Final report

ELEGANCY – Enabling a Low-Carbon Economy via Hydrogen and CCS

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2020-12-15, *Svend Tollak Munkejord*
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Contents

Summary and key messages

ELEGANCY is 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 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 consists of 22 partners from industry and academia/research. More information can be found at the project website, www.elegancy.no.

Key messages

- 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 be cut 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 sustainable biomass resources.
- CCS is an efficient and safe way to eliminate CO_2 emissions.
- The Hydrogen Pathway needs appropriate financial, regulatory and political frameworks.
- Hydrogen should form 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.

1 Short description of activities and final results

The purpose of this document is to provide a summary of the project, while balancing readability, level of detail and self-contained information. Section 0 first gives a very brief introduction to ELEGANCY, before summarizing the results against the main project objectives. Next, the financial summary is given. Then the achievements in each work package (WP) are outlined. In Section 2, the achieved and expected ELEGANCY impacts are discussed. Section 3 describes the collaboration and coordination in the consortium while highlighting the transnational collaboration. Finally, Section 4 gives an overview of our dissemination and publication activities, including glimpses and details from the three of the successful ELEGANCY events, the Conference hosted in November 2018, the Luncheon Discussion in the European Parliament in January 2020 and the final Webinar Series in June 2020.

Figure 1. The ELEGANCY consortium gathered in Trondheim, Norway, June 2019.

Public deliverables

As this report is issued, all ELEGANCY activities and deliverables have been completed, and all information is available to project partners at the project eRoom. Most deliverables are or will be public, and they can be found at the project website, http://www.elegancy.no. However, at the time of writing, some of the deliverables are in the process of peer review for publication, and the project website will be updated successively.

1.1 Introduction

The ELEGANCY consortium consists of 22 partners, world leaders in their respective fields, comprising highly respected research institutions, technology vendors, natural gas grid operators and international energy and petrochemical companies. ELEGANCY has been a timely project, as the innovative concept of combining CCS with H_2 is being appraised to inform national low-carbon strategies in Europe. Our 12 industry partners were actively involved in the project, and they highlight that ELEGANCY contributed to strengthening the competitiveness and growth of European companies by developing competence and technologies (CCS and H_2) that in the longer run will build new commercial value chains in a low-carbon future.

ELEGANCY R&D provides innovative, cutting edge solutions to key technical challenges for H_2-CCS chains (Figure 2) – 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 employed 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.

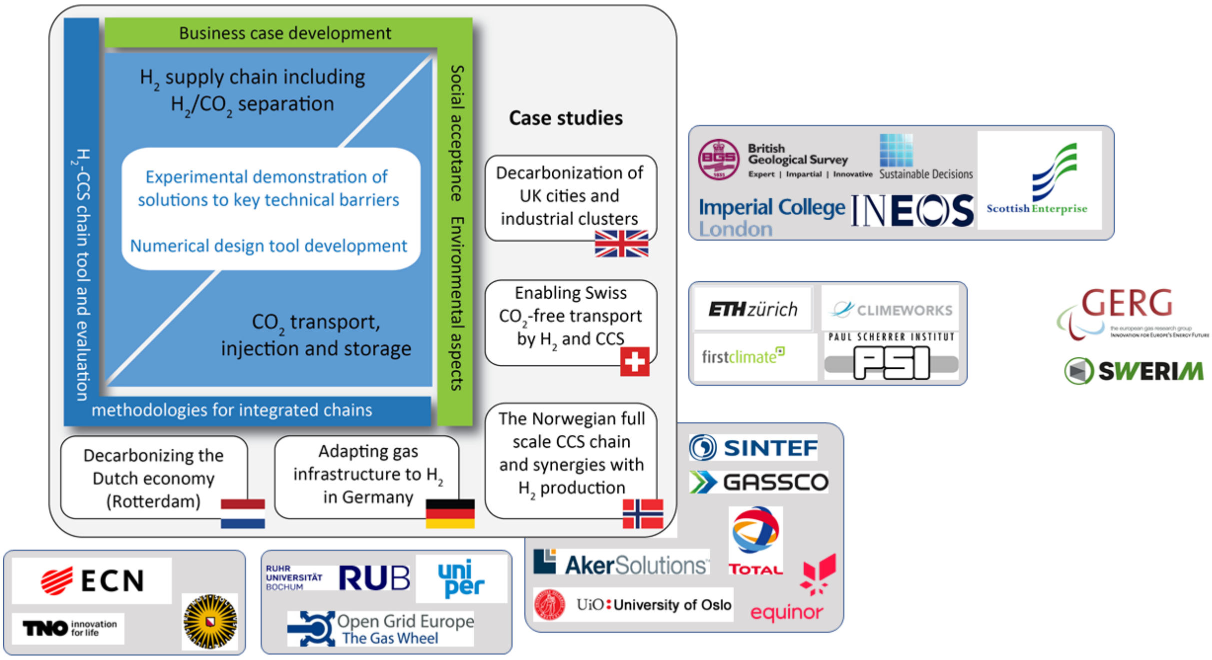


Figure 2. ELEGANCY at a glance.

