. However, DAC may lead to significant additional green CO_2 provision if implemented at large scale and with the corresponding technology cost reductions in the future.

3.4 Carbon capture costs

Although some capturing technologies for separating carbon dioxide from flue gas streams can be used for both high purity or diluted sources, the capturing efficiencies as well as the costs highly depend on the CO_2 concentrations and impurities in the flue gas stream of the CO_2 emitting process. The STORE&GO Deliverable 7.5 "*Report on experience curves and economies of scale*" (see Table 3-1) analyses the differences in costs for specific industry sectors [BZGT18]. Capturing the CO_2 from high concentration sources, like ammonia production plants, show significantly lower costs (25 €/t) in comparison to other processes that show lower CO_2 concentrations in their flue gas. Metal industry, cement production and the pulp and paper sector exhibit costs between 19 and 90 €/t. Capturing the green CO_2 from solid biomass goes along with comparable costs as for the saparation from natural gas [BZGT18]. The CO_2 from biogas upgrading plants can be seen as a low hanging fruit for potential power-to-x conversion technologies, since the CO_2 anounts separated there are available at very low costs, which may be as low as the range of 5 to 9 €/t following Reiter and Lindorfer [ReLi15].

The direct air CO_2 capture technology faces the highest costs for CO_2 provision, in the range of 150 – 475 €/t. This concides with the lower technological maturity level and the very low concentraion of CO_2 in ambient air that the technology needs to cope with. Some predictions expect that the direct air capture costs will decline to levels as low as 22 €/t in the future [BZGT18].

Table 3-1 Average capture costs for CO_2 related to industrial sectors [BZGT18].
Column "Ref." refers to references in original source.

	CO_2 Source	Capture costs *€/t$_{CO2}$*	Year	Exchange rate *USD/EUR*	Ref.
Energy industry; power & heat from fossil fuels	Coal	34 – 42	2017	0.83	[114]
		19 – 47	2015	-	[112]
		20 – 63	2015	0.72	[123]
	Natural gas	63 – 83	2017	0,83	[114]
		54 – 101	2015	-	[112]
		35 – 75	2015	0.72	[123]
	Biomass	54 – 101	2015	-	[112]
Chemical industry	Refinery	29 – 83	2017	0.83	[114]
		44 – 94	2015	-	[112]
		48 1)	2012	-	[124]
		97	2014	0.82	[115]
	Ammonia production	12	2017	0.83	[114]
		23 – 54	2015	-	[112]
		22	2014	0.82	[115]
	Other chemicals	12 – 52	2017	0.83	[114]
		21	2014	0.82	[115]
Iron & steel production		19 – 33	2017	0.83	[114]
		16 – 41	2015	-	[112, 124]
		81 – 83	2014	0.82	[115]

CO_2 Source		Capture costs €/t_{CO2}	Year	Exchange rate USD/EUR	Ref.
Cement, clinker & lime production		22 – 35	2017	0.83	[114]
		33 – 69	2015	-	[112, 124]
		17 – 37 [1)]	2012	-	[124]
		82	2014	0.82	[115]
Pulp, paper & board production		18 – 27	2003	0.79	[116]
		57 – 87	2017	-	[125, 126]
Biogenic CO_2 sources	Biogas upgrading	0 – 90	2012	-	[111]
		5 – 9	2015	-	[112]
	Bioethanol fermentation	12	2017	0.83	[114]
		0 – 18	2011	-	[113]
		25	2014	0.82	[115]
		5 – 9	2015	-	[112]
	Bioethanol fermentation (incl. cogeneration)	83 – 111	2011	-	[113]
		42	2003	0.79	[116]
Direct air capture		150 – 320	2012	-	[111]
		22 [1)]	2012	-	[111]
		150	2010	0.75	[117]
		331 – 423	2011	0.77	[118]
		268 – 309	2013	0.72	[119]
		341 – 475	2014	0.82	[120]
		81 – 201	2018	0.86	[121]

[1)] long term prediction

4 Data on CO_2 from industry and biogas plants

4.1 Data on industrial CO_2 sources

The analysis of industrial CO_2 as a feedstock for power-to-methane energy conversion is based on open data published by the European Pollutant Release and Transfer Register (E-PRTR) database.

> "The ***European Pollutant Release and Transfer Register (E-PRTR)*** is the Europe-wide register that provides easily accessible key environmental data from industrial facilities in European Union Member States and in Iceland, Liechtenstein, Norway, Serbia and Switzerland. […] The new register contains data reported annually by more than 30,000 industrial facilities covering 65 economic activities across Europe. For each facility, information is provided concerning the amounts of pollutant releases […] from a list of 91 key pollutants including heavy metals, pesticides, greenhouse gases and dioxins […].
> The register contributes to transparency and public participation in environmental decision-making. It implements for the European Community the UNECE (United Nations Economic Commission for Europe) PRTR Protocol to the Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters."

[Euro17]

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.[2] [3]

The E-PRTR database collects data for all plants exceeding 100 kt of CO_2 emission per year. All minor emitters are neglected in this work, since data for those plants are not available on the European level. In addition, depending on the reporting year, some emitters happen to drop below the reporting limit due to low capacity utilization, others exceed the threshold only seldom. The data for this work originate from 2015. The choice of industry sectors to be included in this work was made by selecting the largest CO_2 emitting sectors, which will presumably be still operating in a deeply decarbonised 2050 scenario, delivering highly concentrated CO_2 in their flue gas streams suitable for sequestration and the subsequent production of synthetic fuels such as methane via the power-to-gas route. Albeit their large emissions and potential CO_2 post-combustion capture rates in the range of 90 % [Rwep09], data from the fossil power plants of the energy sector are neglected in this work as future CO_2 sources, since the fossil power plants are expected to be shut down or transferred into stand-by operation clearly before 2050. Carbon capture from fossil power plants leads to an immense need for CO_2 storage between the capture step and a potential carbon usage due to temporal mismatch of fossil plant operation and renewable electricity generation (also for the case of gas-fired power plants). The less full load hours remaining fossil back-up plants will operate in the future, the less relevant will be their role as a reliable carbon feedstock for CCU products. Carbon Capture in combination with long-distance CO_2 transport and subsequent storage in underground facilities such as depleted fields or large scale CO_2 caverns are neglected in this work as a technology options for decarbonisation.

---

[2] For the calculations in this report, 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 their main economic activities.
[3] The included list of economic activities represented by the NACE codes in the E-PRTR database can be found in [SCLL19].

Not only the energy sector, also the industry sector will face drastic changes concerning fuel switches e.g. from coal-firing to firing of natural gas (which can be decarbonised by implementing PtG processes). To some extent, solid biomass can be used. In general, a trend towards process electrification may be expected where applicable. All these measures help decision-makers in industry to reduce emissions, and thus reduce 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 are expected to remain the largest available point emitters and may in the future be regarded as carbon sources to deliver the feedstock for carbon-based products, which will be produced along the power-to-X process routes (working hypothesis).

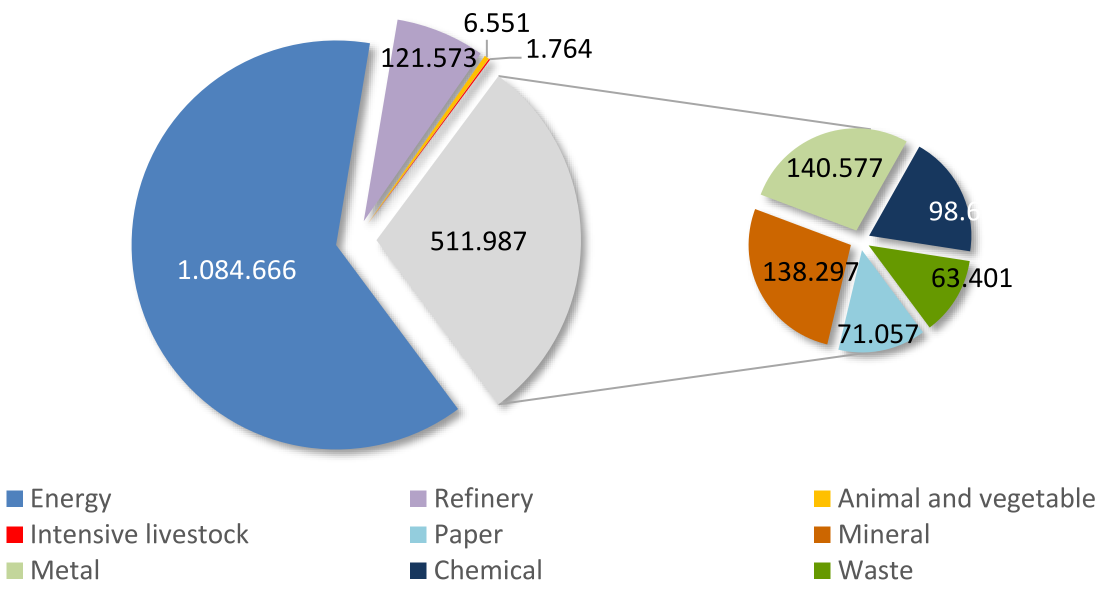


Figure 4-1 The amount of CO_2 emissions (in kt/a) of the selected five industries (right hand side) within the 9 total published CO_2 emissions of the E-PRTR database in 2015 [Euro17]

For 956 plants included in the study, a total of 511 987 kt or almost 512 Mt of CO_2 were inventoried by the database for the year 2015 [Euro17]. The relative emission shares of the five selected industries are illustrated in Figure 4-2.

A decline in the GHG emissions and energy consumption in the manufacturing industry since 1990 was accompanied by the structural changes in the European economy, as well as a developing awareness and policies for environmental protection. Also the energy supply sector has made progress in terms of CO_2 emission reduction due to the same drivers as well as upcoming RE generation. In contrast, continuously rising emissions from the transport sector as well as aviation are observed (see Figure 4-3).

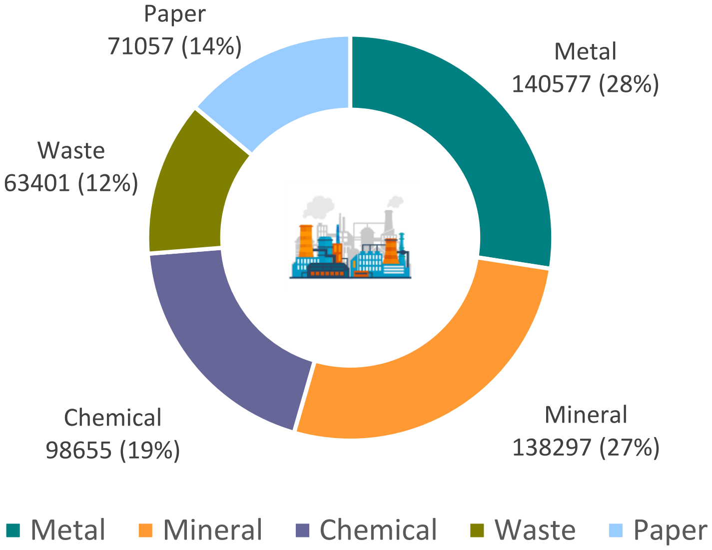


Figure 4-2 CO_2 emissions from the five selected industries in kt, and their relative share in Europe 2015 [own illustration based on Euro00]

In 2017, a total emission decrease of 22 % compared to 1990 was achieved, and the lower demand for energy is a result primarily to energy efficiency measures taken by the EU Member States [Euro18].

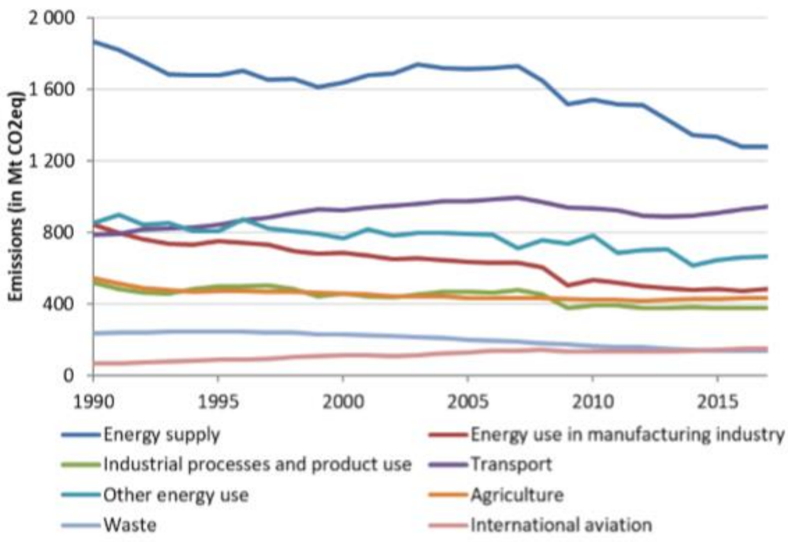


Figure 4-3 EU greenhouse gas emissions by sector 1990 - 2017, EEA (2017) [AnEE18]

4.1.1 Sectoral CO_2 emissions developments

In 2015, the energy intensive industry sectors directly emitted approximately 700 million tonnes of CO_2, which represents a reduction by more than 30 % compared to 1990 levels. The power sector had the biggest emission reduction achieved in the same period. In addition, the final energy consumption of industry was reduced by about 20 %. This was especially noticeable in the energy intensive industries, even though there was no homogeneous reduction in the different industry sub-sectors. The metal and the chemical sectors reduced their GHG emissions by about 60 % between 1990 and 2010 while the reductions in the minerals sector (cement, lime, glass, ceramics) reached

about half of that value (about 30 %) [Euro18]. The total GHG emissions of the chemical sector stabilized in the recent years at levels of about 130 Mt $CO_{2\,eq}$ [Euro19a].
Almost all of the five energy intensive industries showed the similar slight reduction in the emissions in the period of 2010 to 2015, as can be seen in Figure 4-4.

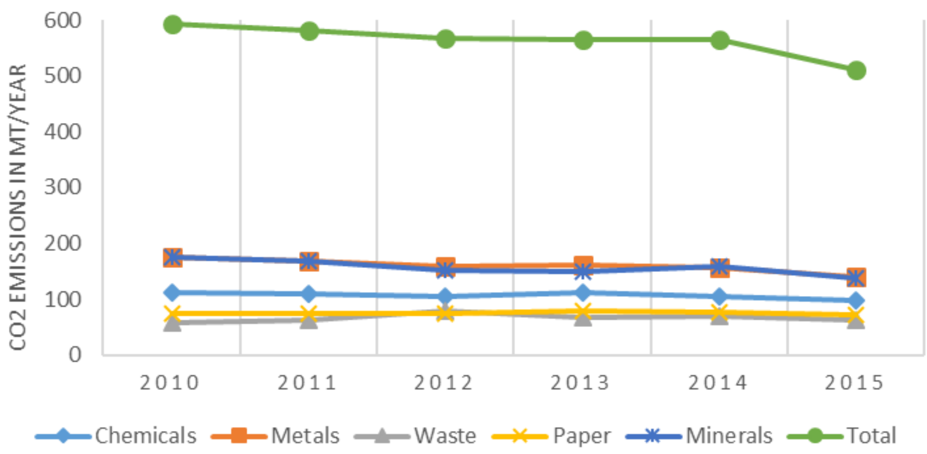


Figure 4-4 The amount of CO_2 emitted in the five studied industries from 2010 to 2015 [Euro17]

4.1.2 Geographical distribution of the analysed industrial CO_2 sources

The national availabilities of CO_2 from the 956 included large-scale industry plants in Europe is shown in the bar chart Figure 4-5.

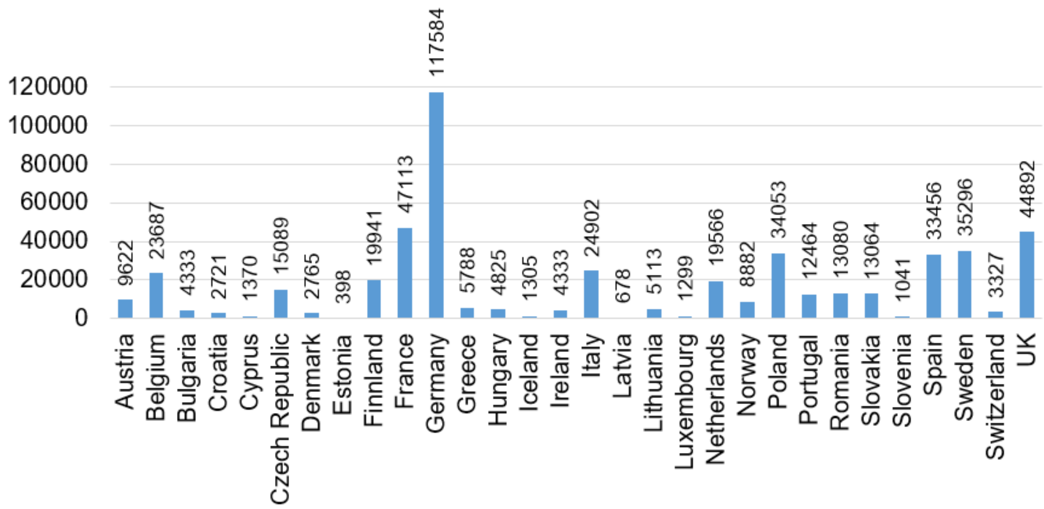


Figure 4-5 Available CO_2 emissions from the 956 industrial plants from the five analysed industrial sectors in Europe ([Euro17], 2017)

The geographical distribution of these CO_2 emissions on the regional level is presented in Figure 4-6. The geographical distribution of the industry sectors is depicted in Figure 4-7.

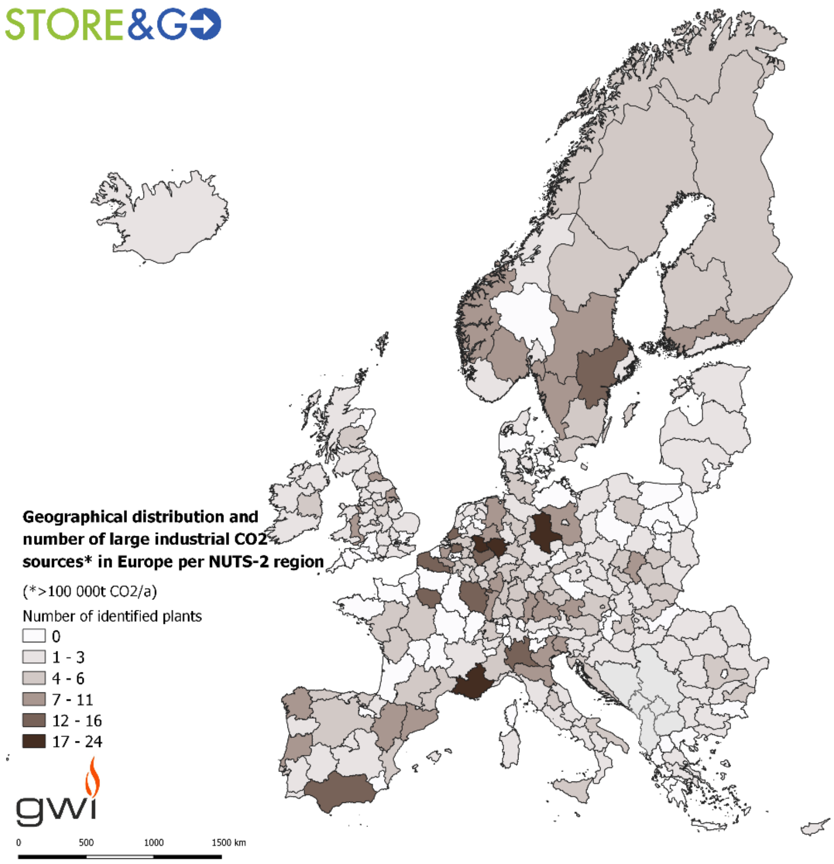


Figure 4-6 Geographical distribution of the large industrial CO_2 point sources in Europe (five analysed industry sectors) on the regional level (NUTS-2)

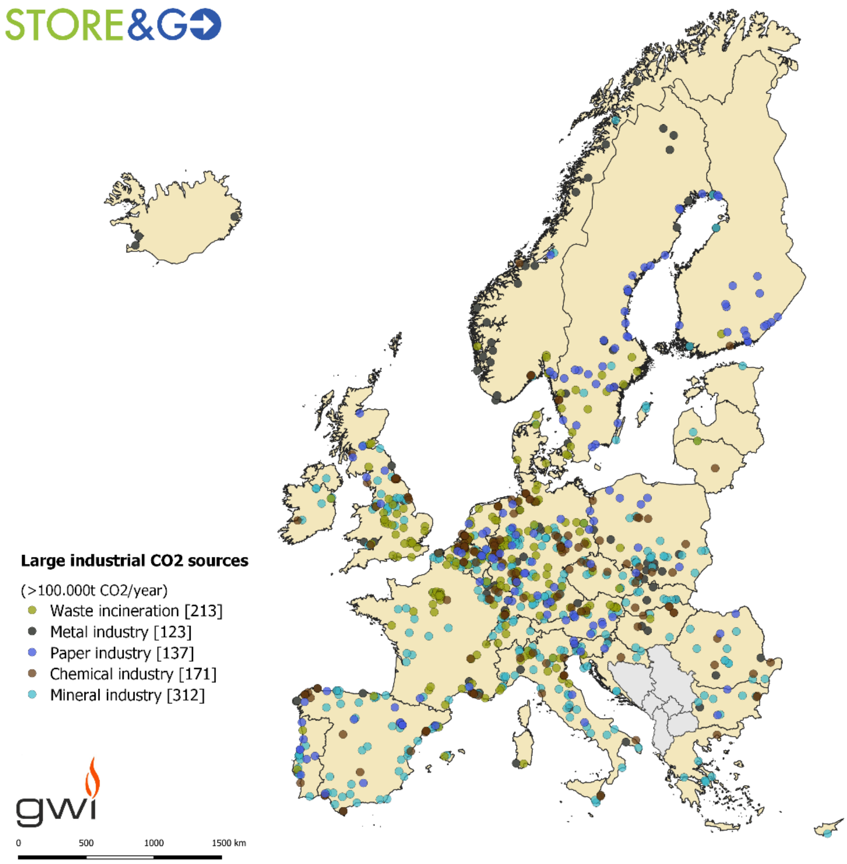


Figure 4-7 Distribution of large-scale industrial CO_2 sources (>100 000t CO_2/a) in Europe by sector

4.2 Data on CO_2 from biogas plants

The data acquisition for identifying today's potential power-to-methane sites using biogenic CO_2 relies on the existing biogas installations. As of today, the large additional potentials for the coupling of solid biomass and methanation technologies cannot be added to the site identification study due to lacking roll-out of solid biomass gasification/pyrolysis. For calculating total power-to-methane potentials in two scenarios, solid biomass however is taken into account (see chapter 9).

This study includes all biogas production sites on which public data was available and could be found during the processing time of this project. A differentiation between biogas plants that produce raw biogas for combustion for electricity generation and plants that possess gas treatment facilities for upgrading the raw biogas to bio-methane allowing the injection in gas grids is not made. Rather, all biogas production sites are regarded as potential methane production sites of the future.

4.2.1 Biogas data acquisition

There are two different bases for calculating the countrywide potentials for possible methane from green CO_2: primary production of biogas in the year 2016 published by Eurostat [Eba18], and a report by D. Thrän and F. Müller-Langer from DBFZ [ThMü11] about future potentials of biomass in Europe.

Eurostat is the European statistical office and collects various data concerning the economy of 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 basis, lastly in 2016. According to Eurostat, biogas production is composed of gases from anaerobic digestion and gases from thermochemical treatment of biomass, such as pyrolysis. Gases from anaerobic digestion mainly include landfill gases, sewage gases and biogases from agricultural holdings. 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 produced amount of biogas [FrSi13].

In the report by Thrän and Müller-Langer [ThMü11], biomass potentials for the majority of the European nations are calculated. Different assumptions concerning the development of forest wood, residuals and energy crops are made and projections based on agricultural characteristics of the studied nations are presented [ThMü11]. Bio-methane is on the one hand produced by anaerobic digestion and on the other hand by thermo-chemical processes. Both methods produce CO_2 as a side product, adding up to the CO_2 potentials from biomass. Four additional national data sets could be manually researched to complement the number of nations studied by Thrän and Müller-Langer. The additional data from authorities and studies were incorporated for Switzerland (CH, Table 1 in [BaBH00]), Norway (NOR, [SDSA11]), and Croatia (HR). The data for Croatia originate from a presentation by the Croatian Ministry of Environment and Energy [JeHS17] and were further confirmed with [BVJJ18] and [Mesa16]. For the case of Iceland (IS), the energy crop and woody biomass potentials were set to zero. An overview of the data sources primarily used for setting up the biogas database of this work can be found in Table 12-1 in the appendix.

Uncertainties

Researching biogas plant sites across Europe is a complex task, as the nature and scope of publicly available data vary widely between countries and often require very different approaches to research. Furthermore, data protection regulations lead to a restriction in the level of detail of the location data of individual countries. Albeit the challenges faced in obtaining the input data, a large number of existing sites throughout Europe are identified and mapped so that a comprehensive dataset of the geographical distribution of biogenic CO_2 sources from the fermentation of biomass is gained.

4.2.2 Geographical distribution of the biogas plants in Europe and biogas production

The geographical distribution of the identified biogas plants in Europe is presented in Figure 4-8 and Figure 4-9. A total number of 16 912 identified plants are included in the study.

The amounts of biogas production are presented in Figure 4-10. The annual biogas production in GWh/a is plotted logarithmically. Germany, the United Kingdom and Italy produce the largest amounts of biogas, and thus also emit the largest amount of renewable CO_2. The resulting production quantities are between 20 000 GWh/a and 100 000 GWh/a, that are distorted by the logarithmic representation. The lowest biogas productions are found for Iceland and Malta, producing less than 100 GWh/a, and therefore not offering large-scale potential for power-to-methane plants. Nevertheless, biogas production takes place in every European country considered.

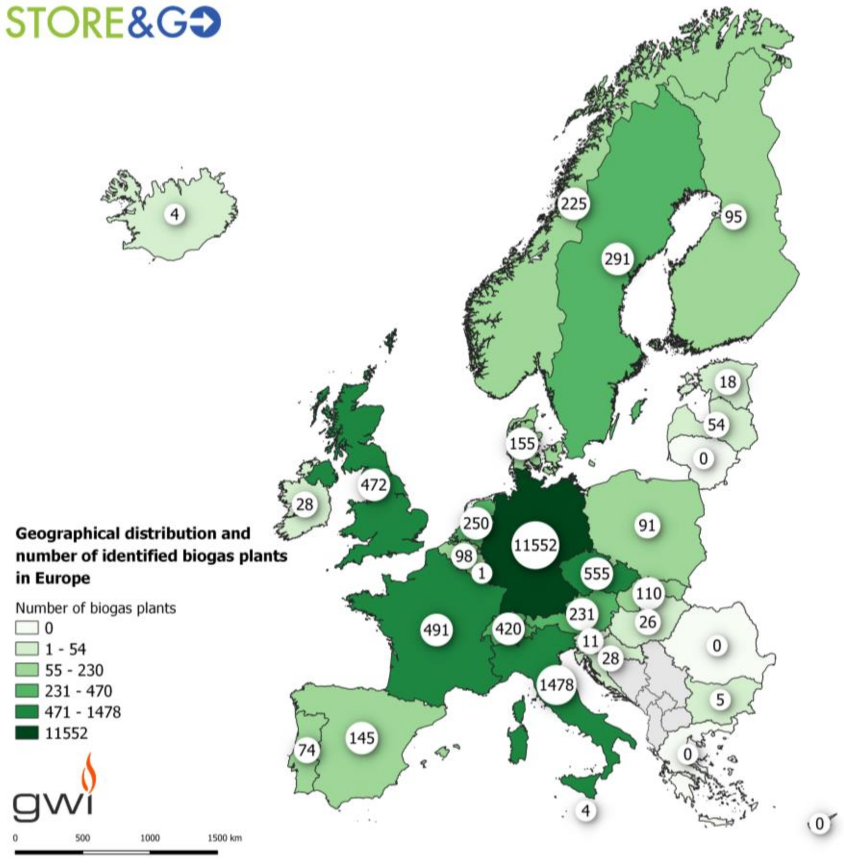


Figure 4-8 Number of identified biogas plants in Europe

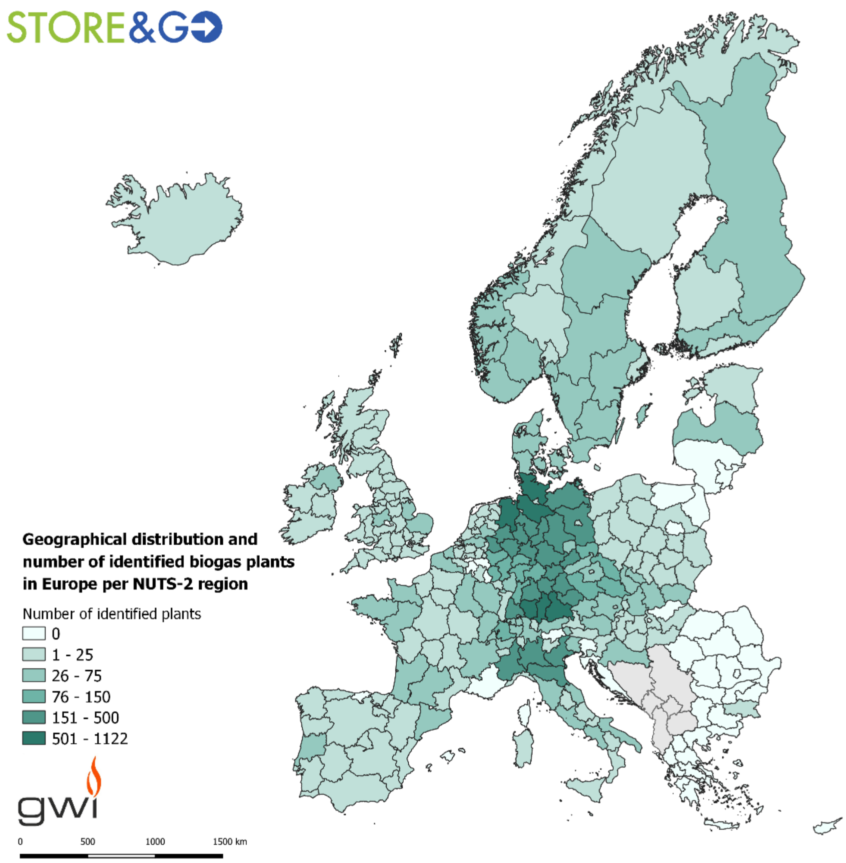


Figure 4-9 Geographical distribution and number of biogas plants per NUTS-2 region

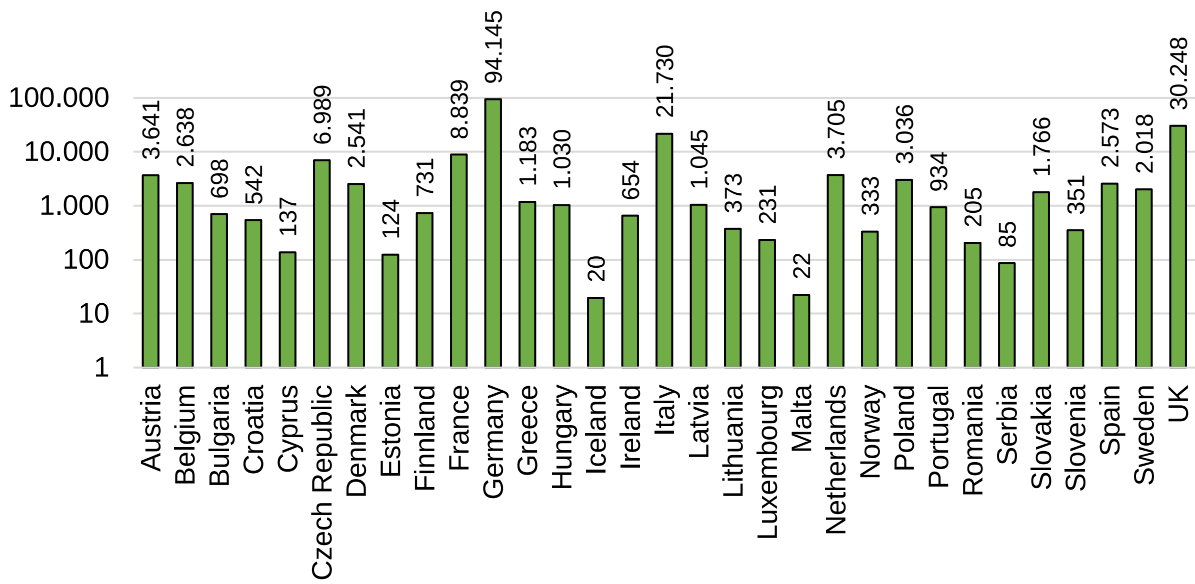


Figure 4-10 Primary biogas production in Europe in 2016 in GWh/a [Euro15]

5 Gas demand in Europe

While the overall European fossil energy demand will drastically decline towards 2050 due to policy measures, the demand for green gases will increase to fill the gap. It is not unlikely that the EU gas uptake (around 5000 TWh in 2016) could remain at similar levels even after the energy transition, just facing a complete fuel switch from fossil to renewable gases such as biomethane, synthetic methane and hydrogen. Due to the high uncertainties of future developments, the future gas demand is very hard to estimate. A number of studies commissioned by the EU ([CDTE16] [Euro18] [Trin18]) open up a range from 1 806 to 4 700 TWh for the total gas demand in 2050, which is in line with a number of scenarios investigated in the STORE&GO project [Blan18]. According to the EU Reference scenario, gas consumption in the EU is expected to remain relatively stable in the coming decades – varying somewhere between 3 900 – 4 400 TWh in 2050. Eurogas estimates that aggregate “gas demand can be up to 4 500 TWh in 2050” and that 70 % of that will be supplied in the form of renewable gas [Euro00a]. Figure 5-1 wraps up literature future gas demands reviewed within the STORE&GO Roadmap Deliverable D 8.10 [RBCG20]. In should be noted that D 8.10 reports on the total gas demands from literature references, in some cases including hydrogen demands, while for the present work, the methane demands are the relevant reference. Therefore, at the end of chapter 9.3, the comparison of projected methane potentials with literature references on gas demand are refined in that respect.

