ENERGY

TRANSITIONING FROM FOSSIL FUELS TO CLEANER ENERGY REQUIRES RAPID ADVANCEMENT OF VARIOUS RENEWABLE ENERGY TECHNOLOGIES, QUICKLY SCALING UP THEIR DEPLOYMENT, AND GREATLY IMPROVING GRID SYSTEMS

Current situation and challenges

Energy is the lifeblood of the EU's economy. The story of economic expansion over the past two centuries is in a large part the story of fossil fuels – first coal, then oil and gas. Today, energy production and consumption is responsible for two-thirds of global anthropogenic carbon emissions. In 2017, fossil fuels still accounted for 73% of Europe's energy consumption, with renewables at just 14% (despite their rapid recent growth), followed by nuclear at 13%.

Fossil fuels have historically dominated the energy market because, simply put, they have the ability to convey a considerable amount of energy in small volumes. They are easily transportable. They can be stored in gas, solid and liquid forms. And they are cheap.

But fossil fuel usage also has significant drawbacks and major limitations. First, fossil fuel usage often wastes a considerable amount of energy, including lost heat from combustion engines, power plants and high-temperature industrial processes. Second, fossil fuels emit massive amounts of the greenhouse gases fueling climate change.

In charting a course toward a future powered by more clean energy, the first step is to identify ways to save energy. In the context of this report, the technology challenges that can help all of us – homeowners, businesses, governments, etc. – save energy are discussed in the Industry, Buildings and Transport sections. However, energy efficiency can only get us so far – it is essential to also decarbonize the energy we produce, transport and consume.

For clean energy technologies to truly be able to supplant fossil fuels, they first must overcome several of their own unique current challenges:

- The amount of clean energy produced must increase dramatically. Doing so will create economies of scale, helping drive down the costs of technologies like floating offshore wind, bifacial solar panels, and green hydrogen.
- To ensure end-users have access to clean power 24/7, clean energy intermittency issues must be addressed.
- Whereas fossil fuels essentially have three main forms (coal, oil and gas) that are able to meet most energy needs, clean energy technologies are more varied, and each technology has its own drawbacks and benefits. Despite this diversity of supply and a wide range of transmission methods, clean power must be easy to access and easy to use.

> ***"We need to accelerate grid investments. Our vision is that we will have integrated systems (power/gas/heat) where the optimization currency will be a ton of CO_2 in complement of euros and enhanced by digital and AI capabilities."***
>
> **Laurent Schmitt.** General Secretary ENTSO-E

Solutions, projects and scale-up

From fossil fuels to clean energy: Volumes and costs

Decarbonized energy carriers are supposed to grow dramatically by 2050[1] – electricity will grow from 2,750 TWh to 3,400 TWh, while hydrogen and its related synthetic fuels will jump from nearly zero to 1,800 TWh.

Supporting the scale-up of renewable energy production is essential, both to increase the volume produced to help offset fossil fuel use, and to leverage economies of scale to lower costs. Europe is poised to achieve technology breakthroughs in the following fields:

- Scale-up of the manufacturing of new solar technologies so they can reach 30% efficiency within five years. This includes multi-junction cells (III-V and/or perovskites on silicon), and large-scale bifacial solar plants that harvest more sunlight.
- 5-6 GW-scale gigafactories that can manufacture these new solar technologies. After 15 years of Chinese market supremacy, this can help Europe regain its competitive edge in solar manufacturing. 19 GW annual production capacity of next-generation modules could be achieved by 2030 if work toward that goal began now.
- The offshore wind industry can work to solve usage constraints as the sea near the shore becomes increasingly crowded. 60% of Europe's offshore wind potential could be unlocked by 2030 by creating 53 GW of floating offshore wind capacity.
- Production costs and performance must be improved for biogas by creating six large-scale biogas competitiveness hubs by 2030.

Solved intermittency and availability

Semi-base and baseload fossil-fuel power generation need to be replaced. This can be achieved through concentrated solar plants in Southern Europe and in Northern Africa (with grid connections). These facilities could potentially provide a 70%-95% load factor – i.e., 6,000-8,000 hours annually of baseload assuming 24/7 availability.

Progress on storage technologies beyond Li-ion is also crucial. Specifically:

- Large-scale renewable + hybrid storage projects to develop viable alternatives to Li-ion batteries.
- Long-duration storage, from six hours to several days.

Finally, the role of digital technologies is key to increase flexibility; increase the control of demand, supply and storage; improve aggregation of demand, etc. Smart digital technologies must be deployed at all scales and locations, including homes, districts, transportation modes, cities, industries, grids, power plants and buildings.

Improve and enhance electric grids

Traditionally, fuels and the power they generate have been consumed separately. Electricity, gas and liquid fuels each have their own supply chains that are largely independent from one another. By 2030, hydrogen will have penetrated the market, and electricity will be used more widely, including in the generation of hydrogen. Sites producing large quantities of renewable energy will be needed in every region in Europe, but not necessarily close to where that energy is consumed. Grids need to expand and be improved as they transport more electricity.

Greener gases, pure hydrogen, CO_2, heat and cooling will also have to be transported or reused in new, circular usages.

Regional approach

Gigafactories can be developed everywhere in Europe. In particular, Central and Eastern European countries that have maintained a strong industrial base (as demonstrated by the region's automotive industry) could benefit.

Regardless of seashore profile, floating offshore wind is applicable in all countries with a coastline.

Solar's potential is particularly strong in Southern Europe and the region could be a key producer of cheap hydrogen which could then be transported via pipelines to Northern Europe.

Impacts

- **€151 billion total market (turnover + investments) per year in 2030.**
- **2.3 million permanent jobs in 2030.**
- **460 MtCO_2 avoided per year in 2030.**

List of projects - ENERGY

From Fossil to Clean: Volumes and costs

#1 - GIGA-SCALE MANUFACTURING CAPACITIES OF NEW GENERATION SOLAR MODULES
Build gigafactories based on perovskite and III-V multi-junction high efficiency cells by 2030

#2 - GENERATE 30% MORE ELECTRICITY PER M² WITH BIFACIAL SOLAR PANELS
Large-scale bifacial solar plant and gigafactory

#3 - MORE LARGE-SCALE FLOATING OFFSHORE WIND
Unlock 80% of Europe's offshore wind potential through a rapid scale-up of new generation floating wind structures

#4 - LARGE-SCALE HYDROGEN PRODUCTION AT €1.5/KG BY 2025-2030
Develop renewables and electrolyzers to scale up low-cost green hydrogen

#5 - BIOMETHANE DESIGN-TO-COST INDUSTRIALIZATION TO DRIVE ECONOMIES OF SCALE
Create six large-scale competitiveness hubs and reduce costs by 30% by 2025

Solved intermittency and availability

#6 - 24/7 AVAILIBILITY OF ELECTRICITY FROM COMBINED SOLAR GENERATION, STORAGE AND GRID
Build trans-Mediterranean grid and electricity daytime baseload with Concentrated Solar Power (CSP)

#7 - EXPLOIT ALL EUROPEAN PUMP STORAGE CAPACITY
Retrofit existing hydro-plants for pump storage

#8 - BUILD COMPETITIVE LEADERSHIP IN ELECTRICITY STORAGE FOR STATIONARY USE
Develop viable short- and long-duration storage alternatives to Li-ion battery

#9 - DIGITAL EVERYWHERE AT CUSTOMER, PRODUCTION AND GRID LEVELS TO SMARTLY SOLVE AVAILABILITY AND INTERMITTENCY
Flexibility along the whole smart energy value chain across Europe at all spatial and temporal scales

Optimize and redesign grids

#10 - REINFORCE ELECTRIC GRIDS FOR 100% RENEWABLE POWER
Develop grids, HVDC, storage and innovative technologies to build a robust grid for all Europe

#11 - TRANSFORM GAS GRIDS INTO A NEW MULTI-FOCUSED RESOURCE
Repurpose Europe's gas grids for biomethane, H_2, and CO_2 and focus them on industry needs and dense urban areas

#12 - MASSIVELY DEPLOY HEATING AND COOLING NETWORKS TO REDUCE FOSSIL FUEL DEPENDENCY IN EUROPEAN CITIES AND HELP OPTIMIZE ELECTRIC GRIDS
District Heating and Cooling (DHC) can leverage thermal storage, thermal efficiency and energy sourced from geothermal, renewables and waste to help improve air quality, reduce noise and curtail heat islands

#13 - COST-EFFECTIVE AND ENERGY EFFICIENT CO_2 AIR CAPTURE AT SCALE
Direct Air Capture to simplify and ease the energy transition challenge

[1] *World Resource Institute, remaining part being industrial processes, agriculture, land use change and waste.*
[2] *1.5TECH scenario https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf*

GIGA-SCALE MANUFACTURING CAPACITIES OF NEW GENERATION SOLAR MODULES

Build gigafactories based on perovskite and III-V multi-junction high efficiency cells by 2030

ENERGY

From fossil to clean energy: volumes and costs

IN A NUTSHELL...