ELEGANCY has been a successful project, as described in the following. Main achievements include

- Research results and findings are publicly available; 55 deliverables are published on the project website, and more are upcoming as articles are accepted for publication in journals.
- Active dissemination to stakeholders and decision-makers:
  - Final event with a large audience: Webinar series on CCS and H_2, June 2020.
  - A luncheon discussion in the EU Parliament, January 2020.
  - A one-day conference in Brussels, November 2018.
  - ELEGANCY representatives disseminated at the Romanian International Gas Conference, CSLF Technical Group Meeting, GHGT-14 and numerous other events.
- Case studies carried out in Germany, the Netherlands, Norway, Switzerland and the UK on the deployment of CCS with H_2, highlighting that H_2 from both natural gas and renewable sources are needed and that the countries are interconnected.
  - Established the H-vision consortium committed to decarbonizing the Rotterdam cluster industry.
  - Identified the key opportunities and constraints for the design of a UK H_2 and CCS infrastructure, including potential H_2 and CO_2 storage capacities, and presented UK business case solutions.

- Identified the role of H_2 and CCS for reaching the Swiss climate targets. Revealed 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.
    - Performed a multi-disciplinary evaluation of decarbonization strategies for the German gas infrastructure using public acceptance, legal and macro-economic insights.
    - Showed that large-scale H_2 production in Norway can enable economies of scale in the development of a Norwegian CCS infrastructure.
- Development and use of an open source whole-chain design tool.
- Issue and industrial application of a business case development toolbox.
- The Swiss Mt Terri experiment on CO_2 migration within a caprock fault was successfully completed.
- The technical feasibility of sharp H_2-CO_2 separation using only one process proven in simulations and the lab.
- New data and models describing thermophysical properties of CO_2 stemming from H_2 production, pipe and well dynamics and flow in the reservoir.

1.2 Overall results against project objectives

The primary objective of ELEGANCY has been to help fast-tracking track the decarbonization of Europe's energy system by exploiting the synergies between two key low-carbon technologies: CCS and H_2. To this end, ELEGANCY has

- Developed and demonstrated effective CCS technologies with high industrial relevance.
- Identified and promoted business opportunities for industrial CCS enabling by H_2 as a key energy carrier by performing five national case studies.
- Validated key elements of the CCS chain by frontier pilot- and laboratory-scale experiments using *inter alia* ECCSEL and EPOS research infrastructure.
- Optimized combined systems for H_2 production and H_2-CO_2 separation by combining basic science with the technology developments necessary for increased TRL of these systems.
- De-risked storage of CO_2 produced from natural gas reforming for H_2 production by providing experimental data and validating models.
- Enabled safe, cost-efficient design and operation of key elements of the CCS chain by developing cutting edge, innovative design and simulation tools.
- Provided an open source techno-economic design and operation simulation tool for the full CCS chain, including H_2 as energy carrier.
- Assessed societal support of key elements of CCS, enabling early identification and mitigation of risks.

Each point is further detailed in Table 1.

Table 1. Overall results against project objectives.

Objective	Progress items
Develop and demonstrate effective CCS technologies with high industrial relevance.	• The versatility of a water gas shift catalyst has been demonstrated in long-term experiments with basic oxygen furnace gas, yielding only 4–5% conversion loss over 1000 hours. • CO_2 and H_2 purification process using vacuum pressure swing adsorption (VPSA) cycles designed and simulated for >30 synthesis gas stream compositions • VPSA process designed and simulated using novel MOF adsorbents leading to improved productivity at cost of higher energy penalty. • CO_2 and H_2 purification lab-scale setup constructed, and VPSA process tested and validated in multiple adsorption-desorption cycles, technology brought to TRL5.
Identify and promote business opportunities for industrial CCS enabled by H_2 as a key energy carrier by performing five national case studies.	• The potential for hydrogen consumption in the five participating countries mapped. • Business risks and investment barriers identified. • Policy-issues, business risks, de-risking instruments, and incentive mechanisms relevant for case-study countries mapped and toolbox issued. • High-temperature heating in refinery furnaces and power production has been identified as potential business opportunities for H_2 in the Rotterdam area. • Assessment of the feasibility of delivering the UK H21 Roadmap recommends a delivery organization with mandate to coordinate UK system-wide business case for all regions and sectors as the business case