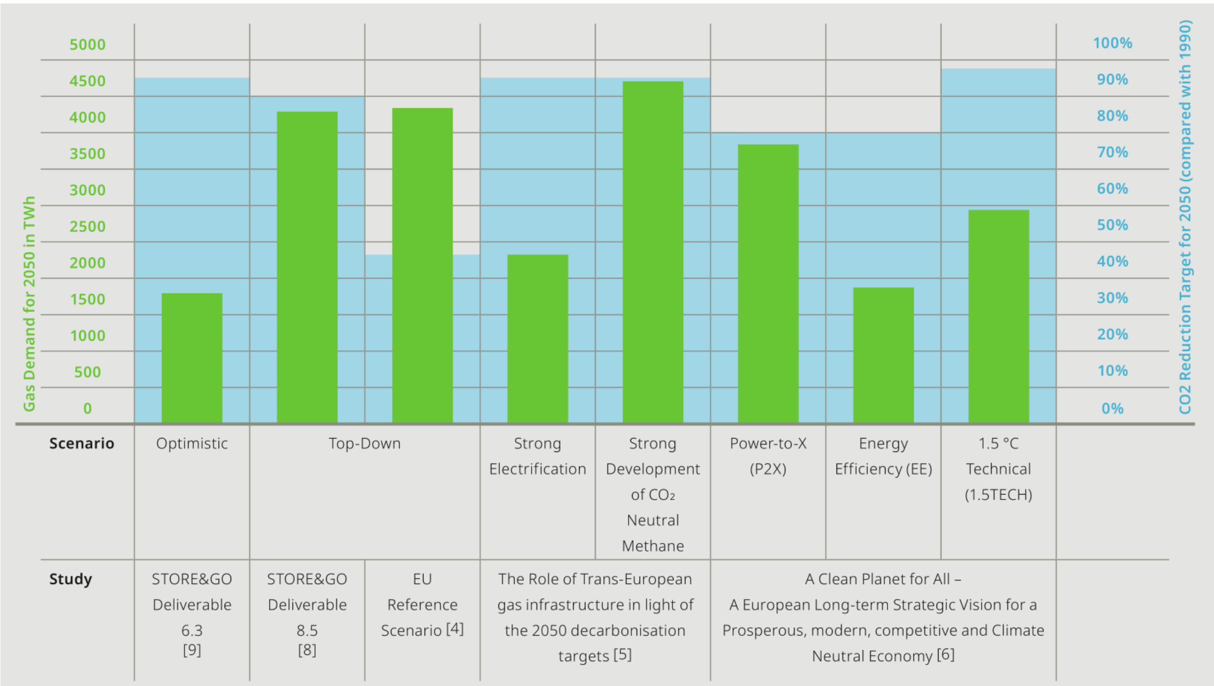


Figure 5-1 Gas demand projections for 2050 from different studies. For more information see the roadmap for large-scale storage based PtG conversion in the EU up to 2050 in Deliverable D8.10 [RBCG20]

For the assessment of the methanation potential calculations conducted in this work, the highest and lowest future gas demands will be taken into account in terms of a range of possible future developments. Thus, the outcomes of the study may be evaluated by means of their potential level of satisfaction of the future European renewable gas demand.

In Deliverable D 7.5 it is shown that the potential for substituting natural gas in the industry sector in the European Union will be approximately 3 107 PJ (863 TWh SNG). There would be an additional potential for about 1 398 PJ (388 TWh) of green hydrogen, due to the substitution of all oil derivatives in the industrial sector and more than 906 PJ (or 252 TWh) if all coal-derived products from the iron and steel industry are substituted in the course of process adaptation. The total need for installed electrolyser power in the industry sector in Europe in the year 2050 then would be around 425 GW [BZGT18].

Considering the PtG potentials, different scenarios for 2050 have been analysed in the Deliverable D6.3 “Impact Analysis and Scenarios design”. In about half of the investigated scenarios, the PtG capacity is in the range of 40 GW to 200 GW. By considering liquefied methane as an energy carrier also, the PtG capacity would increase by 122 GW. The PtG capacity will lead to an installed electrolyser power in the range of about 73 to 993 GW (based on the assumption of a total power-to-methane efficiency of 55 %) [Blan18].

The final energy demand in 2050 as described by the EU Reference scenario is presented in Table 5-1 [CDTE16].

Table 5-1 European and global final energy demand in 2050 by sectors [CDTE16]

Sector	European[1] [TWh]	Global[2] [TWh]
Mobility	4 166	37 169
Industry	3 059	40 914
Residential	3 390	42 066
Power	3 920	39 843

[1]… According to EU-Reference Scenarios 2016 [144]
[2]… According to World Energy Scenarios 2016 of the World Energy Council [147]

Based on these assumptions, the estimated shares of SNG and hydrogen in 2050 and the required installed power of electrolysers and methanation units were calculated and presented in STORE&GO Deliverable D 7.5 [BZGT18], leading to different numbers compared to D 6.3 [Blan18]. These scenarios are shown in Figure 5-2 for Europe and global, for different RE production scenarios (low, medium and high).

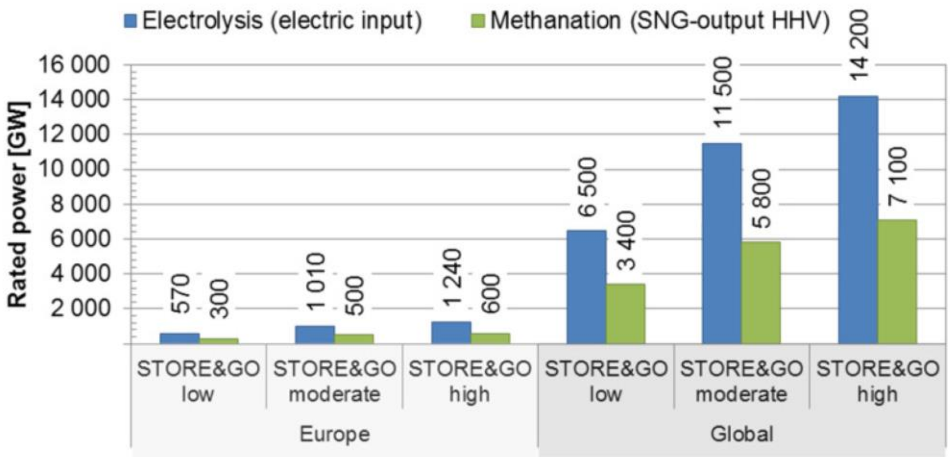


Figure 5-2 STORE&GO Scenarios from Deliverable D 7.5. Necessary installed power of electrolysers and methanation units in 2050 [BZGT18]

The analysis showed that at a European level there can be a need for up to 1 240 GW of installed electrolyser power and 600 GW methanation (SNG output capacity). The values from the various work packages and tasks within the STORE&GO project tend to be at similar or slightly higher levels compared to literature [BZGT18].

6 Renewable energy production site data and potentials across Europe

6.1 Obtaining detailed location data (bottom-up approach)

For the geographical analyses and calculation of the power-to-methane (PtM) potentials, a geographically detailed identification of the RE production sites is necessary. In this chapter, the required data sources are presented (in addition to the previous report on the method, Deliverable D8.7). The geo-informational processes were performed based on the open source software QGIS [Qgis17].

Geographical units

Nomenclature of territorial units for statistics (NUTS) is a hierarchical system for dividing the economic territory of the EU for collecting regional statistics. There are four NUTS levels that build on top of each other. The spectrum ranges from the national level of the NUTS-0 regions to the province level (NUTS-1), to the regional (NUTS-2) and finally the municipal level (NUTS-3) [Euro00b]. For small nations in terms of the number of inhabitants, the region levels 1, 2 and 3 may also be identical to each other. NUTS-2 are the basic regions for the application of regional development policy. All analyses in this report are done and presented based on either the NUTS-0 and NUTS-2 level valid for 2016 as displayed in Figure 6-1.

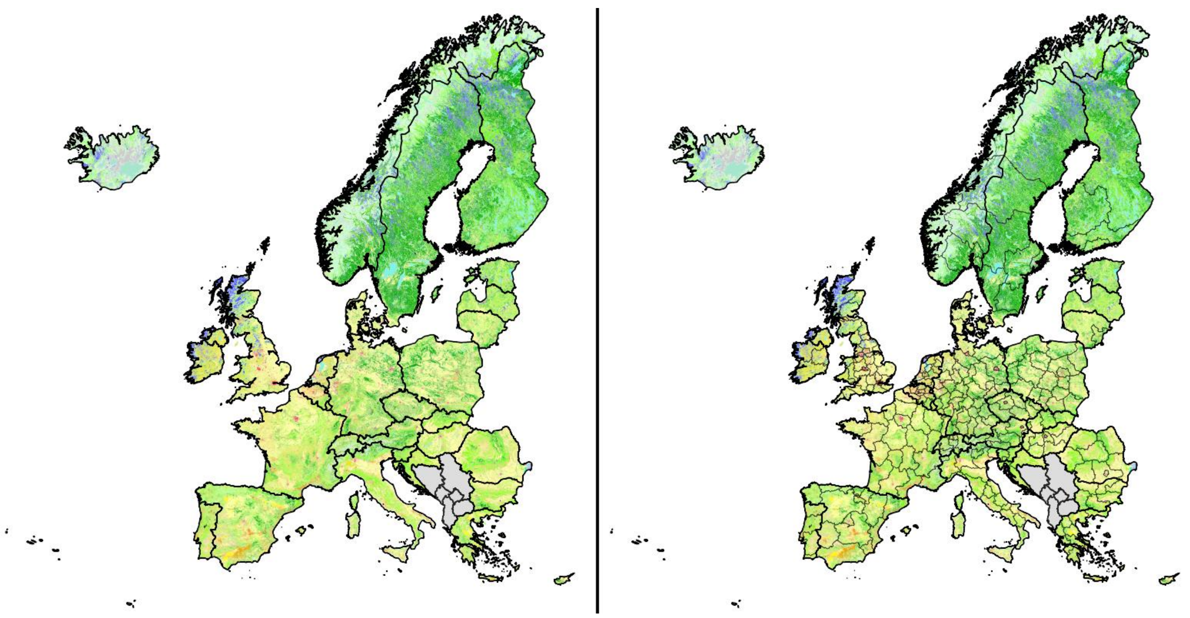


Figure 6-1 Territorial units in Europe: Preview and comparison of NUTS-0 (left, black lines) and NUTS-2 (right, light grey polygons)

Global Power Plant Database (GPPD)

The Global Power Plant Database (GPPD) is an international open source database for power plants around the world. The database contains information about locations (geo-localized), fuel type, plant capacity and generation. Around 30 000 conventional and regenerative plants from 164 countries are listed in the database. Those can be downloaded as excel documents and imported into QGIS due to geo-localization [Wri19].

Industrial Maps

The Industrial Maps are comparable to the GPPD. They as well are based on an international open source database; however, they are not limited to power plants only. In total there are 26 map databases available for 255 countries or regions, e.g. Aluminium Industry Map, Gold Mining Map or Solar Energy Map (SEM). As the data bases are not downloadable, the available data from a total of 2 110 SEM plants were manually exported into an excel document and then imported into QGIS. In this way, data for solar power plant locations in 19 European countries could be determined [Indu19].

CORINE Land cover and Natura 2000

Corine Land Cover (CLC) stands for “Coordination of Information on the Environment” and is a project of the European Environment Agency (EEA) for the categorisation of land areas in Europe. Natura 2000 is an EEA mapping of breeding and resting places for rare and endangered species. It covers the 28 Member States of the European Union, including land and sea areas. In the future, the data set is to be extended to an area of about 630 000 km^2 in Europe, and further habitat types are to follow as well. Iceland, Switzerland and Norway are not included in the Natura 2000 data set, which is to be considered in the potential evaluations of this work. The Natura 2000 data set covers an area of about 630 000 km^2 in Europe, further habitat types are to follow in the future to further increase its content [Cope00, Euro19b]. For this work, the 2018 CLC and Natura 2000 datasets were used.

6.2 Photovoltaic potential

Solar energy is the largest primary source of renewable energy that can be used for both power and heating generation. It is one of the technologies that has undergone the greatest development over the last 10 years, with significant cost reductions [Ise19].

In 2015, around 220 GW of PV systems were installed worldwide and produced around 243 TWh of electricity, which in turn accounted for almost 1 % of the global electricity generation [Iren00]. By the end of 2018, the capacity has been expanded to more than 515 GW and produced around 443 TWh of electricity (or 1.7 %) [Ise19]. Within the EU, the highest solar electricity potentials are found in the southern member states, where levels above 1 500 $kWh/kW_{installed}$ may be achieved, while northern Europe faces only half of that potential (Figure 6-2). The installed solar power capacity in the EU exceeded 100 GW in 2016 and represented 3.4 % of the EU’s electricity production (3.6 % in 2018, 4.3 % in 2019) [Agor20, Eu16].

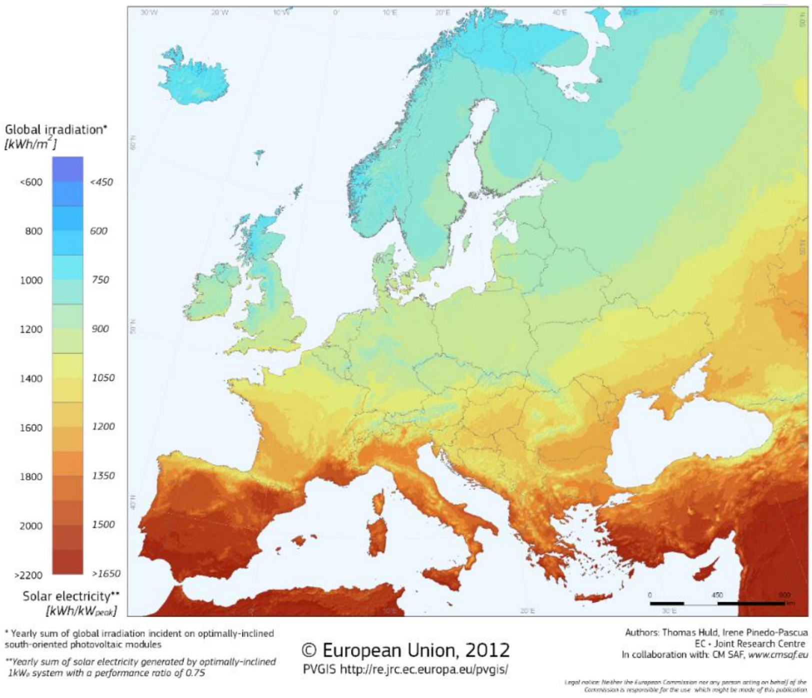


Figure 6-2 Photovoltaic Solar Electricity Potential in European Countries [HuPi12]

Between 2010 and 2017, Fraunhofer ISE reports a global Compound Annual Growth rate of PV installations of 24 % [Ise19]. New developments are leading to an increase in efficiencies, product lifetime and capacity factors (solar tracking systems). This is supported by the learning curve of PV modules, as the progressive development of new and improved modules leads to higher efficiencies, lower production costs and, at the same time, an extended service life [Vdma19]. Figure 6-3 shows the learning curve for PV modules exhibiting strong developments in the recent years. The last data points at the end of 2017 and 2018 report on module prices of 0.34 US$/$W_p$ and 0.24 US$/$W_p$ respectively [Vdma19].

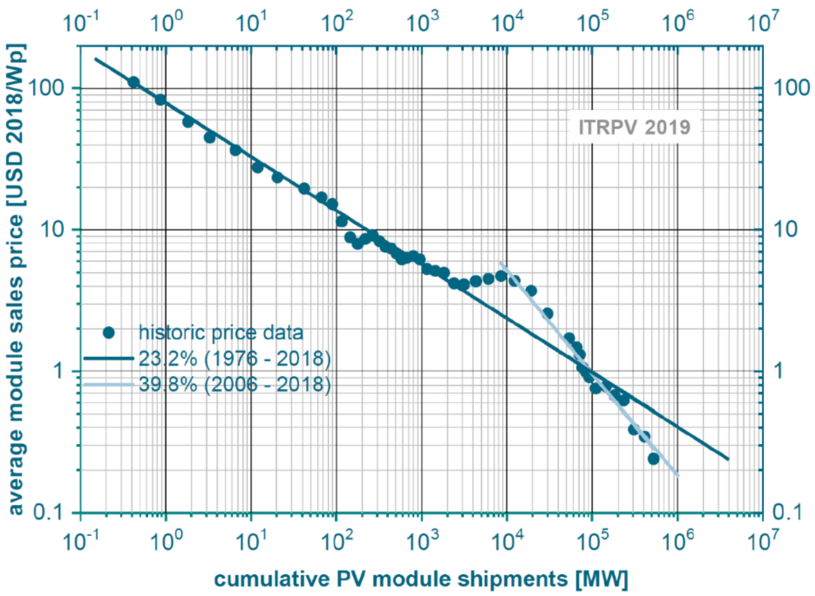


Figure 6-3 PV module price development and worldwide installed capacity [Vdma19]

The milestone of one terawatt of globally installed PV capacity is expected to be reached in the next years, but still requires significant progress in development and production [Sola00].

6.2.1 Photovoltaics costs

The prices of the PV systems have fallen drastically in the recent years, and it is expected that the investment (CAPEX), as well as operating costs (OPEX) will continue to fall in the future, as seen in Figure 6-4 [VMBM19]. Another element for the future PV costs forecast will be the single- or multi-axis tracking systems. Tracking PV systems follow the position of the sun. This helps to reduce electricity generation costs due to higher full-load hours and therefore higher energy yields, and to compensate for the higher CAPEX and OPEX compared to non-tracking systems. Currently the market share of single-axis systems is 45 %, and 55 % is forecasted to be reached for the end of 2020. A Finnish study from 2018 shows that the application of single-axis PV systems can increase the global electricity generation from PV from 47 % to 59 % compared to PV systems without a tracking system, i.e. an increase of around one quarter [AfBB18], [VMBM19], [Vdma19].

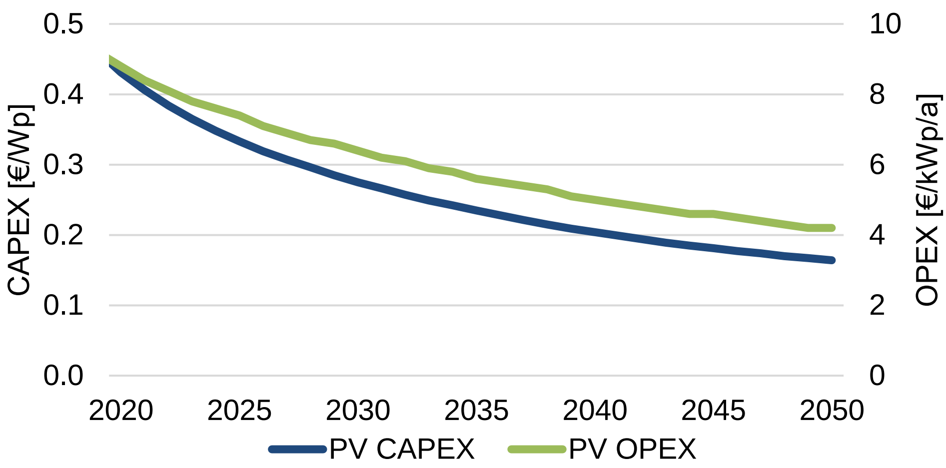


Figure 6-4 Evaluated cost development of utility-scale PV plants from 2020 to 2050 [VMBM19]

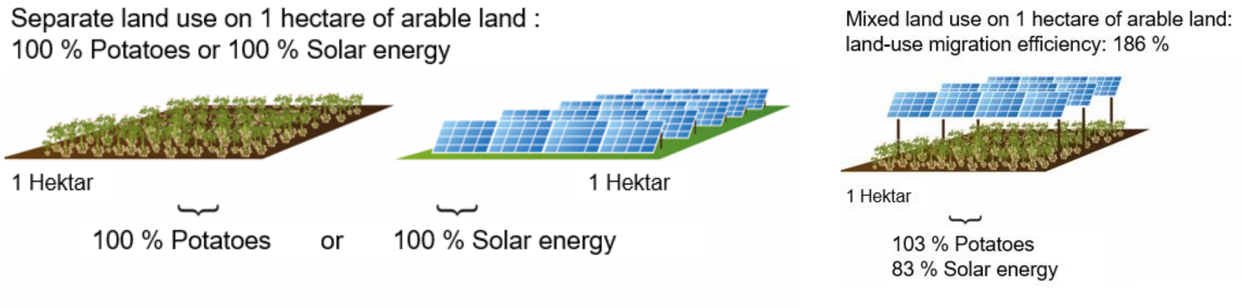
6.2.2 Agro photovoltaics (APV)

Future potentials for PVs can be seen in the development of agricultural areas with PV systems, also known as “agro photovoltaics” (APV) (Figure 6-5). The PV modules are installed on pillars so that agricultural machinery can continue working the soil and harvesting the crops beneath them. In order to keep the plants under the APV supplied with sunlight, semi-transparent solar modules are mainly installed [Ref19]. According to initial calculations, APVs in Germany have a potential of around 80 GW when considering a building area of 1 % of today’s total agricultural area.

Figure 6-5 Agro photovoltaics [Ref19]

Worldwide, 2 GW of APV systems have already been installed [Wirt20]. Depending on plant specifications and location, the efficiency of the synergetic land use varies between 135 % and 186 %. Figure 6-6 shows an example of the comparison of a potato field with a single land use (a) and with APV land use (b). During hot summers or in arid regions, plants and livestock can benefit from the shading of APV's. Plants and livestock are to some extent protected from weather events such as hail [Ref19].

APV systems create synergy effects for farmers, since the electricity can be used locally, for example for electric tractors and/or be fed into the local power grid. Since biogas plants are typically found close to agricultural fields, one advantage here is that the electricity generated by PVs can be made available for local power-to-gas and methanation plants.



a) b)

Figure 6-6 Land use of APV for a potato field, a) separate land use b) mixed land use [Ise00b]

To determine the installable capacity of APVs in 2019, 5.5 m²/kW$_p$ are assumed for the area required. This corresponds to an efficiency of 18 % at an irradiation of 1 000 W/m² (STC conditions) [Frau15, Pvss19]. Compared to PV, APV requires about 3.5 times the space, which corresponds to 19.25 m²/kW$_p$ (~515 kW$_p$/ha) [BBGO12].

For PV systems that are not installed on agricultural land, such as quarries and landfills, a surface area of 13 m²/kW$_p$ is required with the same efficiency [Frau19]. This results in a land consumption of about 760 kW$_p$/ha. The installable capacity within a certain polygon within a geo-information dataset can be calculated by dividing the available area by the respective area requirement of PV or APV.

To determine the generated electricity, the installable capacity was multiplied by the average full load hours of a country. The current full-load hours for the 31 countries are shown in Figure 6-7. The value for Iceland was calculated as a ratio of the values for Finland and Iceland from [Jrce06] and then fitted to the value for Finland [PfSt16].

It is assumed that an increase in the efficiency of PV over the next 30 years, including the integration of innovative concepts such as bifacial PV modules, will lead to an average efficiency of 30 % [Frau15]. This leads to a land requirement of 857 kW$_p$/ha for APV and 1 261 kW$_p$/ha for PV. To increase full load hours by 25 % compared to conventional PV systems, it was assumed that each PV system is installed in conjunction with single-axis tracking systems (see Figure 6-8).

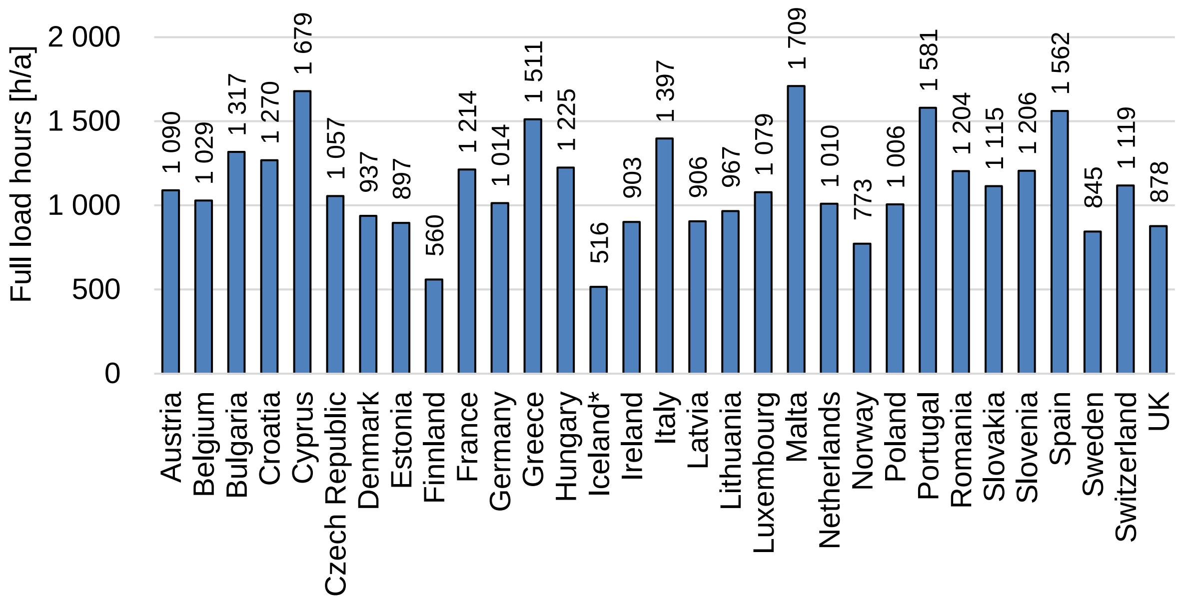


Figure 6-7 Average full load hours for PV installations in Europe (1985–2015). Plants oriented to south with 35° angle of inclination (CM-SAF SARAH) [PfSt16]

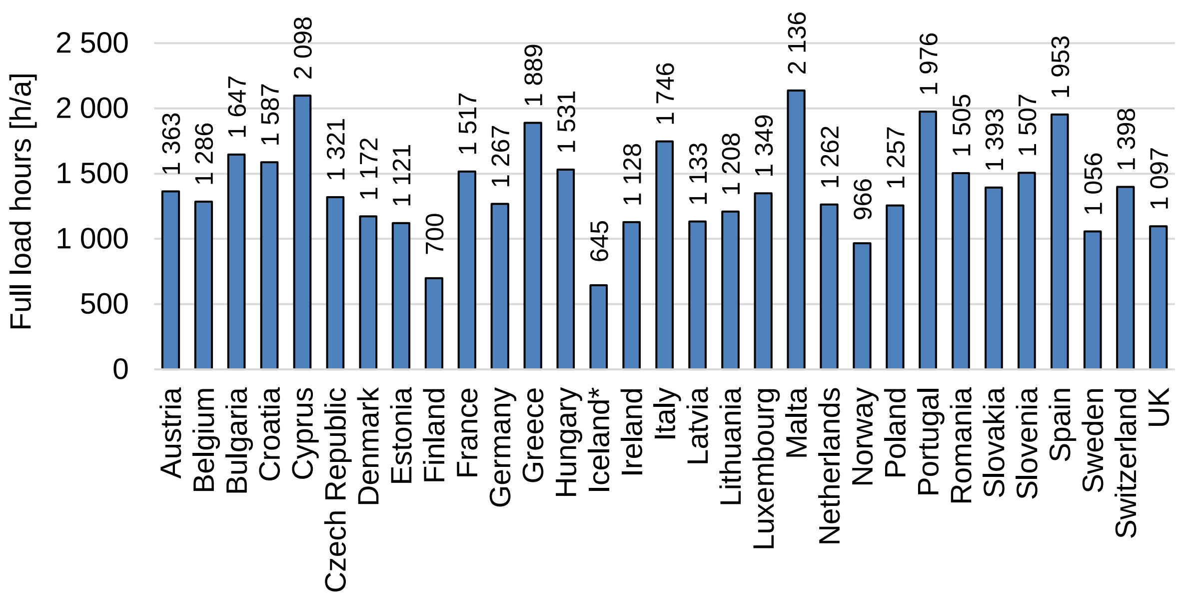


Figure 6-8 Assumed increased average full-load hours for tracking-PV installations (single-axis) in Europe 2050. Plants oriented to south with 35° angle of inclination (CM-SAF SARAH) [PfSt16]

6.2.3 Obtaining data on utility-scale photovoltaics installations

Currently, the most widespread variants of PV systems are mounted on roofs or in the countryside areas (as utility-scale systems) due to the generally preferred simple and inexpensive construction. Although roof-mounted PVs show advantages (no additional land is needed, thus agricultural areas, forests or other natural areas remain intact), the output generated by small-scale PVs on roofs is not sufficient for the operation of PtG plants. Utility-scale PV systems (>500 kW), which are built on open spaces, can feed electricity into higher voltage grids, thus leading to less transportation losses, and therefore are better suited for PtG. Almost all PV systems imported from SEM (Solar Energy Map, see 6.1) and GPPD (Global Power Plant Database, see 6.1) have an electrical output >500 kW. Some exceptions can be found in the data sets (that only provide slightly less than 500 kW) but they are still taken into account in this study for potentially supplying electricity to a PtG plant, for example after a further expansion step or future re-powering.

SEM contains data of 2 110 utility-scale PV systems in Europe, based on a precise coordinate data set. Solar-thermal power plants, at first, were not recognizable when extracting the data. Since Spain is the only country in Europe in which electricity is commercially generated via solar-thermal power plants, each location in Spain had to be manually checked. This implies a comparison with Google Maps and, if necessary, deletion of individual locations. As a result, a total of 2 099 SEM locations were identified that formed the basis of the identified PV locations for the further analysis.

The GPPD data set contains 2 802 entries for utility-scale PV in Europe, however, the coordinate data set is not as precise as the one of SEM, i.e. in France. Nevertheless, the GPPD is a useful appendage to the SEM data, particularly as it contains precise coordinate data for the Czech Republic and the United Kingdom. Before importing the data from GPPD into the GIS model at GWI, the first step was to match SEM and GPPD data to remove duplicate entries. In the GIS modelling environment, a buffer analysis was carried out to compare the data sets. Creating a radius of 10 km around each located SEM-PV system allowed to determine whether a GPPD-PV system is present in the vicinity and, if necessary, to delete identified redundant data points. To ensure unique data points additional online maps as well as public satellite data were used for manual comparison. In total, there were additional 1 077 identified locations from the GPPD added to the resulting PV data layer consisting of a total of 3 176 utility-scale PV systems.

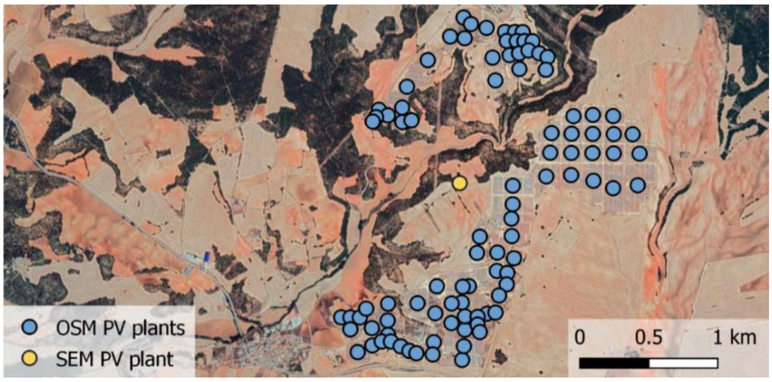


Figure 6-9 Photovoltaic park in Spain as shown by the OSM database (blue dots) and SEM database (yellow dot)

Finally, the data from OSM were added. The entries in OSM are specified and described by means of a “tag”. However, since OSM is a public database, PV systems or solar thermal power plants may be inserted with technically wrong tags. The tags entered by the various OSM contributors are filtered by a query, displayed geographically and exported. With 90 257 points, the OSM database is the largest, but also the most error-prone database among the considered data sources. OSM contains a 30 % share of inner-city PV systems that are installed on roofs. For the analysis in this report, the PV installations on roofs were not considered, instead focus was laid on utility-scale installations that may be erected on unused spaces and agricultural land with presumably less boundary conditions and at larger scale. In the GIS environment, urban areas and cities defined by the CLC were used to filter out roof installations, the vast majority of those being small-scale PV plants. This reduced the OSM database to a total of 63 007 remaining data points.

During the data review, it was found that larger utility-scale PV systems in OSM are in some cases divided into several smaller PV plants (database entries). For example, OSM may display a single solar power plant as multiple data points on the map (see blue data points in Figure 6-9). In cases in which a specific site was already included by the SEM/GPPD dataset (yellow data point in Figure 6-9), the OSM data were removed in order to prevent duplicates of the plant.

In order to locate these duplicates, a buffer analysis was performed for the data records of SEM and GPPD. A buffer zone, with a radius of 1 km, was created around the 3 176 identified SEM and GPPD sites. All data points of OSM located in the circles were checked to avoid duplicates of the PV systems from SEM and GPPD. Lastly, a manual check of the remaining OSM PV sites followed. As a result, a total of 10 769 identified sites represent the OSM data set. That led to a total of 13 945 identified sites for the three data sets from SEM, GPPD and OSM.

In Austria and Switzerland, 353 PV plants were identified with SEM, GPPD and OSM. Due to the small number of localized PV sites these countries, a manual search for further PV plants was conducted. With the help of the imported public maps, 187 additional locations were determined. Following the CLC categorisation (categories 111 and 112), urban areas were neglected, reducing the number of additional data points to total of 100 PV locations. Adding these points to the previously identified sites resulted with the final number of 14 045 identified PV utility-scale systems for further analyses in STORE&GO.

The distribution of the 14 045 identified PV utility-scale systems in Europe is presented in Figure 6-10. Most of the identified PV plants were located in Italy and Germany with 3 838 and 3 474 plants, respectively. Other countries like Greece, Spain and the United Kingdom also exhibit a significant number of installed utility-scale PV systems (more than 1 000 systems per country), followed by France and Czech Republic.