- **Issue:** The efficiency of crystalline silicon cells is reaching its technical limits. Moreover, in the last 15 years China has produced most of the world's solar PV
- **Solution:** Multi-junction cells associated with silicon industrial know-how to reach higher levels of field efficiency. Large scale 4.0 factories to drive down costs and allowing large reallocation of production to Europe
- **Key impacts:** 37.9 MtCO_2e avoided, €1.8 billion total market, 14,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

An innovative EU next-gen PV program would rely on two pillars: (i) structured industrial and R&D partnerships to innovate and test rapidly; (ii) large manufacturing plants to scale up innovation. The main project focus is on increasing manufacturing facilities while R&D/industrial clusters are described here as support infrastructure. Both are outlined as follows:

Project type 1: Solar R&D and industrial clusters

Establish three R&D and industrial clusters by 2021 to support continuous improvement, with the must-have objective of deeply integrating technological innovation with manufacturing processes:

- One in Germany to leverage first-class R&D labs (ISC Konstanz, Fraunhofer ISE, Solar Factory of the Future, FAU, etc.), and strong R&D partnerships like Solliance with manufacturers.
- One in Italy to leverage first class R&D labs (University of Rome Tor Vergata, Italian Institute of Technology, University of Naples, etc.) and the experience of manufacturers such as Enel.
- One in Lithuania, in association with western EU R&D institutions: to leverage the competencies of existing module manufacturers.

Projects that inspired this analysis: French IPVF industrial and R&D cluster.

Project type 2: Giga-scale manufacturing plants for the production of new-generation cells

Build manufacturing plants for the production of multi-junction cells (III-V and/or perovskites on silicon) with individual output capacity in the 3-10 GW range.

- The manufacturing plants will supply the expected EU demand with part of the production exported. Ultimately, these new cells are likely to be mounted as bifacial modules to further boost panel yields (see #2 for specific projects on bifacial technology).
- The manufacturing plants can be deployed in Germany, Italy, France, Spain and Eastern Europe as they have industrial know-how which can be scaled up, with the support of specific manufacturers (Enel, Burger Meyer, Wacker Polysilicon AG, etc.) and R&D and industrial clusters.

Projects that inspired this analysis: Oxford PV and Burger Meyer 125 MW perovskite-on-silicon solar cell manufacturing line. Chinese plants with current silicon technologies in the 3-10 GW size range. Industry 4.0 manufacturing plants in other industries (e.g. BOSCH).

Why this technology and project are needed to reach net-zero

Net-zero scenarios modelled by the JRC show that Europe must install up to 600 GW PV generation capacity by 2030 and over 1 TW by 2050[1] to reach its climate and energy objectives . The European market will grow 10-15% per year and reach close to 80 GW by 2030. In this race, Europe has a unique opportunity to develop and deploy new generation PV modules.

New generations of cells such as III-V and perovskites are instrumental to Europe's come-back on the PV scene. Combined with standard silicon cells, multi-junction structures now reach over 40% efficiency in labs. The theoretical efficiency of crystalline silicon cells cannot exceed 30%, and is often far lower in practice. For instance, average efficiency in the EU stands at around 12%. Europe has world class solar R&D programs, but little concrete application pilots and manufacturing lines, while Asian players have been betting on these technologies. For example, the Chinese GCL announced the extension of its perovskites production line from 10 MW to 1 GW by 2021, to quickly gain market share.

Europe has world-class solar clusters in IPVF (FR), Fraunhofer (DE), and IMEC (BE) with other important clusters in EPFL (CH), and ECN (NL). In such clusters research and industry must closely work together to face the following challenges for a quick and strong take-off of these technologies in 2022-2025:

- adapt well-proven silicon manufacturing solutions to deploy multi-junction module production.
- increase the perovskite cells size and durability.
- divide the manufacturing cost of III-V materials by two orders of magnitude.
- lauch first manufacturing lines by 2022-2025.

All R&D projects funded by European governments and the EU should have a strong industrial component, and reciprocally no industrial projects should be funded without an R&D component to maintain innovation and competitiveness.

From the regulatory perspective, tenders also need to include environmental criteria such as embedded CO_2 emissions, social criteria such as local jobs, and efficiency criteria per square meter.

Impacts

	2030	2050
CLIMATE IMPACT	**37.9 $MtCO_2e$ avoided**	**253.2 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€1.8 billion total market** €3.7 billion cumulated investment by 2030, €400 million yearly average (2020-2030) €1.4 billion turnover in 2030	**€4.9 billion total market** €3.4 billion cumulated investment by 2050, €200 million yearly average (2030-2050) €4.7 billion turnover in 2050
JOBS	**14,000 total jobs** 6,000 construction jobs for investment 8,000 production jobs for turnover	**31,000 total jobs** 3,000 construction jobs for investment 28,000 production jobs for turnover

#1 [1] https://www.researchgate.net/publication/340320166_How_photovoltaics_can_contribute_to_GHG_emission_reductions_of_55_in_the_EU_by_2030

GENERATE 30% MORE ELECTRICITY PER M²
WITH BIFACIAL SOLAR PANELS

Large-scale bifacial solar plants and gigafactories

ENERGY

From fossil to clean energy: volumes and costs

IN A NUTSHELL...

- **Issue:** Current PV efficiency reaches its limits and deployment can be hampered by land use constraints
- **Solution:** Bifacial solar plants harvest light reflected from the ground via the Albedo effect to increase efficiency by 9%, and generate up to 40% more power when combined with tracking systems
- **Key impacts:** 18.9 MtCO_2e avoided, €900 million total market, 7,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Project type 1: High-yield bifacial solar farms with tracking systems by 2030

Set up PV farms combining several technologies (bifacial/soil coverage/tracking systems) by 2030.

- Bifacial panels can be mounted with perovskites/II-V technology cells (see project #1 for projects on new generation solar panels).
- They can be deployed across Europe, and increased efficiency can help open less sunny/profitable markets in Northern and Eastern Europe.
- Solar plant developers, solar module components manufacturers (of tracking systems, inverters, etc.) and R&D labs must cooperate on these projects to ensure incremental innovation, cost reduction and efficiency monitoring.

Projects that inspired this analysis: 2 MW SoliTek bifacial solar plant is the first of its kind in Europe. Equipped with top of the line bifacial glass-glass solar panels and a horizontal single-axis sun tracking system, it will generate up to 30% more electricity than a conventional solar power plant, for an investment of €2.6 million.

Project type 2: Giga-scale bifacial manufacturing plants

Build bifacial module gigafactories of 5 GW capacity by 2030.

- The manufacturing plants will supply the expected EU demand with part of the production exported. Ultimately, these new cells are likely to be mounted as bifacial modules to further boost panel yields (see #2 for specific projects on bifacial technology).
- The manufacturing plants can be deployed in:
  - Italy: to leverage existing bifacial solar manufacturing capacities.
  - Spain: to take advantage of the dynamic local PV market, skilled and flexible workforce and proximity with potential export markets in North Africa.
  - Lithuania: which has already deployed bifacial modules production capacities, and started installing the first EU bifacial module plants.

Projects that inspired this analysis: Enel's Catane 200 MW cell production facility launched in 2019 could be replicated to drive down costs and generate manufacturing jobs in the EU.

Why this technology and project are needed to reach net-zero

Net-zero scenarios modelled by the JRC show that building up to 600 GW PV generation capacity by 2030 and over 1,000 GW by 2050 would contribute to reach a 55% GHG reduction by 2030 and net-zero emissions by 2050[2]. The European market will grow 10-15% per year and reach close to 50 to 80 GW by 2030. In this race, Europe has a unique opportunity to develop and deploy new generation PV modules.

Bifacial PV collects light from reflection of the ground to reach about 9%[3] supplementary efficiency. The developers of initial projects claim potential efficiency gains of 20-25%. Their higher upfront costs are compensated over the project's lifetime, especially since bifacial modules are more resistant and have longer warranties (up to 30 years).

Analysts expect this technology to take up between 40 and 60%[4] of the European PV market by 2030. While Asian players are just gearing up and adapting their production lines to this new technology, some EU players such as Norwegian REC or German SolarWorld Industries have started to bet on their ability to ramp-up production and regain market shares in PV.

In addition to contributing to pan-European re-industrialization, deploying additional solar panel capacity will contribute to reaching the EU's net-zero ambition, while limiting the land-use that large solar projects require.

To reach this target, sustained deployment of bifacial PV farms and a rapid ramp-up of manufacturing capacities across Europe are key. From a regulatory perspective, public institutions can support deployment by setting efficiency requirements per square meter in public tenders and accelerating permits.

Impacts

	2030	2050
CLIMATE IMPACT	**18.9 $MtCO_2e$ avoided**	**162.5 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€900 million total market** €1.9 billion cumulated investment by 2030, €0.2 billion yearly average (2020-2030) €700 million turnover in 2030	**€3.2 billion total market** €2.9 billion cumulated investment by 2050, €100 million yearly average (2030-2050) €3 billion turnover in 2050
JOBS	**7,000 total jobs** 3,000 construction jobs for investment 4,000 production jobs for turnover	**20,000 total jobs** 2,000 construction jobs for investment 18,000 production jobs for turnover

#2 [2] https://www.researchgate.net/publication/340320166_How_photovoltaics_can_contribute_to_GHG_emission_reductions_of_55_in_the_EU_by_2030
[3] https://www.nrel.gov/docs/fy19osti/74090.pdf
[4] https://www.dnvgl.com/to2030/technology/solar-pv-powering-through-to-2030.html and https://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf

MORE LARGE-SCALE FLOATING OFFSHORE WIND

Unlock 80% of Europe's offshore wind potential through a rapid scale-up of new generation floating wind structures

ENERGY

From fossil to clean energy: volumes and costs

IN A NUTSHELL...

