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ELEGANCY – ENABLING A LOW-CARBON ECONOMY VIA HYDROGEN AND CCS

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Abstract

ELEGANCY was an ERA-Net Cofund ACT project with the aim to help fast-tracking the decarbonization of Europe's energy system via hydrogen and CCS. This has been achieved by overcoming or highlighting specific scientific, technological and economic/legal barriers and by undertaking five national case studies adapted to the conditions in the partner countries Germany, the Netherlands, Norway, Switzerland and the UK. ELEGANCY had 22 partners from industry and academia/research. This paper gives a brief overview of the project and some main results.

Keywords: CO_2 capture and storage (CCS), hydrogen, full chain

1. Introduction

The low-carbon economy needs CO_2 capture and storage (CCS), as a key technology to mitigate CO_2 emissions [21], including emissions from industrial processes that would otherwise be difficult to abate [43]. The low-carbon economy also needs hydrogen (H_2) as a low-carbon energy vector – depending on how it is produced.

The main idea behind the ELEGANCY project [4] was that combining CCS and H_2 could give a double benefit. Large amounts of clean H_2 can be produced from natural gas (NG) with CCS, thus providing the decarbonization of power, heating and transport based on an existing fuel and infrastructure. This would also provide a commercial model for industrial CCS, and it would build necessary bridges towards a system increasingly based on hydrogen produced from renewable sources.

2. Project overview

ELEGANCY R&D provides solutions to key technical challenges for H_2-CCS chains (Figure 1) – on both a systems and component level. This includes CO_2 transport, injection and storage, as well as H_2-CO_2 separation – directly increasing the TRL of selected components to 5 where large-scale demonstration is possible. The research generated and analysed new experimental data from world-class research infrastructure, such as ECCSEL and EPOS facilities. To enable application of this research, ELEGANCY developed an innovative, open-source design tool for a fully integrated H_2-CCS chain. Finally, taking a fully integrated approach, the project studied business development opportunities, public perceptions of H_2 and CCS, and environmental aspects of H_2-CCS chains. All the research findings and tools were applied to five national case studied, each designed to account for the specific and conditions and preferences in each of the participating countries. The ELEGANCY case studies are described in more detail in Refs. [25, 26]. The work breakdown structure and technical topics included in the project are further described in Figure 2.

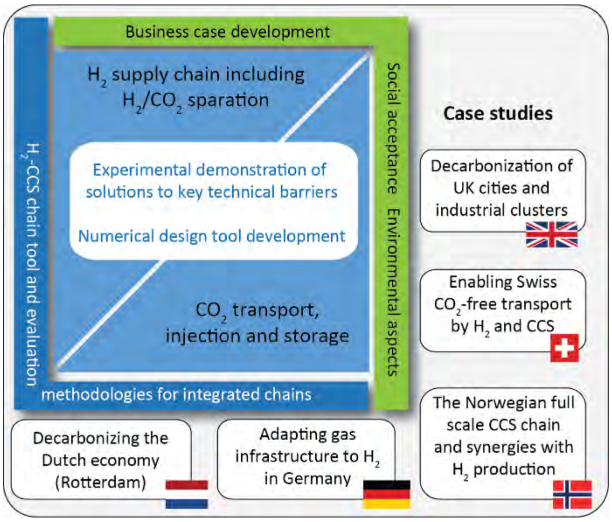

Figure 1: Overview of ELEGANCY research.

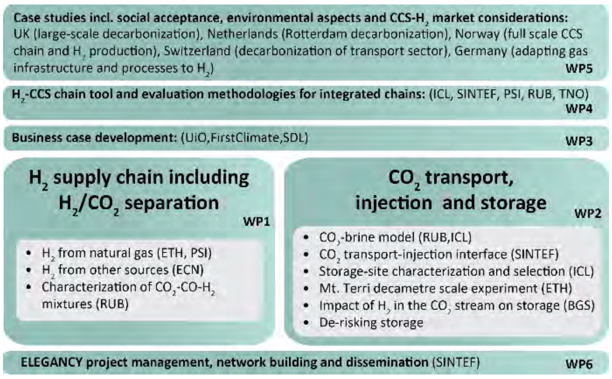

Figure 2: ELEGANCY work breakdown structure.