	for hydrogen and CCS is revealed when evaluated in a net zero emission context. • The role of H_2 and CCS in reaching the Swiss climate targets has been revealed. 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. • The potential for increasing the attractiveness of Norway as a large-scale storage location showed. 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. • Best case option for decarbonization of the German gas infrastructure derived. Solution consists of dedicated hydrogen pipeline to serve regions with large potential hydrogen demand, injection of hydrogen into the existing gas infrastructure and ship-transport of CO_2 to the Dutch border.
Validate key elements of the CCS chain by frontier pilot- and laboratory-scale experiments using inter alia ECCSEL and EPOS research infrastructure.	• The decameter-scale CO_2-storage experiment at Mt. Terri was performed successfully. • Depressurization data for CO_2-rich mixtures in a pipe were collected, analysed and compared to models.
Optimize combined systems for H_2 production and H_2-CO_2 separation by combining basic science with the technology developments necessary for increased TRL of these systems.	• CO_2 and H_2 purification process using vacuum pressure swing adsorption (VPSA) cycles designed and simulated/optimised for >30 synthesis gas stream compositions. • Matlab-Aspen routine developed for mathematical optimisation of solvent-based CO_2 capture from synthesis gas. • Optimisation finalised of integrated H_2 production and CO_2 capture facilities, including steam methane reforming, autothermal reforming biomass gasification, solvent, and sorbent-based capture and fed with natural gas and/or biogas and/or biomass. Optimisation included integrated techo-environmental models, allowing optimisation on environmental KPIs in addition to technical KPIs.
De-risk storage of CO_2 produced from natural gas reforming for H_2 production by providing experimental data and validated models.	• Experiments to measure CO_2 and H_2 solubility in brines performed. • An experimental set-up to expose UK storage strata to H_2 impurities in a CO_2-rich stream was established and put into operation. • Rock samples from potential CO_2 storage sites characterised, and CO_2-adsorption experiments conducted.
Enable safe, cost-efficient design and operation of key elements of the CCS chain by developing cutting edge, innovative design and simulation tools.	• A model for CO_2 injection wells with a near-well reservoir under dynamic conditions developed. • Accurate property model for CO_2-rich CCS mixtures for use with seawater like brines implemented. • Model simulating the injection of a CO_2-H_2 mixture into a deep saline aquifer developed. • Dynamic models have been developed for H_2 production with integrated CCS, H_2 and CO_2 compression, storage, etc. • Open-source GIS packages have been developed to enable ease of integration with the design optimisation framework
Provide an open source techno-economic design and operation simulation tool for the full CCS chain, including H_2 as energy carrier.	• A H_2-CCS chain tool developed and distributed among partners. • The H_2-CCS chain tool was applied to the UK, Norwegian and Dutch case studies. • The chain tool is publicly released with documentation in GitHub as an open-source, open-access modelling framework.
Assess societal support of key elements of CCS, enabling early identification and mitigation of risks.	• A systematization of acceptance regarding H_2-CCS chains was developed to identify chances and risks for social acceptance. • Stakeholder-interviews have been conducted and analysed. • Public perception of different scenarios in the H_2-CCS chain surveyed for the Swiss case. • A methodology developed to include factors important for community acceptance early in the site-screening process.

ELEGANCY enables a low-carbon economy via H_2 and CCS, because:

1. Advanced CO_2 capture technologies – either optimally designed amine-based or newly developed adsorption-based – coupled with either Steam Methane Reforming or Auto-Thermal Reforming (using either natural gas or biomass as feedstock) improve the Life Cycle Analysis performance of hydrogen production with CCS.

2. New thermodynamic modelling tools and new CO_2 transport experiments, in both surface laboratories and deep ones, strongly enhance our understanding of the underground storage of CO_2, particularly when originated from hydrogen production.
3. Thorough analysis of technical and economic interdependencies and exchange with numerous stakeholders allow for the design of business models and market mechanisms to enable a low-carbon hydrogen economy based on fossil-carbon and biomass.
4. Newly developed network modelling tools enable the design of hydrogen and carbon dioxide networks, which – depending crucially on the distribution of hydrogen demand and on the location of CO_2 storage sites, as well as on the nature of the feedstock – best compromise between carbon footprint and costs.
5. The enhanced understanding of scientific, technical and economic aspects of hydrogen production with CCS acquired in the WPs 1 to 4 not only leads to a clear assessment of the challenges faced in the different implementation of the technology chains in the five countries and the corresponding case studies, but it also identifies pathways and opportunities.
6. ELEGANCY has educated scores of European scientists and engineers, of graduate and undergraduate students, in the science and technology related to the hydrogen economy and to the sustainable implementation of CCS.

Financial results

The reported costs per partner and work package is found in Table 2, and the budget is found in Table 3. The costs correspond well to the budget with less than a 2% deviation in the total, where the deviations are mainly due to variations between budgeted and reported in-kind costs.

Table 2: Reported cost per partner per work package (kEUR), 2017-08 -- 2020-11.