- **Issue:** Nearshore shallow sea is already saturated with industrial activities, while 80% of Europe's offshore wind resource potential is located in water more than 60 m deep, which is too deep for conventional offshore wind installations
- **Solution:** Large scale floating wind turbine projects will drive down costs on offshore wind farms
- **Key impacts:** 48.6 $MtCO_2e$ avoided, €26.6 billion total market, 399,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Floating wind farms at GW scale

- WindEurope's High Scenario calls for 99 GW of offshore wind installations by 2030. According to the 1.5TECH EU scenario, developed for the European Commission, 450 GW must be installed by 2050[5].
- The project aims to boost commercial deployment of floating wind, with the deployment of deep-water floating wind farm projects at GW scale to drive down costs.
- Projects should be deployed in seas in the north of Europe. Both deep waters (between 50 m and 220 m) and high wind speeds are abundant in the North Sea, and off the coast of Scotland and England in the Atlantic. As such, countries around the North Sea are a strong knowledge cluster, with most offshore wind capacity installed and several floating wind projects etiher commissonned or under construction.
- Estonia, Latvia and Lithuania are also good areas for capacity deployment, given large untapped potential in the Baltic Sea.
- Portugal, Spain and France are also developing floating wind pilots. Their projects should be deployed on the Atlantic coast and in the Mediterranean, where deep waters start close to the coastline.
- Developing these projects requires continued cooperation between wind farm developers and electrical and mechanical system engineering companies to improve the reliability of platforms and drive down costs.
- Government/regulatory bodies have a crucial role in setting targets and creating offshore wind tenders. National ambitions, as outlined in the National Energy and Climate Plans, also need to be raised.

Why this technology and project are needed to reach net-zero

Wind power is a key enabler in Europe's transition towards a net-zero emissions economy, delivering low-carbon electricity and supporting world-class regional industrial value chains. Onshore wind may represent just two-thirds of installed capacity by 2030, and offshore wind will be key to achieving Europe's climate and energy goals. The National Energy and Climate Plans (NECP) of all Member States project over 70 GW of aggregate installed offshore wind capacity by 2030[6]. However, according to the European Commission's long-term climate strategy scenarios, a much higher capacity will be required to reach its net-zero target[7], with up to close to 450 GW of offshore wind by 2050.

At the pre-commercial level, as noted by the Wind Europe association[8], 6 floating offshore wind projects are to be commissioned between 2019 and 2020 in Europe (in Portugal, Spain, Sweden and the UK), and a total of 11 will have begun production by 2023. For example, the 25 MW WindFloat Atlantic floating wind project, 20 km off the coast of Portugal, is in its last phase of construction. Once operational, it will supply electricity to 60,000 homes with three wind turbines of 8.4 MW each.

Despite this enormous deployment potential, just 4-5 GW are expected to be installed by 2030. Projects are moving to commercial scale but an accelerated deployment is needed, especially in the permitting and capacity auction stages. Larger deep offshore volumes will play a crucial role in driving down costs, from around €200/MWh to €40-60/MWh before 2030. To achieve this, 100 floating wind projects are needed by 2030 to deliver the EU's offshore wind deep water potential and competitive leadership.

Impacts

	2030	2050
CLIMATE IMPACT	**48.6 $MtCO_2e$ avoided**	**331.1 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€26.6 billion total market** €184.8 billion investment by 2030, €18.5 billion yearly average (2020-2030) €8.1 billion turnover in 2030	**€85.2 billion total market** €900 billion investment by 2050, €30 billion yearly average (2020-2050) €55.2 billion turnover in 2050
JOBS	**398,000 total jobs** 277,000 construction jobs for investment 121,000 production jobs for turnover	**1,278,000 total jobs** 450,000 construction jobs for investment 828,000 production jobs for turnover

#3 [5]*https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf (figure 24)*
[6] *https://windeurope.org/newsroom/news/necp-analysis-permitting-problems-still-a-major-stumbling-block/*
[7] *1.5TECH scenario (one of the 2 scenarios out of 8 reaching net-zero emissions by 2050) plans up to 1200 GW installed wind capacity by 2050, among which 450 GW of offshore. https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf*
[8]*https://windeurope.org/wp-content/uploads/files/policy/position-papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf*

LARGE-SCALE HYDROGEN PRODUCTION AT €1.5/KG BY 2025-2030

Develop renewables and electrolyzers to scale up low-cost green hydrogen

ENERGY

From fossil to clean energy: volumes and costs

IN A NUTSHELL...

- **Issue:** At around €6 per kg, green hydrogen is not competitive today with fossil energies (parity at €1/kg equivalent to €25/MWh)
- **Solution:** Create gigascale integrated hydrogen projects and electrolyzer factories to increase volumes and bring costs down to €1.5 per kg in Southern Europe and €3 per kg in Northern Europe as soon as 2030
- **Key impacts:** 38.2 $MtCO_2e$ avoided, €10.6 billion total market, 150,000 jobs in 2030

Innovation bet | **Acceleration and scale-up** | Drive to market scale

Project opportunity and ambition

The goal is to ramp up industrial demand and large-scale supply rapidly, bringing green hydrogen costs down to competitive levels with natural gas, liquid fuels and grey hydrogen (€1.5 per kg in Southern Europe, €3 per kg in Northern Europe).

Project 1: Deploy giga-scale green hydrogen production sites

Establish three R&D and industrial clusters by 2021 to support continuous improvement, with the must-have objective of deeply integrating technological innovation with manufacturing processes

Identify specific locations, with existing infrastructures (such as significant gas grid, and industrial players of different types) and potential for renewable energy. They will produce and deliver green hydrogen to multiple industrial offtakers. Symbiosis economy will be generated between captured CO_2 from steel and cement industry with liquid e-fuel plants combining hydrogen with reused CO_2.

Deploy five electrolyzer plants of 1 GW capacity each by 2025.

Develop dedicated large-scale low-cost renewable energy generation capacity to supply the electrolyzers. Depending on the nearby potential, develop GW size plants of offshore wind, onshore wind, and solar photovoltaic.

Examples of regions to target in priority for the industrial hubs include: South Holland-Zeeland-Antwerp in the Netherlands and Belgium, Rhein-Ruhr region in Germany, Tarragona in Spain, Marseille-Fos, Rhône and Dunkerque in France, Lombardy-Veneto in Italy, Bratislava-Vienna in Slovakia and Austria.

Main stakeholders include local authorities, solar PV and wind power plant developers, utility companies, gas grid operators, electrolyzer producers, industry players (in industrial chemistry, electronic component manufacturing, metalworking, glass, and hydrogen vehicles production).

Projects that inspired this analysis: 2x40GW Hydrogen Europe initiative, NorthH$_2$ project in the Netherlands, Green Spider project in Spain

Project 2: Deploy giga-scale electrolyzer manufacturing plants

Currently the main electrolyzer manufacturers are European. Upscale the size of plants and upgrade the plant floors to Industry 4.0 best practices to feed the market and maintain the production in Europe.

Why this technology and project are needed to reach net-zero

Hydrogen is a versatile energy carrier. Today it is widely used in industrial processes and in specific merchant applications. In Europe the equivalent of 325 TWh were used in 2015[9]. However today, 95% of the global production is produced from gas and coal[10]. Nine tons of CO_2 are emitted for each ton of hydrogen produced with steam methane reforming (SMR), corresponding to 270 gCO_2 per low heating value kWh of hydrogen and 225 gCO_2 per high heating value kWh of hydrogen. The current cost of hydrogen produced with fossils for the industry in captive and merchant uses is in the €1 to €1.5 range per kg out of the plant.

Green hydrogen created through electrolysis with decarbonized electricity provides a promising opportunity to significantly reduce carbon emissions. The final objective is to replace most fossil fuels with green hydrogen and its derivated synthetic fuels. Hydrogen Europe states that hydrogen has the potential to replace up to 665 TWh and 2,251 TWh of fossil demand respectively in 2030 and 2050[11], in industry, transportation, buildings and energy sectors. The 1.5Tech scenario prepared for the European Commission displays similar figures, with 1,791 TWh in 2050 split in 790 TWh of hydrogen consumed directly in final sectors, 523 TWh used to produce e-gas and 476 TWh to produce e-liquids.

Cost is a major challenge, as €25 per MWh of natural gas is equivalent to €1 per kg of hydrogen, and €0.6 per liter of gasoline (cost without tariffs) is equivalent to €2.5 per kg of hydrogen, while electrolysis with the current cost of wind and solar PV renewables are closer to €6 per kg.

Increasing both supply and demand is key in reducing costs, and can best be achieved in places where existing assets can be leveraged. These places include industrial clusters, solar or wind power plants, renewable curtailment, and extensive gas grids.

In Northern Europe the cost of hydrogen could drop to €3 per kg by 2030, with a giga-scale approach to hydrogen electrolyzer plants in selected industrial clusters and electricity provided by large offshore wind farms.

In Southern Europe and North Africa the cost of hydrogen could drop to €1.5 per kg by 2030, with a giga-scale approach to hydrogen electrolyzer plants with electricity provided by large solar plants, associated with wind, and transport to Northern Europe through shipping and grids.

Impacts

	2030	2050
CLIMATE IMPACT	**38.2 $MtCO_2e$ avoided**	**129.4 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€10.6 billion total market** €1 billion cumulated investment by 2030, €100 million yearly average (2020-2030) €10.5 billion turnover in 2030	**€33.5 billion total marke** €1.3 billion investment by 2050, €65 million yearly average (2030-2050) €33.5 billion turnover in 2050
JOBS	**150,000 total jobs** 2,000 construction jobs for investment 149,000 production jobs for turnover	**491,000 total jobs** 1,000 construction jobs for investment 490,000 production jobs for turnover

#4 [9]https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf
[10]https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf
[11]ibidem

BIOMETHANE DESIGN-TO-COST INDUSTRIALIZATION TO DRIVE ECONOMIES OF SCALE

Create six large-scale competitiveness hubs and reduce costs by 30% by 2025

ENERGY

From fossil to clean energy: volumes and costs

IN A NUTSHELL...