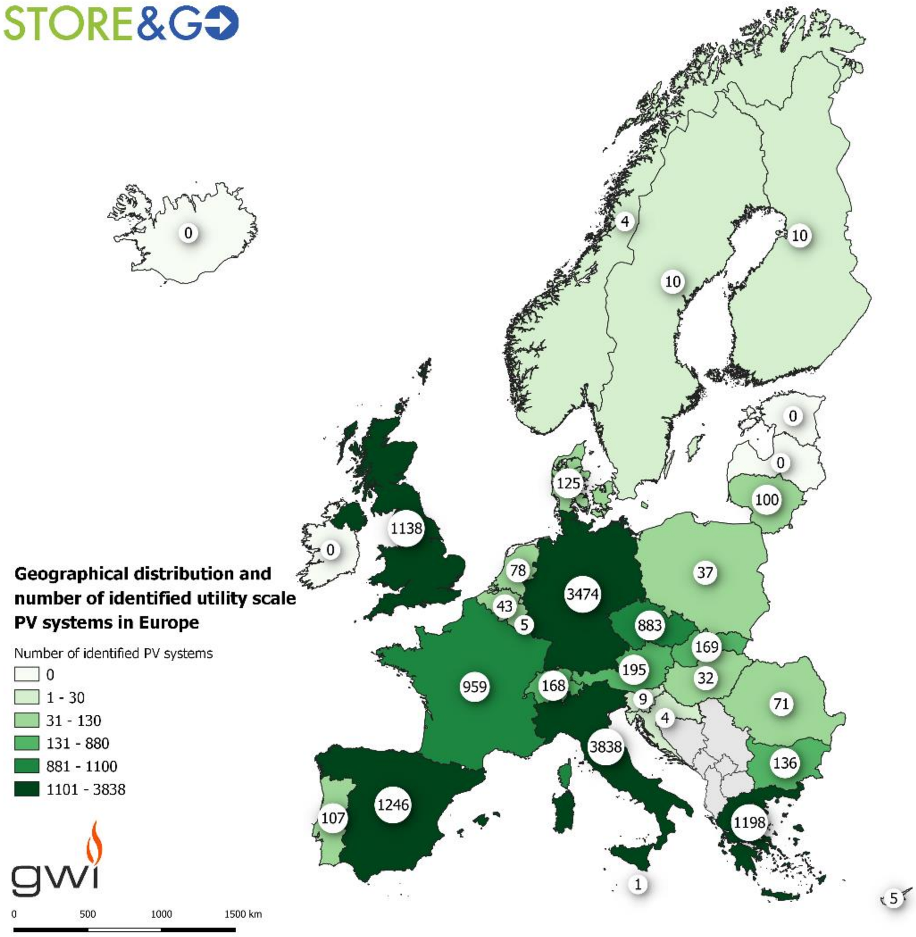


Figure 6-10 Geographical distribution and number of identified utility-scale PV systems in Europe

The majority of the PV systems are located in southern Europe (Figure 6-11), where largest production outputs per installed capacity are achieved due to the highest solar irradiation intensities in Europe (see Figure 6-2). However, the number of installed PV systems in the Czech Republic, Germany and the south of England are outstanding, considering the lower solar irradiation in comparison with South Europe (Figure 6-2). Foreseeably, following the lowest regional potentials, the lowest degrees of utility-scale PV installation can be found in the Scandinavian nations.

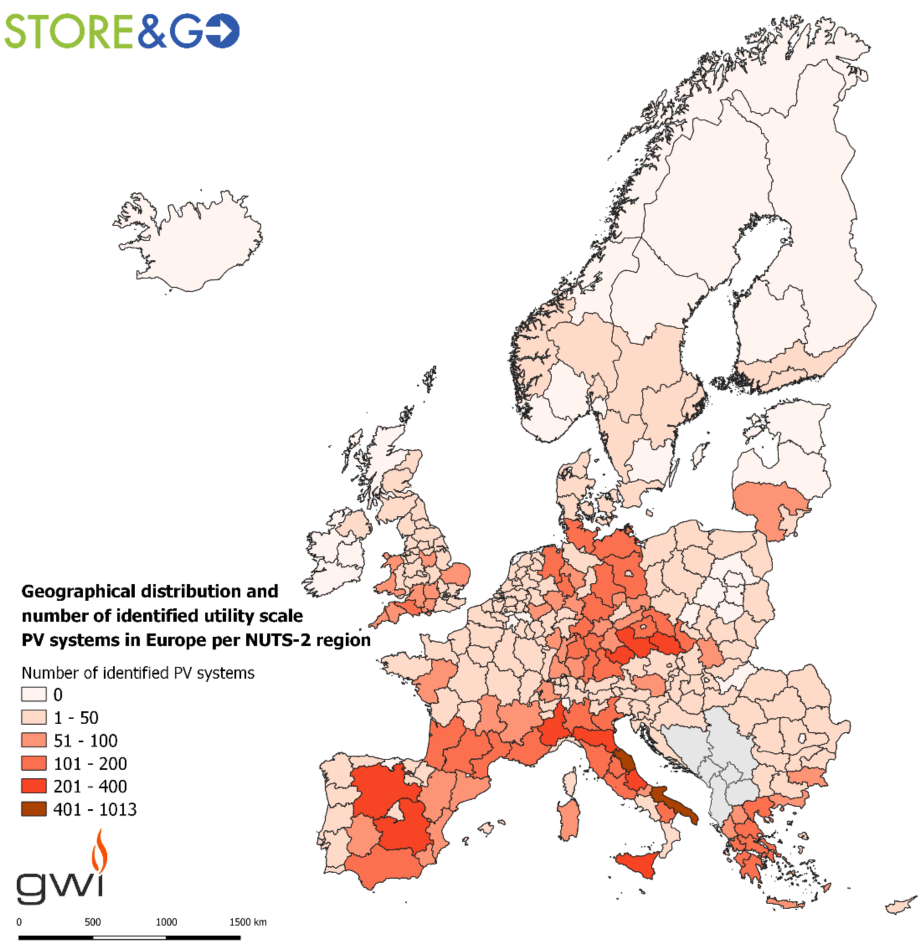


Figure 6-11 Geographical distribution of identified utility-scale PV systems in Europe per NUTS-2 region

6.3 Wind power potential

In 2017, wind power covered around 11.5 % of EU's total electricity demand. With a total installed net capacity of 169 GW (153 GW onshore and 16 GW offshore) and 336 TWh of generated electrical energy, wind energy is the largest form of renewable power generation in Europe [Wind00].

According to WindEurope, the potential for offshore wind energy in Europe is high enough to meet the complete European electricity demand on the balance-sheet, while on-shore wind could theoretically produce almost twice as much [LTJP19] with potentials representing almost all regions of Europe, but predominantly in the Northern Sea region as well as the Baltic Sea and the Mediterranean Sea.

The advantage that wind turbines offer to PtG plants is that they offer larger full-load equivalent hours compared to PV systems. However, using both RE sources further increases the number of full load hours for the operation of a PtG plant. Using the synergy of both RE sources has a positive effect on the expected operating costs, therefore the coupling of a PtG plant with wind turbines and PV plants should be preferred and will be focussed in this work. A detailed analysis of PtG plant design and operation strategies for wind power, PV and control market (both wind and PV powered) electricity supply can be found in Gorre *et al.* [GRKS20].

6.3.1 Obtaining data on wind turbine locations

For the analysis of potential PtG plant sites, geographically high-resolution site data of all wind turbines in the countries under consideration was necessary.

The data was obtained via the online map service OSM, as already described in the previous chapter. This database identified 93 009 wind turbines (as of January 2019). As the database contains also wind turbines that are far off the European land, i.e. Grand Canary or most offshore wind turbines being further away than 10 km from the shore, a buffer analysis was completed and only those that were located within the borders of the EU27+4[4] countries were taken into account. That resulted in a total of 87 945 identified wind turbines for further analysis. Information on the locations of the wind turbines from OSM can be regarded as reliable, however, data regarding the installed capacities of the wind turbines was missing. As of 2017, 29 844 wind turbines with a total capacity of 56 154 MW were in operation in Germany, resulting in an average capacity of 1.88 MW per wind turbine [Wind00]. It is assumed that modern wind turbines exhibit installed electrical capacities of at least 2 MW [KoFB19]. Old turbines with lower capacities are expected to be exchanged in the course of future repowering projects that lead to an increased overall installed capacity without the need for additional development of sites. This work focusses on the exact locations of the wind turbines and their geographical relationships with suitable CO_2 sources rather than their location-specific capacities.

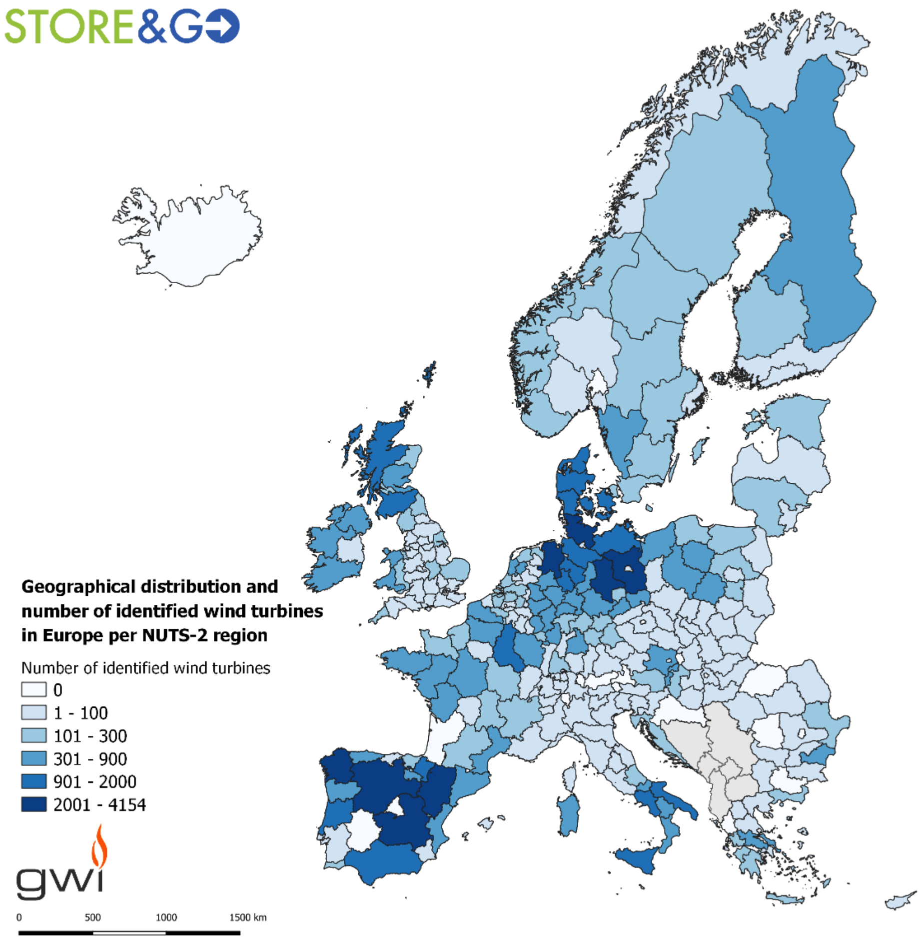


Figure 6-12 Geographical distribution of identified wind turbines in Europe per NUTS-2 region

[4] EU27+CH+IS+NOR+UK

Particularly high numbers of wind turbines can be found in Denmark, Germany, France, United Kingdom, Italy and Spain. The density of the wind turbines by NUTS-2 regions is presented in Figure 6-12. Areas exhibiting between 1 000 to 4 000 wind turbines can be identified as high-density wind power areas. In regions with high density of wind energy plants (dark blue areas in Figure 6-12), the possibility of coupling with an industrial or a biogas plants appears more probable, resulting in an enhanced PtM potential. The number of wind turbines will continue to increase in the coming years, so that the number of regions with high wind turbine densities will increase accordingly. The total numbers of onshore wind turbines on the national level included in the study are depicted in Figure 6-13.

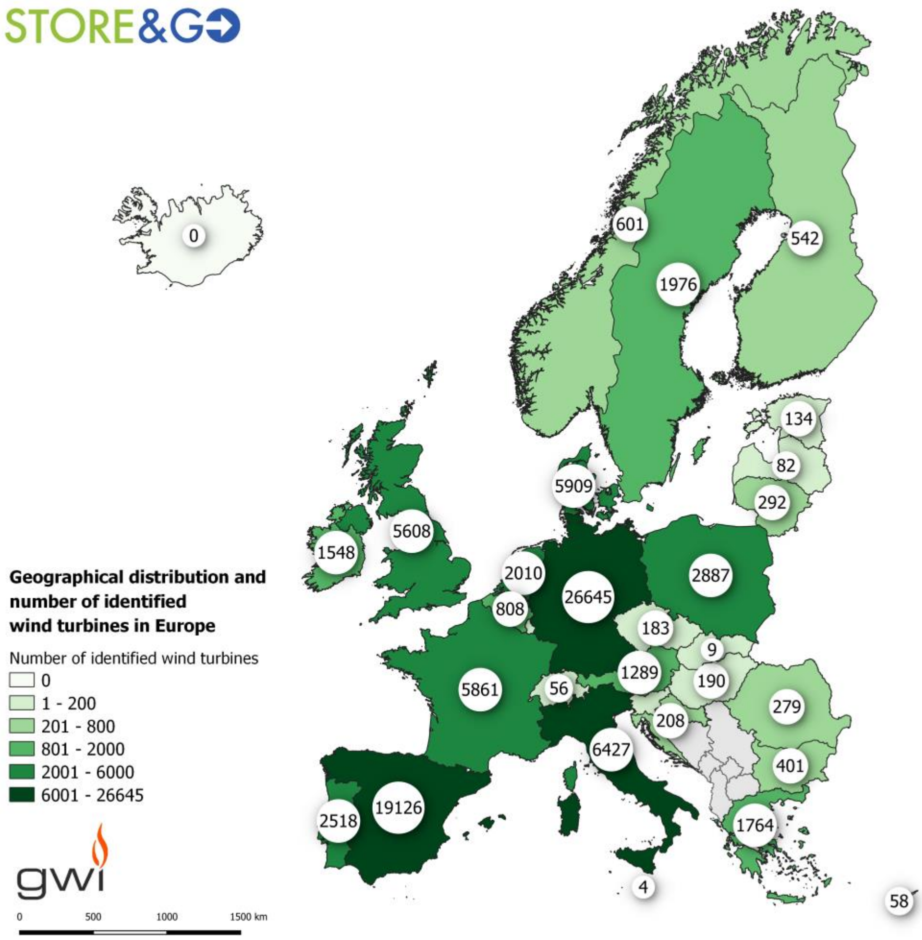


Figure 6-13 Geographical distribution of identified onshore wind turbines on the national level in Europe

6.4 Table of localised RE plants on the national level

Table 6-1 shows the numbers of identified wind turbines and utility-scale PV systems per state in the EU27+4 as integrated in the present study. Figure 6-14 on the following page represents their geographical distribution on the national level.

Table 6-1 Numbers of identified utility-scale PV systems and wind turbines in Europe

Country	Utility-scale PV systems	Wind turbines
Austria	195	1 289
Belgium	43	808
Bulgaria	136	401
Croatia	4	208
Cyprus	5	58
Czech Republic	883	183
Denmark	125	5 909
Estonia	0	134
Finland	10	542
France	959	5 861
Germany	3 474	26 645
Greece	1 198	1 764
Hungary	32	190
Ireland	0	1 548
Italy	3 838	6 427
Iceland	0	0
Latvia	0	82
Lithuania	100	292
Luxembourg	5	68
Malta	1	4
Netherlands	78	2 010
Norway	4	601
Poland	37	2 887
Portugal	107	2 518
Romania	71	279
Slovakia	169	12
Slovenia	9	9
Spain	1 246	19 126
Sweden	10	1 976
Switzerland	168	56
United Kingdom	1 138	5 608
Total	**14 045**	**87 495**

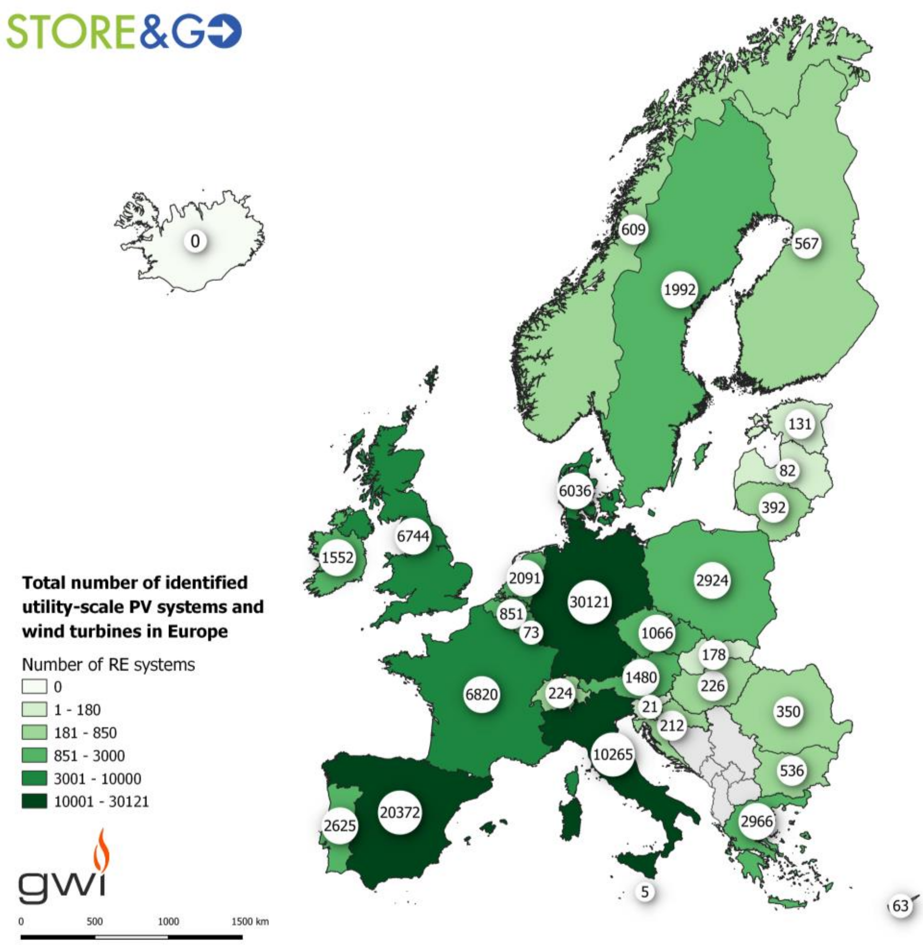


Figure 6-14 Total numbers of included utility-scale PV systems and wind turbines in Europe as an input for the PtM location identification in this work

7 Locational analyses

Potential power-to-methane energy conversion sites as studied here are each based on a CO_2 point source – either biogenic or industrial – that delivers the carbon feedstock for the methanation process. Suitable locations for PtM plants are identified using the secondary criterion of the availability of a renewable energy source (wind turbine or utility-scale PV system) within a 10 km radius.

For the geographical analysis and calculation of the potentials for PtM, the matchmaking between CO_2 sources and RE production sites is made by a geoinformation system approach that creates circular zones around the CO_2 sources and evaluates the number of RE sources within that 'buffer zone'. A central working hypothesis is that for the analysis of power-to-methane potentials in this work, local renewable electricity input must be used. Therefore, all CO_2 sources that lack local large-scale RE production (wind or at least utility-scale PV plants) drop out of the further assessment and are not accounted for in the following potential study. This conservative approach underestimates the number of potential methanation sites centred at CO_2 sources, since electricity supply solely from the grid is not accepted here. A mix however, from local RE production as an input for electrolysis systems and grid-fed operation is not excluded.

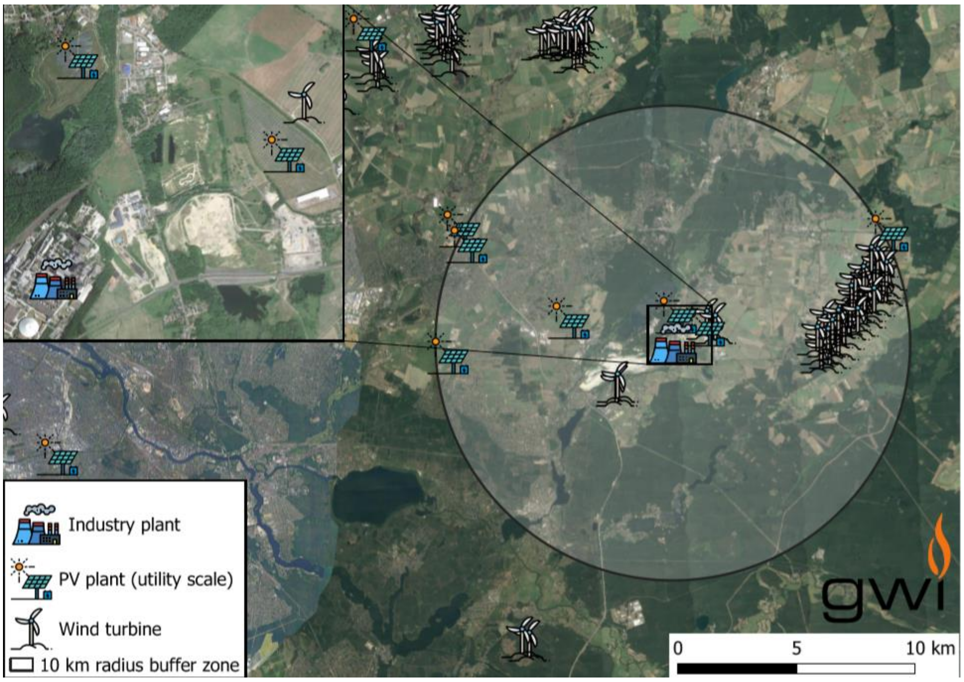


Figure 7-1 Representation of a buffer zone with 10 km radius around an industrial plant that includes wind turbines and utility-scale PV systems [5]

The RE sources considered in this way represent theoretical power sources for PtG plants. All data stem from publicly available data collections on existing plants or have been collected in one-by-one manual research of publicly accessible information such as satellite images or homepages of authorities and associations. The modelled reality however is by far not complete, many more RE plants are expected to exist today, and by far more RE installations will be additionally erected in the years to come. As an interim conclusion it should be noted that the share of RE plants that show the potential of synergies when coupled to a CO_2 source will drastically increase in the future, so that

[5] Icons by *Freepik* from www.flaticon.com

the results elaborated here will identify a growing number of potential PtM energy conversion sites with any future datasets on esp. green CO_2 sources or RE installations used as input.

An example for the buffer analyses is shown in Figure 7-1. The 10 km radius represents the buffer zone around an industrial plant. All wind and utility-scale PV plants located within this zone are considered as potential renewable energy source for a potential PtG plant, located in direct neighbourhood of the CO_2 source.

It is possible for a RE source to be located in the buffer zone of different plants, and thus be counted several times. Since the aim of the analysis is to locate potential PtG sites geographically, the multiple consideration of RE plants is accepted. The presence of large-scale RE installations is proof of the existence of local RE potentials, and the locally observed stages of RE roll-out are generally expected to develop further to clearly higher levels in the future by additional instalments as well as repowering activities.

Three different power-supply options are applied for the analysis. The first one is a site analysis for PtG plants with power-supply only from PV plants. The second option leads to a set of site analyses carried out for power-supply by wind turbines. In the third power-supply option, both RE plant types are required to supply a PtG site in order to benefit from synergies in the load curves for enhancing the power-to-methane full load hours.

7.1 Potential PtM sites identified at industrial CO_2 sources

For the analyses and the refinement of site identification of the potential PtG plants in Europe, a buffer analysis was performed. This enabled the setting-up of local filtering conditions for the plants from the five selected industries.

In Figure 4-6 the location and the number of the large industrial CO_2 sources from the five analysed industries in Europe are shown. The total number of 956 industrial plants are scattered all across Europe. As described, the analysis consisted of creating a buffer zone with 10 km radius around each of the 956 industry plants, and within that area, utility-scale PV systems and/or wind turbines were located.

7.1.1 Industrial CO_2 & local wind power

First, a buffer analysis of the industrial point sources with a potential coupling to wind turbines was performed. A total number of 552 of 956 plants (58 %) were identified for potential local energy coupling with wind turbines. Due to the high presence of industry and wind turbines, 194 of these are located in Germany (35 %). The United Kingdom, France and Spain also exhibit a great potential for PtG with 58, 47 and 39 potential PtG plants, respectively. Although the industry plants are also present in the eastern parts of Europe, the potential for PtG is currently very low due to the lower presence of wind turbines in these regions. The results can be observed in Figure 7-2.

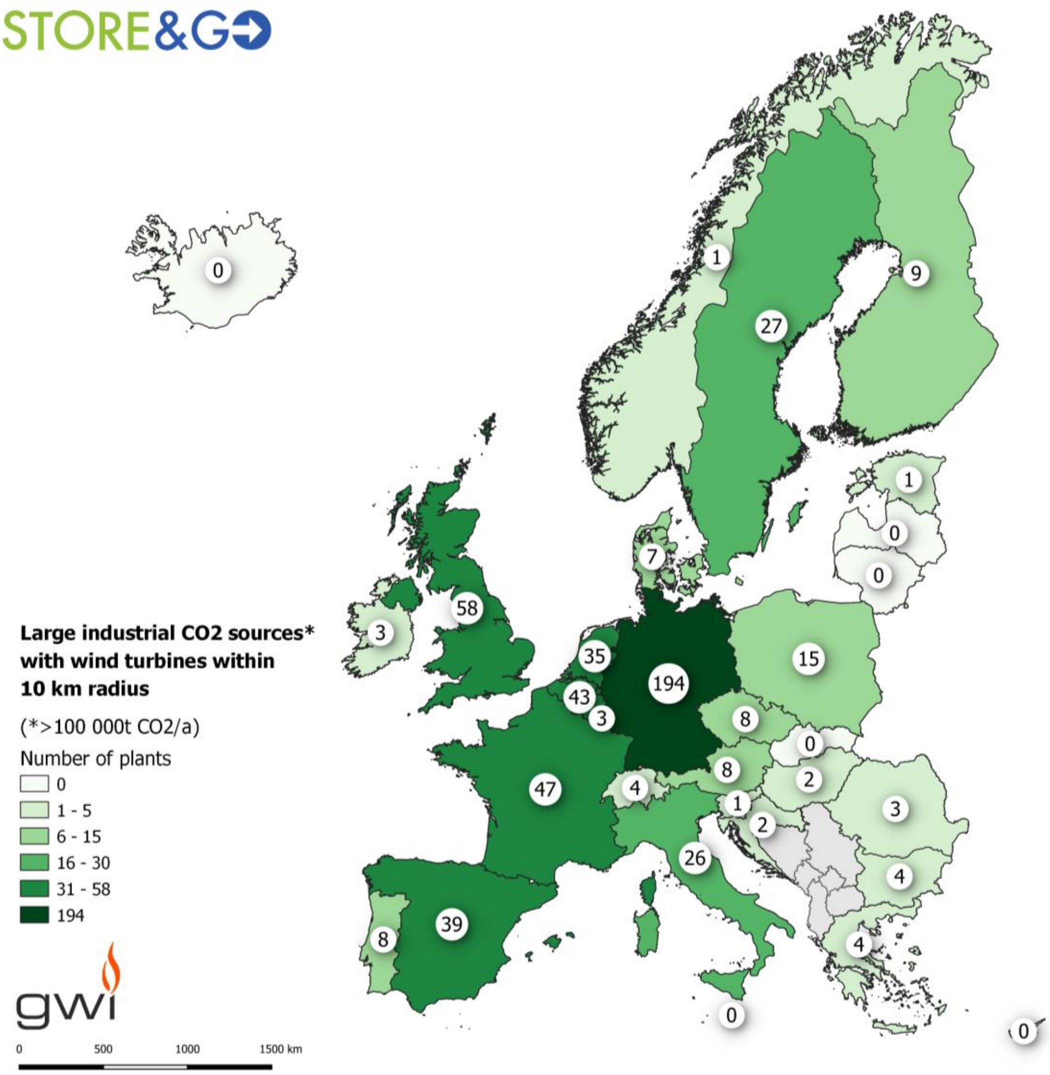


Figure 7-2 Large industrial CO_2 sources (potential PtG plants) in Europe that exhibit a potential for local coupling with wind turbines, 2019

7.1.2 Industrial CO_2 & local utility-scale PV systems

In Figure 7-3 the results of the buffer analysis of the industrial plants that demonstrate the potential of coupling with at least one utility-scale PV system in their 10 km radius area are shown. The potential coupling of PtG plants to solar power generation only leads to completely different plant design, comparably very low PV-based full load hours which should be compensated for by electricity supply from the grid and/or significant buffer storage capacities [GRKS20]. Nevertheless, the analysis is carried out here to elucidate the geographical correlations of the industrial and large-scale PV installations in Europe today. We found the following results: A total of 506 out of 956 plants (53 %) were identified for potential energy coupling with PV plants. A number of 187 of these plants (37 %) are located in Germany, whereas the United Kingdom, Italy and France have almost the same numbers of potential plants with 58, 53 and 52, respectively. The Nordic countries have almost no potential for industrial CO_2 coupling to solar PV plants due to the lack of installed utility-scale PV plants.

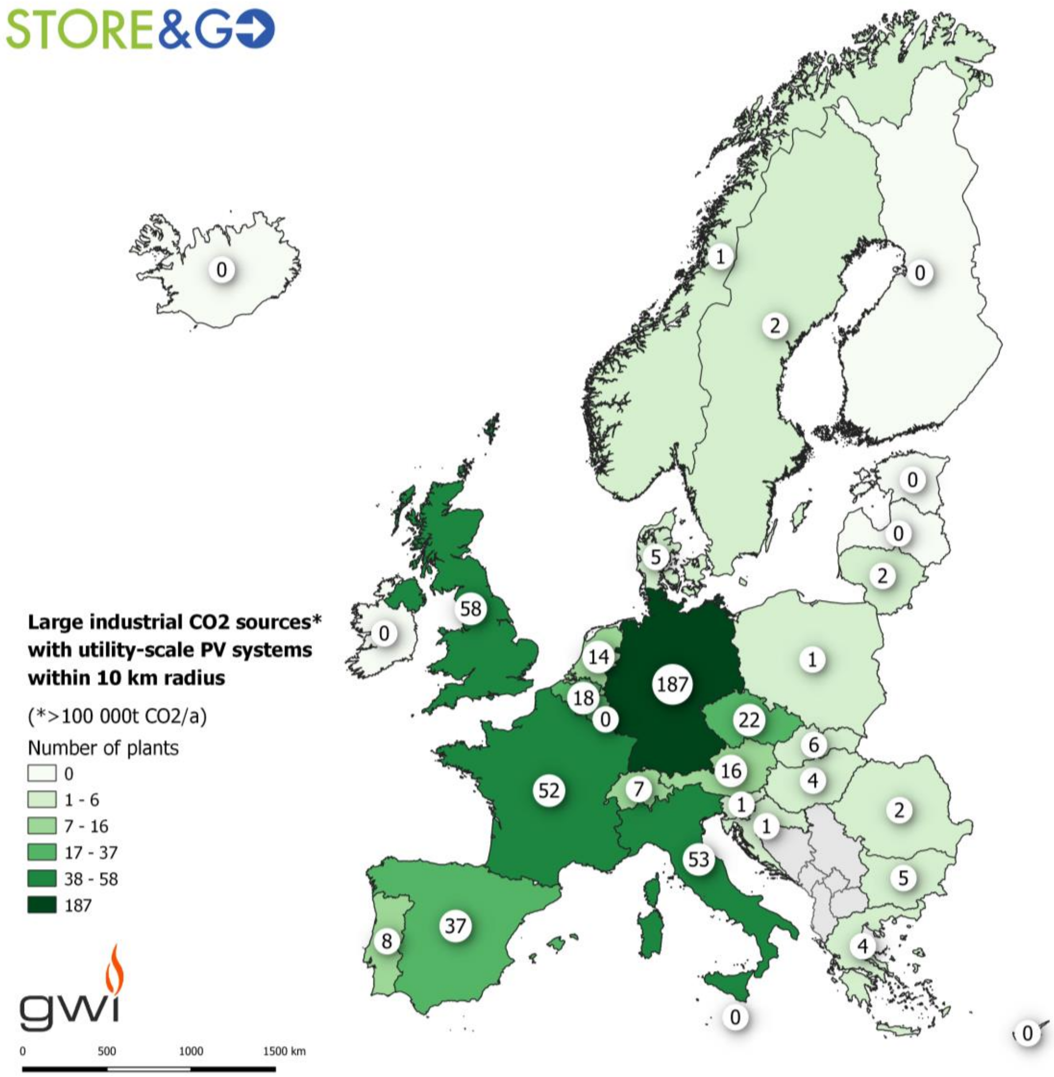


Figure 7-3 Large industrial CO_2 sources (potential PtG plants) in Europe that exhibit a potential for local coupling with utility-scale PV plants, 2019

7.1.3 Industrial CO_2 & local wind power & utility-scale PV systems

Following the previous analyses, an additional analysis was performed to locate those plants that have both, utility-scale PV and wind turbines available in their proximity. The results are presented in Figure 7-4. Up to 316 out of 956 plants (33 %) show local potential for coupling with both RE sources. Of the total number of 217 industrial plants in Germany, 155 plants (71 %) show coupling potential with both RE sources underlining a high potential for PtG in this state with its comparably high degree of RE generation roll-out. On the basis of the selected criteria, 42 synergetic wind plus PV locations were identified in the United Kingdom and 26 potential locations in France.

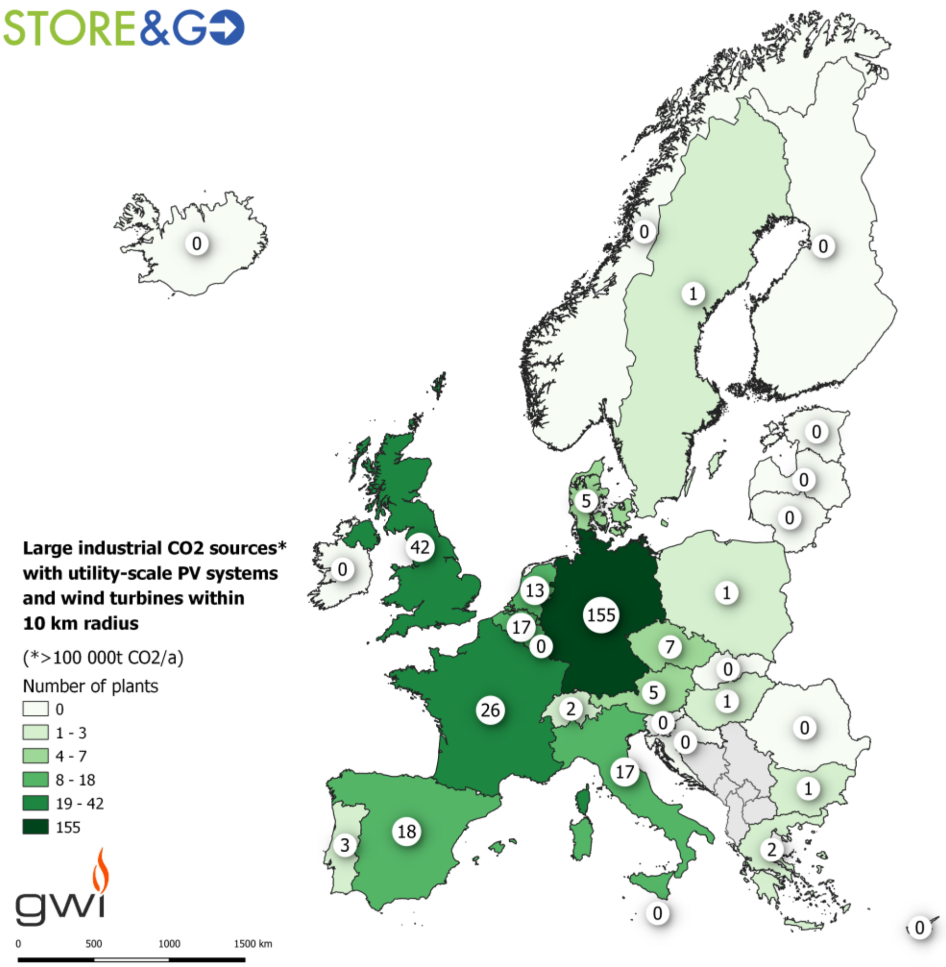


Figure 7-4 Large industrial CO_2 sources (potential PtG plants) in Europe that exhibit a potential for local coupling with both, utility-scale PV plants and wind turbines, 2019

7.1.4 Industrial CO_2 & local wind parks

As the PtM plants located at industrial sites require a significant amount of energy for the electrolysis process (compared to the orders of magnitude smaller biogas plants), it is an obvious additional analysis step to evaluate those sites that exhibit wind parks consisting of 10 to 50 turbines, or even larger wind parks consisting of more than 50 wind in their proximity. This leads to the results shown in Figure 7-5, where it can be seen that as of today, large parts of the highest-potential PtG plants are located in Germany, the Netherlands, Belgium, Spain and the UK. Out of 956 studied industrial CO_2 sources, 221 (23 %) could potentially be coupled with 10 to 50 wind turbines in the radius of interest (light green dots). An additional 100 plants (10 %) have the potential for coupling with more than 50 wind turbines (dark green dots). These 321 plants represent high potential PtM sites.