Reported costs		WP1	WP2	WP3	WP4	WP5	WP6
01 SER	2445	0	1128	0	391	231	695
02 UiO	206	0	0	206	0	0	0
03 AKSO	67	0	0	0	0	67	0
04 GASSCO	0	0	0	0	0	0	0
05 ICL	1734	0	777	411	272	274	0
06 BGS	722	0	151	0	0	571	0
07 SE	172	0	0	0	0	172	0
08 INEOS	31	0	0	0	0	31	0
09 ETH	970	786	0	0	0	185	0
10 PSI	945	0	0	0	231	714	0
11 CW	901	0	0	0	0	901	0
12 FC	336	0	0	203	0	133	0
13 RUB	914	135	168	0	43	568	0
14 OGE	40	0	0	0	0	40	0
15 UES	27	0	0	0	0	27	0
16 ECN	573	546	0	0	0	27	0
17 TNO	732	0	0	0	156	576	0
18 UU	424	3	0	0	0	421	0
19 SWERIM	122	122	0	0	0	0	0
20 GERG	22	0	0	0	0	22	0
21 SCCER	4002	0	3000	0	0	1002	0
22 EQUINOR	0	0	0	0	0	0	0
23 TOTAL							
SUM	15384	1591	5225	820	1092	5961	695

Table 3: Budget per partner per work package (kEUR).

Budget	2017-20	WP1	WP2	WP3	WP4	WP5	WP6
01 SER	2445		1128		391	231	695
02 UiO	206			206			
03 AKSO	67					67	
04 GASSCO	0						
05 ICL	1734		777	411	257	289	
06 BGS	727		149			578	
07 SE	172					172	
08 INEOS	98					98	
09 ETH	1000	856				144	
10 PSI	945				231	714	
11 CW	827					827	
12 FC	332			222		110	
13 RUB	918	135	168		43	572	
14 OGE	40					40	
15 UES	216					216	
16 ECN	627	586				41	
17 TNO	730				158	572	
18 UU	390	24				366	
19 SWERIM	150	150					
20 GERG	34					34	
21 SCCER	4002		3000			1002	
22 EQUINOR	0						
23 TOTAL	0						
SUM	15660	1751	5222	839	1080	6073	695

1.3 WP1 – H_2 supply chain and H_2-CO_2 separation

1.3.1 Objectives

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

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

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

1.3.2 Activities and final results

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 (Streb et al., 2019). The developed VPSA cycle was then applied to relevant syngases from steam reforming and autothermal reforming of natural gas (Streb and Mazzotti, 2020). 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 (Antonini et al., 2020). 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 (D1.1.2) 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. (D1.2.1)

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 (D1.2.1). 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 (D1.2.2). As expected, carbon capture rate is robust to switching from BFG to BOG.
- Cycle design and optimization for BOFG was extensively studied. The highest productivity, at targeted carbon capture rate and carbon purity 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 (D1.3.3, D1.2.3)
- Analysis on engineering and costing of multi-column SEWGS at the SWERIM site in Luleå is reported in deliverable D1.2.4.
- 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 BOFG (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 optimisation of CO_2 capture technology into hydrogen production systems (from natural gas as well as biogenic sources). First, an inventory was made of State-of-the-Art hydrogen production technology with CCS (D1.3.1). In addition, a techno-economic assessment framework was established, in conjunction with, and also used by WP4 (D1.3.3). Based on these two deliverables, 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 (D1.3.2). This led to two journal publications (Gabrielli et al., 2020). 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 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 thermodynamic 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 hydrogen (H_2) with carbon dioxide (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, the speeds of sound were measured for mixtures of H_2 with CH_4 and CO_2 (D1.4.1). Then, shortcomings of the existing model were identified in particular 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. In particular the technically highly relevant representation of phase equilibria could be improved for the mentioned systems (D1.4.2). Finally, the improved mixture model was made available to project partners via a new version of the property software TREND (TREND 5.0).

1.3.3 HSE issues

All three laboratories active in WP1 saw a large safety overhaul, partially sparked by ELEGANCY:

- Task 1.1: The experimental demonstration of advanced VPSA cycles for H_2-CO_2-impurity separation require the handling of explosive / flammable (H_2, CH_4, CO) and toxic (CO) components and therefore, different safety regulations apply. To ensure safe operation, a full risk analysis (FMCA) has been performed in collaboration with HSE specialists from EPFL (external collaboration). In addition/as a consequence, a major overhaul of the laboratories at the Separation Processes Laboratory of ETH Zurich was done: new gas cabinets, CO, H_2, CH_4 sensors and alarm system were installed and are operational since 02/2019. This investment was triggered by ELEGANCY but implies a large safety improvement to the SPL/ETH experimental adsorption facilities in general.

- Task 1.2: Due to an increased safety regime that has been rolled out at ECN>TNO a few months after the start of the Elegancy project, as a consequence of the ECN -TNO merger, and also the reclassification of the explosion class when working with high CO and H_2 concentrations, a large safety overhaul took place. The new safety protocol includes software, automation and control updates, a new explosion protection document, new risk inventories, leakage and strength testing, the installation of extra alarms and improvement to the physical installations. Although triggered by the ECN-TNO merger, this overhaul significantly improves HSE at the ECN SEWGS laboratories and therefore improves safety of experimental work for Elegancy.
- Task 1.4: Safety measures were added to the RUB laboratories (CO sensors, increased air exchange rate, warnings, emergency plan) for the experiments with toxic gases like carbon monoxide. This investment was triggered by ELEGANCY but implies a large safety improvement to the RUB experimental facilities in general.