- **Issue:** The total production volume of biogas is still small, and uptake is occurring at different rates depending on the available sources. Technical & economic barriers (i.e. high investment costs) play a major role in hindering the wider uptake of biogas as a source of sustainable energy.
- **Solution:** A set of industrial and R&D clusters with large demonstrators to share knowledge and to reduce the end-to-end development costs by standardizing the approach in a 'design-to-cost' mode
- **Key impacts:** 87.3 MtCO_2e avoided, €35.1 billion total market, 527,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

- Set up six large-scale biogas R&D and competitiveness hubs by 2025, including coverage of:
  - » Biomethanization infrastructures based on different technologies for biogas production and research tests.
  - » Establish research laboratories to explore technology applications for increasing biodigester efficiency.
  - » Training centers to close the knowledge gap.
- The goal of the project is to overcome the techno-economical barriers[12] in biogas production (such as infrastructural challenges – i.e. limited access to refueling stations and to vehicle gas – or frequent need for repair and lack of attention paid to maintenance of biogas plants), identify the best industrialization pathways for the sector, push down costs of biomethane by at least 30% by 2025, and structure the EU biogas value chain.
- Hubs should be set up where existing know-how exists (leading countries in the biogas production in the EU are Austria, Germany, Italy, Czech Republic, Netherlands and France) and potential commercial demand can be leveraged:
  - » Three hubs could be set up in existing knowledge clusters in Germany, the Netherlands, and Italy. These three countries have among the greatest number of biogas production installations (and the largest). Their strong industrial activities and power needs also contribute, together with progressive regulatory frameworks, to promote biogas technologies.
  - » Despite limited involvement in this industry today, Eastern Europe has significant potential for at least three biogas hubs: Hungary, Lithuania, Latvia and Slovakia use mainly natural gas for heating and power in CHP plants, which could be blended with biomethane. In addition, Poland is a large consumer of natural gas in industrial processes and heat production and could therefore be another potential hub. About a third of the manure and slurry volume provided as the organic waste of agricultural production in Poland could be processed into biogas for local use.[13]
- Various stakeholders are key to the success of the project, notably:
  - » An R&D laboratory with a research focus on microbiome, optimal feedstock, and methanation processes.
  - » Project developers and local authorities keen to ensure technical and commercial success.
  - » Monitoring and control system providers, to develop optimized monitoring solutions to pilot the methanization process and increase yield.
  - » Local feedstock providers (farmers for crop residues and manure, water waste treatment plant).

Projects that inspired this analysis: The CertiMétha project in France gathers key players in the biogas sector (Evergaz, K-REVERT, Biogaz Vallée, and others) around an established infrastructure for biomethanization, with a total investment of €4.8 million. The infrastructure includes an analysis laboratory, digesters from 1 to 400 m3 to test large-scale anaerobic digestion processes, and a training center for biogas engineers. This project will contribute to improving the design of biogas production plants, reducing infrastructure costs in the industry.

Why this technology and project are needed to reach net-zero

Biogas and biomethane are both potential solutions to support the fast decarbonization of multiple economic sectors currently using gas for heating, transport and power production. Additionally, biogas and biomethane have synergies with the circular economy and bioeconomy and generate significant numbers of local jobs[14]. Multiple positive impacts are delivered by biogas (including GHG reduction from farming livestock, biodiversity conservation with sequential cropping, and reduced use of chemical fertilizers) which have been valued at €40-70/MWh of biomethane produced[15].

European policymakers took important decisions in favor of biogas in 2019, with the EU Fertilizing Products Regulation published in June 2019 which opened new markets for digestate and bio-based products[16]; the amended Annex V of REACH published in October 2019 exempts digestate from registration[17]. This provides support to the development of the sector, even though essential mechanisms are still missing, such as a robust European system of Guarantees of Origin (GOs) for biomethane.

Although the technology of anaerobic digestion and conversion to biomethane is already deployed at commercial scale, biogas production suffers from industrial value chain issues (such as a scattered market, lack of coordination between stakeholders, and lack of knowledge sharing). In addition, there are technical issues (such as a lack of knowledge on the microbiome, efficiency and reliability issues, etc.). That is why the cost of biomethane is around €95/MWh today, as compared to the average wholesale price for natural gas at €10/MWh at the end of 2019, a record low in Europe. Even pioneer member state, Germany, only delivers less than 1% of its natural gas demand in biomethane. An industrial value chain approach is necessary to standardize installations and processes to significantly increase volumes and reduce costs.

Impacts

	2030	2050
CLIMATE IMPACT	**87.3 MtCO_2e avoided**	**153 MtCO_2e avoided**
ECONOMIC IMPACT	**€35.1 billion total market** €85.4 billion cumulated investment by 2030, €8.5 billion yearly average (2020-2030) €26.6 billion turnover in 2030	**€51.6 billion total market** €149.7 billion cumulated investment by 2050, €5 billion yearly average (2020-2050) €46.6 billion turnover in 2050
JOBS	**527,000 total jobs** 128,000 construction jobs for investment 399,000 production jobs for turnover	**773,000 total jobs** 75,000 construction jobs for investment 698,000 production jobs for turnover

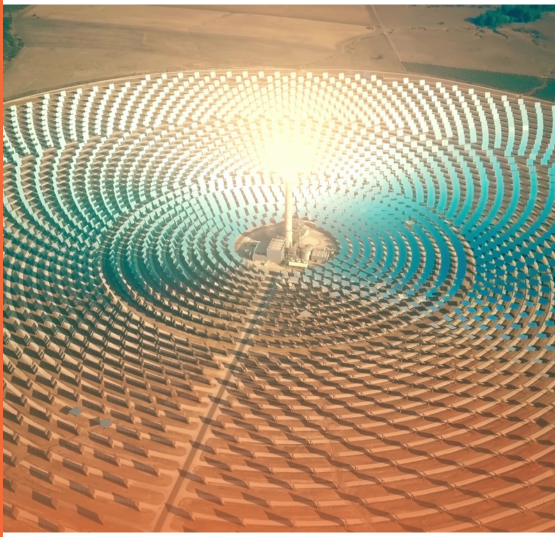
#5 [12] *https://www.sciencedirect.com/science/article/pii/S2211467X19301075*
[13] *thttps://www.mdpi.com/2071-1050/11/22/6515/pdf*
[14] *https://www.ieabioenergy.com/wp-content/uploads/2018/08/anaerobic-digestion_web_END.pdf*
[15] *https://atee.fr/system/files/2019-12/CRE%20Rapport-Gaz%202019.pdf*
[16] *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1009&from=EN*
[17] *https://eur-lex.europa.eu/legal-content/EN/PIN/?uri=uriserv:OJ.L_.2019.259.01.0009.01.ENG*

24/7 AVAILABILITY OF ELECTRICITY FROM COMBINED SOLAR GENERATION, STORAGE AND GRID

Build trans-Mediterranean grid and electricity daytime baseload with Concentrated Solar Power (CSP)

ENERGY

Solved intermittency and availability



IN A NUTSHELL...

- **Issue:** TPV solar plants provide only intermittent power, which is not solved with Li-ion battery storage that only provide one to four hours of storage
- **Solution:** Large scale CSP in EU and North Africa with AC-DC grid, with 15-18 hours storage to provide base production (90-100% load factor) at €50/MWh in 2030
- **Key impacts:** 30 $MtCO_2e$ avoided, €12.3 billion total market, 184,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Concentrated Solar Power (CSP) plants can now provide baseload generation 24/7 when they combine solar fields generating up to three to four times the power of the installed turbine and 14 to 18 hours of storage.

The aim of the project is to leverage solar and land resources around the Mediterranean basin with grid integrations that benefit both the host countries (in terms of investment and jobs) and Europe (in terms of clean power imports and outlets for CSP component manufacturers). Further down the line, these projects can be replicated in Turkey and Algeria.

Build CSP plants by 2030 in Spain, Greece, Cyprus, Southern Italy and Northern Africa.

Combine plants in Southern Morocco and Tunisia with 2,000 km of HV power lines on land and 250 km of subsea HVDC to transport electricity to Southern Europe, via Gibraltar and Southern Sicily. About 65% of the power produced is to be imported to Europe, and 35% is to be consumed locally.

Large volumes will help cut LCOE from €120/MWh in 2019 to less than €50/MWh in 2030 and 25€/MWh in 2050[18]

Main stakeholders include: local utility companies, project developers, and startups innovating in the field of heat storage components (such as ceramics, salt, and sand). Governments also have a key role to play in pushing for solar+storage or specific CSP tenders in Europe.

Projects that inspired this analysis: CSP plant Noor Ouarzazate III in Morocco has 24-hour operating capacity thanks to a 7.5 h molten salt storage (150 MW solar output, 600 MW heat storage), CSP plant Noor Energy 1 in Dubai, 700 MW 15-hour storage, load factor 100%, €75/MWh for CSP.