3. Activities and results

This section briefly summarizes the technical results achieved in the ELEGANCY work packages (Figure 2). For the cases where the results have been published at the time of writing, those publications are cited.

3.1 WP1 – H_2 supply chain and H_2-CO_2 separation

WP1 aimed to enable the production of large volumes of low-carbon H_2 at the scales of interest. To this end, WP1

- Enabled efficient H_2 production and CO_2 capture at different plant sizes.
- Found ways to increase the efficiency and productivity of natural gas/biogas reforming and CO_2/H_2 separation independently of the plant size.
- Integrated H_2 production and CO_2 capture with significant industrial processes such as steel production.
- Characterized the properties of H_2 mixed with CO_2, CO, and CH_4.

The research spanned the range from the phenomenon level (RUB) via lab-scale experiments (ETH and TNO) to the pre-pilot scale (TNO).

Task 1.1: H_2 production with ambient temperature-based technologies PSA/VPSA (ETH, UU)

The primary objective of the work was the development of vacuum pressure swing adsorption technology (VPSA) for the single cycle co-purification of H_2 and CO_2. This was first done in silico and for a generic gas stream [31]. The developed VPSA cycle was then applied to relevant syngases from steam reforming and autothermal reforming of natural gas [32]. The cycle was also used for the modelling and optimization of different H_2 production pathways starting form natural gas or biogas comparing the state-of-the-art technology combination for H_2 purification and CO_2 capture with VPSA [6]. In the first part of the project, we focused on VPSA cycles using existing commercial sorbents. We then evaluated novel materials for VPSA through experimental characterization [8, 33] and modelling and optimization of VPSA process performance. Finally, the new cycle was demonstrated in the ETH inhouse pilot plant: we designed, refurbished, and updated the automation of the lab-pilot and undertook breakthrough and full-cycle experiments, showcasing that the cycle works satisfactorily in practice, bringing the technology to TRL 5.

Task 1.2 H_2 production with enhanced adsorption-based technologies – SEWGS (TNO, SWERIM)

In previous projects, sorption-enhanced water-gas shift (SEWGS) has shown excellent performance under industrial gas loads such as blast furnace gas from steel mills. In ELEGANCY, SEWGS technology was prepared for demonstration as a feasible CO_2 capture technology for another high-volume steel-mill gas, namely basic oxygen furnace (BOF) gas. To produce a H_2-rich gas stream from BOF gas with SEWGS, the following was achieved:

- The catalytic testing of commercial high-temperature water-gas shift (HTWGS) catalyst with BOF gas was finalized. Results and implications have been discussed with the catalyst vendor. The versatility of the (JM) Katalco™ 71-6 WGS catalyst has been demonstrated in long-term experiments, with only 4–5% conversion loss over 1000 hours. This shows that the JM WGS catalyst can be used under the various conditions encountered with steel gases.
- Based on an extensive experimental and modelling campaign it is shown that the SEWGS process can be adapted for operation under the extreme conditions produced by the BOF gas. The experimental and modelling results conclude that large-scale operation is technically feasible with the aid of a split-flow WGS section that also helps minimize S/CO ratios. As expected, the carbon capture rate is robust to switching from blast furnace gas (BFG) to BOF.
- Cycle design and optimization for BOF gas was extensively studied. The highest productivity, at targeted carbon-capture rate (CCR) and carbon purity (CP) was achieved for SEWGS section operating at 35 bar. Obtained CCR was 96%, CP was 98%. To achieve this, two trains with 8 columns in each train is required.
- Analysis on engineering and costing of multi-column SEWGS at the SWERIM site in Luleå has been reported.
- The ELEGANCY results on SEWGS with BOF gas has resulted in the follow up INITIATE (H2020) project (November 2020 – November 2024) to further the development of SEWGS with BOF gas (for the production of Urea) in a real industrial setting at TRL7.