1.4 WP2 – CO_2 transport, injection and storage

1.4.1 Objectives

WP2 focuses on CO_2 storage and on the transport-storage interface. The work will utilize a wide variety of first-class research infrastructure. The WP is characterized by a strong collaboration with the ultimate goal to de-risk CO_2 storage. To this end, WP2 will

- Develop an accurate property model for CO_2-brine in the presence of impurities.
- Mature and validate tools for the safe, efficient and cost-effective design and operation of CO_2 pipelines and injection wells.
- Perform petrophysical chemical analyses for the characterization and selection of storage sites in Switzerland.
- Design and perform decameter-scale experiments at the Mt Terri research rock laboratory to understand the role of CO_2 injection in modifying fault/fracture permeability through seismic and/or aseismic reactivation.
- Reduce uncertainties in injection, storage and monitoring of CO_2 produced by NG reforming for H_2 production.

1.4.2 Activities and final results

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

The objective of this task is to develop a comprehensive model for the thermodynamic properties of reservoir brines containing dissolved gases, especially CO_2 and H_2 impurity. In order to address the lack of experimental data for the solubility of H_2 in brines, the team at ICL has performed experimental measurements. This necessitated the construction of new apparatus that can operate at temperatures up to 200°C and pressures up to 700 bar (D2.1.4). The apparatus was validated by measuring the solubility of CO_2 and H_2 in pure water (D2.1.5). 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 (D2.1.6).

The IAPWS seawater model 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 (D2.1.1). The model was implemented in the thermodynamic property database TREND and published to more than 100 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 (D2.1.3).

Task 2.2 Well dynamics (SINTEF)

Work has been done 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 (Munkejord et al, 2020). 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 (D2.2.2). Finally, experimental observations of two-phase vertical flow of CO_2 have been carried out (D2.2.3). 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 characterise 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. In Zahasky et al. (2020), pore network model predictions of Darcy-scale multiphase flow heterogeneity were validated by two-phase flow experiments. 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 (Wenning et al., 2019), 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 Mt. 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 (Zappone et al., 2018). To this end, we performed a prolonged (12 months) injection of CO_2-saturated saline water in the damage zone of a 3 m think 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 collect data from different independent monitoring systems, such as a seismic network, pressure temperature and electrical conductivity sensors, fiber optics, extensometers, 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 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 weakens the fault. No notable seismic induced event could be detected (D2.4.4).

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

In order to understand the potential for microbial activity to influence CO_2 storage in the presence of H_2 (Gregory et al., 2019), 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% sodium chloride and methanogen up to 18% sodium chloride. 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 (D2.5.4). Additional work is recommended to fully understand the potential microbial interactions that could occur in CCS connected to hydrogen production.

1.4.3 HSE issues

Task 2.1 has included a very detailed risk assessment associated with the handling of fluids under high pressure conditions.

The ECCSEL depressurization facility used in Task 2.2 has undergone comprehensive risk assessments regarding design and operation.

The core-flooding experiments conducted at ICL involve carrying out direct shearing displacements in a fractured rock while imaging the sample by X-ray Computed Tomography. Because the experiments involve the use of elevated pressures (up to 15 MPa), a new X-ray transparent core-holder was commissioned and tested.

One experiment was carried out in the NTNU-SINTEF thermal engineering laboratory after the outbreak of Covid-19. This was done after thorough considerations on infection control and with measures in place. Following the re-opening of the Mt. Terri research laboratory after easing restrictions related to Covid-19, personnel are working on-site in the tunnel in reduced numbers at recommended distance and safety equipment (mask, gloves, disinfectant).

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

1.5.1 Objectives

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, Work Package 3 (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.

1.5.2 Activities and final results

WP3 followed the stepwise approach proposed in the project proposal 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[1] under a Creative Commons **CC BY-ND** license.

The business case framework comprises the following elements:

- **Business model development methodology:** WP3 has 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:** To accompany each step in the process, a suite of analytical and visualization Excel-based 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 (D.3.4.1). 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 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-fertilisation of ideas and results with the ERA-net ACT ALIGN CCUS project.

1.5.3 HSE issues

None.

[1] ELEGANCY publications: https://www.sintef.no/projectweb/elegancy/publications/

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

1.6.1 Objectives

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 is 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.

1.6.2 Activities and final results

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 needs to be developed to ensure that all the multi-scale modelling tools formulated as part of this work package use a unified framework for analysis (D4.1.1a, D4.1.1b, D4.1.1c). In particular, the user requirements of the various tools need to be clearly outlined, 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 package team held bilateral discussions with project partners, potential external users and identified 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 (D4.2.1). 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 has relied on multi-scale modelling, with a consistent set of working assumptions which define the characterisation 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 work package 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 (D4.3.1). 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 to generate 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. Within the work package, 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, 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 (Consumet Github).