Why this technology and project are needed to reach net-zero

CSP progress suffered from plummeting costs of solar PV in recent years to reach only 2.4 GW installed capacity in Europe. However, progress in thermal storage and incremental digital improvement for increased yield means this technology remains an interesting choice for Southern Europe and North Africa, where the solar potential is significant. With the world's largest CSP plant coming online in Dubai (by the end of 2020), CSP technology has set new records in terms of installed generation capacity, storage, LCOE, but also business models. Indeed, the 700 MW CSP capacity with 15-hour storage will provide baseload power 24/7 and hit a price of €70/MWh, under a 35-year PPA[19].

IRENA predicts that Europe could install 5 GW capacity in just a few years if supportive policy and investment frameworks are put in place[20]. New CSP and storage technologies (based on ceramics, and sand) reach 1,000°C of heat, far above the current 550°C theoretical limit, and will help open up new markets such as the industrial sector. New technologies can leverage the knowledge acquired so far on CSP, such as the use of molten salt for storage, and start to move away from old, expensive CSP designs to combine with other renewables such as PV and wind, at a lower cost.

Impacts

	2030	2050
CLIMATE IMPACT	**30 $MtCO_2e$ avoided**	**66.4 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€12.3 billion total market** €32.7 billion investment by 2030, €3.3 billion yearly average (2020-2030) €9 billion turnover in 2030	**€17.7 billion total market** €35.9 billion investment by 2050, €1.8 billion yearly average (2030-2050) €15.9 billion turnover in 2050
JOBS	**184,000 total jobs** 49,000 construction jobs for investment 135,000 production jobs for turnover	**266,000 total jobs** 27,000 construction jobs for investment 239,000 production jobs for turnover

#6 [18]*https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf*
[19]*https://www.acwapower.com/en/projects/noor-energy-1/*
[20]*http://helioscsp.com/european-concentrated-solar-power-capacity-to-reach-as-high-as-5-gw-by-2030/*

EXPLOIT ALL EUROPEAN PUMP STORAGE CAPACITY

Retrofit existing hydro-plants for pump storage

ENERGY

Solved intermittency and availability

IN A NUTSHELL...

- **Issue:** Intermittent power generation (PV solar, wind) needs to triple by 2030, creating the need for long term storage (that is greater than 12 h, lasts several days, and is inter-seasonal)
- **Solution:** Retrofit existing hydro-dams for reversible pump-storage
- **Key impacts:** €4.2 billion total market, 63,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

This project targets the development and upscaling of long-term storage capacity, taking advantage of existing pump storage applications and developing new technologies.

Project type 1: Retrofit existing hydropower installations to store and generate an additional 79 TWh/year of electricity

Connecting an existing dam with a newly built reservoir at differing levels of elevation will create a pumped-storage hydroelectricity (PSH) plant. Key features of the retrofit program will be:

- By 2030, multiply by five[21] the PSH output in the EU.
- Involve existing assets to reduce investment costs.
- Conserve unspoiled environments by retrofitting existing installations, even though EU taxonomy considers hydropower to be harmless towards ecosystems[22].

Project type 2: Go beyond the geographic constraints, and massively adopt new forms of hydro storage. Generate 300 TWh/year[23] of output by 2050.

- Traditional PSH potential is capped by geographical constraints.[24] To by-pass this limit, closed-loop PSH can be used. Closed-loop PSH, unlike most existing PSH, does not rely on a natural water flow. For instance, underground PSH, which is a sub-type of closed-loop PSH, relies on an abandoned mine shaft to fill in the role of the lower water reservoir, such as with the ongoing Callio project in Finland.
- Meanwhile, the MAREX project, a seawater storage initiative, relies on a man-made water reservoir (which is not connected to any fresh water stream, making it closed-loop) located near the sea. The project will help integrate a nearby wind power project by storing up to 6 GWh, and is expected to be completed by 2024[25] at a cost of €700 million[26].

Projects that inspired this analysis: MAREX, GIBREX, GIRONES & RAÏMATS, P-PHES NAVALEO, Callio.

Why this technology and project are needed to reach net-zero

Reaching a net-zero emissions economy requires a full[27] penetration of renewable energy in Europe's electricity mix, involving non-dispatchable renewables, such as wind and solar energy.

Electricity grids and networks need to be flexible and smart to guarantee a balance between power generation and consumption. In 2018, 467[28] TWh/year of variable power (wind and solar PV) was generated in the EU28, with pump storage covering below 7%, at 29 TWh/year[29]. By 2030, intermittent power generation is likely to triple and reach 1,300 TWh/year[30].

Hydro pump-storage has two key advantages:

An established track record: hydro storage has been developed for years in conjunction with national power grids, and has proven to be a reliable balance mechanism, technically as well as economically.

Local economy: hydropower sector can rely on existing, strong industrial clusters in Europe. Projects can be launched quickly, benefitting EU companies and delivering local jobs.

Yet traditional hydropower pump storage (with two mountain dams linked together), even at its maximum potential, will not be nearly enough to enable electricity decarbonisation in Europe. Geographical surveys and studies concluded that the current PSH output can doubled, at most.

Closed-loop PSH could fill in the gap once all montainous potential has been used. Furthermore, closed-loop PSH, though less profitable than traditional PSH, is still more profitable than battery storage. Current closed-loop pumped storage requires a €80/kWhcapacity investment[31], while Li-ion batteries requires €140/kWhcapacity[32]. Furthermore, closed-loop facilities have a longer lifetime than the batteries, making the cost per cycle even more competitive.

Impacts

	2030	2050
CLIMATE IMPACT	**Storage is a lever to renewable penetration (no double counting of the decarbonation)**	**Storage is a lever to renewable penetration (no double counting of the decarbonation)**
ECONOMIC IMPACT	**€4.2 billion total market** €42.1 billion investment by 2030, €4.2 billion yearly average (2020-2030)	**€5.1 billion total market** €102.4 billion investment by 2050, €5.1 billion yearly average (2030-2050)
JOBS	**63,000 jobs**	**77,000 jobs**

#7 [21]*JRC for European Commission, page 9 (storage in 2011) and figure 16 (achievable potential of T2 scenario, at 20 km, EU area) https://setis.ec.europa.eu/system/files/Assessment_European_PHS_potential_online_0.pdf*
[22]*Taxonomy: Final report of the Technical Expert Group on Sustainable Finance*
[23]*To be compared with 467 TWh wind and power generation today (ENTSO-E statistical factsheet 2018), multiplied by 5 to 10 in the 2050 scenarios.*
[24]*JRC for European Commission, figure 16 (achievable potential of T2 scenario, at 20 km, EU area) https://setis.ec.europa.eu/system/files/Assessment_European_PHS_potential_online_0.pdf*
[25]*ENTSO-E project sheet : https://tyndp.entsoe.eu/tyndp2018/projects/storage_projects/1030*
[26]*Operator website : http://www.organicpowerinternational.com/glinsk-energy-storage-hub/*
[27]*EC, figure 23, the least ambitious scenario proposes nearly 56% of solar and wind in the electricity mix by 2050. https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf*
[28]*ENTSO-E statistical factsheet 2018*
[29]*JRC for EC, page 9: https://setis.ec.europa.eu/system/files/Assessment_European_PHS_potential_online_0.pdf*
[30]*https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf*
[31]*TYNDP (Ten Year Network Development Plan) of ENTSO-E. Calculated using several pumped hydro projects: MAREX, GIRONES and RAÏMATS, P-PHES NAVALEO, Gibrex*
[32]*Bloomberg*

BUILD COMPETITIVE LEADERSHIP IN ELECTRICITY STORAGE FOR STATIONARY USE

Develop viable short- and long-duration storage alternatives to Li-ion battery

ENERGY

Solved intermittency and availability

IN A NUTSHELL...

- **Issue:** Li-ion represents more than 80%[33] of the battery storage market in Europe. Promising non-Li-ion storage technologies are not scaling up, despite interesting characteristics for grids
- **Solution:** Develop non-Li-ion stationary battery technologies quickly
- **Key impacts:** €3.5 billion cumulated investment, 5,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Batteries are critical for the decarbonization of the transport[34], power, and building[35] sectors. However, Europe is far from the ultra-high performance (technically and economically) required from current battery technologies.

Regarding stationary uses, although Li-ion battery technology is being developed on a massive scale by the automotive sector, Li-ion might not be the go-to choice for stationary storage for environmental and economic reasons. Many technologies aside from Li-ion are competing to fill this need, including:

- Organic: quinone electrolyte, graphene electrodes
- Flow batteries: vanadium, zinc-bromide
- Zinc-air batteries.

Project: €1.7 billion innovation program for 1-100 MW storage plants, providing 1-12 hours of short to medium duration storage, via 40 tenders

Launch 40+ tenders for new battery technologies to seed European industrial innovation clusters, using contracts for difference on output where relevant:

- 40 tenders, €1.7 billion upscaling budget.
- Conclude tenders before 2025 to facilitate commissioning of project life and enable upscale before 2030.
- Program based on 1 to 100 MW power output, with 1 to 12 hours of storage, and an average 300 MWh capacity.
- Budget around €140/kWh of storage capacity initially with a target to reach €50/kWh in 2030.
- Tender for grid storage as well as behind-the-meter installations, linking with renewable tenders where efficient.
- Technology-neutral tenders, excluding Li-ion.

Why this technology and project are needed to reach net-zero

Reaching a net-zero emissions economy requires a full[36] penetration of renewable energy in Europe's electricity mix, involving non-dispatchable renewables, such as wind and solar energy.

Electricity grids and networks need to be flexible and smart to guarantee balance between generation and consumption. In 2018, 467[37] TWh/year of variable power (wind and solar PV) was generated in the EU28, covering about 15% of electricty demand. By 2030, intermittent power generation is likely to triple and reach 1,300 TWh/year[38].