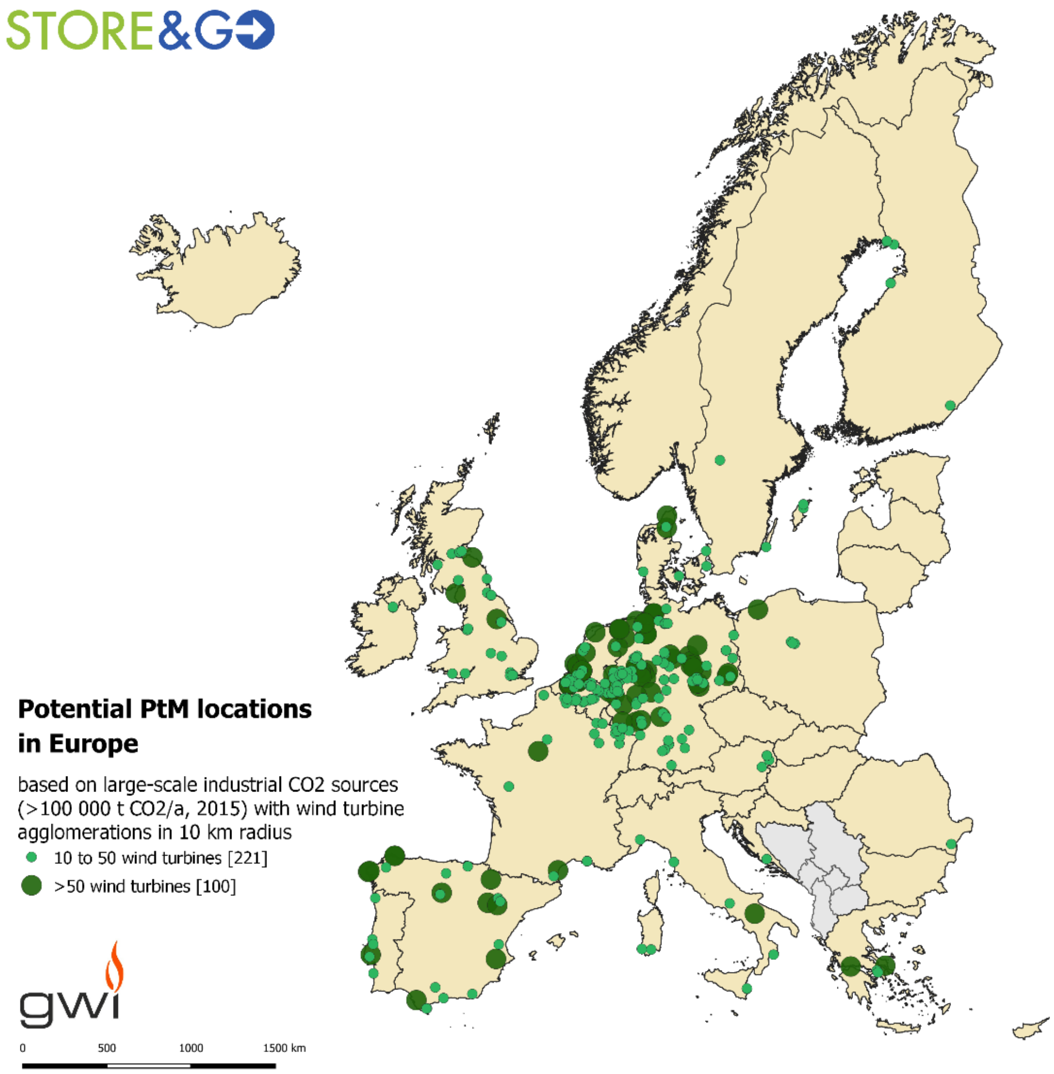


Figure 7-5 Large scale industrial CO_2 sources (potential PtG plants) in Europe that exhibit a potential for local coupling with wind parks, 2019

7.1.5 Industrial CO_2 & local wind parks & utility-scale PV systems

With the aim to couple both RE sources (a mix of wind and PV) to potential PtM plants allowing for enhanced full load equivalents [GRKS20], a further analysis was carried out. The CO_2 point sources that fulfil the local RE-mix availability criterion are presented in Figure 7-6.

Out of the 321 plants identified, which have local correlation to wind parks consisting of 10 or more wind turbines in a radius of 10 km, 145 (65%) plants have additional one or more utility-scale PV plants in their proximity.

A clustering of utility-scale PV plants in analogy to the mentioned groups of 10 or more wind turbines could not be carried out, since large PV installations were found not to correlate in local clusters that appear with typical distances closer than 10 km. In this geographic context, the two RE sources show completely different characteristics, which is due to the high probability of observing wind turbines that are a part of wind parks or at least erected close to other wind turbines due to favourable wind potentials and authorisation procedures. Large PV installations in contrast do not show a tendency to be built in parks with significant capacities in a certain distance. The modular expansion of plants is typically done directly next to existing plants, where areas and authorisations are available. Physically, there is no drawback for the power generation in the case of extensive PV installations, while in the case of wind turbines, the physics of harvesting energy from the wind as well as the need to avoid vibration of components results in a need to keep certain minimal distances.

Seventy large-scale industrial CO_2 sources even correlate with local utility-scale PV installation and large-scale wind parks consisting of more than 50 turbines. These 70 sites (dark green spots in Figure 7-6) bear the highest potentials for power-to-methane identified in this study, based on today's RE generation roll-out and local energy coupling.

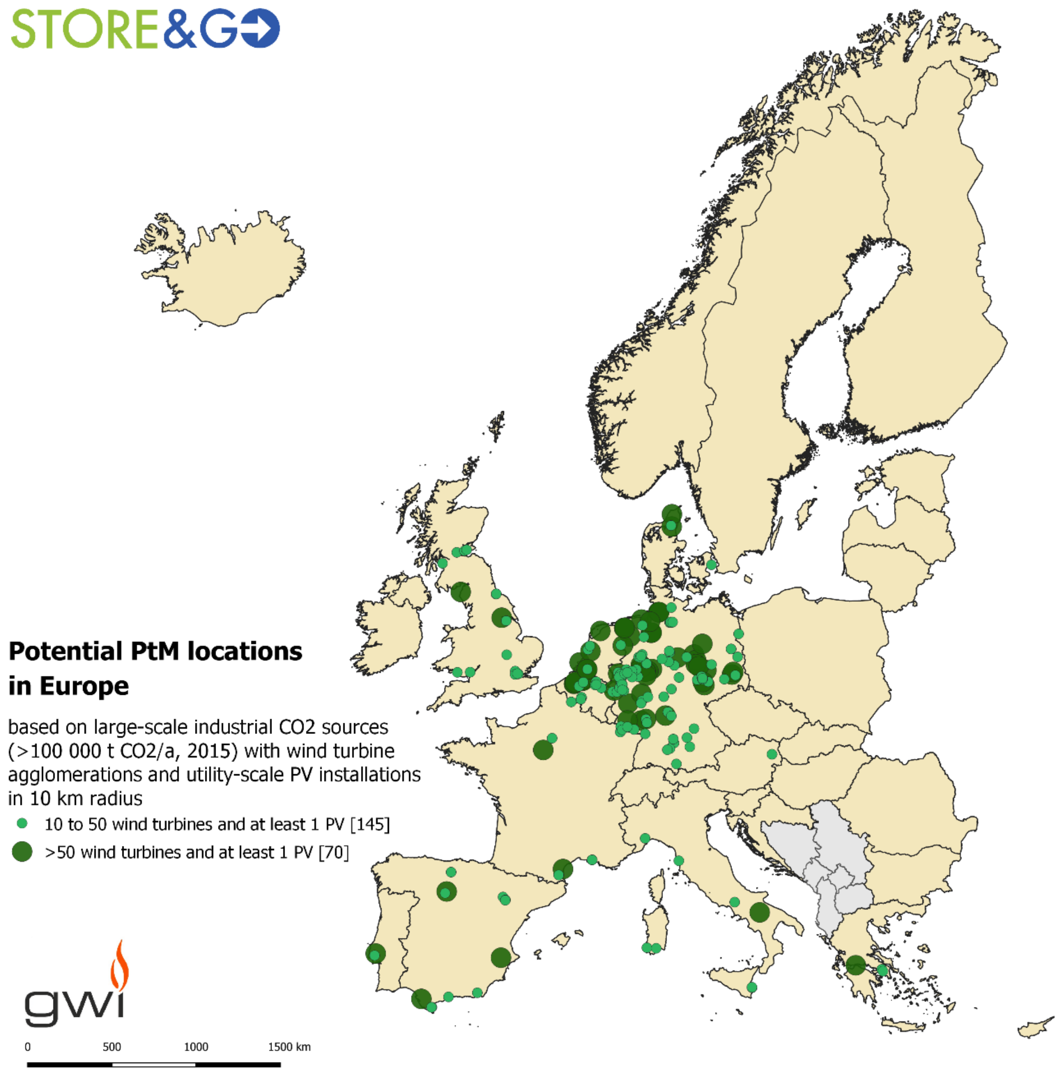


Figure 7-6 Potential PtM locations in Europe, based on the coupling potential of large-scale industrial CO_2 sources with wind parks and min. 1 utility-scale PV system in 10 km radius, 2019

7.2 Potential PtM sites identified at biogenic CO_2 point sources

Similar to the industrial plants, a buffer analysis of the biogas plants was conducted. A potential biogas-PtG plant fulfils the assigned criteria when the biogas plant is positioned in the proximity of a RE source, either a wind turbine or an utility-scale PV plant.

7.2.1 Biogas plants & local wind power

Today's numbers of biogas plants with a potential for local coupling with wind turbines for the countries in Europe are shown in Figure 7-7. Among these, 67 % or 11 261 out of 16 912, exhibit a potential for coupling with at least one wind turbine. Due to the strong biogas rollout level and the high availability of data, 86 % of those plants (or 9 714) are located in Germany.

Denmark exhibits the highest share of biogas-wind turbine sector coupling options, a share as high as 97 % of all biogas plants (151 out of its total 156 identified biogas plants). This correlation is due to the high density of wind power installations in Denmark, counting up to almost 6 000 onshore wind turbines (Figure 7-8).

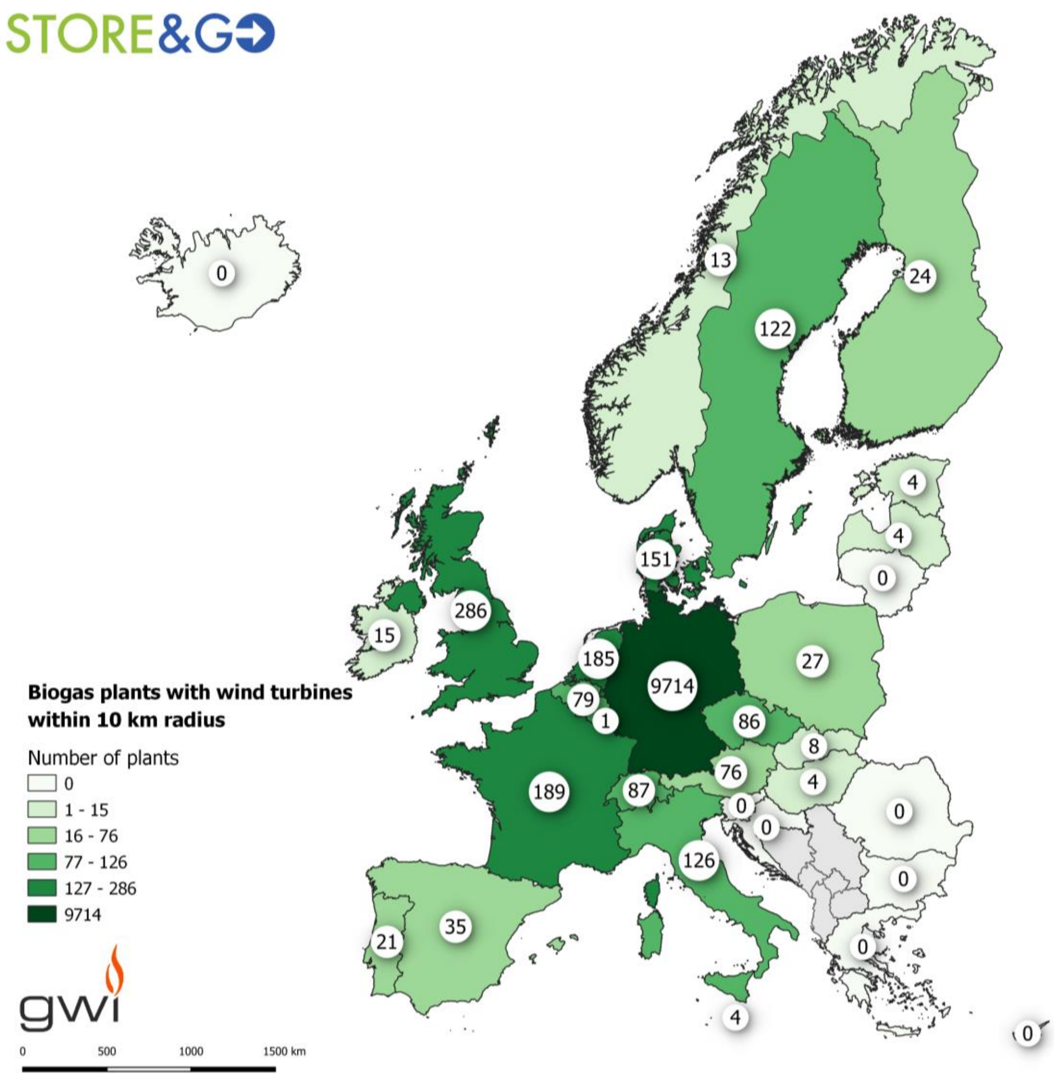


Figure 7-7 Number of identified biogas plants in Europe, that exhibit the potential of coupling with at least one wind turbine within 10 km radius, 2019

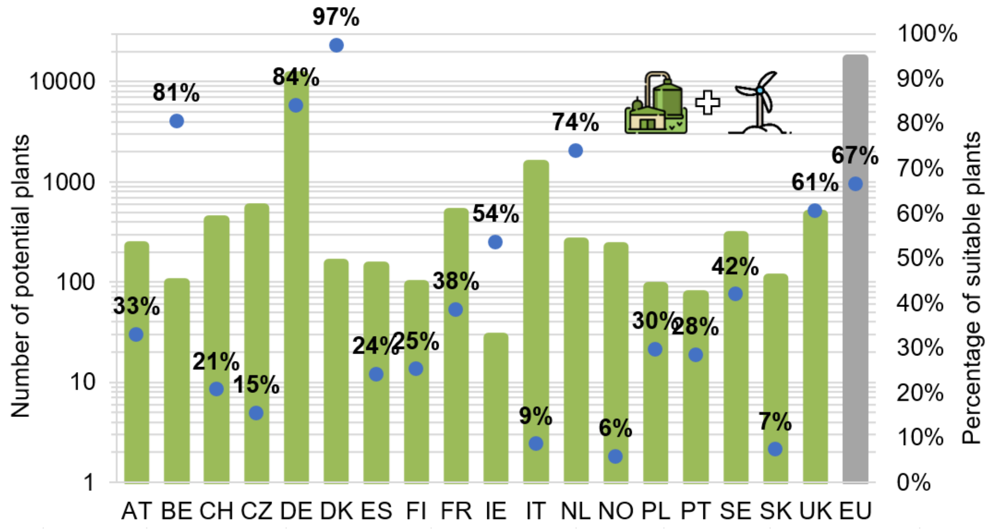


Figure 7-8 Number of identified biogas plants across Europe and share of plants suitable for local power-to-methane energy coupling with wind power generation (based on data from 2019)

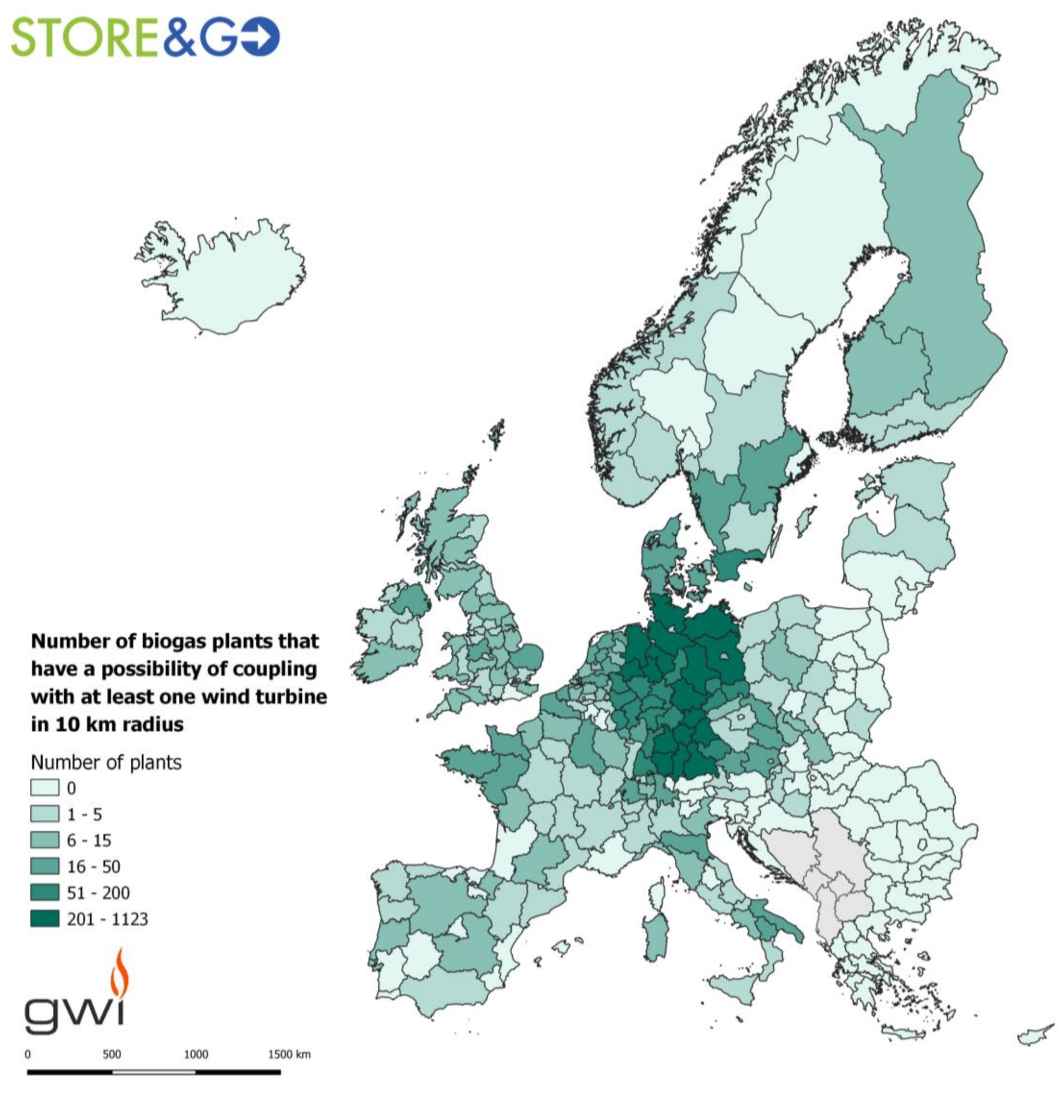


Figure 7-9 Geographical distribution and number of potential PtM plants in Europe 2019, based on the possibility of coupling the biogas plants with at least one wind turbine in 10 km radius, per NUTS-2 region

Norway, exhibiting a small potential for biogas-wind turbine sector coupling (only 6 %), could presumably have a higher share. Most of the biogas plants are located along the coast, and the wind turbines that are located further in the fjords or near-offshore were not included in this analysis, partly because they were beyond the 10 km buffer radius from the biogas plants, partly because the focus was on onshore installations and some data points very close to the coastal line were regarded as offshore installations during the geoinformation data handling process. The potential number of PtM sites based on present RE and CO_2 sources are therefore to some extent underestimated.

In France, a congruence between wind energy and biogas plants can be observed especially in the west, resulting in a number of 189 suitable locations (Figure 7-9).

Due to the small number of wind turbines in northern Italy, where most Italian biogas plants are located (mismatch), only 9 % of the approximately 1 500 biogas plants (126) can benefit from the local sector coupling option studied here. A more detailed evaluation of the wind power and biogas related regional structure of Italy can be found in chapter 7.4.

Although around 19 000 wind turbines have been located in Spain, only 35 potential PtG plants could be identified, based on these selection criteria, due to a very small number of identified biogas plants.

7.2.2 Biogas plants & local utility-scale PV systems

In Figure 7-10 the results of the buffer analysis of the biogas sites that exhibit a potential for coupling with at least one PV system in 10 km radius is presented. In total, 12 498 out of the 16 912 identified biogas plants, or share of 74 % of the total number, conform to this criterion.

In Germany, due to the high number of identified biogas and utility-scale PV plants, 9 426 plants (or 82 % of the total identified biogas plants) reveal a potential for direct coupling with at least one large PV system. The resulting numbers for the European countries are shown in Figure 7-11.

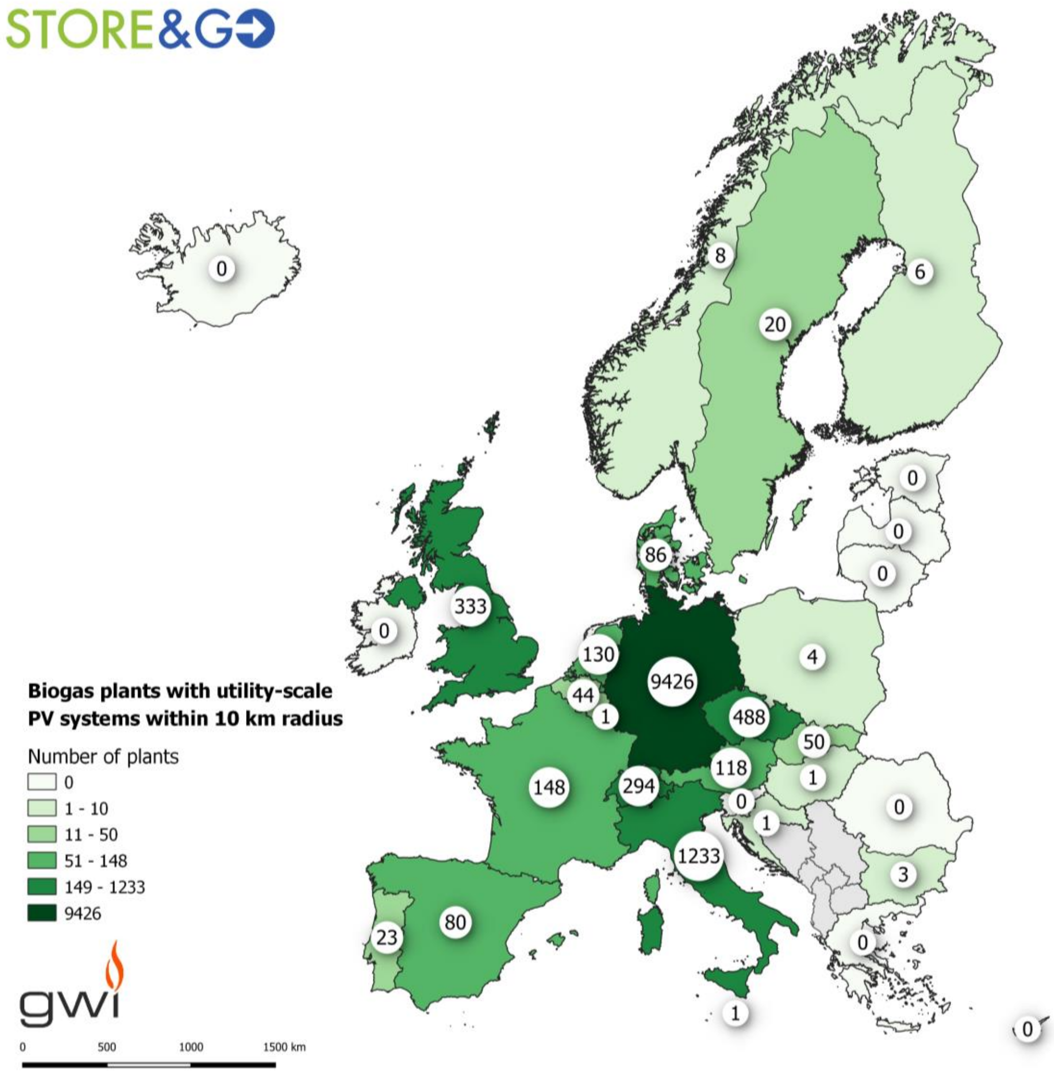


Figure 7-10 Identified biogas plants in Europe 2019 with utility-scale PV systems within 10 km radius

Figure 7-11 displays the share of potential PtM plants on the national level and in the European average.

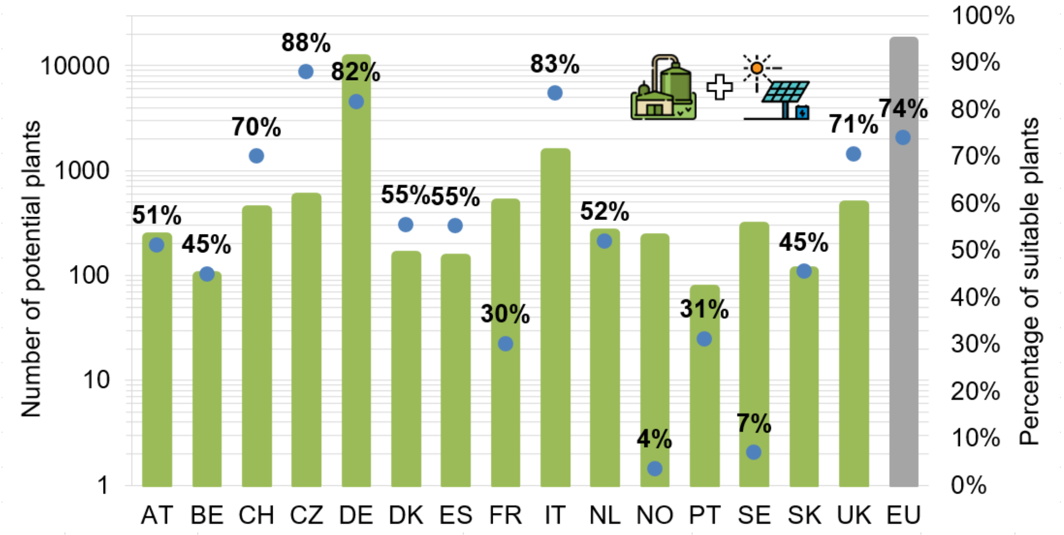


Figure 7-11 Number of identified biogas plants across Europe and share of plants suitable for local power-to-methane energy coupling with utility-scale photovoltaics (based on data from 2019)

For France, 491 biogas plants were identified and included in this study. From those, 148 plants (30 %) comply with the selection criterion to exhibit utility-scale PV systems within a 10 km distance. This is due to the high concentration of PV plants in the south of France, while the biogas plants are being concentrated in the eastern and western part of the country.

The Czech Republic, Italy and the United Kingdom demonstrate PtG shares of 88 %, 83 % and 71 %, respectively. In the Czech Republic, this is due to the high number and wide distribution of PV systems and biogas plants. In Italy, although most of the biogas plants are located in the north of the country where only about a quarter of the Italian utility-scale PV plants have been installed, the total potential for biogas-PV energy coupling via PtM still is very high, resembled by a total number of 1 233 potential locations (also see regional details in Figure 7-20). In the United Kingdom most utility-scale PV plants were built in the south, due to the higher solar irradiation, so the predominant number of potential PtM sites is exhibited in those regions.

Figure 7-12 shows the detailed distribution of the potential biogas-based PtM plants in Europe per NUTS-2 region.

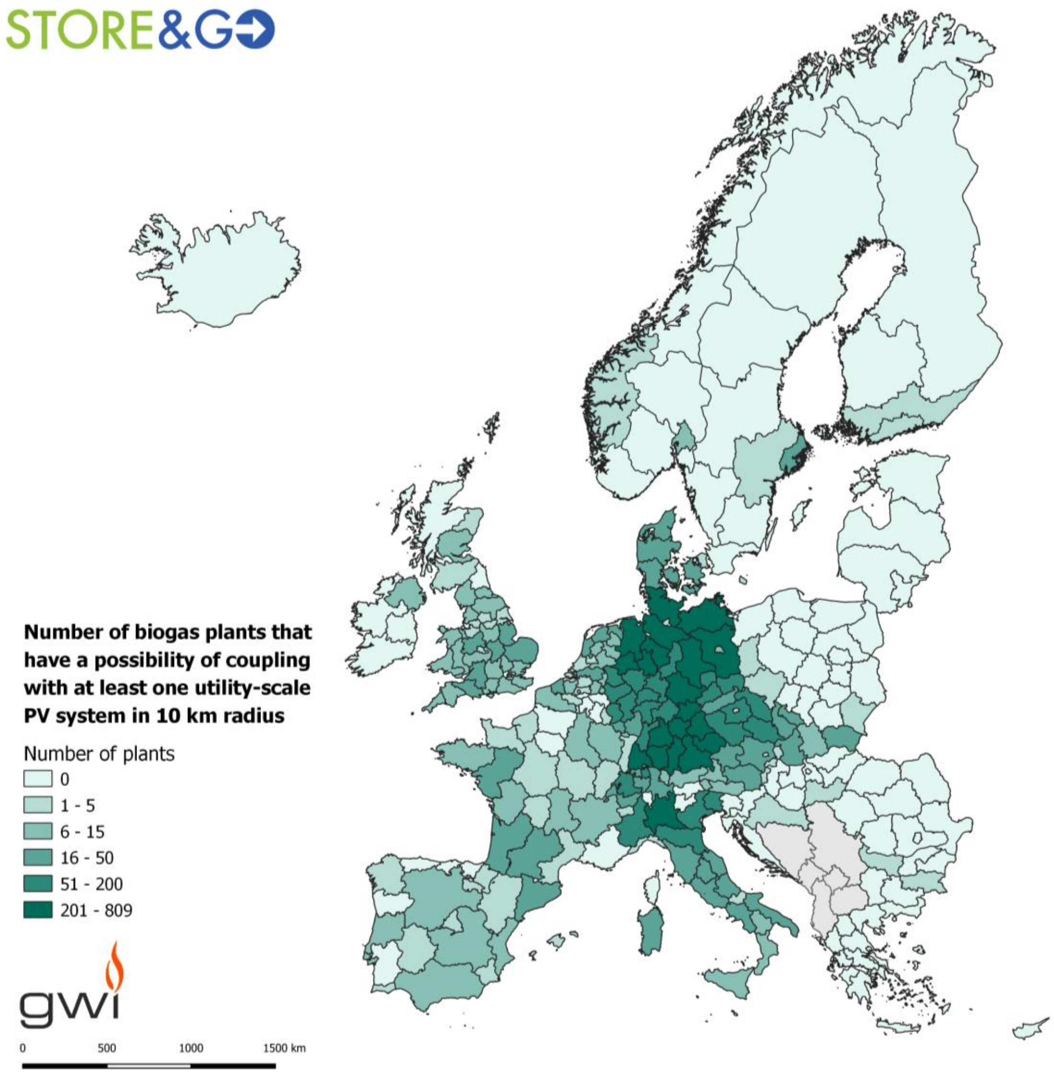


Figure 7-12 Number of potential biogas plants that exhibit the potential of coupling with at least one PV system in 10 km radius, per NUTS-2 region, 2019

7.2.3 Biogas plants & local wind power & local utility-scale PV systems

Finally, an analysis was conducted, considering biogas plants that show availability of both RE sources (wind turbines and utility-scale PV plants) in their proximity. The results are presented in Figure 7-13 and Figure 7-14.

About half, 8 648 out of the 16 912 identified biogas plants (51 %), were found to exhibit the potential for coupling with both RE sources. Of those, 7 850, or 91 %, are located in Germany. As indicated previously, this is due to the high number and synergetic geographical correlation of RE sources and the CO_2 source biogas throughout the country.