Task 1.3 System integration and optimization (ETH, UU)

Task 1.3 involved the integration and optimization of CO_2-capture technology into H_2-production systems (from natural gas as well as biogenic sources). First, an inventory was made of state-of-the-Art H_2 production technology with CCS [7]. In addition, a techno-economic assessment framework was established and used in conjunction with the chain-tool (Sec. 3.4). Based on this work, an integrated techno-environmental assessment study of hydrogen production from natural gas and biogenic sources, combined with CCS was undertaken, identifying optimal plant-wide configurations from both technical and environmental perspective [14]. The technologies analysed are steam-methane reforming (SMR), autothermal reforming (ATR) and biomass gasification for syngas production. CO_2 capture from the syngas was included, using the novel vacuum pressure swing adsorption (VPSA) process developed in Task 1.1, that combines hydrogen purification and CO_2 separation in one cycle. As a reference for comparison, we have included cases with conventional amine-based technology. To this end, we built a mathematical optimization routine that combines the two softwares we used, namely Matlab and Aspen Plus. With the integration of bio-sources we studied the possibility to have negative emissions while producing hydrogen with CCS.

Task 1.4 Thermodynamic property models (RUB)

Finally, at the phenomenon level, RUB managed to develop an improved thermodynamics model for prediction of vapour-liquid equilibria in mixture of H_2 with CO_2 and CH_4. To that end, data for the density of mixtures of H_2 with CO_2, carbon monoxide (CO), and methane (CH_4) were measured with the highly accurate densimeters available at RUB in a wide range of temperatures, pressures, and compositions. Also, speeds of sound were measured for mixtures of H_2 with CH_4 and CO_2. Shortcomings of the existing model were identified for the binary subsystems H_2 with CH_4, CO_2, CO and N_2. Based on this, the mixture models were improved for the systems H_2 with CH_4, CO_2, CO and N_2 impurities. In particular, this is true for the technically highly relevant phase equilibria. Finally, the improved mixture model was made available to project partners via a new version of the property software TREND (TREND 5.0).

3.2 WP2 – CO_2 transport, injection and storage

WP2 focused on CO_2 storage and on the transport-storage interface. The work utilizes a wide variety of first-class research infrastructure. The ultimate goal was to de-risk CO_2 storage. To this end, WP2

- Developed an accurate property model for CO_2-brine mixtures in the presence of impurities.
- Matured and validated tools for the safe, efficient and cost-effective design and operation of CO_2 pipelines and injection wells.
- Performed petrophysical chemical analyses for the characterization and selection of storage sites in Switzerland.
- Designed and performed decameter-scale experiments at the Mont Terri research rock laboratory to understand the role of CO_2 injection in modifying fault/fracture permeability through seismic and/or aseismic reactivation.
- Reduced uncertainties in injection, storage and monitoring of CO_2 produced by NG reforming for H_2 production.

Task 2.1 Thermodynamic property model for CO_2-brine (RUB, ICL)

The objective of this task was to develop a comprehensive model for the thermodynamic properties of reservoir brines containing dissolved gases, especially CO_2 and H_2 as an impurity. ICL performed experiments to address the lack of available data for the solubility of H_2 in brines. This necessitated the construction of new apparatus that can operate at temperatures up to 200°C and pressures up to 700 bar [42]. The apparatus was validated by measuring the solubility of CO_2 and H_2 in pure water [41]. Measurements of H_2 solubility in a concentrated NaCl brine (2.5 mol/kg) were carried out at temperatures of 50, 100 and 150 °C with pressures up to about 400 bar. The results can be expressed in terms of a Sechenov coefficient which relates H_2 solubility in NaCl brine to that in pure water. By analysing the experimental results, together with literature data at lower temperatures, this coefficient has been determined at temperatures between 0 and 150°C [40].

The IAPWS seawater model [20] was combined with highly accurate equations of state to ensure consistent calculations of mixtures of brines with seawater-like composition and CCS-components. Therefore, a complex approach for the combination of pressure and density-explicit models was developed [29]. The model was implemented in the thermodynamic property database TREND and published to more than 150 users in academia and industry on an open-source basis. Further, a more advanced brine model based on Pitzer's equations was studied. These equations allow for flexible salt compositions and are more suitable for the description of brines at storage conditions.