Scaling up storage and system services (frequency and flexibility) is critical for Europe's net-zero emissions future. Batteries provide aforementioned services, and have the following two advantages, compared to other technologies:

- Battery system services can be activated faster than mechanical devices (such as pumped hydro).
- Battery scalability allows for decentralized use, including behind the meter (where power is generated or consumed).

Tenders to foster alternative chemistry innovation can develop European alternatives to Li-ion to prepare for 2030 renewable electricity markets and meet the net-zero emissions 2050 target. The tender design should include a technology roadmap that targets the delivery of a €50/kWh cost by 2030, from today's Li-ion costs of €140/kWh[39].

For reference, in 2019, 1 GWh[40] of utility scale battery storage capacity was commissioned in Europe. The tenders proposed previously implies 12 times (12 GWh of capacity) this amount, spread across several years.

Impacts

	2030	2050
CLIMATE IMPACT	**Storage is an enabler that does not directly cut significant emissions.**	**Storage is an enabler that does not directly cut significant emissions.**
ECONOMIC IMPACT	**400 million total market** €3.5 billion investment, €350 million yearly average (2020-2030)	**€1.9 billion total market** €38 billion investment, €1.9 billion yearly average (2030-2050)
JOBS	**5,000 jobs**	**29,000 jobs**

#8 [33]IRENA, figure 1, « UTILITY-SCALE BATTERIES: INNOVATION LANDSCAPE BRIEF »
[34]See project #45 (batteries for transport)
[35]See project #32 (disruptive buildings with renewables and electrical and thermal storage)
[36]EC, figure 23, the least ambitious scenario proposes nearly 56% of solar and wind in the electricity mix by 2050. https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf
[37]ENTSO-E statistical factsheet 2018
[38]https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf
[39]Bloomberg
[40]European Market Monitor for Energy Storage (EMMES). 1.4 GWh in 2018.

DIGITAL EVERYWHERE AT CUSTOMER, PRODUCTION AND GRID LEVELS TO SMARTLY SOLVE AVAILABILITY AND INTERMITTENCY

Flexibility along the whole smart energy value chain across Europe at all spatial and temporal scales

ENERGY

Solved intermittency and availability

IN A NUTSHELL...

- **Issue:** In the past, energy flexibility and availability were provided by the large share of dispatchable fossil production. In the future, the availability of energy and stability will be challenged by additional uses of electricity and the intermittency of renewable energy
- **Solution:** Improve system flexibility with smart solutions at all space and time scales. Develop digital solutions combined with demand response, storage, dispatchable decarbonized production and smart operation of grids
- **Key impacts:** €31 billion total market, 466,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Flexibility and smart energy developments are needed to solve energy intermittency and availability issues at all space scales (such as customer, building, district, city, region, country, and pan-European scales), and in different temporal windows, including by second, hour, day, intraday, weekly and seasonal. Digital is a key component in all the smart market segments detailed below. The digital chain includes the deployment of sensors and actuators, edge computing, local and wide area communication, control command applications and platforms, analytics and AI solutions, data business and operating models.

Projects aiming at enhancing energy availability and flexibility should articulate one or several of the following technology and market segments:

- Smart homes and smart building at renovation or newbuild scale. Involved technologies include smart appliances, monitoring, control and automation of storage, loads and decentralized energy resources (DER), energy management system (EMS), building management system (BMS), HAN gateway, meters, communication infrastructure.
- Smart districts, Smart cities. Involved technologies will articulate the hypervision of services (such as waste, cleaning, lighting, mobility, energy, etc.) to the citizen with the requirements of energy availability and flexibility through smart management of the demand and of the service infrastructures and offers.
- Smart mobility. Involved technologies include the management of EV charging infrastructure, of charging hourly demand, of alternative shared and public mobilities (i.e. demand response).
- Smart renewable power plants. Technologies combine digital infrastructure and energy storage in so-called Virtual Power Plant (VPP).
- Smart system management at national and regional levels (transmission and distribution networks). This technology quest focuses on smart and flexible system management, while the next technology quest #10 will focus on grid equipment and mileage. Smart system management technologies include aggregation services and virtualizing both demand and power generation, operations performance of smart grids, smart metering, technical and non-technical leakage control, EMS, WAMS, front-end communication, SCADA, DMS, AMI head end, CMS, DRMS, balance scheduling and grid planning intelligence, prosumer (both consuming and generating energy) information system and customer portals, and billing of innovative tariffs schemes.
- Main stakeholders include public authorities, energy regulators, TSOs, utilities, citizens' associations, and project developers.

The smart projects will include but will not be restricted to electricity. In the past, waste of energy has been important due to the separate vertical management of the energy carrier's production, storage and usage. Symbiosis is increasingly required between electricity, thermal and gas worlds at each level. It will be even more necessary with the uptake of new carriers such as hydrogen, e-gas and e-liquids.

Projects that inspired this analysis: European Commission's initiative BRIDGE (portfolio of smart grids and energy storage projects), Equigy Project (collaboration of European TSOs on flexibility platforms), INTERFLEX project (use of local flexibilities to relieve distribution grid constraints and increase share of renewables), FlexCoop (demand response for energy cooperatives), INVADE (flexibility management platform for e-vehicles and batteries).

Why this technology and project are needed to reach net-zero

The deployment of smart solutions can help to make distribution grids more flexible, to cope with more frequency variations and to reduce imbalances between supply and demand. They can enable active consumers and energy communities, supporting their participation in the energy markets. All segments of the power industry are affected by these changes. In Europe, investments remained stable at nearly USD 50 billion[41], with rising expenditures allocated to upgrading and refurbishing the existing grid as variable renewables and electrification become more important. Additionally, there are around 1,000 R&D and demonstration projects totaling around EUR 5 billion of investment, out of which 80% are invested in smart network management, demand-side management and integration of distributed generation and storage[42].

Solutions include implementing interconnectors, measuring energy flows in real-time, integrating renewable energy and new forms of consumption (such as electric vehicles) and managing efficiently energy storage, with the help of digital and automated tools. From this, flexibility should emerge both on a spatial scale (taking the form of a smart building or a smart city, for instance) and a temporal scale (from second and intra-hour generation prediction to inter-seasonal scale).

The Equigy Project for instance, launched in April 2020, gathers several European transmission system operators to develop an energy flexibility platform in order to better integrate variable renewable energy generation and mitigate the resulting fluctuations of supply and demand. This innovative digital infrastructure is already being deployed in four countries: the Netherlands, Germany, Italy and Switzerland. More broadly, the BRIDGE Initiative, created by the European Commission in 2014, is an investment avenue with a total budget of €484 million dedicated to various energy flexibility projects, involving over 500 companies.

Impacts

	2030	2050
CLIMATE IMPACT	**Grids are considered enablers not directly cutting a considerable level of emissions.**	**Grids are considered enablers not directly cutting a considerable level of emissions.**
ECONOMIC IMPACT	**€31 billion turnover**	**€43.5 billion turnover**
JOBS	**466,000 jobs**	**652,000 jobs**

#9 *[41]https://www.iea.org/reports/smart-grids*
[42]https://ses.jrc.ec.europa.eu/

REINFORCE ELECTRIC GRIDS FOR 100% RENEWABLE POWER

Develop grids, HVDC, storage and innovative technologies to build a robust grid for all Europe

ENERGY

Optimize and redesign grids

IN A NUTSHELL...

- **Issue:** New and future electricity flows, offer and demand balancing and the management of power quality will challenge the existing grid, due to massive electrification, hydrogen and renewable generation uptake
- **Solution:** Develop new grids and reinforce existing grids based on new production and consumption flows. Conventional and HVDC lines can help increase grid reliability, renewables integration and jobs creation. Underground cabling needs to be considered
- **Key impacts:** €16.6 billion total market, 250,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Project type 1: Refurbish and extend the existing grids for EHV and bidirectional energy flows

Invest in refurbishing and extending the existing power grid to adapt it for increased variable energy flows. Invest in new electricity routes in the production zones are changing; there is a higher demand for electricity due to new uses linked to green hydrogen and electrification. Grids must support the evolution of the future electricity consumption profile both in TWh and load factors.

Reinforcing the grid's concern lines, stations and substations including switch breakers, transformers, capacitors, reactors, reclosers, meters and their control-command systems is required.

Project type 2: Develop and upscale use of new grid technologies

- Key and innovative technologies that have the potential to transform power delivery include:
- High and medium voltage equipment (FACTS, PMU, RTU),
- HVDC,
- Ultra-high voltage transmission,
- Superconductivity.

Scaled up investments in new technologies need to be implemented in Europe by 2030 and 2050 in order to prepare electric grids to the next level of requirements regarding the growing quantity of intermittent power.

Main stakeholders: TSOs, ENTSO-E, cable industry players and associations (such as Europacable), regulators, project developers, utilities, and citizens associations.

Clusters: Large European companies such as Siemens, ABB, Schneider and large TSOs drive this market, rather than local clusters.

Projects that inspired this analysis: Various advanced projects at EU level already identified as Projects of Common Interest are key for renewables integration, grid stability, resilience, and flexibility. They should be supported to avoid delays, especially in the North Sea region and other national corridors.

Why this technology and project are needed to reach net-zero

In 2020, Europe had 1,000 GW of production assets connected by 300,000 km of transmission lines and 10,000,000 km of distribution lines, the latest being served by 240,000 direct employees[43]. According to the ENTSO-E-G Ten Years Network Development Plan (TYNDP), the grid will have to connect 1,400 GW production by 2030 and 1,800 GW by 2050[44].