In addition to the work on work towards the H_2-CCS chain tool, a life cycle assessment tool for passenger cars has been made openly available (carculator). 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 Integration of component models into system models and deliver overall design and operational toolkit for 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 (D4.3.1) as is, 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 (Chain-tool Github), 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 optimisation frameworks have been developed in Python and released on a software hosting platform. These tools are accompanied with 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 decarbonisation of heat and industry in the UK (Sunny et al., 2020, Sunny et al., 2019), 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 are in communication with Gasunie regarding the outputs from the case study.

1.6.3 HSE issues

No HSE issues arose during the work. However, our toolkit does include lifecycle environmental analysis and therefore can be used to ensure that future H_2-CCS systems do not generate unintended environmental consequences.

1.7 WP5 – Case studies

1.7.1 Objectives

The five national case studies in WP5 aim at accelerating the implementation of H_2-CCS systems in the participating countries of ELEGANCY and at adapting technological and business case solutions to national and regional conditions, and market opportunities. In particular, the

- Dutch case study (Task 5.2) assesses significant decarbonization of the Dutch, with Rotterdam and Tata Steel clusters as real case studies, industry through:
  (i) introduction of clean H_2 as raw material and energy carrier for its base industries and utilities,
  (ii) CO_2 capture at large single point emitters, CO_2 offshore storage and CO_2 utilization,
  (iii) Optimal integration of CO_2 capture and H_2 with the Dutch energy system.
- Swiss case study (Task 5.3) studies the integration of H_2 production and CCS with the objective of understanding its potential for the decarbonisation of road transport as well as for accelerating the Swiss roadmap for the geological sequestration of CO_2 and for generating negative CO_2 emissions.
- UK case study (Task 5.4) supports the H21 Roadmap project, for large-scale deployment of H_2-CCS through the wider application of the H21 Leeds City Gate findings to many UK cities and Grangemouth as an industrial site case study.
- German case study (Task 5.5) aims at identifying feasible infrastructure concepts – and their prerequisites – for the transport and export of CO_2 and for adapting the gas grid to increasing amounts of decarbonized H_2, which can enable the accelerated (partial) decarbonization of the German infrastructure through H_2-CCS chains.
- Norwegian case study (Task 5.6) evaluates the benefit of converting Norway's large natural gas resources to H_2 with CCS, primarily to satisfy the expected growth in worldwide demand of H_2 as an energy carrier and additionally to mitigate emissions in offshore platforms, the transport and industrial sectors. The case study also studies the possible synergies with the Norwegian full-scale CCS project.

1.7.2 Activities and final results

Case studies – overall summary

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 with – 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.

The performed investigations within the five case studies cover broadly important aspects when assessing the possibilities of H_2 and CCS value chains and further planning. This is shown in Figure 3. Thus, knowledge sharing between the national case studies and comparison of methodologies and results has added transnational value to the work package.