Task 2.2 Well dynamics (SINTEF)

Work has been carried out to quantify thermal and flow transients in CO_2-injection wells and CO_2-transportation systems. To this end, a well-flow model accounting for multiple components and phases and employing modern numerical methods has been developed. This has been coupled to a near-well reservoir model, where the response of the reservoir model influences the well model. The results show that such a coupling is necessary to capture the correct transients in the order of hours or days, which is relevant for e.g. intermittent CO_2 injection from ships [24]. Tube-depressurization experiments have been carried out for CO_2-N_2 and CO_2-He, showing a significant influence of 2 mol-% of impurities. To our knowledge, these are the first experiments of this kind incorporating high-speed temperature measurements [23]. Finally, experimental observations of two-phase vertical flow of CO_2 have been carried out [18]. Both experimental series serve model development and validation.

Task 2.3 Petrophysics and chemistry for site characterization and selection (ICL)

The main objective for this task is to understand and characterize fluid transport in both intact (reservoir) and damaged (seal) rocks, including those from the Mont Terri field site. A major technical challenge is to quantify the impact of heterogeneities on CO_2 flow and trapping in representative rock systems, so that measurements carried out in the laboratory are useful for upscaling. Pore network model predictions of Darcy-scale multiphase flow heterogeneity were validated by two-phase flow experiments [47]. A second technical challenge is to quantify fracture properties under stress conditions and their effect on fluid transport. Understanding how caprock may fail is in fact key for the safe exploitation of the storage complex and to design contingency measures. We successfully conducted experiments on both reference rock types [46], and on Opalinus claystone from the Mont Terri field site to investigate the interplay between mechanical deformation and flow. The experiments on Opalinus claystone are of particular note, as they reveal the self-sealing properties of the rock when exposed to brine, as a result of clay-swelling.

Task 2.4 Mont Terri experiment: Fault slip and trapping (SCCER)

The experiment (CS-D) aims at improving our understanding on the main physical and chemical mechanisms controlling the migration of CO_2 through a fault-damage zone in a caprock, and the impact of the injection on the transmissivity in the fault [48]. To this end, we performed a prolonged (12 months) injection of CO_2-saturated saline water in the damage zone of a 3 m thick fault in the Opalinus Clay, a clay formation that is a good representative of common caprocks for CO_2 storage at depth. The mobility of the CO_2 within the fault is studied at decameter scale. We collected data from different independent monitoring systems, such as a seismic network, pressure temperature and electrical conductivity sensors, fiber optics, extensometers, and in situ mass spectrometer for dissolved-gas monitoring. The observations are complemented by laboratory data on collected fluids and rock samples. While injecting at a pressure just below the limit for fault opening and reactivation, we could observe that the flow is minimal and confined in tiny fractures that cannot be detected by classical geophysical measurements. Results also indicates some potential porosity decrease in the region immediately near the injection. An exposure to relatively high pressure, prolonged for 12 months, does not further weaken the fault. No notable seismic induced event could be detected.

Task 2.5 Understanding the impact of H_2 in a CO_2-rich stream on the storage strata (BGS, SCCER)

To understand the potential for microbial activity to influence CO_2 storage in the presence of H_2 [17], a series of experiments were completed. The results indicated that the hydrogen could stimulate microbial activity leading to an increase in microbial biomass, particularly sulphate reducers which can potentially use the hydrogen as an electron donor. Sulphate reduction also occurred when hydrogen was not present but seemed to be at a much lower rate. Methanogenesis also occurred under both conditions. Evidence of sulphate reducing organisms was seen up to 15% NaCl and methanogen up to 18% NaCl. Together this new data suggests that hydrogen impurities may increase microbial activity which could have an effect on microbial gas production (particularly hydrogen sulphide) and consumption in the reservoir, and have potential impacts on mineralogy. Additional work is recommended to fully understand the potential microbial interactions that could occur in CCS connected to hydrogen production.

3.3 WP3 – Business case development for H_2-CCS integrated chains

The vision of ELEGANCY includes not only technical and scientific objectives, but also an ambition to investigate regulatory, policy, commercial and market issues around H_2-CCS chains in order to accelerate their deployment. Within this scope, WP3 was aimed at developing a publicly available business-case assessment framework and templates which included a methodology to identify and select suitable business models for H_2-CCS projects.

WP3 followed the stepwise approach for the development of the business case framework. The business case framework developed in this work package provides a standardized approach for assessing the business context of H_2-CCS opportunities, identifying and mitigating business risks and investment barriers of a project, and ultimately selecting suitable business models that can deliver the project based on appropriate public and private sector risk sharing. The framework applies to case studies within ELEGANCY as well as to CCUS infrastructure chains broadly and the relevant resources are made publicly available for external use [4] under a Creative Commons CC BY-ND license.