A significantly adapted network infrastructure is required to decarbonize EU's electricity. High-voltage direct current (HVDC) is an increasingly important method for transferring large amounts of electrical power for the pan-European transmission grid, but the deployment of meshed HVDC offshore grids is currently being hindered by the high cost of converter technology, lack of experience with protection systems and fault clearance components and immature international regulations and financial instruments.
As described in the EU Governance Regulation of the Clean Energy Package, member states must reach 15% interconnection by 2030. Grid expansion lags renewable power development in various countries. A major hurdle for infrastructure projects is the permitting process. Although there were some simplifications to accelerate grid expansion on a federal level, these simplifications must be adopted at the local level, but local processes are not always updated promptly. Additionally, local resistance complicates the permitting process which translates into delays in grid expansion projects.

Further, electrical power transmission with lower losses is critical to the success of renewables. This is illustrated by the fact that solar power insolation factors range from 9% to 18% across the EU. If 10% of annual renewable generation projects were to relocate to a better location, it would increase global output by 5%.

Impacts

	2030	2050
CLIMATE IMPACT	**See opposite column**	**Grids are enablers in the decarbonization of the power production mix. No additional CO_2 emission reductions are realized beyond reducing emissions from power generation.**
ECONOMIC IMPACT	**€16.6 billion total market** €166.4 billion investment by 2030, €16.6 billion yearly average (2020-2030)	**€8.3 billion total market** €249 billion investment by 2050, €8.3 billion yearly average (2020-2050)
JOBS	**250,000 jobs**	**125,000 jobs**

#10 [43]*https://www3.eurelectric.org/powerdistributionineurope/*
[44]*https://tyndp.entsoe.eu/tyndp2018/*

TRANSFORM GAS GRIDS INTO A NEW MULTI-FOCUSED RESOURCE

Repurpose Europe's gas grids for biomethane, H_2, and CO_2 and focus them on industry needs and dense urban areas

ENERGY | Optimize and redesign grids

IN A NUTSHELL...

- **Issue:** The share of conventional fossil gases will shrink with decarbonization, electrification and greater use efficiency. In parallel, hydrogen, CO_2, biomethane and e-gas will need to be transported
- **Solution:** Retrofit existing natural gas grids to transport H_2 and CO_2 and develop new-built H_2 and CO_2 networks, starting from industrial clusters. In dense areas, adapt natural gas grids to green gas requirements. In less dense areas, decommission gas grids to concentrate green gas availability in dense areas
- **Key impacts:** €31.2 billion cumulated investment and 47,000 jobs in 2030

Innovation bet | **Acceleration and scale-up** | Drive to market scale

Project opportunity and ambition

An innovative EU next-gen PV program would rely on two Reshape Europe's gas network infrastructures to fit the H_2 CCUS and synthetic fuels projects by 2030 and beyond. Before 2030, start focusing on industrial clusters, key ports and key interconnections needed by the hydrogen and CO_2 circular economy. In Europe, there are 30 integrated steel plants with blast furnaces, 250 cement plants, 80 refineries, and 50 fertilizer plants[45]. These installations are often gathered in industrial clusters and are well connected to motorway, water and rail corridors. Ten major port areas handle over 100 mt of annual goods, gather concentrations of the above industrial sites and are starting and ending points to the freight corridors, typically Rotterdam, Amsterdam, Antwerp, Hamburg, Bremerhaven, Marseille-Fos, Le Havre, Sines, Valencia, Genova, and Trieste.

Project type 1: Develop 2,000 km of CO_2 grids

CO_2 grids are needed inside industrial clusters or ports to connect sites capturing CO_2 (steel, cement, refineries) with sites reusing CO_2 to generate liquid e-fuels, e-gas and possibly with inland or submarine sequestration sites: 1,000 km of new grids and 1,000 km of converted methane grids in main industrial clusters and ports by 2030. This enables 100-200 km grid for a few large international port areas, 10-100 km in several inland industrial clusters, one or two inter-regional and submarine connections.

Project type 2: Develop 10,000 km of H_2 grids by 2030

The development of H_2 grids should focus on helping to massify hydrogen production and to quickly lower costs. Start with connecting large renewable plant areas with onsite hydrogen generation (offshore wind in North Sea, wind in Eastern Europe, solar PV in Southern Europe) to consumption areas. Connect consumer industries such as cement, steel, refineries, e-fuel plants in a few important ports and industrial areas. Before 2030, there could be:

- 5,000 km new onshore and offshore H_2 grids.
- 5,000 km switch of existing gas grids to H_2.

Project type 3: Transform and better allocate gas grid purposes (reverse, H_2, focusing on denser areas)

- Focus available green gas (biomethane, H_2) in urban areas and industrial clusters.
- Decommission gas grids in the lower density areas.
- By 2030 transform 700,000 km of grids to smarter grid: reverse compression between pressure levels to ease biomethane and H_2 injection, manage variable energy content, intraday demand response and storage.

Why this technology and project are needed to reach net-zero

Several types of European gas grids exist today:

- Gas (methane) grids: 4,800 TWh consumed yearly today. 250,000 km of transport grids and 2,000,000 km of distribution grids[46]. Reducing natural gas consumption in Europe is a requirement in all net-zero scenarios, even in 'transition countries' after 2030, once they have moved away from coal with an intermediary step relying on gas. Greening the gas content is possible with biomethane of a maximum potential of 800 TWh, with hydrogen.
- Hydrogen grids: 1,500 kilometers exist in Northern Europe (BE, NL, GE, FR) between industrial clusters[47]
- The CO_2 grids were estimated to be 1,300 km long in Europe[48] (mostly UK, NO, some in NL, DE, FR).

In the future, a big transformation of gas grids will reshape their usage:

- Gas grids transport ten times more energy than power grids for the same investment cost per kilometer. Hence, it will become more cost-competitive to transport hydrogen rather than electricity, both on short and longer distances (submarine, mainland).
- Residential and commercial buildings will need less energy and no gas at all in low-density areas (heating pumps, solar roof, biomass, etc.).
- Hydrogen will become a key energy carrier. The required amount of renewable power capacity is at least twice the GW capacity of electrolyzers producing the hydrogen. Production and use are not necessarily neighbors, although more widespread H_2 use will change this.
- Hydrogen grids will be needed to transport the hydrogen produced by mega-scale plants (50-200 MW) or giga-scale plants (1-3 GW) to industries for their own processes or to plants synthetizing e-liquid fuels.
- Carbon captured from industrial clusters and large ports will be transported to plants that will produce C-liquid fuels. In 2050, the 1.5Tech scenario plans a production of 45 MToe of e-gas and 41 MToe of e-fuel, needing 270 Mt of CO_2 coming from direct air capture and from industrial processes.

Impacts

	2030	2050
CLIMATE IMPACT	**See opposite column**	**Gas grids are enablers of the gas energy transitions (Biomethane, Power to H_2 to X, CCS). No additional CO_2 savings.**
ECONOMIC IMPACT	**€3.1 billion total market** €31.2 billion investment by 2030, €3.1 billion yearly average (2020-2030)	**€5 billion total market** €151.4 billion investment by 2050, €5 billion yearly average (2020-2050)
JOBS	**47,000 jobs**	**76,000 total jobs**

#11 [45]Capgemini analysis based on maps published by the corresponding European business associations. Rounded figures.
[46]Capgemini analysis based on ENTSO-G, CEER and MARCOGAZ sources. Rounded figures.
[47]Shell hydrogen study, 2017 (BE 613 km, GE 376 km, FR 303 km, NL 237 km)
[48]https://ieaghg.org/docs/General_Docs/Reports/2013-18.pdf

MASSIVELY DEPLOY HEATING AND COOLING NETWORKS TO REDUCE FOSSIL FUEL DEPENDENCY IN EUROPEAN CITIES AND HELP OPTIMIZE ELECTRIC GRIDS

District Heating and Cooling (DHC) can leverage thermal storage, thermal efficiency and energy sourced from geothermal, renewables and waste to help improve air quality, reduce noise and curtail heat islands

ENERGY

Optimize and redesign grids

IN A NUTSHELL...

- **Issue:** Heat is a major part of European energy needs. It is mostly produced from fossil fuels, as are most existing district heating networks. Individual air conditioning for commercial and residential sectors is growing quickly and placing stress on the grid
- **Solution:** Shift existing industrial and DHC networks to decarbonized energy (geothermal energy, biomass, waste). Create new decarbonized DHC networks
- **Key impacts:** 197.4 $MtCO_2e$, €8.9 billion total market, 133,000 jobs in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

Project type 1: Shift existing fossil heating networks to geothermal energy

The project goal is to convert 300 DHC systems with existing coal, gas or fuel heating networks to geothermal energy by 2030, and 600 by 2050.

- Lead surface exploration campaigns in cities or industry platforms across Europe by 2023 (currently using gas, oil or coal), use the best subsoil know-how from the oil industry. Launch tenders for drilling operations, with decreasing costs for increasing volumes (as in Mexico).
- At the surface level, upgrade the existing heating networks with up-to-date 4.0 smart grid control and command, and customer metering.
- A dedicated Georisk fund will secure private financing for the exploration. The public guarantee against the risk of not finding resources lowers financial fees. Each public euro invested in the guarantee fund generates €10-€20 of final investment.
- Main stakeholders include city authorities, energy service and subsoil companies, utilities, developers, and georisk funds.