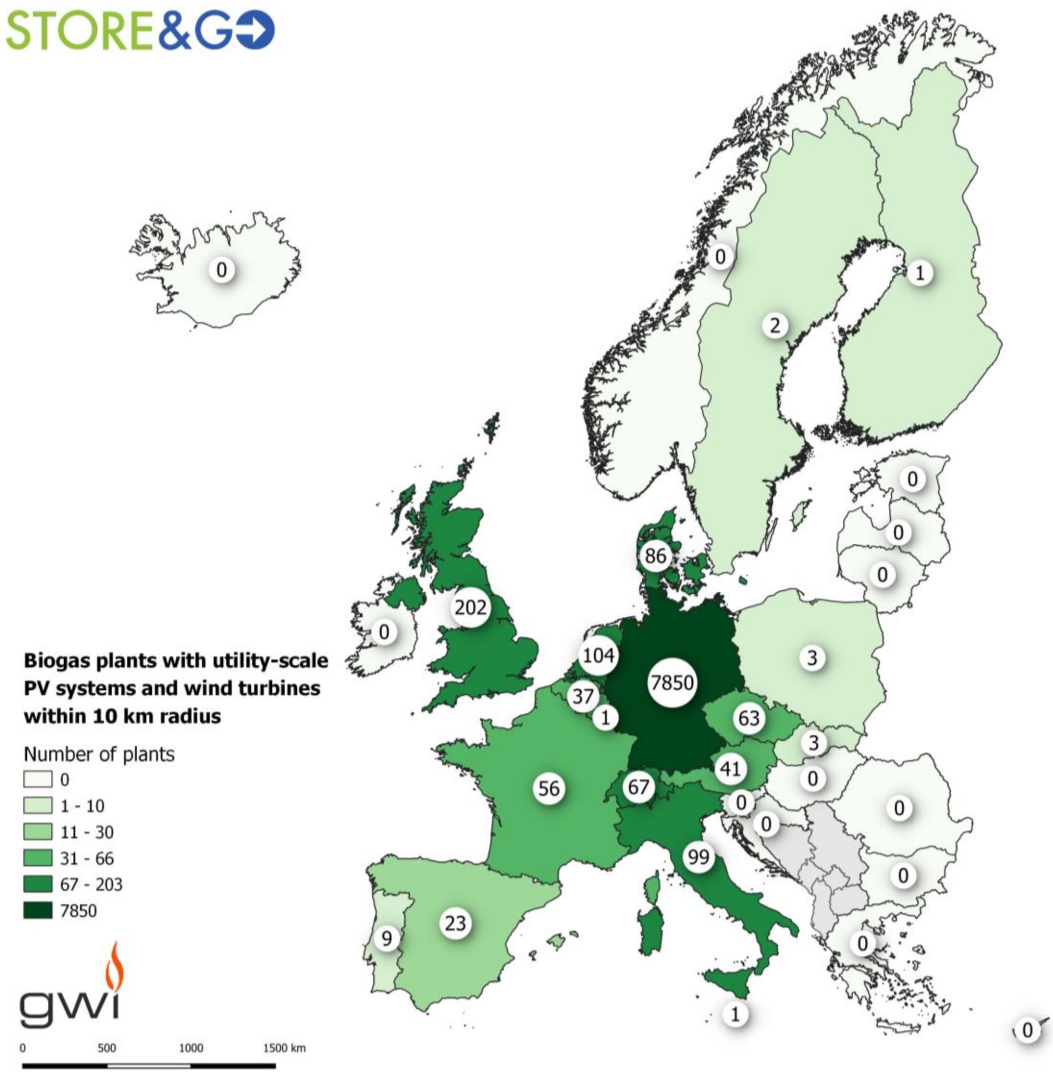


Figure 7-13 Identified biogas plants that exhibit a potential for coupling with at least one utility-scale PV system and wind turbines within 10 km radius, 2019

Italy displays a drastic drop in the PtG potential in this selection criteria, compared to the PV potential analysis, due to the geographical discrepancy of the wind turbines in correlation to the biogas plants. Only 99 plants from total of 1 504 biogas plants (7 %), exhibit the availability of both RE sources in the buffer area. Denmark, with 86 potential PtM plants, was found to have a chance of 55 % for each biogas plant to be in close neighbourhood with both PV and Wind power generation. This is the second highest share after Germany, while the United Kingdom and the Netherlands demonstrate shares of 43 % and 42 %, respectively. In Czech Republic, 63 or 11 % of the biogas plants show availability of both RE sources. The reason for this is the small number of wind turbines being erected in the continental region. The distribution of potential biogas-based PtM sides in Europe is presented in Figure 7-14.

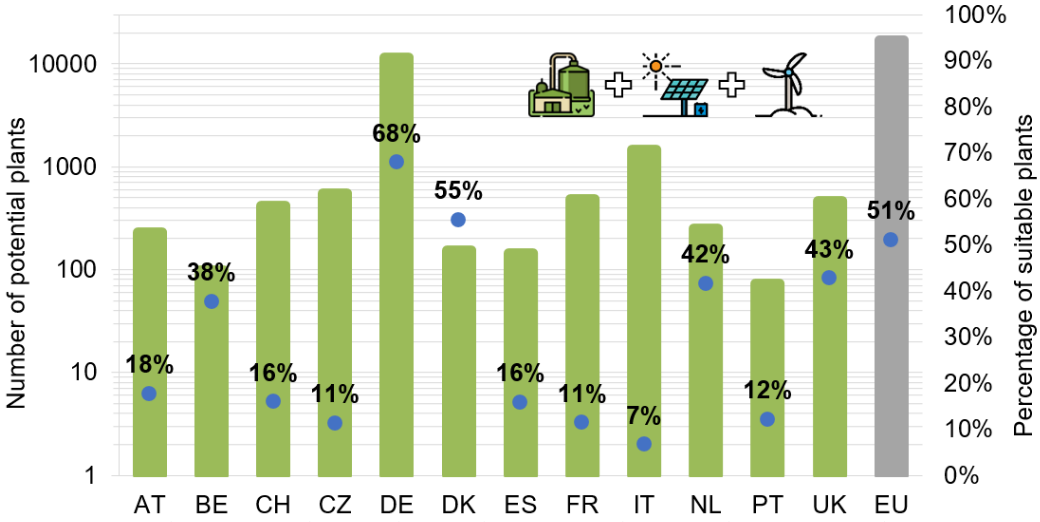


Figure 7-14 Number of identified biogas plants across Europe and share of plants suitable for local power-to-methane energy coupling with utility-scale photovoltaics <u>and</u> wind power (based on data from 2019)

7.3 Joined results for industrial and biogenic CO_2 sources

In addition to the maps generated for industrial (grey) and biogenic (green) CO_2 sources separately, the sectoral results were also plotted with joined numbers. The total number of identified CO_2 sources as well as their distribution in Europe is presented in Figure 12-1 (appendix). From a total of 17 868 point sources, 11 769 (66 %) are located in Germany, due to the large number of biogas plants. France, Czech Republic and the UK exhibit about 500 to 600 CO_2 sources included in this study.

7.3.1 Industry and biogas plants exhibiting a potential for coupling with least one RE source in 10 km radius

The buffer results for the combined CO_2 sources (green and grey) that show a potential for energy coupling with at least one RE source in their 10 km radius is presented in Figure 7-15. Almost all CO_2 point sources 15 789 (88 %), exhibit RE availability in their proximity, underlining the great potential for sector coupling by methanation technologies in almost all European countries already today. Only about 2 % of all potential PtM plants in this buffer analysis are based on grey CO_2, resulting in 316 potential large-scale PtM plants based on grey CO_2 compared to the 15 473 smaller dimensioned potential PtM plants based on green CO_2.

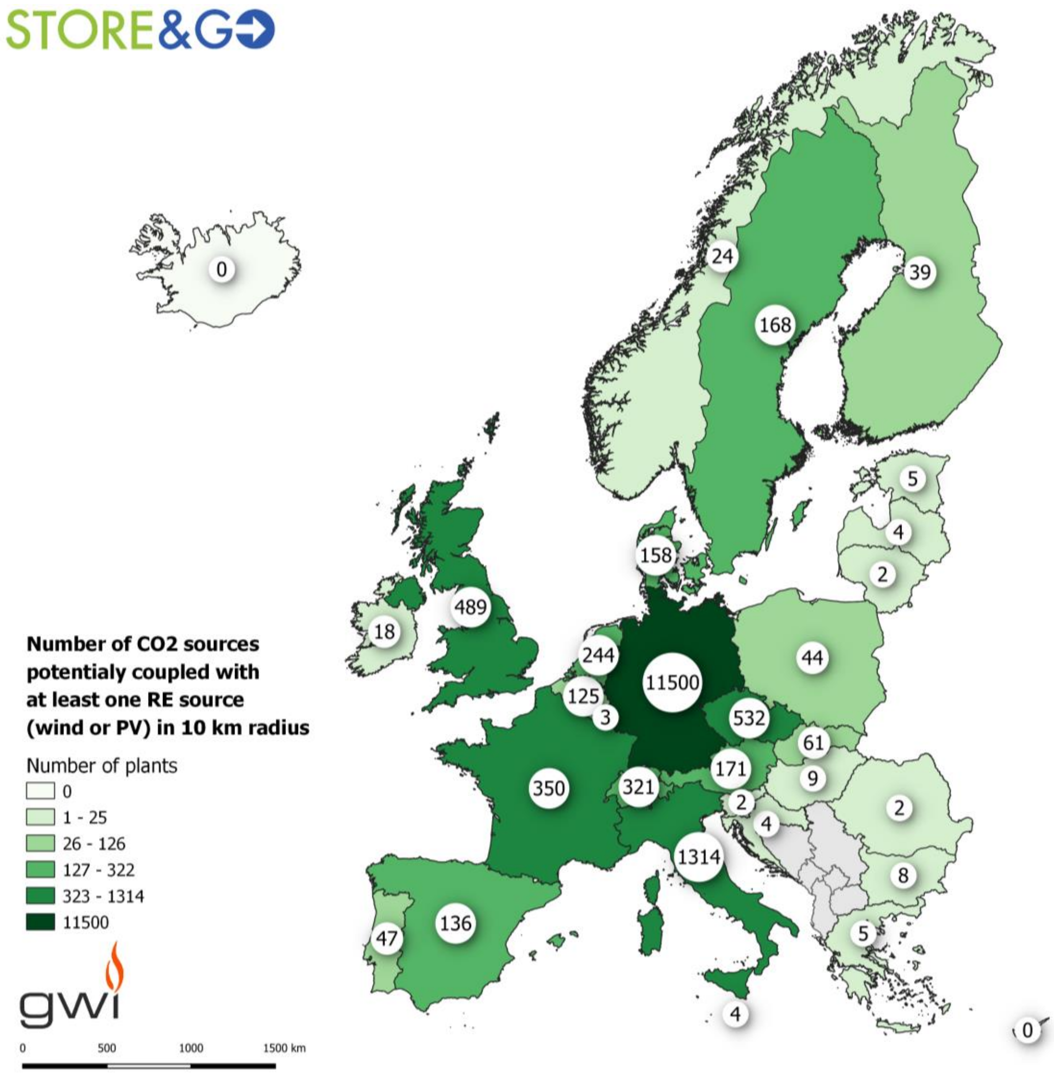


Figure 7-15 Geographical distribution and number of CO_2 point sources (biogas and industry plants) that exhibit a potential for local coupling with at least one RE source (wind or PV) in 10 km radius, 2019

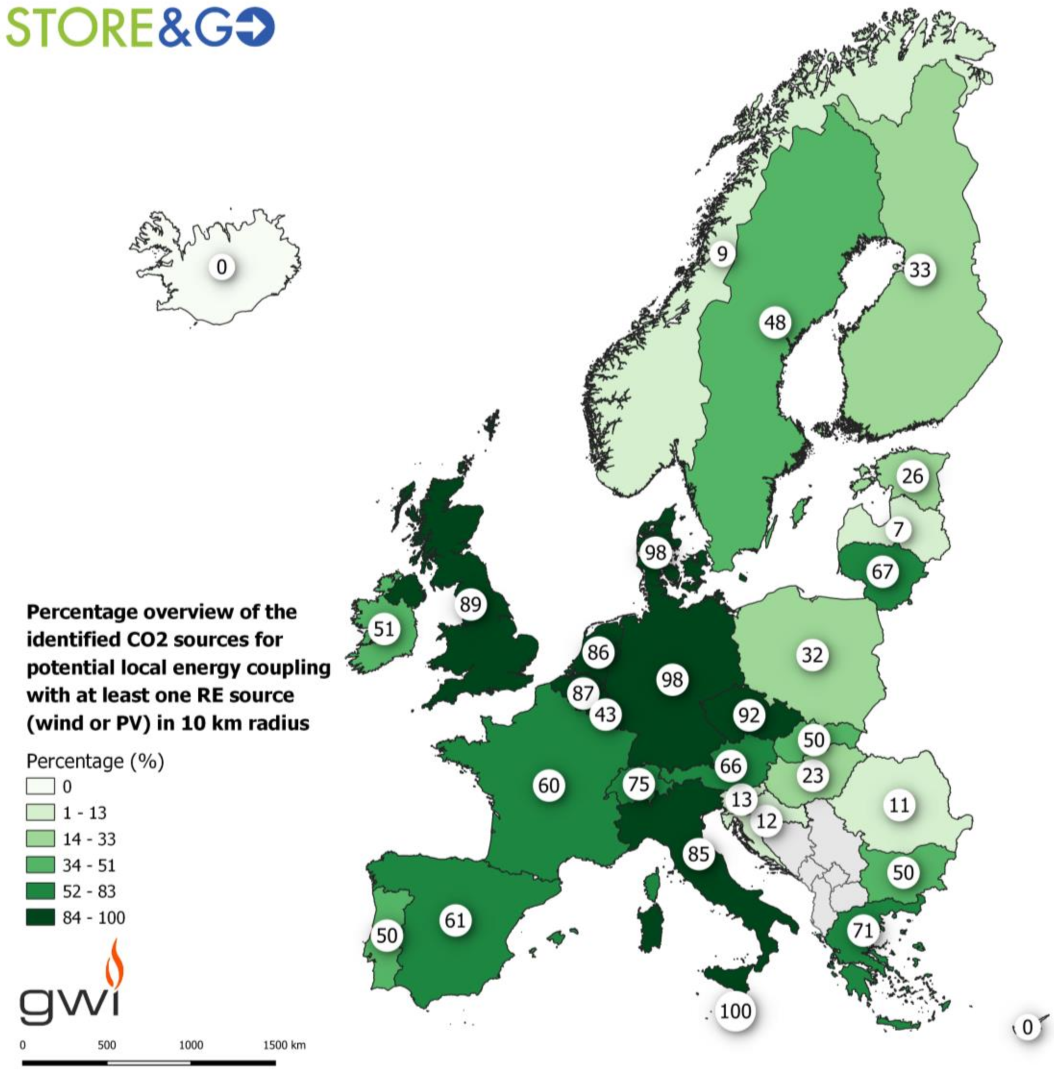


Figure 7-16 Percentage overview of all CO_2 sources (green and grey) that exhibit the potential for coupling with at least one RE energy source (wind or PV) in 10 km radius, 2019

The percentage distribution of potential PtM plants for each country in Europe is shown in Figure 7-16. Malta unveils a 100 % PtM potential of its CO_2 sources, due to its small number of biogas plants (four biogas plants and no industrial plants identified), but fair availability of PV in the small-sized country. All biogas plants located in Malta could potentially be directly coupled to a RE source. Wind power plant erection however, although planned in recent years is so far lacking behind.

In Denmark and Germany 98 % of the CO_2 sources have potential to be coupled with at least one utility-scale RE installation in their proximity. Czech Republic has very high potential for PtM plants as well, with 92 % of its CO_2 sources showing geographic correlation to local RE installations. United Kingdom, Belgium and the Netherlands as well as Italy follow with 89 %, 87 %, 86 % and 85 %, respectively. The smallest shares of potential PtM sites among the CO_2 sources is observed in the eastern European countries, due to the small numbers of identified biogas plants and few utility-scale PV systems. All results for nations with a minimum of 8 identified sites are also summed up in the bar chart diagram Figure 12-3 in the appendix.

7.3.2 Industry and biogas plants exhibiting a potential for coupling with both RE sources in 10 km radius

In addition to the previous analyses, a second approach investigated the share of potential PtM sites with synergies due to combined coupling with both wind turbines and utility-scale PV plants.

It was found that 51 % of the biogas plants and 33 % of the industrial plants show potential for local energy coupling based on availability of both RE sources in 10 km radius. The geographical distribution is shown in Figure 7-17, while Figure 7-18 presents the national shares. From a total of 8 964 potential locations, 8 005 are located in Germany, 244 are found in the UK, while Denmark and Italy have 117 and 116 of the highly synergetic locations. Spain, on the other hand, shows a comparably large amount of RE sources, however synergetic local coupling of wind power, PV and CO_2 sources appears unfeasible in many cases, due to a regional mismatch between the highest Spanish wind power potentials and the distribution of CO_2 sources. In this specific buffer analysis, the Nordic countries offer hardly any potential PtM locations, due to the low solar irradiation in the north and therefore small amounts of installed large-scale PV systems. Eastern Europe shows a small potential for Wind+PV PtM locations due to the small identified numbers of biogas plants and PV systems.

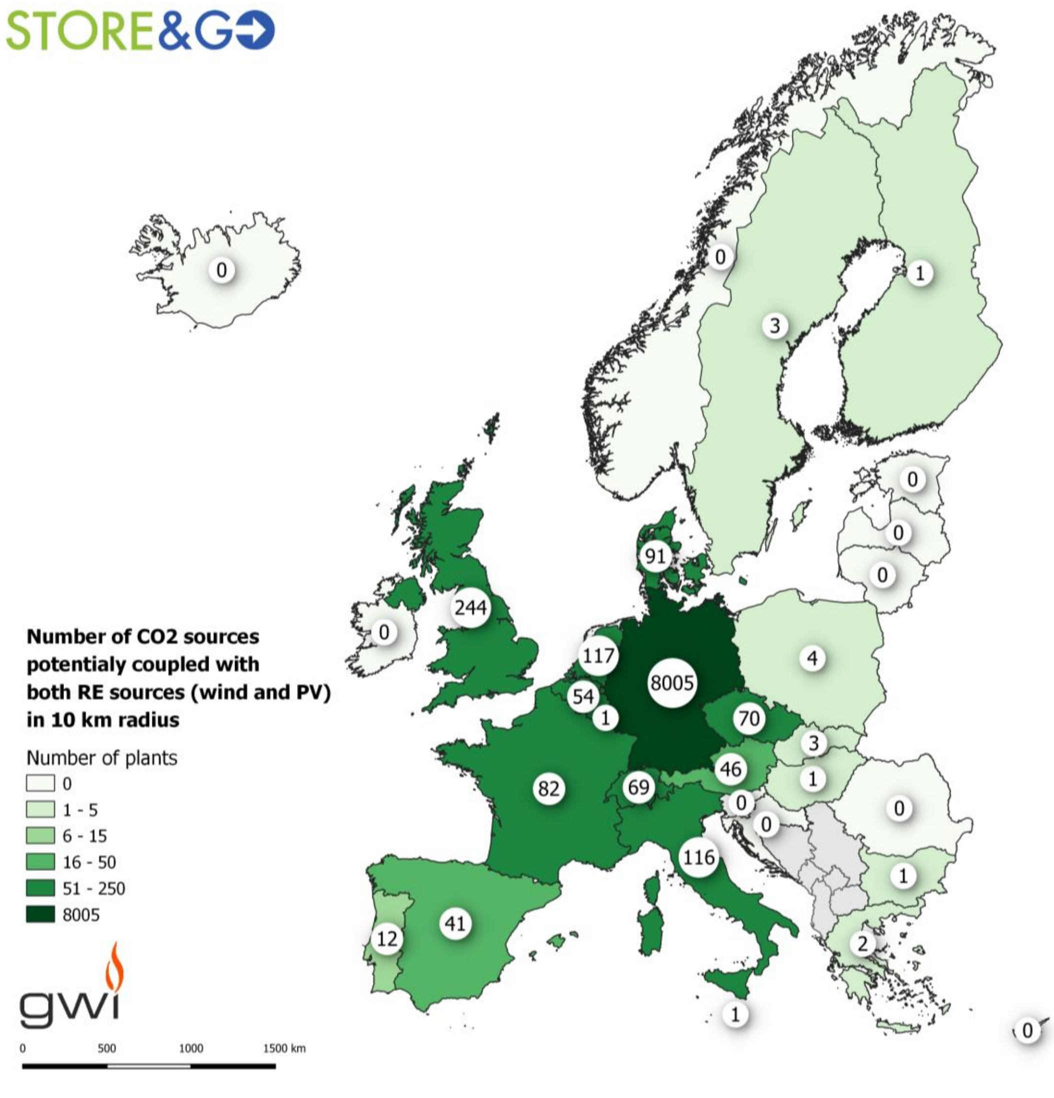


Figure 7-17 Geographical distribution and number of CO_2 point sources that exhibit the potential of local coupling with both RE sources (wind and PV) within 10 km radius, 2019

Although the numbers of potential sites for the highly synergetic coupling of CO_2 with both RE sources is smaller than the numbers described in the previous chapters, it can be anticipated that with deeper penetration of renewable electricity generation across Europe and an increase of the number of biogas plants, all countries will show significant improvements in the numbers of potential PtM sites.

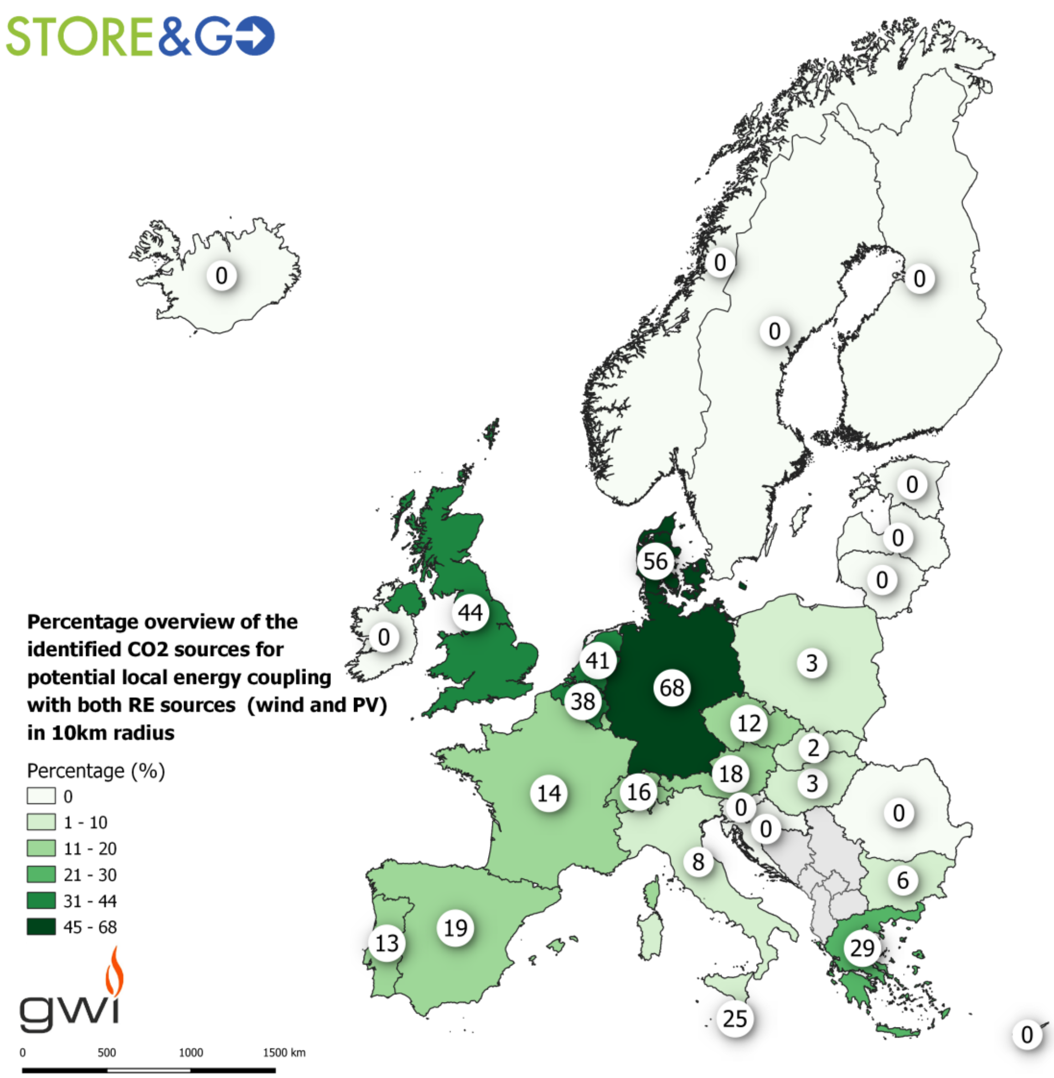


Figure 7-18 Share of identified CO_2 point sources that exhibit the potential of local coupling with both RE sources (wind and PV) in 10 km radius, 2019

All results for nations with a minimum of 8 identified sites are also summed up in the bar chart diagram Figure 12-4 in the appendix.

A summary of the location analyses presented in chapter 7 is given in Table 12-2 in the appendix of this report, where all combinations of criteria and the results in total numbers as well as the relative shares can be seen at a glance.

7.4 Examples: Distribution of biogas plants and wind turbines in Germany and Italy

Germany accounts for almost 70 % of the total identified biogas plants in Europe. The biogas plants are spread across whole country. The highest density of suitable sites for PtM in Europe is located in northern Germany with over 750 to 1 000 potential plants in some NUTS-2 regions. This is primarily due to the concentrated joint presence of wind power generation and biogas plants in that region, leading to typical distances between biogas plants and wind turbines of less than 10 km in many cases.

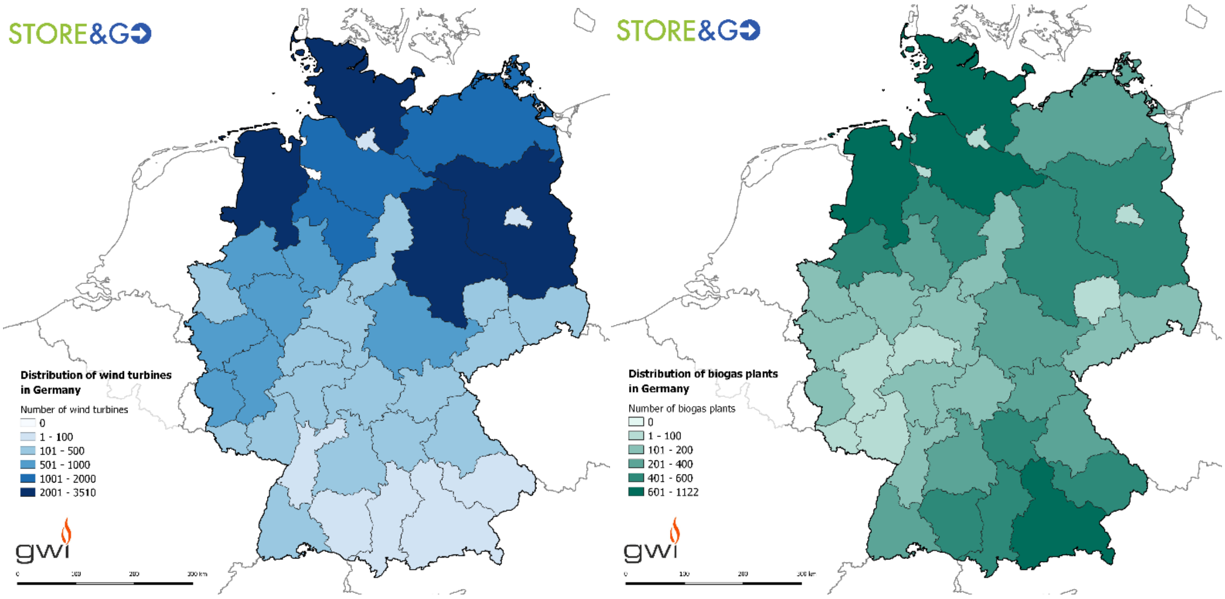


Figure 7-19 Distribution of wind turbines (left) and biogas plants (right) by NUTS-2 regions in Germany, 2019

In the south of Germany, the roll-out of biogas production is at comparable levels as in the north, however it correlates with a smaller number of wind turbines (Figure 7-19). The comparison of the maps shows this mismatch. Thus, less potential sites for local coupling of the two renewable plant types via methanation were identified.

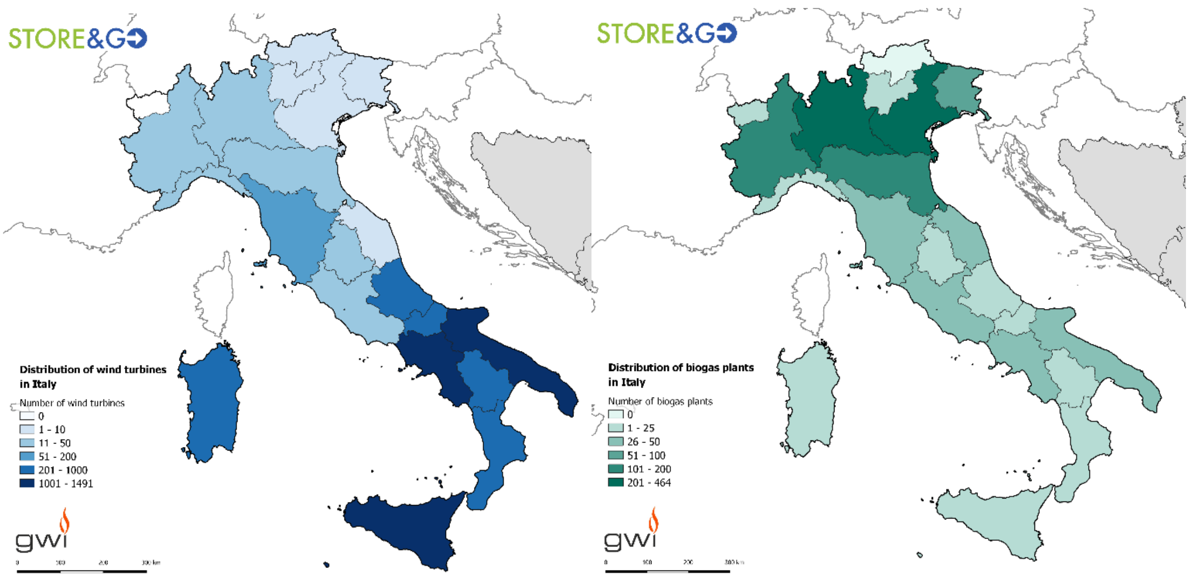


Figure 7-20 Distribution of wind turbines (left) and biogas plants (right) by NUTS-2 regions in Italy, 2019

The comparably small number of possible PtM sites identified in Italy in the previous chapters can be understood when analysing Figure 7-20. Even more than in southern Germany, a regional mismatch of the roll-out levels of the RE feedstocks essential for PtM energy conversion is due to this result. On the one hand, Italy is one of the leading European countries in terms of both the number of identified biogas plants (almost 1 500 plants) and wind turbines (almost 6 500). On the other hand, there are only 120 biogas plants exhibiting a potential of coupling with wind turbines, corresponding to only 9 % of all identified Italian biogas sites. This is below the average of other countries. The regional discrepancy between the locations of the biogas plants in the north and the wind turbines in the south (Figure 7-20) leads to a situation, where the local coupling of biogas and wind power plants – as studied here – will only be possible in rare cases. Rather, a grid-connected power-to-methane plant operation design will be necessary at most Italian locations given by the CO_2 sources.

8 Detailed analysis – Case studies for the STORE&GO locations

This chapter presents case studies for each of the three STORE&GO demo sites located in Germany, Switzerland and Italy. The surrounding areas of the demonstration sites were examined in detail to assess whether a local sector coupling with the currently available RE sources is possible. Potentials for additional PV plants in the proximities of the STORE&GO sites are taken into account.

Local analyses of the above explained geo-datasets were carried out for each of the demo sites. With the identified RE sources, assumptions for the potentially available capacities had to be made. The average installed capacity of an existing wind turbine was assumed to be 2 MW. The output of the PV systems was estimated based on their sizes and local sun irradiation data [Rene00]. The potential areas for PV and APV were determined and categorised with the help of the CLC and Natura 2000 datasets described in chapter 6.1. The values for land requirements for PV systems were adopted for 2050. Based on Jacobson *et al*. [JDBG17], the share of the theoretical area of APV required to supply the balance sheet electricity needs of today in each country was calculated (appendix, Figure 12-2). This arbitrarily chosen level of PV roll-out was assumed to be achieved across Europe to have an indicative reference amount of APV areas needed for a theoretical roll-out at this high levels in the future. To calculate the potential output of the PV covered areas, the average full-load hours for the three locations were defined depending on their coordinates (Figure 8-1). The full-load hour equivalents are based on average values of 1-axis tracking PV systems [Rene00]. This decision was made for all utility-scale PV installations, as the trend towards this technology is already evident today and dominating use of tracking PV systems is expected for the future [Vdma19].

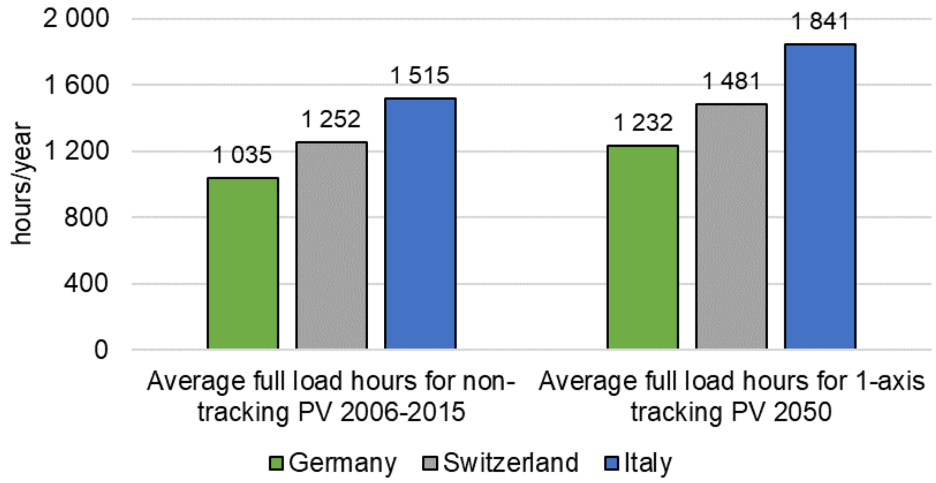


Figure 8-1 Average full load hours for PV, with non-tracking (left) and 1-axis tracking (right) technology, at the three STORE&GO demonstration sites; data from [Rene00]

Case Study Falkenhagen, Germany

The STORE&GO power-to-methane demonstration site *Falkenhagen* in Germany can be found in the north-eastern region close to one of the main pipelines of the German gas transportation grid as displayed in Figure 8-2. The buffer area around the Falkenhagen plant is shown in Figure 8-3. The 10 km radius includes various RE generation sites and substations of the electricity system as well as biogas plants and the gas transportation grid. In Falkenhagen, a hydrogen injection plant has already been operative before the start of the STORE&GO project [Ener00].