The business case framework comprises the following elements:

Business model development methodology: We have developed an overall methodology which may be applied to select business models for H_2-CCS and other CCUS opportunities. The process is divided into four distinct steps, from the definition of the case-study scope and assessment of the market background, to business and investment risk identification and mitigation, and ultimately business-model selection. Once a business model is selected, business cases can be defined and assessed to various levels of detail depending on the stage of the project concept. For this purpose, a supplemental methodology is available. As business model preferences can change with changing business contexts as well as with the maturity of a project, the combined selection and assessment process is iterative.

Tool-kit [4]**:** To accompany each step in the process, a suite of Excel-based analytical and visualization tools has been designed and produced to facilitate the identification of key issues and promote collaborations early-on in the project development process. The tools cover: (i) assessment of the macroeconomic, fiscal and policy background, (ii) analysis of market failures, (iii) identification of policy needs and financial support gaps, (iv) evaluation of business risks and investments barriers as well as available mitigation measures, (v) selection of potential business models at system and sector level, and (vi) business case definition and assessment.

Guidance materials: A full description of the concepts and approach of the framework are detailed in four public interim reports of WP3 and in available recorded webinars.

The overall results and findings, including a compilation of the Excel tools' utility and functionality, are presented in a Synthesis Report on business case development for

H_2-CCS integrated chains [28]. The Synthesis Report provides a useful catalogue and index to the detailed interim reports. In addition, the legal research has been further developed in journal publications on de-risking the hydrogen-CCS supply chain through law, and on the identification of legal principles for gas market re-design for ensuring hydrogen and CCUS compatible gas networks.

WP3 actively engaged with key stakeholders in industry, government, European institutions and NGOs throughout the course of the ELEGANCY project via a series of workshops, interviews and collaboration with the Zero Emissions Platform (a European Technology and Innovation Platform under the Commission's Strategic Energy Technologies Plan). The workshops served the dual purpose of disseminating results and obtaining feedback and input for the WP3 programme. WP3 also ensured cross-fertilization of ideas and results with the ERA-net ACT ALIGN CCUS project.

3.4 WP4 – H_2-CCS chain tool and evaluation methodologies for integrated chains

To aid the commercial implementation of a H_2-CCS network, there needs to be extensive analysis on its technical feasibility in conjunction with integrated assessment under multiple criteria. There is a need for a powerful computational tool that can analyse various potential applications for H_2-CCS chains in a robust manner. The primary focus of ELEGANCY WP4 was to address this need and provide the necessary tools and techniques for analysing large scale H_2-CCS chain networks in the form of a modelling tool-kit.

Task 4.1 Define specifications for the open-source multi-scale systems modelling framework for H_2-CCS chain tool and evaluation (ICL, SINTEF, PSI, TNO, RUB)

A consistent methodological approach was needed to ensure that all the multi-scale modelling tools formulated as part of this work package used a unified framework for analysis [34-36]. In particular, the user requirements of the various tools need a clear outline, with clear expectations of model functionalities. This task involved close interactions with anticipated users of the modelling tools to plan the integration of software modules. As an outcome, three specifications – user requirements, functional and technical requirements were developed and publicly released to provide transparency.

Task 4.2 Define performance metrics (process, economic and environmental) for integrated assessment (PSI, ICL, SINTEF, TNO, RUB)

The core utility of the chain-tool developed within this work package is its applicability to a range of design problems. To enhance the broader use of the tool, the work took input from the project consortium and potential external users, thus identifying key features of interest. These discussions have been critical in the formulation of a set of performance metrics that are relevant for decision-making in the context of H_2-CO_2 infrastructure design [9]. These performance metrics include economic, environmental, and thermodynamic performance measures. The outcome of this task was publicly released, allowing potential users to understand the calculation methodology along with the set of working assumptions.