Projects that inspired this analysis: HeatNet NWE, REWARDHeat, Sinfonia, Guarantee funds across the EU.

Project type 2: Create new decarbonized district heating or cooling networks

The project goal is to launch 2,100 DHC networks by 2030 in the locations identified in project type 1, and 5,600 by 2050 (30% market share).

- Networks may be deployed where relevant, leveraging 4th-generation DHC (4DHC) experimented through the HeatNet project and on 5DHC currently tested in the REWARDHeat project. Northern countries will focus on district heating networks (preferring geothermal heating pumps), while southern countries (such as Greece, Italy and Spain) will deploy cooling networks.
- Projects must be implemented at European or national levels, but they must be managed at a local level.
- Studies must be launched as soon as possible, as the study and the operational phase will require time.
- Occasionaly, geothermal/climatic profiles are identified to classify project locations, in order to encourage European cities in similar situations to share key learnings.
- Authorizations will be required for regulatory purposes.
- Main stakeholders include city authorities, energy service and subsoil companies, utilities developers.

Projects that inspired this analysis: HeatNet NWE, REWARDHeat, Sinfonia, Vienna Viertel Zwei, Flexynets, STORM.

Why this technology and project are needed to reach net-zero

DHC networks are a way to introduce massively decarbonized heat from sources like biomass, geothermal energy, heat pumps, and waste energy. A cooling network in parallel, based on absorption or large-scale heating pumps, can generate heat that is either recycled for district heating networks or stored in the subsoil for later usage, greatly increasing the global efficiency.

Heating and cooling in buildings and industry represents over 50% of the final energy demand in the EU[50], and relies mainly on fossil fuels, which put at risk both European energy independence and climate goals. There are today around 5,000 district networks providing 10% of European heating needs (556 TWh[51]), and up to 25-50% in Eastern and Nordic countries. These heating networks are still fueled at 65% with coal, gas and oil.

Using fossil fuels for individual heating in cities is a major source of air pollution and microparticles. Plus, coal-based heating networks are highly emissive, often old, and typically found in industry platforms or in Central and Eastern European cities. Additionally, the need for cooling increases with climate change, and individual cooling systems contribute to peaks of power demand, expensive additional investments in power grids, noise, heat islanding, metallic waste from appliances, high refrigerant leakage and a lower overall performance than in a centralized system.

Deep geothermal networks represent a complementary solution for heating and cooling, reducing emissions, air pollution, small particles, noise, power peaks, needs for more grid investment as well as heat islanding. Additionally, the geothermal potential for new networks or the retrofit of existing ones is very high: areas with geothermal district heating potential already constitute 25% of the EU population[52].

Fourth-generation district heating networks with ultralow temperature water loops and decentralised heating pumps — together with geothermal or waste sources — are solutions for net-zero buildings and are already widespread in new districts.

Impacts

	2030	2050
CLIMATE IMPACT	**Project type 1 (existing): 4.9 $MtCO_2e$ avoided** **Project type 2 (new): 192.6 $MtCO_2e$ avoided**	**Project type 1 (existing): 9.7 $MtCO_2e$ avoided** **Project type 2 (new): 288.9 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**Project type 1 (existing): €600 million total market** €6 billion cumulated investment by 2030, €0.6 billion yearly average (2020-2030) **Project type 1 (existing): €0.6 billion total market** €6 billion cumulated investment by 2030, €0.6 billion yearly average (2020-2030)	**Project type 1 (existing): €0.4 billion total market** €12 billion cumulated investment by 2050, €0.4 billion yearly average (2020-2050) **Project type 1 (existing): €0.4 billion total market** €12 billion cumulated investment by 2050, €0.4 billion yearly average (2020-2050)
JOBS	**Project type 1 (existing): 9,000 total jobs** **Project type 2 (new): 124,000 total jobs**	**Project type 1 (existing): 6,000 total jobs** **Project type 2 (new): 112,000 total jobs**

#12 [49]Based on mechanisms set by the Georisk project: https://www.georisk-project.eu/
[50]https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en?redir=1
[51]https://www.euroheat.org/wp-content/uploads/2016/03/DHC-Vision-for-DHC-2012.pdf
[52]https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/geodh_final_publishable_results_oriented_report.pdf
[53]http://www.afpg.asso.fr/wp-content/uploads/2019/08/APFG_GUIDE_BoucleEau_05082019.pdf

COST-EFFECTIVE AND ENERGY EFFICIENT CO_2 AIR CAPTURE AT SCALE

Direct Air Capture to simplify and ease the energy transition challenge

ENERGY

IN A NUTSHELL...

- **Issue:** Direct air capture is essential in all net-zero and 1.5 TECH scenarios, but strong challenges remain, such as caustic material use, high energy intensity and cost
- **Solution:** Direct air capture pilot plants to improve the technology, business models and reduce costs
- **Key impacts:** €20 million total market in 2030

Innovation bet

Acceleration and scale-up

Drive to market scale

Project opportunity and ambition

- Set up ten direct air capture plants of 2,400 tCO_2 annual capture capacity, associated with renewable power generation and waste heat generation to supply low-carbon energy.
- The aim of the project is to foster technology improvements to reduce the negative impact of such technology and drive down costs, to prepare for future needs in sectors where emissions are impossible to abate and where direct carbon removal will ease the energy transition.
- All ten plants should be built in areas with potential offtakers for the captured CO_2 to make projects more profitable:
  - Seven plants should be built in the Netherlands and Northern Germany to lever the presence of industrial players, especially refineries. As the Rotterdam area sets to become a major hydrogen industrial cluster with synthetic fuel producers, demand for CO_2 will rise significantly.
  - Three plants should be built in Spain in order to leverage cheap solar energy and make use of large amounts of curtailment. The large concentration of greenhouse gases produced in crop culture necessitate a rapid and efficient roll-out of CO_2 capture.
- Such projects will be developed in partnership with:
  - Industrial offtakers (such as farming, oil, and chemical companies) in order to create commercial outlets and create industrial synergies. For instance, the heat needed for the DAC process could be recovered from waste heat of industrial stakeholders/power plants nearby.
  - Renewable energy developers.
  - R&D labs should be involved to follow the impact and support incremental improvements, particularly to reduce energy intensity.

Projects that inspired this analysis: Climeworks created modular CO_2 collectors that can be stacked to build machines of any size, aiming at industrialization of construction with larger volumes. Their Zurich plant captures CO_2 used to grow crops in a greenhouse nearby. Ultimately the company aims at selling that service as an offset by burying CO_2 underground. The energy used is produced by solar and heat from municipal waste incinerators on which the CO_2 collectors sit. The plant costs between €2.5 and €3.5 million, and uses 2.5 MWh of heat and 0.5 MWh of power per ton of CO_2 as it captures 900 tCO_2 per annum.

Why this technology and project are needed to reach net-zero

Most IPCC scenario modelling 1.5°C paths include a share of carbon dioxide removal, and the two European Commission scenarios reaching net-zero target by 2050 show extensive use of carbon dioxide removal (CDR), including Direct Air Capture technologies (DAC) from 2050. The 1.5Tech scenario plans 266 $MtCO_2$ capture and 200 $MtCO_2$ of direct air capture. While technologies like BECCS are preferred due to their ability to provide negative emissions, they also have side effects such as impact on air quality and need for large biomass resources. Thus, a mix of various technologies may prove useful.

Several low- and high-temperature DAC technologies are under investigation, launched by half a dozen companies in the world, with a few pilots and commercial examples in operation. Several challenges remain for a large-scale deployment of this technology:

- The current scale of operations does not offer fixed technological costs. The IEA[54] estimates the cost to be within a wide range of $100-$1000 per captured ton of CO_2. Players such as Climeworks-Antecy, Global Thermostat, Carbon Engineering claim to be able to decrease the cost within a €50-€100 range per tCO_2 by 2030.
- The process is highly energy-intensive (for both electricity and heat): 0.14-0.22 Mtoe/$MtCO_2$ extracted[55] , e.g. a middle value of 2 TWh per $MtCO_2$ captured according to the IEA.
- A review of the low-temperature (LT) and high-temperature (HT) processes led in 2018 by the LUT University[56] estimates the need in energy to 1.5 TWh of electricity for HT process and 0.25 TWhel plus 1.75 TWhth for the LT process. Heat can be provided by low-grade waste energy.
- In all cases the LUT study foresees a better competitiveness for LT process, which costs in favorable conditions as in Morocco could lower down to €60-€100 per tCO_2 range and €20-€50 per tCO_2 in 2050. The higher figure represents the cost if the heat must be paid for, the lower figure if free waste heat is reused.

Impacts

	2030	2050
CLIMATE IMPACT	**0.02 $MtCO_2e$ avoided**	**160.4 $MtCO_2e$ avoided**
ECONOMIC IMPACT	**€20 million total market** €80 million investment by 2030, €8 million yearly average (2020-2030) €10 million turnover in 2030	**€8.3 billion total market** €53.5 billion investment by 2050, €1.8 billion yearly average (2020-2050) €6.5 billion turnover in 2050
JOBS	**300 total jobs** 100 construction jobs for investment 200 production jobs for turnover	**124,000 total jobs** 27,000 construction jobs for investment 97,000 production jobs for turnover

#13 [54]*https://www.iea.org/reports/direct-air-capture*

[55]*Ibidem.*

[56]*Techno-economic assessment of CO_2 direct air capture plants, Mahdi Fasihi, Olga Efimova, Christian Breyer, LUT university, 2018*