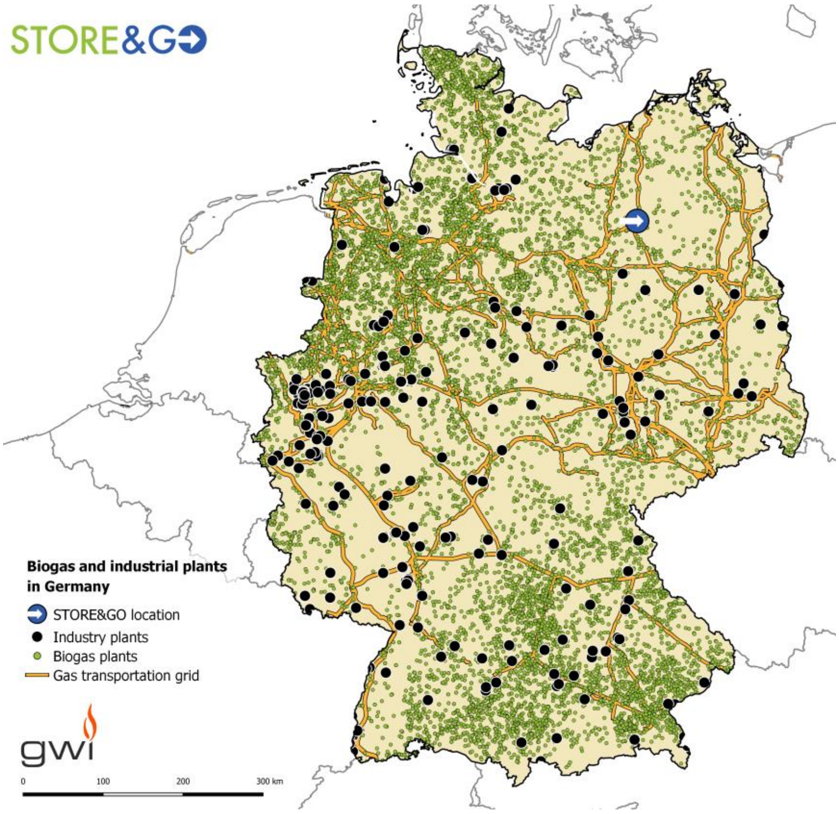


Figure 8-2 Distribution of industrial and biogas plants in Germany including the main pipelines of the German gas transportation grid and the Falkenhagen PtM demonstration plant

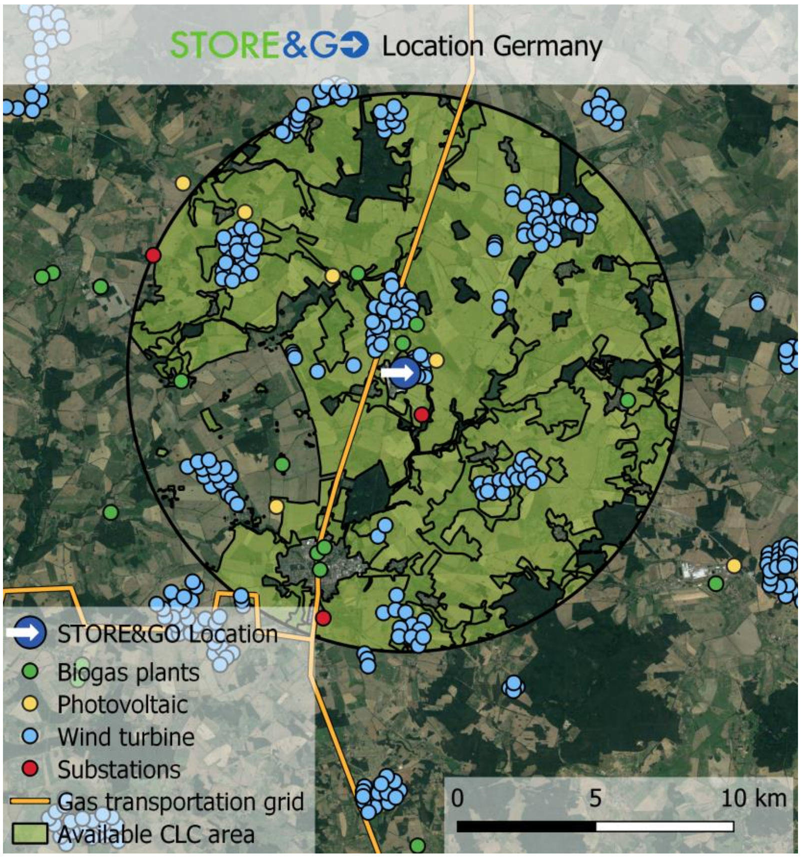


Figure 8-3 STORE&GO site Falkenhagen, Germany with 10 km buffer area

More than 322 MW of installed wind turbine capacity and 28 MW of installed PV, generate around 790 GWh of electricity in the area around Falkenhagen each year. The load curves as well as the full load hours of the installed RE in the buffer of the STORE&GO site are shown in Figure 8-4. With nine other potential PtM plants within the 10 km buffer zone, part of the local renewable electricity production might face usage competition if all potential PtM plants were realised. However, about 24 000 hectares of agricultural land are available for further installation of RE systems. With the installation of APV on 3.9 % (Figure 12-2) of the area, the installed PV capacity in 2050 would be around 800 MW and would produce additional 985 GWh of electricity per year. This corresponds to an increase in the current local RE electricity production of around 125 %. The increase in PV electricity production can thus compensate for the lower electricity production of wind turbines in the summertime (Figure 8-4), due to the higher solar radiation in that season. The trans-regional electricity transport infrastructure can also be relieved.

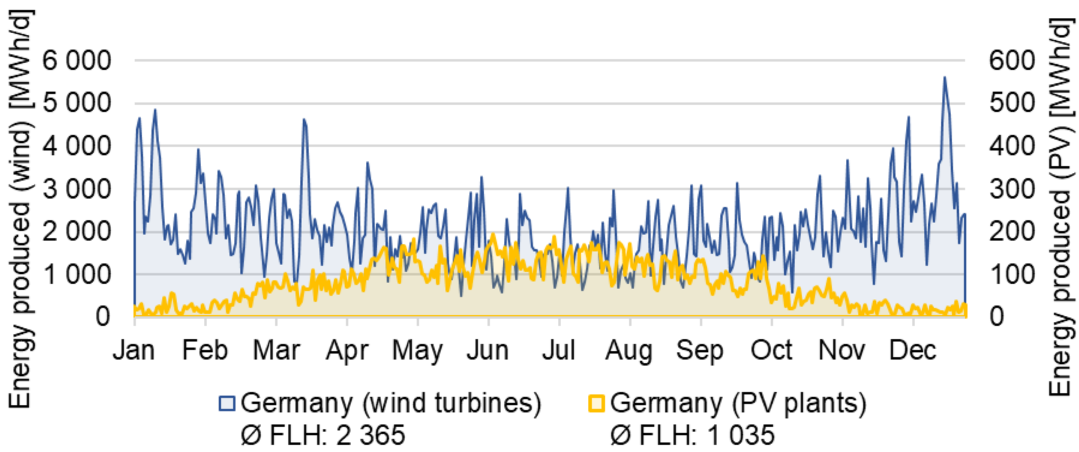


Figure 8-4 Average energy production of wind and PV systems at the Falkenhagen, Germany (2013-2015) (calculation based on [PfSt16]

Case Study Solothurn, Switzerland

The STORE&GO location Solothurn is located in the north of Switzerland, near to the main piplelines of the Switzerlands' gas transportation grid, as can be seen in Figure 8-5. Most of the biogas plants are located fairly close to the pipelines, and the same applies for the industrial plants in Switzerland.

The STORE&GO site Solothurn is shown in Figure 8-6, with a 10 km buffer area and RE sources in its vicinity.

An annual electricity production of about 4.7 GWh can be realised by the 1.6 MW of PV and 2 MW of installed wind turbine capacity. Eleven additional potential biogas PtM plants were identified in the analysed area. In addition to the already existing PV plants, 861 MW of APV capacity can be installed on 7.3 % (Figure 12-2) of the 13 759 ha suitable CLC area by 2050. This corresponds to an electricity production of 1 275 GWh/a, which is about 270 times the current renewable electricity production. If the Solothurn site and the other potential PtM plants in its vicinity were to be supplied with energy locally, they would therefore be dependent on PV power supply due to the low installed wind turbine capacity in the region, with new projects facing a lack of social acceptance. The average load curve for the area surrounding the STORE&GO site is shown in Figure 8-7.

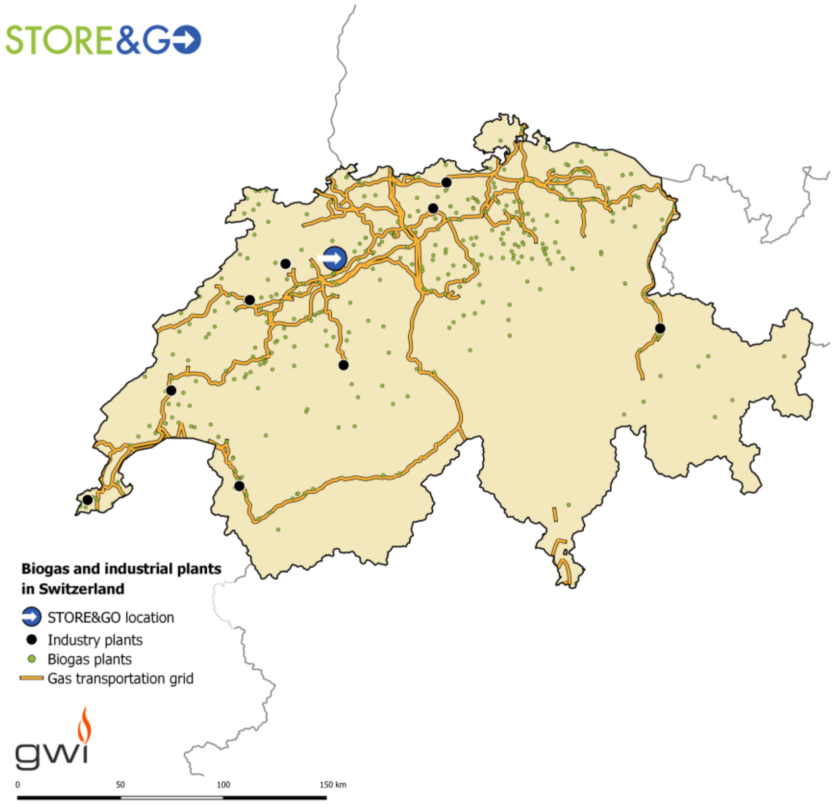


Figure 8-5 Locations of the included energy-intensive industrial and biogas plants and the Solothurn PtM demonstration site in Switzerland, including the main pipelines of the gas transportation grid

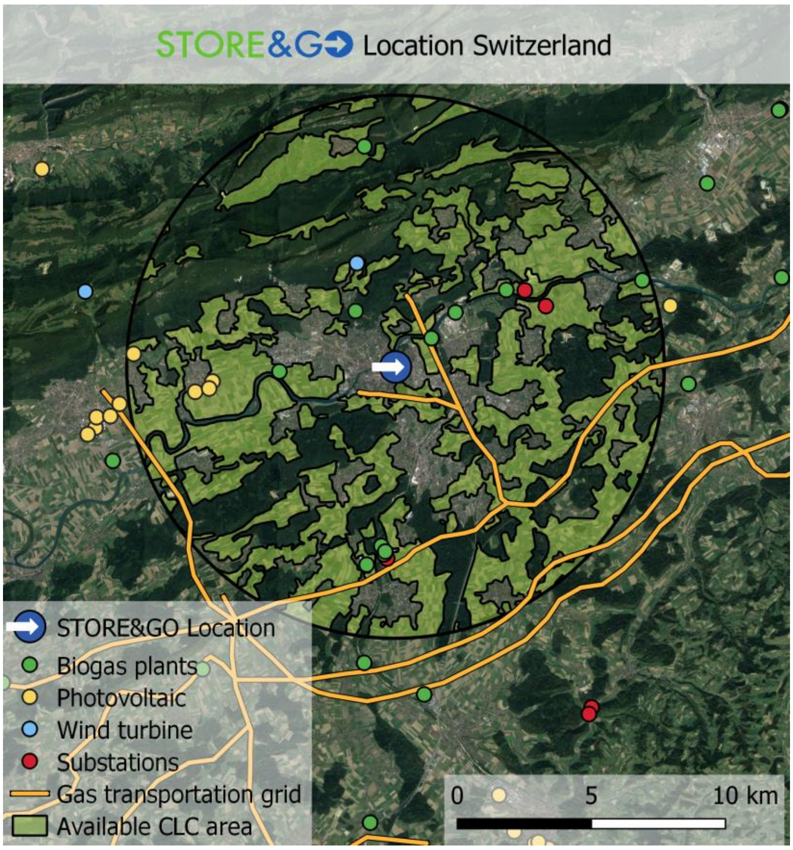


Figure 8-6 Location of the STORE&GO site Solothurn, Switzerland, with 10 km buffer area

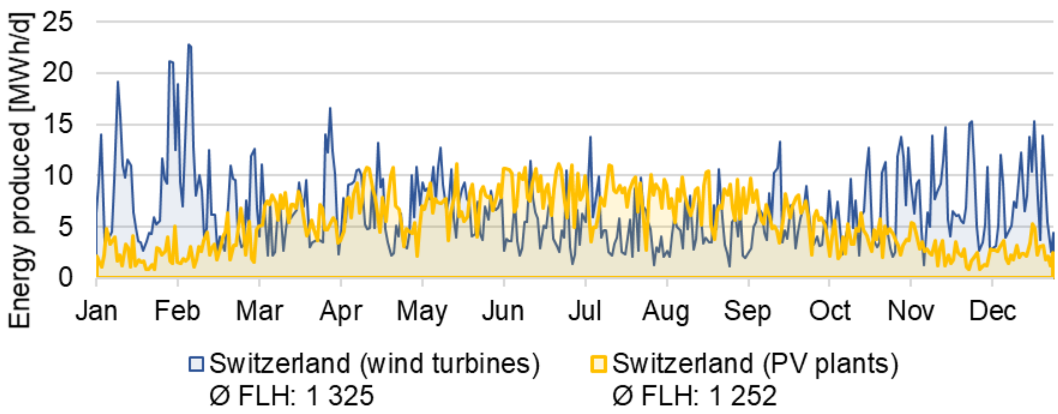


Figure 8-7 Average energy production of wind and PV systems at Solothurn, Switzerland 2013-2015 (calculation based on [PfSt16]

Case Study Troia, Italy

The Italian STORE&GO demonstration site Troia is located in the south of the country, near to the main piplelines of the Italian gas transportation grid (Figure 8-8). Most of the biogas plants are located in the north of Italy, as well as most of the industrial plants.

The Italian STORE&GO site with the surrounding RE sources and potentially suitable agricultural areas (CLC) for APV installations is shown in Figure 8-9. With approximately 37.3 MW of installed PV capacity and 256 MW of installed wind turbine capacity, approximately 684 GWh of electricity is generated annually. The corresponding average load curves are presented in Figure 8-10. On 4.3 % (Figure 12-2) of the theoretical potential area of 29 080 ha, a total of 1 150 MW PV capacity can be installed by 2050. Accordingly, about 2 117 GWh of electricity could be produced, which is 3 times more than the current renewable electricity production in the area around the Troia site.

Figure 8-8 Location of the included energy-intensive industrial plants and biogas plants in Italy and the Troia PtM demonstration site, including the main pipelines of the Italian gas transportation grid

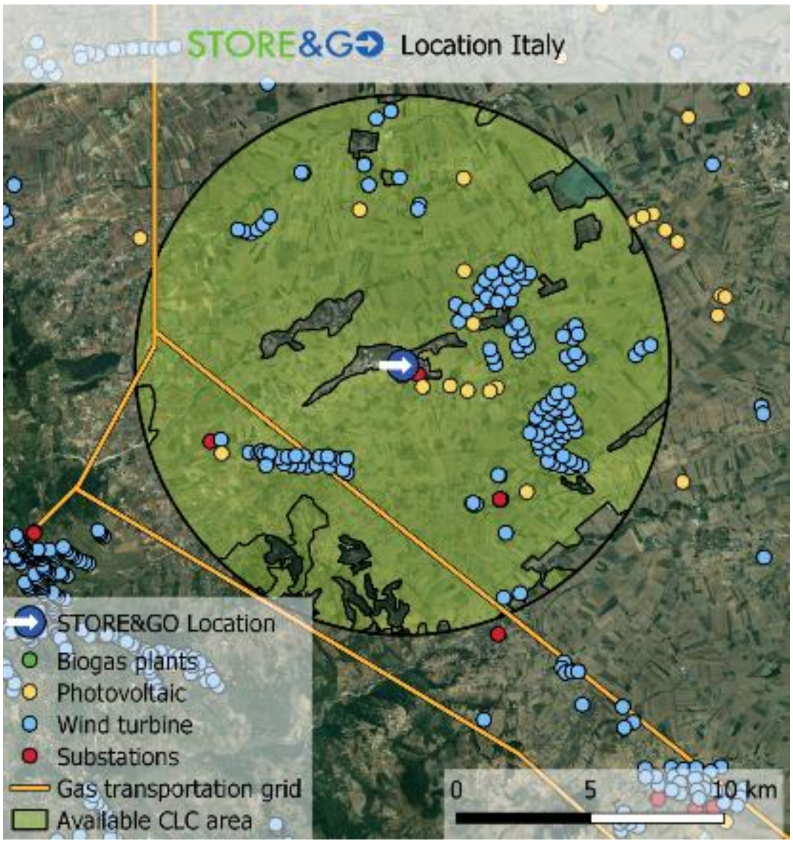


Figure 8-9 STORE&GO site Troia, Italy with 10 km buffer area

The potential addition of 1 150 MW of PV capacity until 2050 can be seen as a positive effect on the year-round renewable electricity production, since similar as in Germany, this compensates for the lower energy production from wind turbines during the summer months.

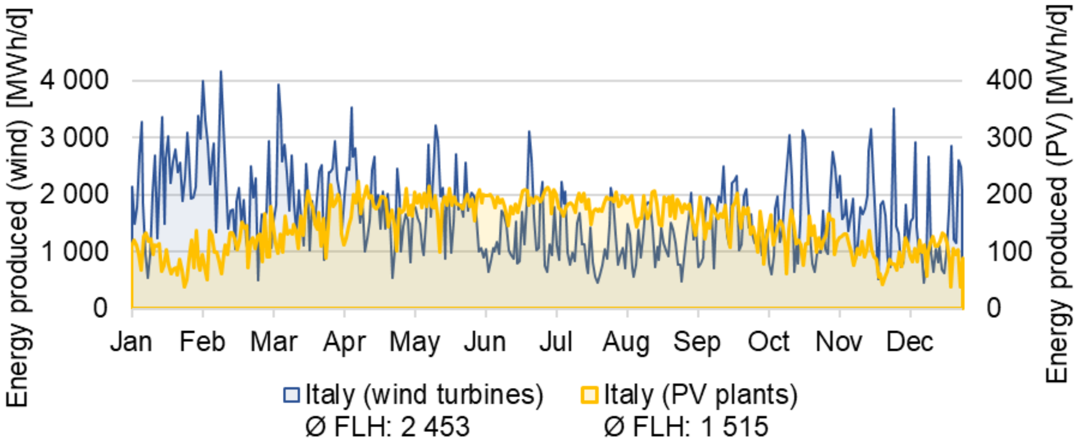


Figure 8-10 Average energy production of wind and PV systems in Troia, Italy, 2013 – 2015 (calculation based on [PfSt16]

Figure 8-11 summarizes the assumed additionally installed PV capacities for the respective STORE&GO locations until 2050 as a comparison of non-tracking and 1-axis tilt PV systems with an average increase of 20 % in electricity output.

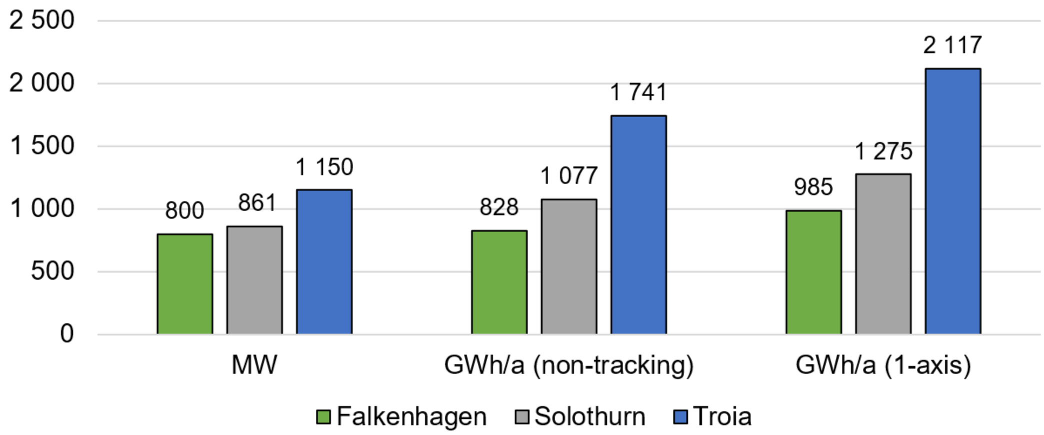


Figure 8-11 Potential additional PV capacities and energy generation for the buffer radii around the STORE&GO PtM demonstration sites, with non-tracking and 1-axis tracking systems for 2050

The methanation potentials at the STORE&GO sites benefit from the installation of additional RE plants and an expected high future degree of agricultural residual biomass use for energy conversion purposes. Assuming todays existing biogas facilities and agricultural used share of land as well as additional tilt-axis PV system installation, the resulting methane potentials for the proximities of the STORE&GO locations amount to 46.4 GWh/a, 6.4 GWh/a and 133.5 GWh/a, respectively (Figure 8-12).

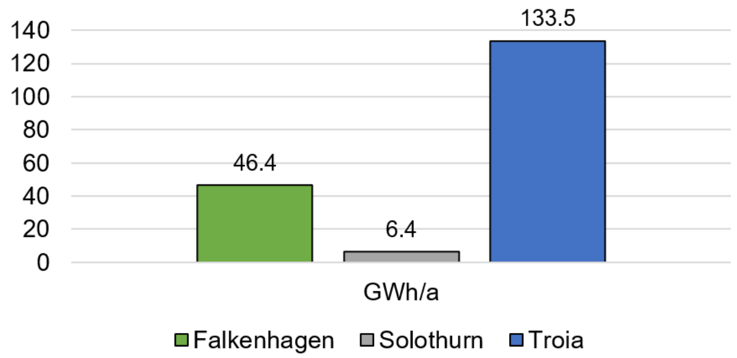


Figure 8-12 Methane potential within the proximity of the STORE&GO PtM demonstration sites (10 km buffer zones) for 2050

9 Methanation potentials in Europe

This chapter presents the potential annual methane production quantities that could be achieved by 2050 in Europe (EU27+CH+IS+NOR+UK). The above analysed CO_2 amounts predominantly stem from biomass complemented by remaining industrial sources and are taken into account for the projections[6], which are based on two scenarios.

In a future relying on large-scale methanation as common practice throughout the EU, notable quantities of CO_2 will be required as a feedstock. As described, two major CO_2 sources were considered in this analysis: biomass as a ***green*** CO_2 source, and industrial processes, which are considered to be based on fossil energy carriers and therefore classified as ***grey*** CO_2 sources. The availability of biomass in general will be reliable and many times over today's degree of exploitation, but limited as a matter of principle. At the same time, very strict CO_2 reduction targets will lead to substantial replacement of fossil fuels in the energy-intensive industries via fuel-switch to hydrogen or electricity as well as general efficiency gains and alternative production routes. Accordingly, less CO_2 from today's industrial sources will be available. In order to achieve an almost complete decarbonisation of the energy-intensive industry sectors, a CO_2 reduction of 90% and more is to be expected, drastically affecting the potential SNG production from the grey sources. The major part of the future green gas demand will have to be covered by SNG produced from green CO_2.

The following two scenarios have been developed:

- ***The Limited CO_2 Availability Scenario*** is based on an extremely deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 95 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, which is essential for the studied scenarios, a conservative estimation is made by further reducing the minimal biomass potentials for residues and forestry to 1/3 of the values calculated by Thrän and Müller-Langer [ThMü11]. The energy crop potentials are even reduced to 1/6 in order to consider lacking social acceptance and ecologic drawbacks of energy crop cultivation. By these steps, an ecologic rather than maximal exploitation of European biomass potentials is considered. At the same time, the strict limitation to the biomass availability accounts for evolving usage competitions that the energy sector will face. In this scenario the deep decarbonisation of the industry sector results in small remaining gas demands from this sector. Green gas production therefore mainly follows the energy path to meet the decentralised heating and hot water demands of the commercial and domestic sectors.

- ***The Balanced CO_2 Availability Scenario*** is based on a deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 90 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, a balanced estimation was made based on the same assumptions for biomass from residues and forestry but loosened restriction of the exploitation of energy crop potentials (1/3 of literature values by [ThMü11]). In this scenario, the future energy system compensates remaining gas demands from the energy-intensive industries by producing more synthetic methane in Europe based on both, slightly higher remaining grey CO_2 amounts as well as intensified energy crop utilisation.

[6] Calculation of methane production amounts as published in Deliverable [SCLL19]

The results of both scenarios, separately for the biomass and the industrial sources, are presented in the following subchapters.

In addition to the analysed CO_2 sources, an alternative green CO_2 feedstock for methanation can be *direct air capture* (CO_2 captured from air). Currently direct air capture is the most expensive technology option for CO_2 provision (see chapter 3). Nevertheless, its production potential is solely limited by its energy demand. Direct air capture is not accounted for in this potential study and may lead to additional green methane production if implemented in large scale. For covering a remaining gap between the production potential and the future gas demand, i.e. the future green gas demand, various import options will develop. Green gases produced outside the EU may for example be imported by sea in liquefied form. Nevertheless, if Europe exploits its green methane potentials presented here, today's fossil fuel and energy import dependencies will be reduced significantly.

9.1 Methane production potential from industrial CO_2

The methane production potential based on the remaining CO_2 feedstock from large-scale industrial plants was calculated based on data from 956 industrial plants from five analysed industrial sectors as described in the chapter 4.1 (E-PRTR data-base [Euro17]). The available CO_2 was presented in Figure 4-5 and Figure 4-6. The results read as follows.

For the ***limited CO_2 availability scenario**,* the total methane potential reaches 130 TWh/a. For the ***balanced CO_2 availability scenario***, 260 TWh/a of synthetic methane can potentially be provided by PtM plants coupled to the large-scale industrial CO_2 sources included in the study.

The distribution of these methane amounts per country for this scenario is presented in Figure 9-1.

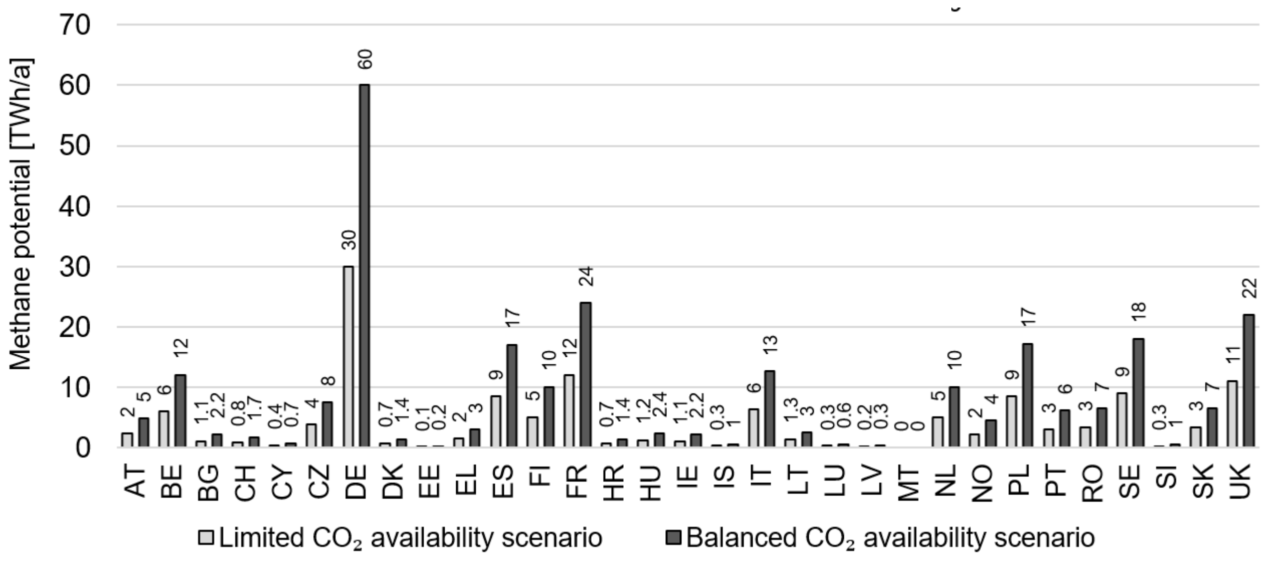


Figure 9-1 Potential methane production for 2050 in Europe based on industrial CO_2 sources in a limited as well as a balanced CO_2 availability scenario

Germany has the largest number of energy-intensive industrial plants in Europe. As a consequence, it exhibits the largest PtM potentials with 30 TWh/a in the *limited* and 60 TWh/a in the *balanced scenario* for 2050 under the assumptions of the present work. France (12 to 24 TWh/a), the UK (11 to 22 TWh/a) and industry nations like Sweden, Spain, Poland, Italy, Belgium and the Netherlands follow.

9.2 Methane potential from biomass

Estimates of the biomass potentials across Europe differ widely, ranging from 1 000 to 8 300 TWh [Faai18]. In this analysis, the calculation for the methane potential for 2050 is based on the biomass potentials published in a study by Thrän and Müller-Langer [ThMü11] as well as own research and assumptions.

For the ***limited CO_2 availability scenario,*** the total potential methane produced from green CO_2 sources in Europe amounts to 1 190 TWh/a in 2050. For the ***balanced CO_2 availability scenario***, the total methane production potential reaches 1 390 TWh/a, thus outperforming the 2050 potentials for industry-based CO_2 usage for methanation technologies by far. The national distribution of the results for Europe 2050 is presented in Figure 9-2.

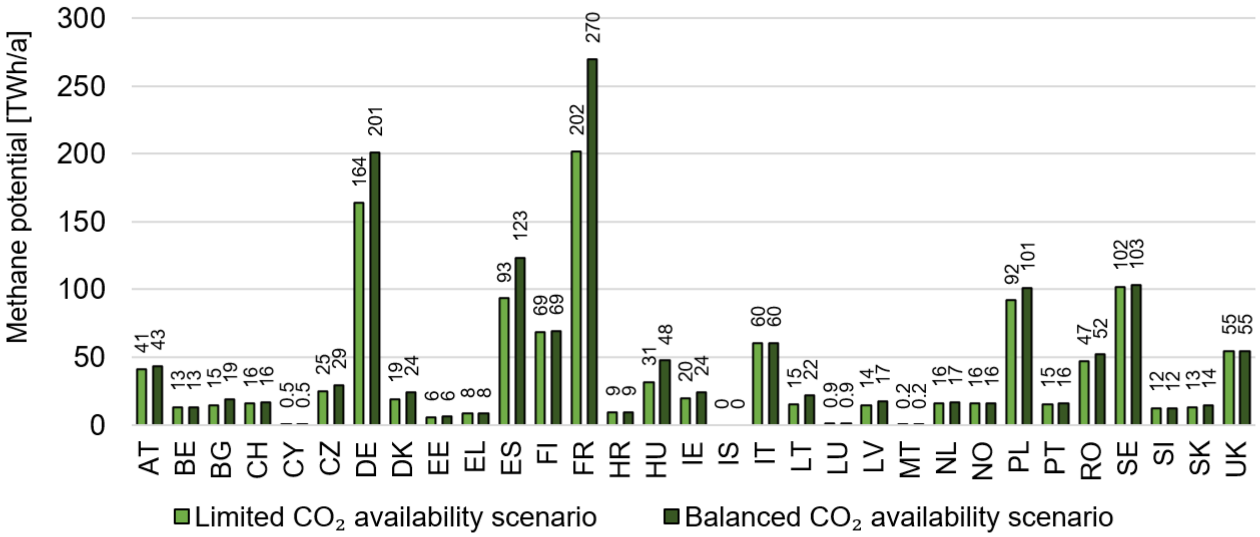


Figure 9-2 Potential methane quantities for 2050 in Europe, from the green CO_2 sources, in a limited and a balanced CO_2 availability scenario

France, due to its highest energy crop potentials in Europe (up to 82 TWh/a, [ThMü11]) and high potentials for residues, exhibits the highest methanation potentials based on CO_2 from green sources in the EU27+4, reaching values of 202 and 270 TWh/a, respectively. Germany exhibits potentials of 164 to 201 TWh/a in this case, followed by nations with large potentials for agricultural production as well as residues, waste water etc. such as Spain, Sweden, Poland, Italy, the UK, Romania, Hungary and Austria.

Compared to the *limited CO_2 availability scenario*, the relative distribution of the potentials in Europe in the *balanced scenario* is affected in terms of more pronounced weighting of the energy crop share of their potentials. Thus, the share of agricultural land plays a significant role for energy supply in a deeply defossilised future that is built on sustainable synthetic fuels and products and is therefore depending on a carbon feedstock. In the literature source by Thrän and Müller-Langer also the national needs for (agricultural) food production are taken into account, leading for some strongly import-dependent nations to zero energy crop potentials [ThMü11]. This consideration of the conflicting interests for land use led to the working hypothesis that in general, domestic food production is to be preferred over energy carrier production. As a result, densely populated nations with limited food production potentials like the UK were assumed to have zero energy crop potentials. The present study follows this argumentation. As a consequence, the respective nations show equal green CO_2 potentials and correspondingly equal methane production potentials in both scenarios (Figure 9-2).

The results for the European distribution of power-to-methane potentials lead to the conclusion that all across the continent considerable potentials exist with respect to the availability of CO_2 sources and geographically correlating RE generation. A large part of the power-to-methane potentials will be concentrated in the European countries with the largest agricultural areas, as well as in the Scandinavian nations due to their biomass potentials based on wood. In addition to the methane production from local sources studied here, many more options of synthetic gas demand coverage will exist in the future for the import of e.g. green methane. Regions with a lack of biomass sources may for example profit from the existing gas transportation networks that allow for methane transport just like today. In addition, CO_2 capture from air may become a competitive choice in certain regions or under certain regulatory regimes.

9.3 Total methane potential 2050

Finally, the potential methane production quantities from both the biomass-based and the remaining industrial CO_2 sources shall be presented. The total methanation potential based on all above presented input data, boundary conditions and assumed future developments sums up to values of **1 320 and 1 650 TWh/a**, for the ***limited CO_2 availability scenario*** **and the *balanced scenario***, respectively.

The allocations of the methane potentials throughout Europe for 2050, based on both scenarios, are shown in the following bar graph representation (Figure 9-3) as well as in the **European methanation potential maps** Figure 9-4 and Figure 9-5.