Task 4.3 Build detailed process and models of all components in H_2-CCS chain (ICL, SINTEF, RUB, TNO)

The model-building approach relied on multi-scale modelling, with a consistent set of working assumptions which define the characterization of an engineering process, at both a regional and network-level. This task is essential for the development of the tool as detailed component models allow users to simulate individual modules, whilst focusing on their elements of interest. The different project partners have each produced various models (e.g. hydrogen production, CO_2 separation, gas transport and compression, end-use, etc.) in a relevant simulation environment [22]. These models have all been publicly released and used for analysing regional H_2/CO_2 infrastructure design in the UK, where it has shown potential for cost-reduction through appropriate management of pipeline transmission pressures and storage infrastructure.

Task 4.4 Develop a metamodeling approach for different components of the H_2-CCS chain for use in steady state design mode and dynamic operation mode (SINTEF, ICL, PSI, TNO)

Computational complexity is a key issue that needs to be resolved when performing detailed dynamic simulations across the H_2-CCS chain. Large process systems with multiple plants, connecting infrastructure and storage often take long system times to be simulated and the computational burden may be prohibitive in certain cases. Abstractions of the more detailed process models were developed and implemented in OpenModelica. For example, a detailed thermodynamic equation of state was reduced to a simpler polynomial regression model with adapted range of validity, resulting in a significant reduction in computation time. Rather than using an ad-hoc approach to model reduction, a formal "metamodeling" tool, Consumet, was developed, enabling effective and accurate model reduction. Consumet can be used to sample a series of data points across the simulation space (using detailed models) and generate output data, which can be used for the formulation of simpler, yet accurate mathematical relations. This tool is publicly released for potential use with a range of process systems beyond H_2-CCS, allowing for greater impact [2].

In addition to the work towards the H_2-CCS chain tool, a life cycle assessment tool for passenger cars has been made openly available [1]. This was used in the Swiss case study to do economic and environmental evaluation of different types of cars under various driving and energy supply scenarios.

Task 4.5 Integrate component models into system models and deliver overall design and operational *toolkit for the H_2-CCS chain (ICL, SINTEF, RUB, PSI, TNO)*

This final activity combines all the various outputs from the earlier tasks to produce an overall modelling tool that can be applied to analyse the design and operation of H_2-CO_2 networks. In particular, detailed component models are released [22], with the reduced order modelling framework from Task 4.4. Furthermore, reduced-order models are assimilated to produce an open-source and open-access operational modelling toolkit [3], which is capable of simulating over 50 individual process plants and associated infrastructure at half-hour intervals over the course of an annual time horizon, within a few minutes of CPU time on a standard laptop. Additionally, design optimization frameworks have been developed in Python and released on a software hosting platform. These tools are accompanied by life-cycle assessment datasets and appropriate documentation to enhance usability. The chain-tool can evaluate a range of regional systems and provide insights on robust deployment pathways, investment breakdowns, multi-criteria decision-making.

The chain-tool has provided insights on H_2/CO_2 infrastructure design for the decarbonization of heat and industry in the UK [37, 38], with its findings disseminated for appraisal by key national stakeholders such as the Committee on Climate Change, HMG's Department of Business, Energy & Industrial Strategy, National Grid, etc. Similarly, the Dutch case study team is in dialogue with Gasunie regarding the outputs from the case study.

3.5 WP5 – Case studies

The ELEGANCY case studies have accelerated the implementation of H_2 and CCS chains in Europe by:

- Establishing the H-vision consortium committed to decarbonizing the Rotterdam cluster industry.
- Developing a Roadmap for decarbonization of the Dutch economy.
- Quantifying the role of H_2 and CCS along with – and not in contrast to – the deployment of renewable energy and large energy-storage facilities.
- Presenting a CO_2-supply profile, validating the UK storage capacity and developing an optimal injection strategy for the most promising storage sites, sufficient for the planned decarbonization by the H21 North of England, Acorn and Cadent projects.
- Identifying the key opportunities and constraints for the design of a UK H_2 and CCS infrastructure, including significant potential H_2 storage capacity, and presenting UK business case solutions.
- Identifying the role of H_2 and CCS for reaching the Swiss climate targets. Negative emissions are required to compensate emissions from non-energy sectors, and to reach the net-zero target in 2050. These are best realized with a combination of H_2 production from biomass resources and CCS.
- Revealing the need for a two-pronged approach for CCS in Switzerland due to the characteristics of Swiss geology that are challenging for the deployment of CCS; 1) improve the understanding of the Swiss subsurface, 2) develop alternatives, i.e. the export of CO_2 to storage sites such as planned by the Northern Lights consortium.
- Performing a multi-disciplinary evaluation of decarbonization strategies for the German gas infrastructure using public acceptance and legal insights as guidance on infrastructure concepts and macro-economic insights to understand the prerequisites for a successful transition.
- Showing that large-scale H_2 production in Norway for export and national demand can help to enable significant economies of scale in the development of a Norwegian CCS infrastructure, thus increasing the attractiveness of Norway as a large-scale storage location for European CO_2 emissions.