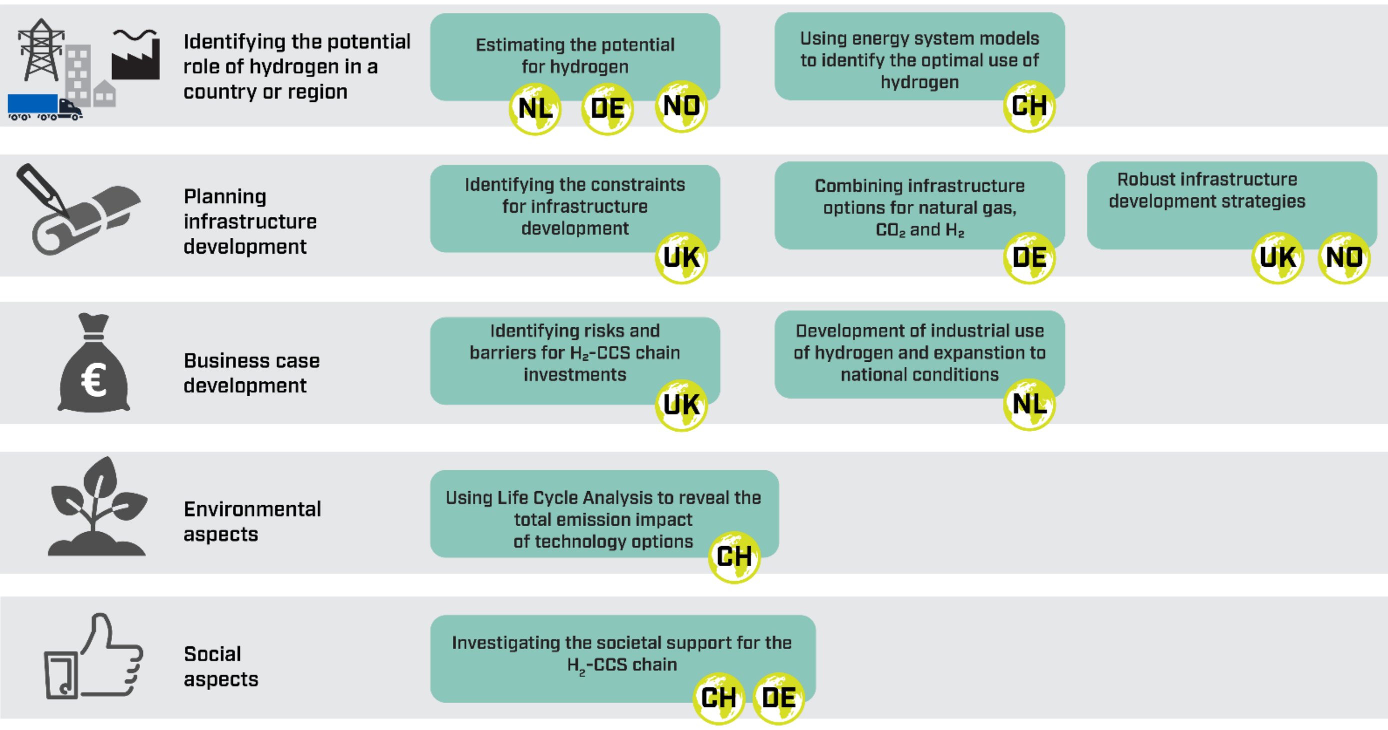


Figure 3: Topics covered by the five case studies of ELEGANCY.

Dutch case study

The Dutch case study consists of several research activities focused on the decarbonization of the Dutch industry, and ranging from technical/modelling works, to case study applications and stakeholders' involvement. The Dutch case study has been assessed based on several tools that have been developed within ELEGANCY and consultation meetings with the industry. On the one hand, it investigates the potential replacement of natural gas by H_2 in the existing Rotterdam industrial cluster, where natural gas, refinery gas, and fuel oil are currently used as energy sources for power generation and heating purposes. The focus of this case study is on the so-called 'blue hydrogen' in which H_2 is produced in one or more newly-built, central facilities using natural gas, off-gas, and refinery fuel gas as the feedstocks and almost all CO_2 generated is captured and permanently stored in depleted off-shore gas fields. The Rotterdam case study had a crucial role and resulted in an early active role of the industry in the H-vision project. There have been several outreach moments that have been organised by the Dutch CATO meet projects, in which the results of the Rotterdam case study have been presented. It must be noted that the industrial continuation of the project in the H-vision project is a great result of the WP5 Dutch case study. The work has revealed that the socio-economic industrial cluster in Rotterdam is significant and that H_2 will play a vital role in the reduction of CO_2 emissions (D5.2.1). The tools from WP3 on business case, market failures, and risks and the spatial model of WP4 have been applied to develop and define the potential solution space for the Dutch Case in Industrial Cluster of the Rotterdam port. Also, cost data on H_2 production is aligned with the input from the industrial platform members. The H_2-CCS chain tool has been tested and refined by applying it to the Rotterdam cluster as well as the to the national level, (D5.2.6). The amount of H_2 utilization has been assessed in close consultation with the industrial stakeholders in light of all CO_2 mitigation options available. Moreover, the amount of available supply of fuel gas has been requested. It is worth noting that the impact of electrification and the surplus of off-gas has not been considered for the Rotterdam case study. Accordingly, a data set for H_2 demand and available fuel-gas has been composed based on specific industrial sites.

The estimated total H_2 utilisation in the port of Rotterdam requires a blue-hydrogen production capacity of 900.000 Nm^3/hr. The H_2 demand will yield around 3.8 Mt per annum in CO_2-emissions reductions. The refinery fuel gases and industrial off-gases are the main feedstocks for the blue-hydrogen production, and the remaining part will be from natural gas (approx. 40%). The modifications and revamps must be planned in line with a major overhaul; moreover, care must be taken for the implementation of different H_2 combustion processes. Therefore, in the first phase, H_2 firing will be implemented as a hybrid solution. As such, there will be a growing increase for H_2 use, and by 2032 all relevant furnaces will be partly or fully switched to H_2 firing.

As a second case study for the decarbonization of the Dutch industry, a thorough analysis of the TATA Steel Ijmuiden production site was carried out (D5.2.5). The work was executed in close consultation with TATA experts. The work aimed at quantifying the role of carbon capture and/or clean H_2 in decarbonizing steel production from integrated steelworks. Real production and energy demand profiles at hourly resolution were gathered and analysed. Furthermore, the impact of three decarbonization measures, namely electrification of heat, implementation of an electric arc furnace, and implementation of the Hisarna process, on the energy demands was assessed. With this vast set of data, optimal energy systems for the three different decarbonization measures and for a reference case were designed. It was found that none of the investigated measures allow for timely deep decarbonization, while both CCS and H_2 would allow to decarbonize the process side as well as the energy system side.