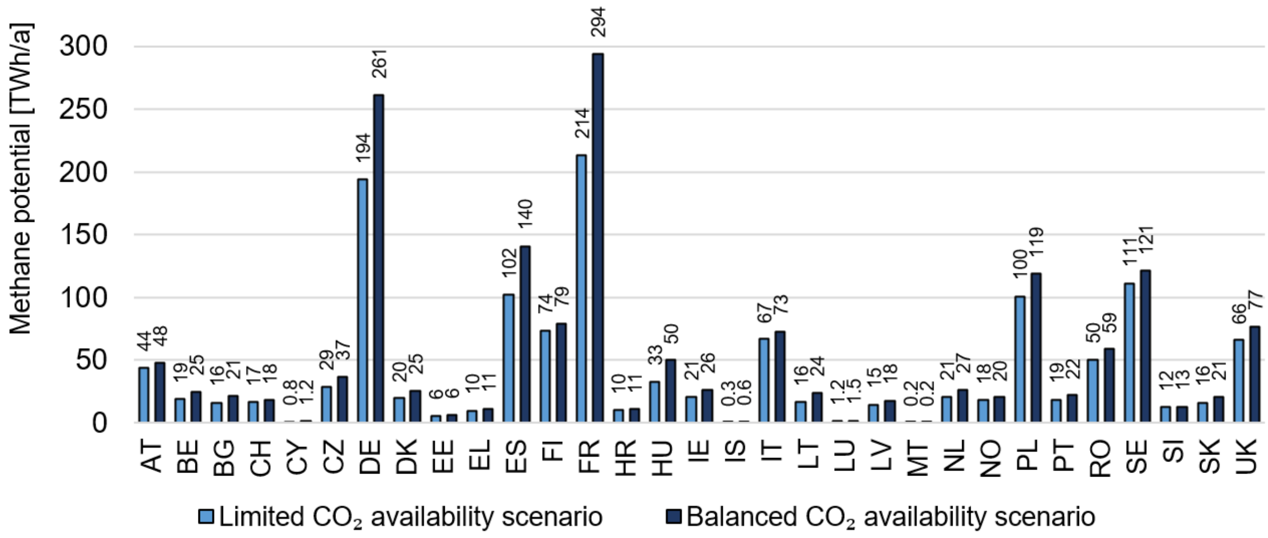


Figure 9-3 Total potential methane in 2050 in Europe, from green and grey CO_2 sources, in a *limited CO_2 availability scenario* and a *balanced scenario*

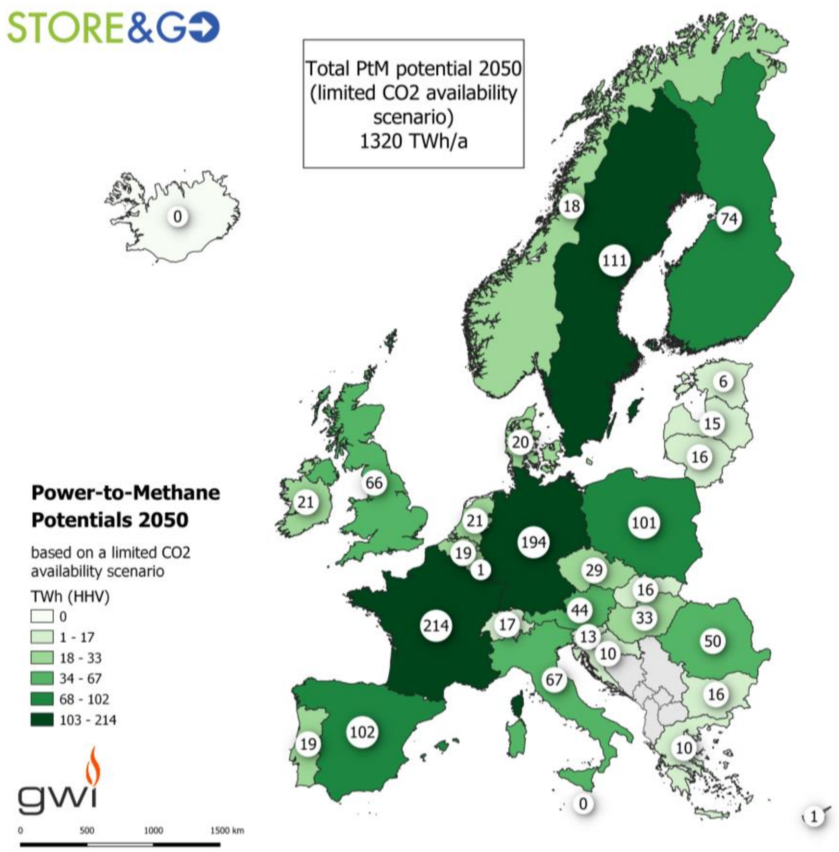


Figure 9-4 Power-to-methane potentials for 2050, based on a *limited CO_2 availability scenario*

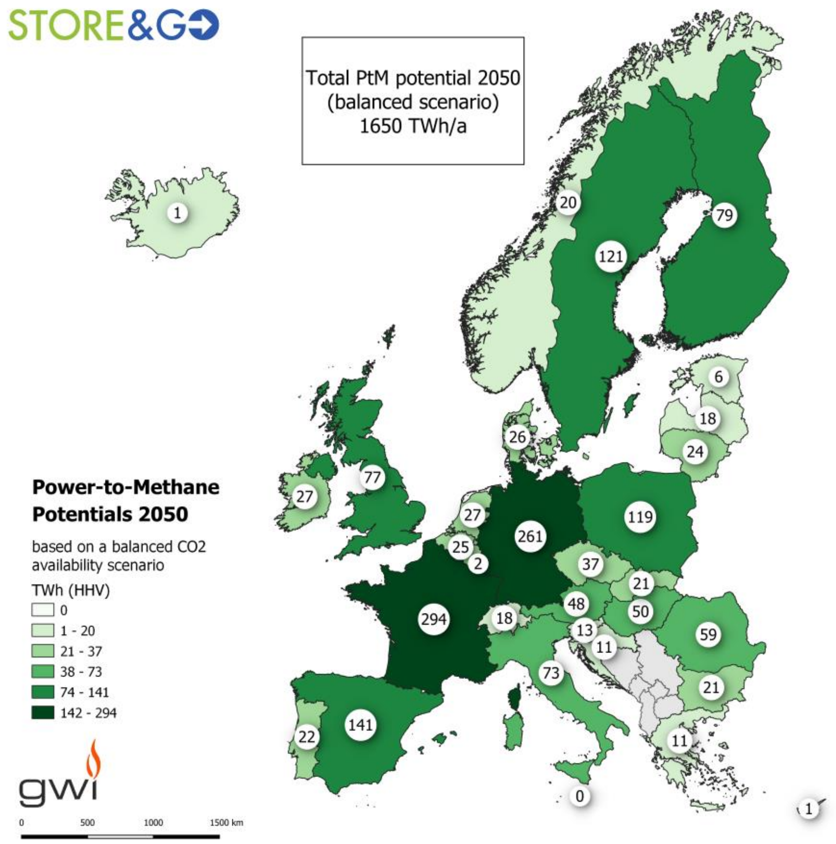


Figure 9-5 Power-to-methane potentials for 2050, based on a *balanced CO_2 availability scenario*

With the aim to evaluate the potential of the methane amounts calculated in this work to cover future methane demands, a comparison with five considered references was done. A similar comparison is described in detail in Deliverable D8.10 [RBCG20], however it should be noted that in contrast to the total gas demand discussed in D8.10, the present work focusses on future methane demands. For references that include a differentiation between e.g. methane and hydrogen demands, the methane demands were chosen for comparison with the present findings. Figure 9-6 shows expected methane demands 2050 ranging from 750 to 4 400 TWh [Blan18, CDTE16, Euro18, JeSB18, Trin18]. The comparison of the potential methane production from both, the *balanced CO_2 availability scenario* (green bar) and the *limited CO_2 availability scenario* (orange bar) shows that synthetic methane production – even under the very conservative assumptions made in this work – can contribute to the future satisfaction of the European gas demand to large extent.

The lowest reference gas demand in the comparison is provided by the Strong Electrification scenario from the final report 'The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets' [Trin18] and amounts for 750 TWh/a. This value for a deeply decarbonised future should be compared to the *limited CO_2 availability scenario* from the present work. The respective share of **demand coverage** for this value pair is **176 %.** For this extreme scenario, which is not typical for the spectrum found in literature, the methane production potential calculated here would by far cover the full future methane demand (Figure 9-6).

When considering the highest reference methane demand from the EU reference scenario 2016, amounting to 4 400 TWh/a [CDTE16], the corresponding scenario from the present work for comparison should be the *balanced CO_2 availability scenario.* The share of potential **demand coverage** for this value pair is about **38 %.**

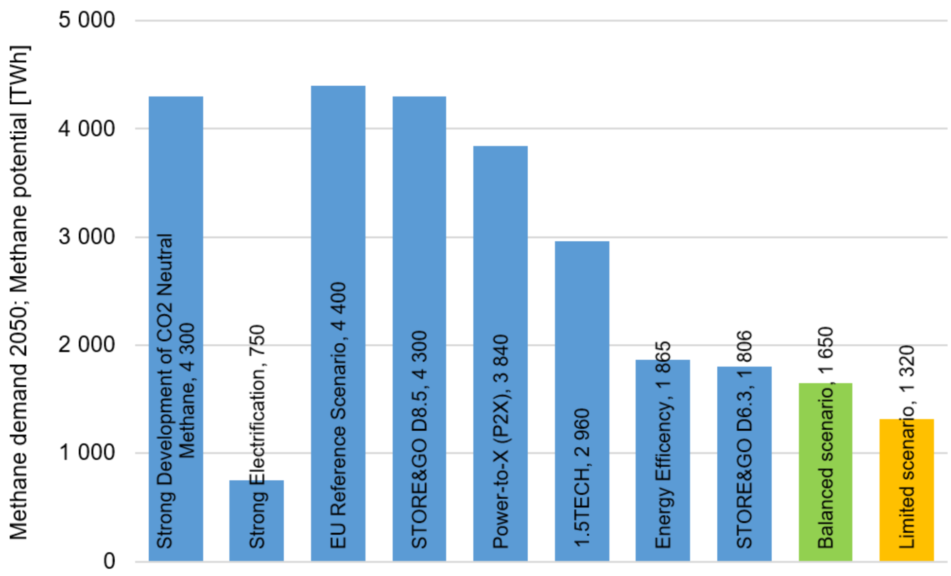


Figure 9-6 Power-to-methane potentials 2050 from the *limited CO_2 availability scenario* and the *balanced CO_2 availability scenario* from this work compared to a range of the expected future methane demand in Europe from literature references; blue bars from left to right refer to [Trin18] (x2), [CDTE16], [JeSB18], [Euro18] (x3), [Blan18]

For the provision of hydrogen for the methane production potentials calculated here, correspondingly large quantities of electricity are required. A rough estimate based on future efficiencies of 0.85 for SOEC electrolysers and 0.75 for methanation reactors yields a total efficiency of 0.64. For that case, about 2 060 TWh to 2580 TWh renewable electricity input would be needed in Europe per year to produce all of the potential methane for the respective scenarios. This estimation neglects the option of heat integration, which may lead to significantly higher efficiencies wherever feasible, reducing the electricity demand at suitable locations.

Under the assumptions of renewable electricity use for the electrolysis and a dominating use of green CO_2 for methanation in the future, it can be concluded that the power-to-methane technology has the potential to contribute significantly to increase the share of renewable energy use in Europe. Synthetic gases and biogases bring in the advantages of long-term, even seasonal storability and easy transportability via the existing extensive transportation and distribution grids all-over Europe.

For the end-user in the domestic, commercial or industrial settings as well as in the mobility sector, a switch to synthetic gas use does not implicate a need for replacing end-use technology. Thus, a swift fuel switch towards synthetic gases and biogas without the erection of new infrastructures or the redesign e.g. of industrial processes becomes possible. This is for example true for the thermal process industry, where an electrification of the existing production processes is not possible. Methane production using CO_2 from biomass and remaining industrial sources may therefore play a crucial role in the energy system of the future.

10 Summary

10.1 Wrap-up of this report

The **objectives of this work** were to identify suitable locations for power-to-methane in Europe and to estimate the methane production potential for 2050.

The **location identification** is based on the concept of coupling existing CO_2 sources with locally available renewable energy sources, i.e. wind turbines and utility-scale PV systems. As CO_2 sources that deliver the required carbon feedstock to the potential PtM plants, biogas plants were considered and energy-intensive industrial point emitters were taken into account as well.

The **data acquisition** was performed by researching public available data on renewable energy generation and biogas production sites (see e.g. annex, Table 12-1) as well as manual research to confirm or extend the available data. For the industrial CO_2 emissions, the European Pollutant Release and Transfer database was exploited (see chapter 4).

A **geo-information data model** was used to calculate the local correlations of CO_2 availability and renewable energy production throughout Europe. CO_2 sources exhibiting large-scale renewable energy generation from either wind power plants or utility-scale PV installations within a radius of 10 km were identified as potential power-to-methane energy conversion sites enabling local energy sector coupling and the production of methane.

The highly-resolved datasets allow to access more details on the power-to-methane potentials on the local scale. Additional information such as the locations and distances between potential energy conversion sites and substations from the electricity system can be visualised and included in the assessments. The local land use e.g. in terms of the exact polygons of agricultural land may be utilised for example to model future erections of photovoltaic plants, as presented in the **case studies** of Chapter 8.

The **projections of the 2050 methane production potentials** via the power-to-methane route were carried out on national level. Since the design of this study centres on the development of power-to-methane plants around existing CO_2 sources, the production potentials were assessed on the basis of two scenarios for the future availability of CO_2, a *limited CO_2 availability scenario* and a *balanced CO_2 availability scenario*, respectively.

The **power-to-methane maps** presented in chapter 9 provide insights into the possibilities of developing a methanation technology rollout starting from the status quo of renewable energy infrastructure in Europe.

As an outcome of the performed analyses, the following key results can be summarized.

10.2 Key results

Potential locations for power-to-methane based on CO_2 & local RE coupling

The geo-informational results (Chapter 7) show that potentials for power-to-methane exist all across Europe, as most of the CO_2 point sources exhibit RE generation in their proximity already today (at least one RE source, wind or utility-scale PV in 10 km radius). 15 789 out of 17 868 (88 %) CO_2 point sources were identified for potential local energy coupling with RE. Of the large countries with respect to area, Denmark and Germany exhibit the highest shares (98 % of the located points) due to the high numbers of wind turbines and CO_2 sources (mainly biogas). For the small nation of Malta, even a 100 % share has been found. The geographical distribution is shown in Figure 10-1, while the percentage of suitable plants by country is presented in Figure 12-3 and Table 12-2 (appendix).

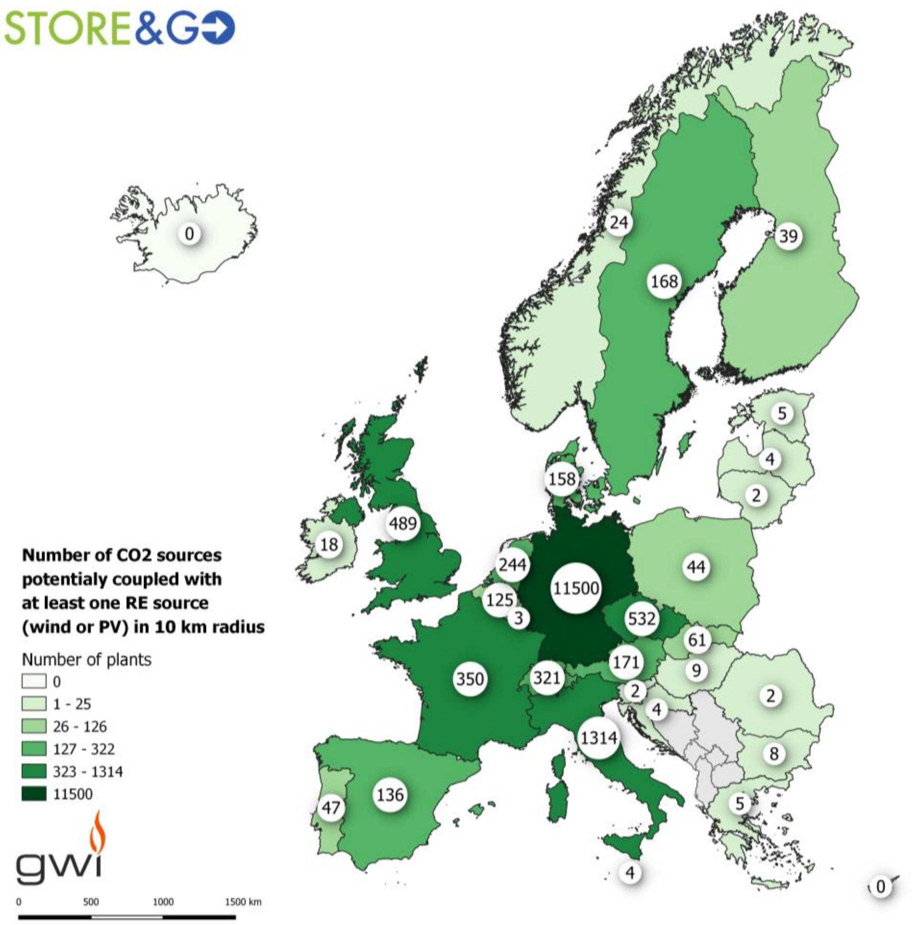


Figure 10-1 Geographical distribution and number of CO_2 point sources (biogas and industry plants) that exhibit a potential for local coupling with at least one RE source (wind or PV) in 10 km radius in 2019. An average of 88 % of the European CO_2 sources included in this study fulfil this criterion.

Potential locations for power-to-methane based on CO_2 & local RE mix

Already today, 51 % of the biogas plants and 33 % of the industrial CO_2 sources (an average of 50 % of all CO_2 sources included in the study) exhibit potential for local energy coupling, based on availability of **both** considered RE sources (wind and utility-scale PV) in a 10 km radius. High geographical correlation of local energy coupling was found for 316 industrial and 8 648 biogas plants. As of today, from the identified 8 964 point sources, 8 005 are located in Germany. With the anticipated deeper penetration of renewable energy generation across Europe, all states are expected to show an increase in the power-to-methane potentials, reaching and even exceeding the high level of the German geographical correlation of CO_2 sources and RE production. The geographical distribution is shown in Figure 10-2. The share of potential plants fulfilling the criterion of proximity to both investigated RE sources are displayed in Figure 7-18 and Figure 12-4.

A summary of the location analyses presented in chapter 7 is given in Table 12-2 in the appendix of this report, where all combinations of criteria and the results in total numbers as well as the relative shares can be seen at a glance.

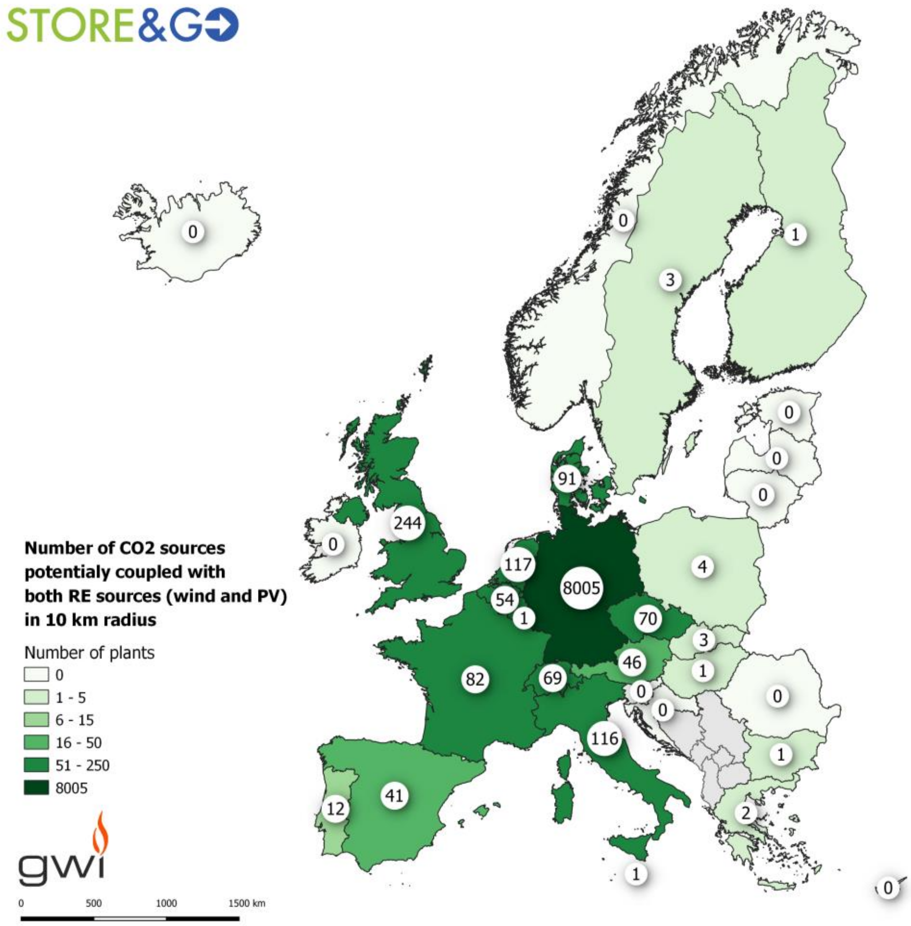


Figure 10-2 Geographical distribution and number of CO_2 point sources that exhibit the potential of local coupling with both RE sources (wind and PV) within a 10 km radius in 2019. An average of 50 % of the European CO_2 sources included in this study fulfil this criterion.

Case studies for the STORE&GO demonstration sites

In chapter 8, case studies for each of the three STORE&GO demonstration sites located in Germany, Switzerland and Italy were presented to give a more detailed local insight into the developed dataset as well as the different local characteristics. Potentials for additional PV plants in the proximities of the STORE&GO sites are taken into account. The results for the local focus areas are summarised in Figure 10-3. The figure shows the very different characteristics and potentials for power-to-methane production using local RE and CO_2 sources in all three locations. Falkenhagen and Solothurn exhibit a strong biogas production. Falkenhagen and Troia have 161 and 128 wind turbines within the 10 km radius, while Troia and Falkenhagen already exhibit notable PV-covered areas. All locations show strong potentials for (A)PV roll-out, since suitable space e.g. for combined agricultural and photovoltaic use exist in all three cases, leading in the shown exemplary buffer zones to PtM potentials of 46.4 GWh/a, 6.4 GWh/a and 133.5 GWh/a, respectively.

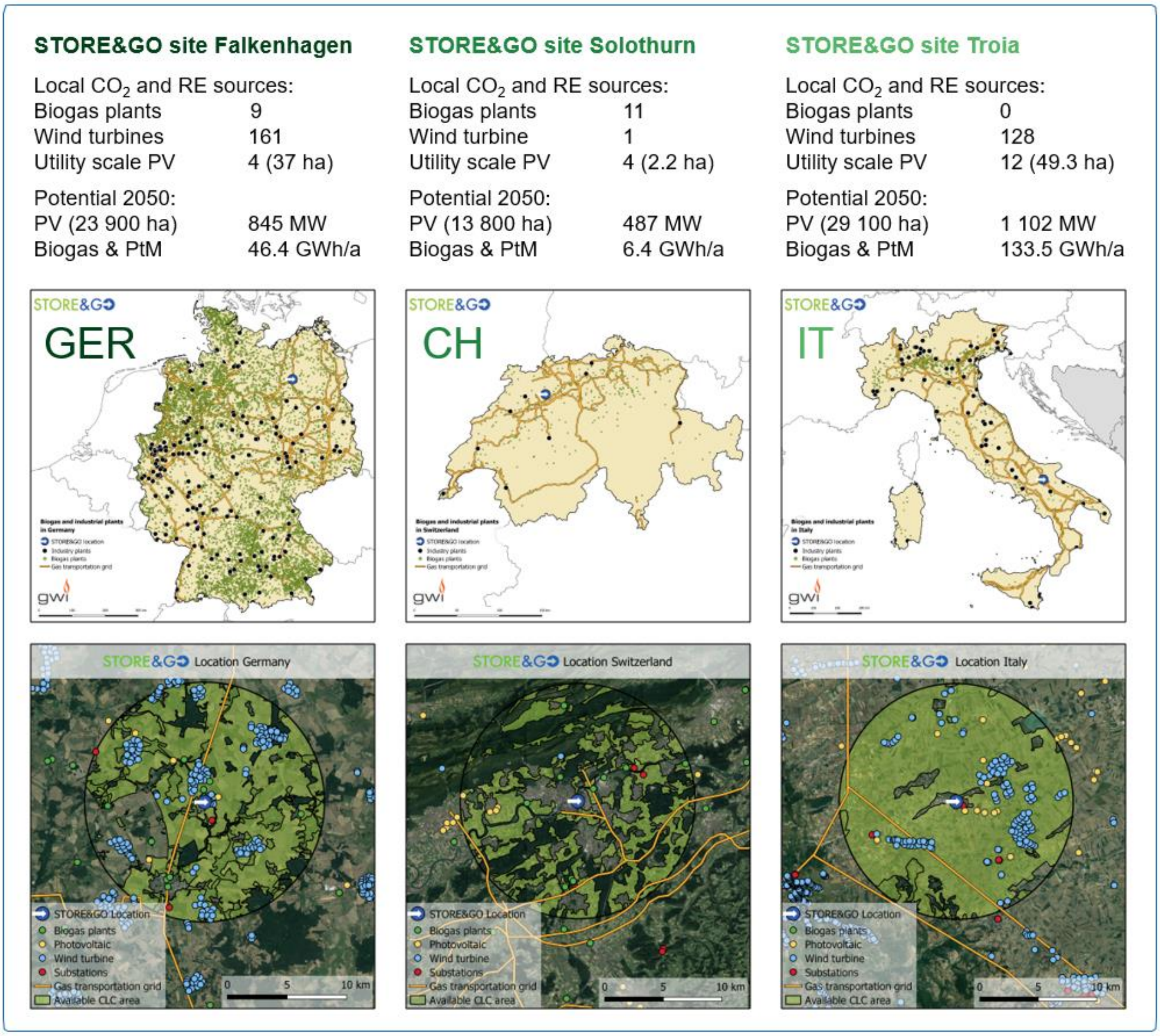


Figure 10-3 Summary of the case studies on the proximities of the STORE&GO PtM demonstration plants.

European Power-to-Methane Potential Maps

Finally, this report presents two European Power-to-Methane Potential Maps that show projections for the potential methane production in 2050 (see chapter 9). Calculations were based on the following scenarios:

- ***The Limited CO_2 Availability Scenario*** is based on an extremely deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 95 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, which is essential for the studied scenarios, a conservative estimation is made by further reducing the minimal biomass potentials for residues and forestry to 1/3 of the values calculated by Thrän and Müller-Langer [ThMü11]. The energy crop potentials are even reduced to 1/6 in order to consider lacking social acceptance and ecologic drawbacks of energy crop cultivation. By these steps, an ecologic rather than maximal exploitation of European biomass potentials is considered. At the same time, the strict limitation to the biomass availability accounts for evolving usage competitions that the energy sector will face. In this scenario, the deep decarbonisation of the industry sector results in small remaining gas demands from this sector. Green gas production therefore mainly follows the energy path to meet the decentralised heating and hot water demands of the commercial and domestic sectors.

- ***<u>The Balanced CO_2 Availability Scenario</u>*** is based on a deep decarbonisation of the energy-intensive industries, resulting in a CO_2 emission reduction of 90 % across the investigated sectors compared to 2015 levels. Concerning the biomass availability, a balanced estimation was made based on the same assumptions for biomass from residues and forestry but loosened restriction of the exploitation of energy crop potentials (1/3 of literature values by from [ThMü11]). In this scenario, the future energy system compensates remaining gas demands from the energy-intensive industries by producing more synthetic methane in Europe based on both, slightly higher remaining grey CO_2 amounts as well as intensified energy crop utilisation.

The total 2050 PtM potential based on the *limited CO_2 availability scenario* is 1 320 TWh/a. The methane share produced from industrial CO_2 is 130 TWh/a, while the methane from the green CO_2 sources amounts to 1 190 TWh/a, demonstrating the dominating role of biogenic carbon sources in the deeply defossilised future investigated here. The allocation of the methane potentials throughout Europe are presented in Figure 10-4.

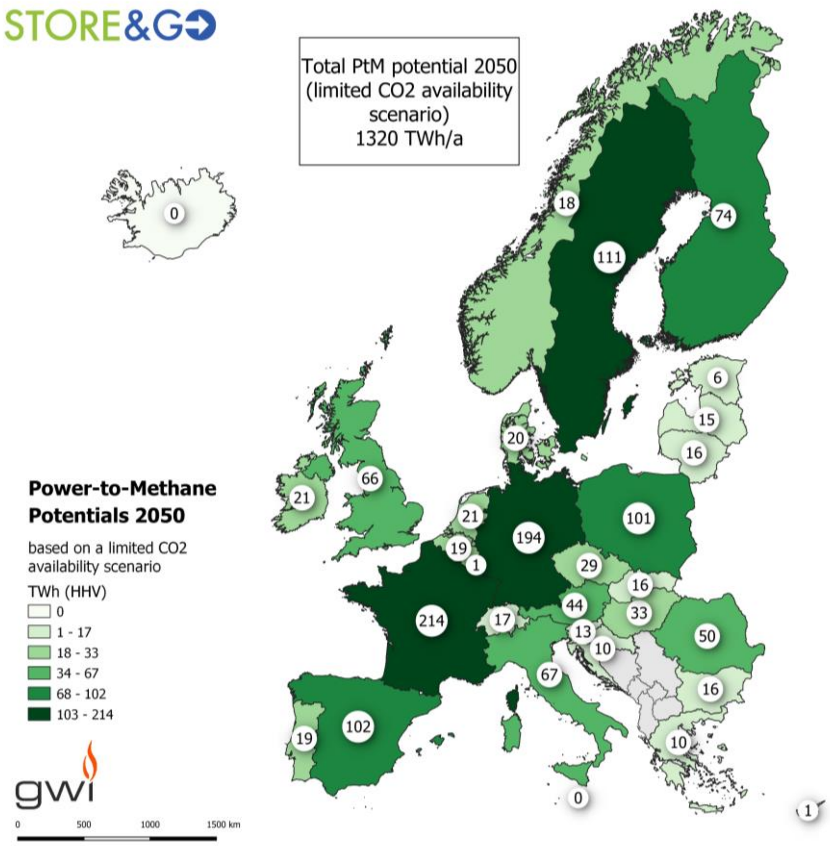


Figure 10-4 Power-to-methane potentials for 2050, based on a *limited CO_2 availability scenario*

The PtM potential for 2050 based on the *balanced scenario* amounts to 1 650 TWh/a. The share of the potential methane from industrial CO_2 sources is 260 TWh/a, and the methane from the green sources 1 390 TWh/a. The methane potentials in Europe for 2050 in the balanced scenario on the national level is displayed in Figure 10-5.

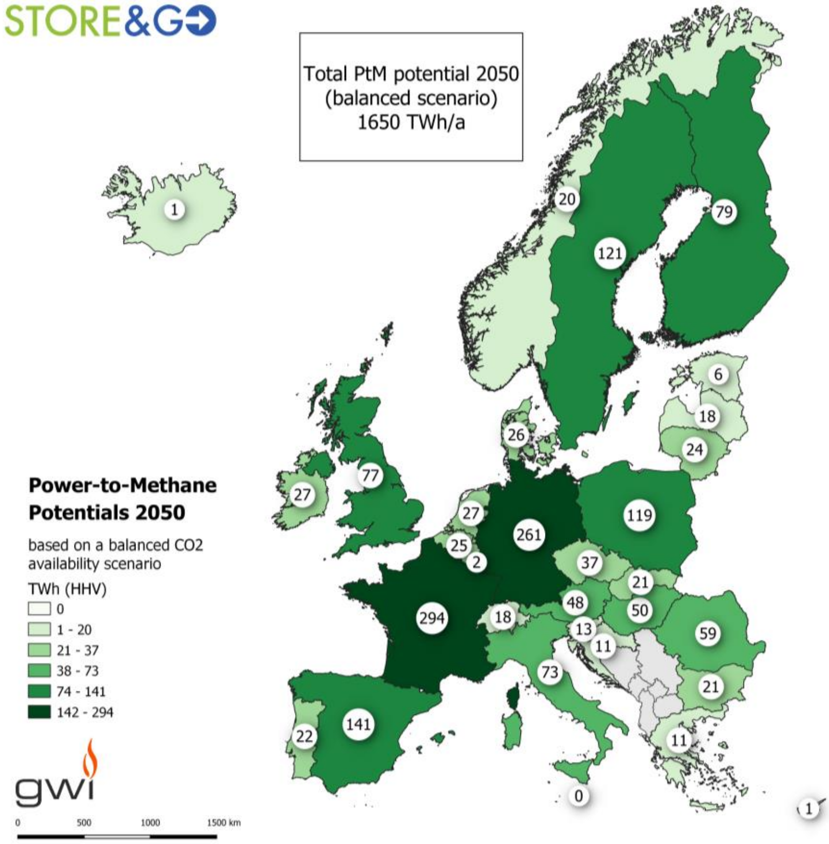


Figure 10-5 Power-to-methane potentials for 2050, based on a *balanced CO_2 availability scenario*

The outcomes of the study may be evaluated by means of their potential level of satisfaction of the European methane demand 2050 as found in literature. The results of this assessment correspond to approximately 38 – 176 % of the 2050 methane demand for the indicated scenarios. The comparison of the methane potentials with literature methane demands 2050 is shown in Figure 10-6.