Further details are given in Refs. [5, 10-13, 15, 16, 19, 27, 30, 39, 44, 45].

4. Education and training

By educating and training the next-generation academics and industrials in the form of summer interns, master's students, PhD candidates and postdocs, ELEGANCY will have a lasting effect. The following number of education and training positions have been involved in ELEGANCY:

- Summer interns: 6
- Masters students: 14
- PhD candidates: 11
- Postdocs: 17

5. Dissemination

Dissemination is key to accelerating CCS deployment, not just to enhance R&D efforts, but perhaps more importantly since deployment requires industrial and political willingness as well as public acceptance. Open and engaging communication of scientific results has therefore been a core strategic activity in ELEGANCY. Major efforts have been the ELEGANCY Conference, a luncheon discussion in the European Parliament, and the ELEGANCY webinar series. Information about, and slides from these meetings can be found on the project website [4].

The website also contains a brief project description, and, importantly, an up-to-date publications page where all public deliverables can be downloaded. There is also a "news" section displaying glimpses from project work, and a newsletter that users could describe to, containing a digest of the latest news items.

In January–November 2020, there have been 8950 page views, which on average were read by the users for 1 min 50 sec. These are good numbers and indicate that the users find what they search for and read the contents of the page. The number of unique users was 1117 in 2018, increasing to 1273 in 2019 and 1587 in 2020 (until 3 December). In 2020, the users were from Norway (319), the UK (256), Germany (240), the Netherlands (151) and Switzerland (129), and also from Belgium (79), France (79), Italy (69) and the USA (69). This may be indicative of an increasing interest for CCS.

ELEGANCY has also established a Twitter account (@ELEGANCY_ACT) which is used to diffuse project-related news, and videos from key events have been published on Youtube.

ELEGANCY has since its start-up year used the SINTEF Blog (a scientific blog aimed at researchers, partner organizations and other industry stakeholders) actively to communicate research results and project activities.

6. Conclusion

ELEGANCY has helped fast-tracking the decarbonization of Europe's energy system by combining CCS and H_2, by overcoming specific scientific, technological and economic/legal barriers, and by undertaking five national case studies adapted to the conditions in the partner countries.

Based on our work and the project results, we conclude as follows.

- Europe is dependent on all main available decarbonization options – including hydrogen and CCS – to address the European-parliament declared climate emergency from November 2019 and reduce CO_2 emissions by 55% by 2030 and further to net zero by 2050.
- The European parliament has also supported greater action for implementing commercial-scale CCS.
- Hydrogen can be delivered at scale – fast-tracking the 2050 net-zero emission goal.
- Fuel-switching to hydrogen will:
  - Curb emissions from distributed sources, such as transport, industrial processes, heating and cooling.
  - Quickly decarbonize heavy industry in the EU and so maintain economic activity and jobs.
- Hydrogen produced both from renewable energy sources and from natural gas with CCS will be needed.
- Climate-positive hydrogen from biomass with CCS can play an important role in compensating CO_2 emissions from hard-to-abate sectors, despite limited resources of sustainable biomass.
- CCS is an efficient and safe way to eliminate CO_2 emissions.
- The Hydrogen Pathway needs appropriate financial, regulatory and political frameworks.
- Hydrogen should become an important part of the future European energy system.
- A comprehensive hydrogen infrastructure is required, also using existing assets.
- Open-access infrastructure for CO_2 transport and storage is required – being able to permanently store CO_2 will enable new pathways to climate neutrality.
- Full-scale deployment of hydrogen with CCS should start now.
- Recommended key principles for market re-design are:
  - Integrated energy system planning and governance tools.
  - Efficient and coordinated permitting procedures.
  - Access to the grid and gas grid conversion.
  - Operation of transport networks and related infrastructures.

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