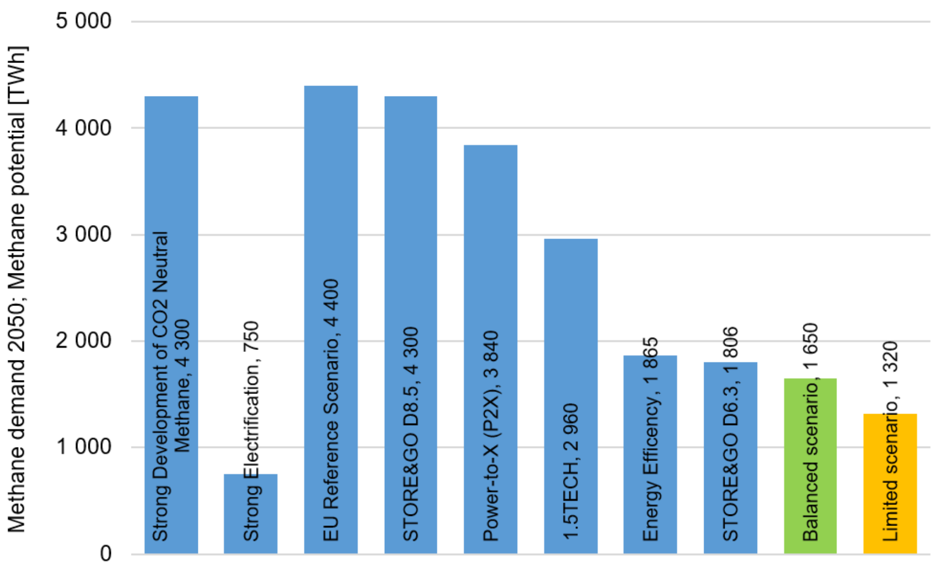


Figure 10-6 Power-to-methane potentials 2050 from the *limited CO_2 availability scenario* and the *balanced CO_2 availability scenario* from this work compared to a range of the expected future methane demand in Europe from literature references; blue bars from left to right refer to [Trin18] (x2), [CDTE16], [JeSB18], [Euro18] (x3), [Blan18]

11 Bibliography

[AaEH18] AARNES, JORG ; EIJGELAAR, MARCEL ; HEKTOR,A, ERIK: *Hydrogen as an energy carrier An evaluation of emerging hydrogen value chains* : DNV-GL Group Technology & Research - Position Paper 2018, 2018

[AfBB18] AFANASYEVA, SVETLANA ; BOGDANOV, DMITRII ; BREYER, CHRISTIAN: Relevance of PV with single-axis tracking for energy scenarios. In: *Solar Energy* Bd. 173 (2018)

[Agor20] AGORA ENERGIEWENDE: The European Power Sector in 2019 (2020)

[AnEE18] ANDERSON, GRAHAM ; EMELE, LUKAS ; EUROPEAN ENVIRONMENT AGENCY: *Approximated EU GHG inventory: proxy GHG estimates for 2017*, 2018 — ISBN 978-92-9480-008-4

[Audi13] AUDI: *Audi e-gas*. URL https://www.audi-technology-portal.de/de/mobilitaet-der-zukunft/audi-future-lab-mobility/audi-future-energies/audi-e-gas. - abgerufen am 2015-09-14. — Audi Technology Portal

[BaBH00] BAIER, URS ; BUCHS, MATTHIEU ; HERMLE, SANDRA: NATIONAL POLICY FRAMEWORK IN SWITZERLAND, S. 8

[BBGO12] BECK, M. ; BOPP, G. ; GOETZBERGER, A. ; OBERGFELL, T. ; REISE, C. ; SCHINDELE, S.: Combining PV and Food Crops to Agrophotovoltaic – Optimization of Orientation and Harvest: 5 pages / 27th European Photovoltaic Solar Energy Conference and Exhibition; 4096-4100 (2012)

[Blan18] BLANCO, HERIB: *STORE&GO - Deliverable D6.3 - Impact Analysis and Scenarios design*, 2018

[Bund18] BUNDESMINISTERIUM FÜR BILDUNG UND FORSCHUNG: *Praxistest startet: Forschende recyceln Hüttengase; Project Carbon2Chem*. URL https://www.bmbf.de/de/praxistest-startet-forschende-recyceln-huettengase-6964.html. — bmbf.de

[BVJJ18] BILANDZIJA, NIKOLA ; VOCA, NEVEN ; JELCIC, BARBARA ; JURISIC, VANJA ; MATIN, ANA ; GRUBOR, MATEJA ; KRICKA, TAJANA: Evaluation of Croatian agricultural solid biomass energy potential. In: *Renewable and Sustainable Energy Reviews* Bd. 93 (2018), S. 225–230

[BZGT18] BÖHM, HANS ; ZAUNER, ANDREAS ; GOERS, SEBASTIAN ; TICHLER, ROBERT ; KROON, PIETER: *STORE&GO - Deliverable D7.5 - Report on experience curves and economies of scale* (Project Deliverable), 2018

[CDTE16] CAPROS, P ; DE VITA, A ; TASIOS, N ; EVANGELOPOULOU, S ; FORSELL, N ; FRAGIADAKIS, K ; FRAGKOS, P ; FRANK, S ; U. A.: *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg : Publications Office, 2016 — ISBN 978-92-79-52373-1

[Cemc00] *CEMCAP*. URL https://www.sintef.no/projectweb/cemcap/

[Cope00] *Copernicus Corine Land Cover*. URL https://land.copernicus.eu/pan-european/corine-land-cover/clc2018. — Copernicus Corine Land Cover

[Demo14] *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, 2014

[DeOS00] DEERBERG, GÖRGE ; OLES, MARKUS ; SCHLÖGL, ROBERT: Carbon2Chem CO2-Reduzierung durch cross-industrielle Kooperation der Stahl-, Chemie- und Energiebranche, Fraunhofer UMSICHT, thyssenkrupp AG, Max-Planck-Institut für Chemiche Energiekonversion

[Dnvg18] DNV GL: *ENERGY TRANSITION OUTLOOK 2018 A global and regional forecast to 2050*. Høvik, Norway : DNV GL, 2018

[Doyl18] DOYLE, AMANDA: Europe’s first waste-to-chemistry facility provides solution for non-recyclable plastics. In: *The Chemical Engineer* (2018)

[Eba18] EBA: Statistical report of the European Biogas-Association (2018)

[Eba19] EBA: European Biogas Association - Annual Report 2019 (2019)

[EDGG20] ENGIE ; DGC ; GWI ; GAS.BE ; CEA ; DVGW EBI ; BDR THERMEA GROUP ; ELECTROLUX ; U. A.: THyGA - Testing Hydrogen Admixtures for Gas Appliances; EU Project; FCH JU; grant agreement No. 874983 (2020)

[Ener00] *Energy storage - Power-to-Gas*. URL https://www.uniper.energy/storage/de/geschaeft/power-to-gas. - abgerufen am 2020-04-02. — Uniper

[Envi20] ENVIRONMENT AGENCY: *Pollution inventory reporting – incineration activities guidance note Environmental Permitting (England and Wales) Regulations 2016 Regulation 61(1)*. Horizon House, Deanery Road, Bristol BS1 5AH : Environment Agency, 2020

[Eu00] EU: *Waste to Chemistry - Rotterdam*. URL https://w2c-rotterdam.com/about-us

[Eu16] EU: *EU energy in figures Statistical pocketbook 2016*. Belgium : European Commision, 2016 — ISBN 978-92-79-58247-9

[Euro00a] EUROGAS: *Eurogas Roadmap 2050*. Brussels

[Euro00b] EUROSTAT: *NUTS- Nomenclature of territorial units for statistics classification*. URL https://ec.europa.eu/eurostat/web/nuts/background

[Euro15] EUROSTAT: *Energy statistics – quantities, annual data*. Brüssel, 2015

[Euro17] EUROPEAN ENVIRONMENT AGENCY: European Pollutant Release and Transfer Register (E-PRTR), European Environment Agency (2017)

[Euro18] *European Commission report: IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773 “A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*. Brussels, Belgium : European Commission, 2018

[Euro19a] EUROPEAN CHEMICAL INDUSTRY COUNCIL CEFIC: 2020 Facts & Figures of the European chemical industry (2019)

[Euro19b] EUROPEAN ENVIRONMENT AGENCY: *Natura 2000 data - the European network of protected sites*. URL https://www.eea.europa.eu/data-and-maps/data/natura-10

[Faai18] FAAIJ, ANDRE P.C.: Securing sustainable resource availability of biomass for energy applications in Europe; review of recent literature. In: , 2018

[Frau15] FRAUNHOFER ISE: Current and Future Cost of Photovoltaics: Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems (2015)

[Frau19] FRAUNHOFER ISE: Aktuelle Fakten zur Photovoltaik in Deutschland (2019)

[FrSi13] FRANK GRAF ; SIEGFRIED BAJOHR: *Biogas - Erzeugung, Aufbereitung, Einspeisung*. 2. Auflage. Karlsruhe : Deutscher Industrie-Verlag, 2013

[GaRM13] GAZZANI, MATTEO ; ROMANO, MATTEO ; MANZOLINI, GIAMPAOLO: Application of Sorption Enhanced Water Gas Shift for Carbon Capture in Integrated Steelworks. In: *Energy Procedia* Bd. 37 (2013), S. 7125–7133

[GRKS20] GORRE, JACHIN ; RUOSS, FABIAN ; KARJUNEN, HANNU ; SCHAFFERT, JOHANNES ; TYNJÄLÄ, TERO: Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. In: *Applied Energy* Bd. 257 (2020), S. 113967

[Grol09] GROL, ERIC: Technical assessment of an integrated gasification fuel cell combined cycle with carbon capture. In: *Energy Procedia* Bd. Volume 1, Issue 1 (2009), Nr. Energy Procedia 00 (2008) 000–000

[H2fu00] *H2Future*. URL https://www.h2future-project.eu/technology. — H2Future project

[Hilz17] HILZ, JOCHEN: CO2 Capture with Carbonate Looping for Industrial Application.

[Hori00] HORIZON 2020: *Research and demonstration project STORE&GO, grant agreement No 691797*. URL http://www.storeandgo.info/. - abgerufen am 2016-04-15

[HoSS17] HORNBERGER, M. ; SPÖRL, R. ; SCHEFFKNECHT, G.: Calcium Looping for CO2 Capture in Cement Plants – Pilot Scale Test. In: *Energy Procedia* Bd. 114 (2017), S. 6171–6174

[HSRF17] HILLS, THOMAS P. ; SCEATS, MARK ; RENNIE, DANIEL ; FENNELL, PAUL: LEILAC: Low Cost CO2 Capture for the Cement and Lime Industries. In: *Energy Procedia* Bd. 114 (2017), S. 6166–6170

[HuPi12] HULD, THOMAS ; PINEDO-PASCUA, IRENE: *PVGIS - European Union 2012; WC - Joint Research Centre in collaboration with CM SAF*. URL https://ec.europa.eu/jrc/en/pvgis

[HuRV16] HUTTENHUIS, PATRICK ; ROELOFFZEN, ANDY ; VERSTEEG, GEERT: CO2 Capture and Re-use at a Waste Incinerator. In: *Energy Procedia* Bd. 86 (2016), S. 47–55

[Hydr17] *Hydrogen scaling up A sustainable pathway for the global energy transition* : Hydrogen Council, 2017

[Iea19] IEA: *Review of Fuel Cell Technologies with CO2 capture for the Power sector* (IEAGHG Technical Report), 2019

[Indu19] *Industry About - Worldwide industrial information - Industry Maps*. URL https://www.industryabout.com/energy/5580-solar-energy. — Industry About - Worldwide industrial information -

[Iren00] IRENA: *Renewable Capacity Statistics 2017 IRENA*

[Ise19] ISE, FRAUNHOFER: Photovoltaics Report - FraunhoferInstitute for Solar Energy Systems, ISE.

[JDBG17] JACOBSON, MARK Z. ; DELUCCHI, MARK A. ; BAUER, ZACK A.F. ; GOODMAN, SAVANNAH C. ; CHAPMAN, WILLIAM E. ; CAMERON, MARY A. ; BOZONNAT, CEDRIC ; CHOBADI, LIAT ; U. A.: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. In: *Joule* Bd. 1 (2017), Nr. 1, S. 108–121

[JeHS17] JELAVIC, VLADIMIR ; HERENCIC, LIN ; STANKIC, IGOR: REZULTATI PROJEKTA IZRADE STRUČNIH PODLOGA ZA IZRADU STRATEGIJE NISKOUGLJIČNOG RAZVOJA RH ZA RAZDOBLJE DO 2030. GODINE S POGLEDOM NA 2050. GODINU-Projekt Ministarstva zaštite okoliša i energetike.

[JeSB18] JEPMA, CATRINUS ; SPIJKER, EISE ; DEN BOON, OKKIE: *STORE&GO - Deliverable D8.5 - The short, medium and long term perspectives of various dedicated market segments for 'green gases'*, 2018

[Jöns00] JÖNSSON, JOHANNA: Analysing different technology pathways for the pulp and paper industry in a European energy systems perspective, S. 124

[Jrce06] JRC - EUROPEAN COMMISSION JOINT RESEARCH CENTRE: *Photovoltaic Solar Electricity Potential in European Countries*. Italy, 2006

[JVSF17] JORDAL, KRISTIN ; VOLDSUND, MARI ; STØRSET, SIGMUND ; FLEIGER, KRISTINA ; RUPPERT, JOHANNES ; SPÖRL, REINHOLD ; HORNBERGER, MATTHIAS ; CINTI, GIOVANNI: CEMCAP – Making CO2 Capture Retrofittable to Cement Plants. In: *Energy Procedia* Bd. 114 (2017), S. 6175–6180

[KoFB19] KOMUSANAC, IVAN ; FRAILE, DANIEL ; BRINDLEY, GUY: *Wind energy in Europe in 2018-Trends and statistics*. Belgium : Wind Europe, 2019

[LMSP17] LEESON, D. ; MAC DOWELL, N. ; SHAH, N. ; PETIT, C. ; FENNELL, P.S.: 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. In: *International Journal of Greenhouse Gas Control* Bd. 61 (2017), S. 71–84

[LTJP19] LONGA, DALLA ; T., KOBER ; J., BADGER ; P., VOLKER ; I., HIDALGO GONZALEZ: Wind potentials for EU and neighbouring countries - Input datasets for the JRC-EU-TIMES Model. In: *European Commission* (2019), S. 65

[Mesa16] MESARIĆ, MATIJA: RENEWABLE ENERGY IN CROATIA (2016), S. 59

[MeTo13] MESFUN, SENNAI ; TOFFOLO, ANDREA: Optimization of process integration in a Kraft pulp and paper mill – Evaporation train and CHP system. In: *Applied Energy* Bd. 107 (2013), S. 98–110

[MRZM20] MOUMIN, GKIOKCHAN ; RYSSEL, MAXIMILIAN ; ZHAO, LI ; MARKEWITZ, PETER ; SATTLER, CHRISTIAN ; ROBINIUS, MARTIN ; STOLTEN, DETLEF: CO2 emission reduction in the cement industry by using a solar calciner. In: *Renewable Energy* Bd. 145 (2020), S. 1578–1596

[MZRM19] MARKEWITZ, PETER ; ZHAO, LI ; RYSSEL, MAXIMILIAN ; MOUMIN, GKIOKCHAN ; WANG, YUAN ; SATTLER, CHRISTIAN ; ROBINIUS, MARTIN ; STOLTEN, DETLEF: Carbon Capture for CO2 Emission Reduction in the Cement Industry in Germany. In: *Energies* (2019)

[PfSt16] PFENNINGER, STEFAN ; STAFFELL, IAIN: Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. In: *Energy* Bd. 114 (2016), S. 1251–1265

[Pvss19] PVS SOLARSTROM: *Standard-Testbedingungen STC in der Photovoltaik*, 2019

[Qgis17] QGIS DEVELOPMENT TEAM: *QGIS Project*. URL https://www.qgis.org/en/site/. - abgerufen am 2017-02-16. — QGIS Project

[RBCG20] RASMUSSON, HANS ; BOLLIEN, ARMIN ; CIGARIDA, HRISTINA ; GERSTEIN, DIETRICH ; GRAF, FRANK ; ISIK, VOLKAN ; JEPMA, CATRINUS ; SCHAFFERT, JOHANNES ; U. A.: *STORE&GO - Deliverable D8.10 - Roadmap for large-scale storage based PtG conversion in the EU up to 2050*, 2020

[Ref00] BRIGITTE PECHAR: Linz bekommt die größte Wasserstoff-Pilotanlage der Welt

[Ref09] IEA: *Cement Technology Roadmap 2009 Carbon emissions reductions up to 2050*, 2009

[Ref11] KARIN PETTERSSON: *Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO2 Emission Balance*. Sweden, CHALMERS UNIVERSITY OF TECHNOLOGY, 2011

[Ref19] FRAUNHOFER: Agrophotovoltaik: hohe Ernteerträge im Hitzesommer, FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE (2019)

[ReLi15] REITER, GERDA ; LINDORFER, JOHANNES: Evaluating CO2 sources for power-to-gas applications – A case study for Austria. In: *Journal of CO2 Utilization* Bd. 10 (2015), S. 40–49

[Rene00] *Renewables Ninja*. URL https://www.renewables.ninja/. — Renewables.ninja

[Rwep09] RWE POWER: CO2-Wäsche, RWE Power Essen, Köln (2009)

[SCLL19] SCHAFFERT, JOHANNES ; CIGARIDA, HRISTINA ; LANGE, MANFRED ; LEVEDAG, DARIO ; COQUETTE, DOMINIK: *STORE&GO - Deliverable D8.7 - Report on data and methods used for the potential analysis of power-to-methane in Europe*. Essen, Germany, 2019

[SDSA11] SCARLAT, NICOLAE ; DALLEMAND, JEAN-FRANCOIS ; SKJELHAUGEN, ODD JARLE ; ASPLUND, DAN ; NESHEIM, LARS: An overview of the biomass resource potential of Norway for bioenergy use. In: *Renewable and Sustainable Energy Reviews* Bd. 15 (2011), Nr. 7, S. 3388–3398

[Sola00] *SolarPower Europe*. URL https://www.solarpowereurope.org/

[SsLV00] SSAB ; LKAB ; VATTENFALL: *HYBRIT fossil-free steel*. URL http://www.hybritdevelopment.com/

[THJS12] TROST, TOBIAS ; HORN, SÖNKE ; JENTSCH, MAREIKE ; STERNER, MICHAEL: Erneuerbares Methan: Analyse der CO2-Potenziale für Power-to-Gas Anlagen in Deutschland. In: *Zeitschrift für Energiewirtschaft* Bd. 36 (2012), S. 173–190

[ThMü11] THRÄN, DANIELA ; MÜLLER-LANGER, FRANZISKA: *Biogas Erzeugung, Aufbereitung, Einspeisung; Chapter 2: Potenziale in Deutschland und Europa*. München : Oldenbourg Industrieverlag, 2011. — S. Bajohr, F. Graf (publ.) — ISBN 978-3-8356-3197-7

[Trin18] TRINOMICS: The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets - final report (2018)

[Twen00] *Twence project - Producing sodium bicarbonate using carbon dioxide captured from the flue gasses of waste incineration (NaHCO3)*. URL https://www.co2sbc.eu/. — Twence project

[Vdma19] VDMA: *International Technology Roadmap for Photovoltaic (ITRPV) 2018 Results, Tenth Edition*. Germany : VDMA, 2019

[VMBM19] VARTIAINEN, EERO ; MASSON, GAËTAN ; BREYER, CHRISTIAN ; MOSER, DAVID ; ROMÁN MEDINA, EDUARDO: Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. In: *Progress in Photovoltaics: Research and Applications* (2019), S. pip.3189

[VMPE12] VATOPOULOS, K ; MOYA, J. A ; PARDO, N ; EUROPEAN COMMISSION ; JOINT RESEARCH CENTRE ; INSTITUTE FOR ENERGY AND TRANSPORT: *Prospective scenarios on energy efficiency and CO2 emissions in the EU iron & steel industry*. Luxembourg : Publications Office, 2012

[Wind00] *Wind Europe*. URL https://windeurope.org/

[Wirt20] WIRTH, HARRY: *Aktuelle Fakten zur Photovoltaik in Deutschland*. Germany : FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE, 2020

[Wri19] WRI: *Global Power Plant Database*. URL http://datasets.wri.org/dataset/globalpowerplantdatabase. — World resources institute - Global Power Plant Database

[ZaCo10] ZAKKOUR, PAUL ; COOK, GREGORY: CCS Roadmap for Industry: High-purity CO2 sources Sectoral Assessment – Final Report, Unpublished (2010)

12 Appendix

Table 12-1 National numbers of identified biogas plants and energy-intensive industrial plants considered as CO_2 sources for potential Power-to-methanation plants and primary data sources of the biogas data research

	Number of included CO_2 sources from energy-intensive industries	Number of included biogas plants	Total number of included CO_2 sources	Data format of biogas data source	Primary biogas data source
Austria	29	231	260	Raster dataset	[ÖST15]
Belgium	45	98	143	Vector dataset	[DLV13]
Bulgaria	11	5	16	Vector dataset	[REP19]
Switzerland	10	420	430	Vector dataset	[HOC16]
Cyprus	1	0	1	No data	-
Czech Republic	24	555	579	Vector dataset	[CZB19]
Germany	217	11552	11769	Vector dataset	[BUN18]
Denmark	7	155	162	Vector dataset	[ENE16]
Estonia	1	18	19	Vector dataset	[EES14]
Greece	7	0	7	No data	-
Spain	77	145	222	One-by-one research +	[AEB19]
Finland	24	95	119	Vector dataset	[SUO18]
France	93	491	584	Text dataset	[SIN19]
Croatia	6	28	34	One-by-one research	[HRV17]
Hungary	13	26	39	One-by-one research	[SOL13]
Ireland	7	28	35	One-by-one research	[AHK17]
Iceland	3	4	7	One-by-one research	[GUÐ09]
Italy	70	1478	1548	Text dataset	[GSE19]
Lithuania	3	0	3	No data	-
Luxembourg	6	1	7	Vector dataset	[DLV13]
Latvia	1	54	55	Raster dataset	[LBA14]
Malta	0	4	4	One-by-one research	[WAS19]
Netherlands	35	250	285	Raster dataset	[RIJ19]
Norway	31	225	256	Vector dataset	[AVF18]
Poland	45	91	136	Vector dataset	[GRA19]
Portugal	20	74	94	Vector dataset	[ENE19]
Romania	18	0	18	No data	-
Sweden	59	291	350	Text dataset	[ENE18]
Slovenia	4	11	15	One-by-one research	[POJ09]
Slovakia	11	110	121	One-by-one research	[POJ09]
United Kingdom	78	472	550	Vector dataset	[ADB19]
TOTAL	**956**	**16912**	**17868**		

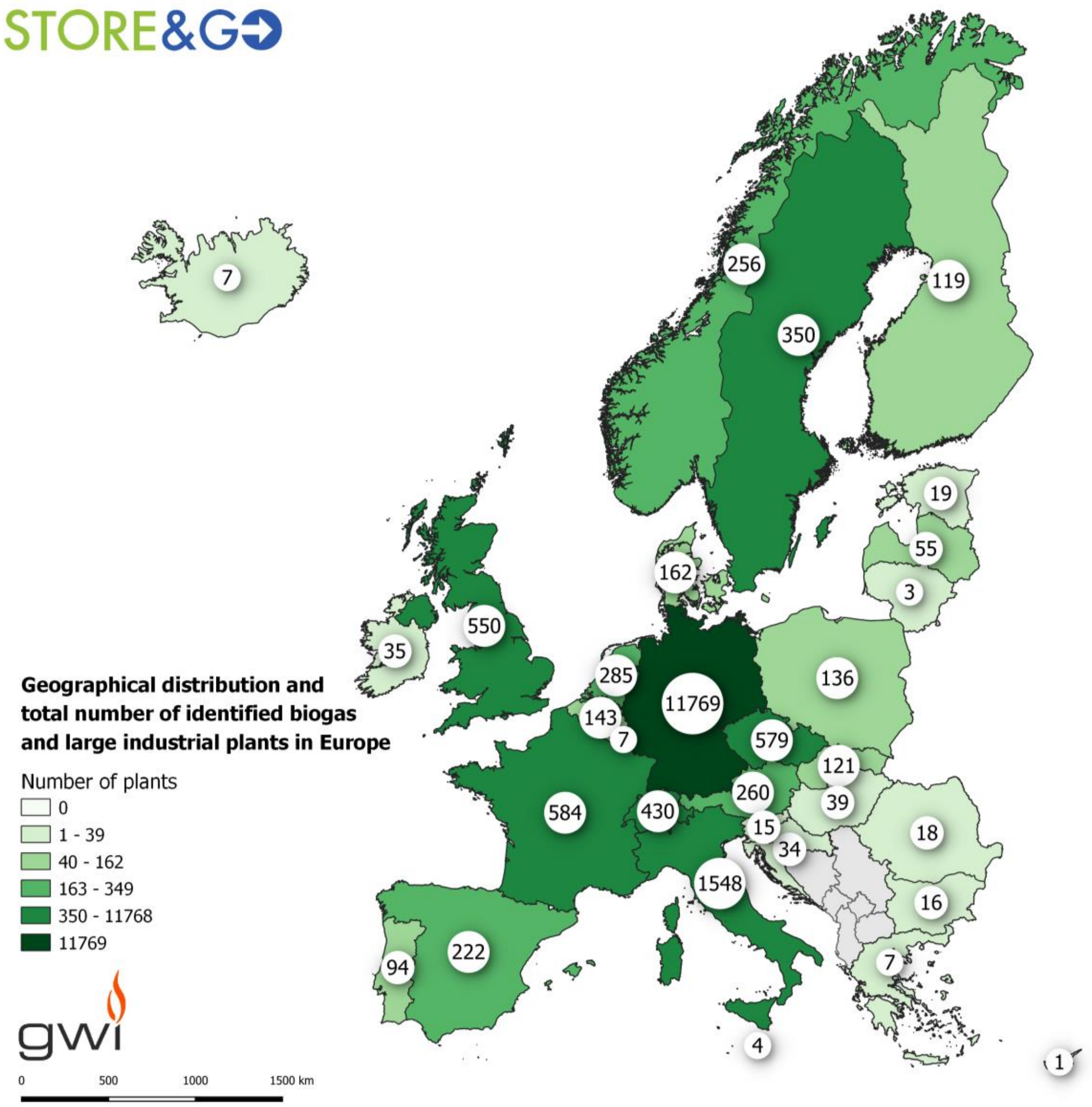


Figure 12-1 Total number of identified biogas and industrial plants in Europe

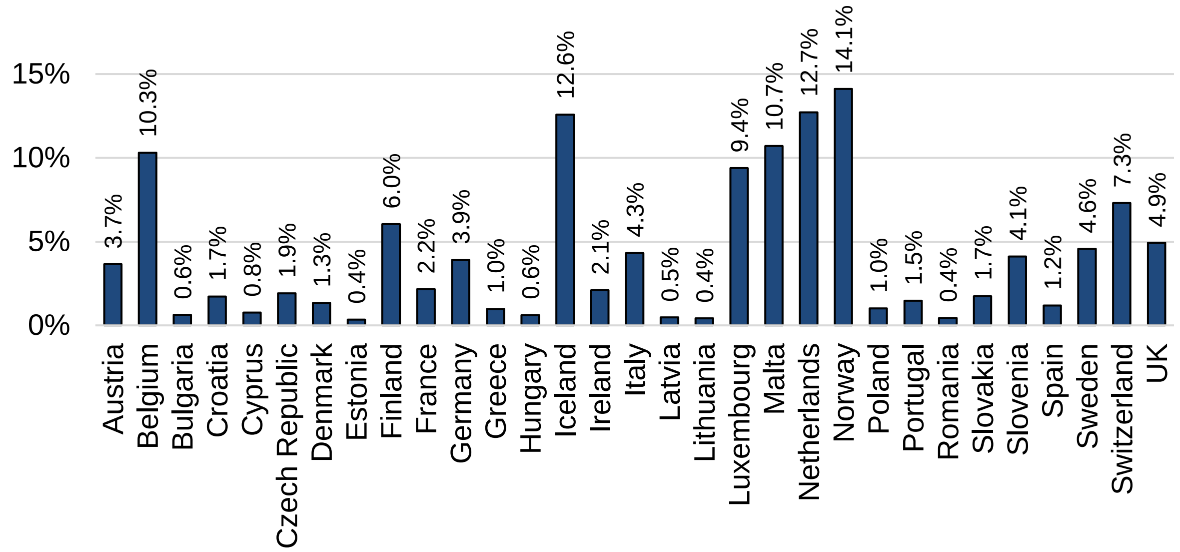


Figure 12-2 Proportion of theoretically required agricultural land for APV installations to cover national balance-sheet electricity demands in 2050; calculation based on [JDBG17]

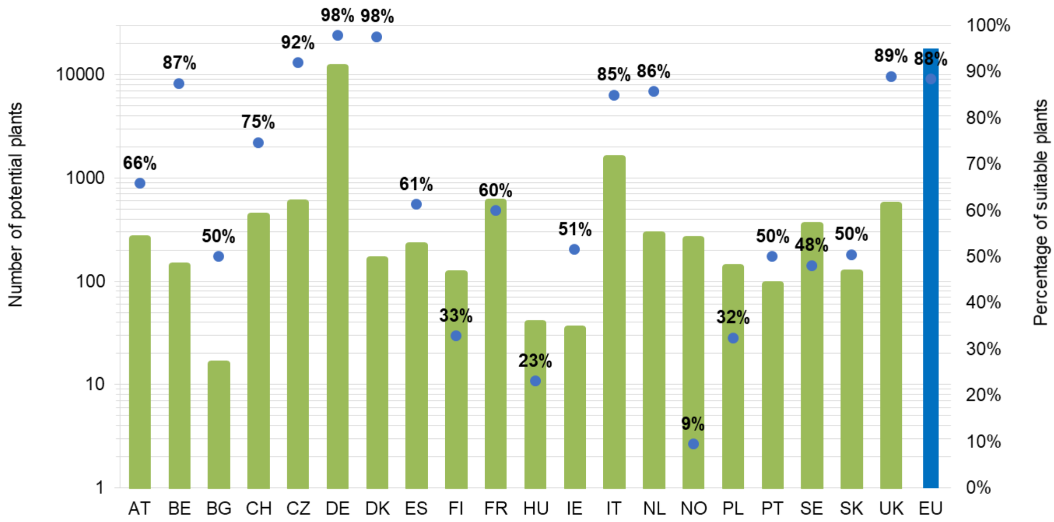


Figure 12-3 Number of identified CO_2 sources and share of plants suitable for local energy coupling with at least one RE source (wind or PV) in 10 km radius; nations with min. 8 sites are shown

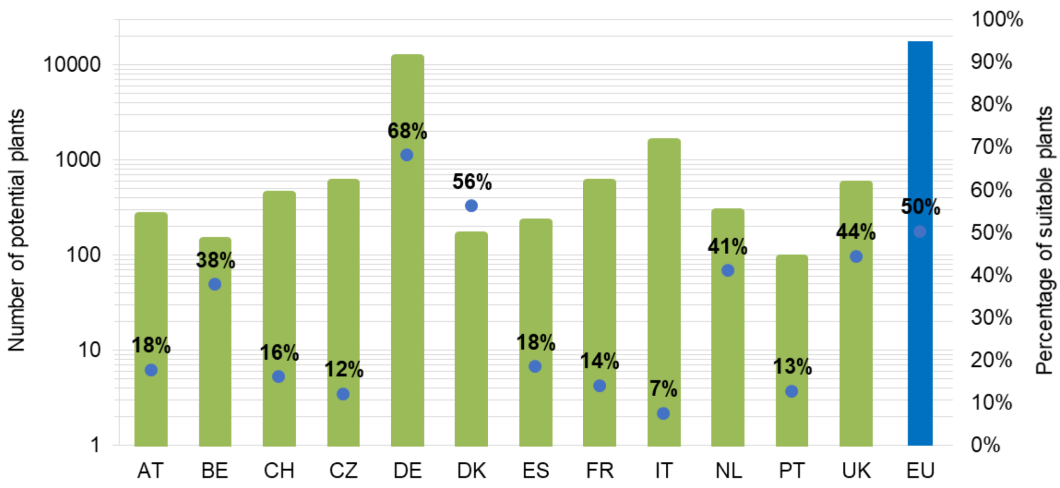


Figure 12-4 Number of identified CO_2 sources and share of plants suitable for local energy coupling with both RE source (wind and PV) in 10 km radius; nations with min. 8 sites are shown

Table 12-2 Summary of results from the potential PtM site identification

		Input data			Results from buffer analyses															
		No. of included biogas plants	No. of included industrial CO2 sources	sum	Biogas + PV	%	Biogas + Wind	%	Biogas + PV + Wind	%	Industry + PV	%	Industry + Wind	%	Industry + PV + Wind	%	Biogas or Industry + PV and Wind	%	Biogas or Industry + PV or Wind	%
Austria	AT	231	29	260	118	51	76	33	41	18	16	55	8	28	5	17	46	18	171	66
Belgium	BE	98	45	143	44	45	79	81	37	0	18	40	43	96	17	38	54	38	125	87
Bulgaria	BG	5	11	16	3	60	0	0	0	0	5	45	4	36	1	9	1	6	8	50
Switzerland	CH	420	10	430	294	70	87	21	67	0	7	70	4	40	2	20	69	16	321	75
Cyprus	CY	0	1	1	0	-	0	-	0	-	0	0	0	0	0	0	0	0	0	0
Czech Republic	CZ	555	24	579	488	88	86	15	63	0	22	92	8	33	7	29	70	12	532	92
Germany	DE	11552	217	11769	9426	82	9714	84	7850	1	187	86	194	89	155	71	8005	68	11500	98
Denmark	DK	155	7	162	86	55	151	97	86	1	5	71	7	100	5	71	91	56	158	98
Estonia	EE	18	1	19	0	0	4	22	0	0	0	0	1	100	0	0	0	0	5	26
Greece	EL	0	7	7	0	-	0	-	0	-	4	57	4	57	2	29	2	29	5	71
Spain	ES	145	77	222	80	55	35	24	23	0	37	48	39	51	18	23	41	18	136	61
Finland	FI	95	24	119	6	6	24	25	1	0	0	0	9	38	0	0	1	1	39	33
France	FR	491	93	584	148	30	189	38	56	0	52	56	47	51	26	28	82	14	350	60
Croatia	HR	28	6	34	1	4	0	0	0	0	1	17	2	33	0	0	0	0	4	12
Hungary	HU	26	13	39	1	4	4	15	0	0	4	31	2	15	1	8	1	3	9	23
Ireland	IE	28	7	35	0	0	15	54	0	0	0	0	3	43	0	0	0	0	18	51
Iceland	IS	4	3	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Italy	IT	1478	70	1548	1233	83	126	9	99	0	53	76	26	37	17	24	116	7	1314	85
Lithuania	LT	0	3	3	0	-	0	-	0	-	2	67	0	0	0	0	0	0	2	67
Luxembourg	LU	1	6	7	1	100	1	100	1	1	0	0	3	50	0	0	1	14	3	43
Latvia	LV	54	1	55	0	0	4	7	0	0	0	0	0	0	0	0	0	0	4	7
Malta	MT	4	0	4	1	25	4	100	1	0	0	-	0	-	0	-	1	25	4	100
Netherlands	NL	250	35	285	130	52	185	74	104	0	14	40	35	100	13	37	117	41	244	86
Norway	NO	225	31	256	8	4	13	6	0	0	1	3	1	3	0	0	0	0	24	9
Poland	PL	91	45	136	4	4	27	30	3	0	1	2	15	33	1	2	4	3	44	32
Portugal	PT	74	20	94	23	31	21	28	9	0	8	40	8	40	3	15	12	13	47	50
Romania	RO	0	18	18	0	-	0	-	0	-	2	11	3	17	0	0	0	0	2	11
Sweden	SE	291	59	350	20	7	122	42	2	0	2	3	27	46	1	2	3	1	168	48
Slovenia	SI	11	4	15	0	0	0	0	0	0	1	25	1	25	0	0	0	0	2	13
Slovakia	SK	110	11	121	50	45	8	7	3	0	6	55	0	0	0	0	3	2	61	50
United Kingdom	UK	472	78	550	333	71	286	61	202	0	58	74	58	74	42	54	244	44	489	89
TOTAL	**EU27+4**	**16912**	**956**	**17868**	**12498**	74	**11261**	67	**8648**	1	**506**	53	**552**	58	**316**	33	**8964**	50	**15789**	88

Acknowledgements

The authors thank F. Graf, S. Verleger, D. Trimis, A. Loukou and V. Isik for the perfect coordination of the project as well as valuable inputs for discussion and J. Hüttenrauch for valuable feedback and proof-reading of this Deliverable.