As part of the Dutch case study, the impact of H_2 on the Dutch power system and its integration with renewable power generation was investigated with detailed technical models and hourly time resolution (Gabrielli et al, 2020, and Weimann et al, 2021). It was found that a net H_2 demand significantly affects the technology portfolio and makes seasonal storage less critical. Industrial hydrogen demand will therefore play an important role in the transition to an optimal hydrogen and renewable energy economy.

For the final business case assessment and the H_2 roadmap, the Eye model, a simulation model of electricity systems, has been extended with a H_2 market platform. The Eye model can now analyse the behaviour in the energy systems as a result of changes in fuel prices, changes in renewable energy capacity, new energy carrier H_2 for power generation and changes in demand response capacity, H_2 storage, and the growing increase of renewable H_2. The spatial model is closely linked to the output of the Eye model, and both form the basis of the road map scenario assessment for H_2 in the Netherlands.

Swiss case study

The Swiss case study was perfectly timed for two reasons: (i) Switzerland clearly defined in 2019 its climate goals to be net-zero by 2050; and (ii) the energy strategy, that dates back to 2012, is currently being revised by the Swiss Federal Office of Energy (SFOE). This revision is being carried out by a team of consulting firms. In parallel, a large group of researchers from academia and industry is generating scenarios for 2050/60 (see Joint Activity Scenarios & Modelling, www.sccer-jasm.ch). ELEGANCY gives a crucial contribution to the overarching goal of net-zero emissions, as it is clear that hydrogen and CCS will play a key role.

The Swiss case study covers various aspects and disciplines in the context of H_2 and CCS, which can roughly be grouped into above- and below-ground activities. Above-ground activities includes (A1) the generation of H_2 via various thermochemical processes, (A2) the direct capture of CO_2 from the atmosphere, (A3) the life-cycle assessment of various pathways, and (A4) the embedding of the overall chain into a full energy system analysis. The below-ground activities include (B1) the identification of potential storage CO_2 storage sites with focus on geology, (B2) a Multi-Criteria Decision Analysis approach to aid site selection and to properly account for all risks, and (B3) the opportunity to realize CO_2 plume geothermal (CPG) a variant of deep geothermal energy that uses CO_2 as working fluid, and is therefore best combined with CO_2 storage. Both the above- and below-ground aspects are synthesized within (C1) a business case framework and (C2) an assessment of social perception and acceptance.

A1: Thermochemical hydrogen production (ETHZ). An integrated techno-environmental assessment study of H_2 production from natural gas and biogas, combined with CCS has been published and a similar contribution on woody biomass conversion to H_2 will be soon completed. The technologies analysed, both technically and environmentally, are steam methane reforming (SMR), autothermal reforming (ATR) and biomass gasification for syngas production. CO_2 is captured from the syngas with a novel vacuum pressure swing adsorption (VPSA) process, that combines H_2 purification and CO_2 separation in one cycle. The integration of biomass allows negative emissions, while producing H_2 with CCS. The work is strongly linked to WP1.

A2: Direct Air Capture and Storage (DACS, Climeworks) of CO_2 represents a technical, and thus, readily scalable, alternative to the extraction of CO_2 from the atmosphere via biomass growth. Climeworks designed, built, and operated a DAC demonstration unit with a capacity of capturing ca. 10 kg of CO_2 per day. The Demonstrator was employed to test and validate novel adsorption materials with the general objective of further improving the energetic and carbon efficiency, and of reducing the overall DAC costs.

A3: Life Cycle Assessment (LCA, PSI) showed that using biomass for H_2 production with CCS leads to a *net removal of GHG emissions from the atmosphere* and thus represents a very attractive option for fuel production. However, resource potentials are limited. H_2 from natural gas combined with CCS can be a *low-carbon fuel* and therefore contribute to decarbonization of the transport sector. However, the performance regarding GHG reduction depends on process technologies and associated CO_2 capture rates. LCA results for passenger vehicles show that H_2 from the aforementioned thermochemical pathways is competitive in terms of GHG emission reduction with H_2 from electrolysis, if high CO_2 capture rates can be achieved.

A4: Full energy system modelling and scenarios. The full benefit of the H_2-CCS chain can only be reliably assessed within a full energy system modelling framework. The Swiss TIMES Energy Systems Model (STEM) was used to quantify two scenarios: A Baseline scenario (continuation of existing trends) and a Climate scenario (achievement of the goals of the Swiss energy and climate strategy). Results show that the achievement of net-zero GHG emissions in 2050 requires the deployment of CC(U)S and Negative Emission Technologies (NET). More than 80% of the captured CO_2 needs to be exported, as the domestic sequestration potential is small.

B1: Site selection for CCS in Switzerland (UNIGE). A robust site-screening and site-selection workflow has been developed to investigate potential sites for CCS and CO_2-Plume-Geothermal (CPG) in Switzerland. Storage capacity estimates were calculated for sites comprising a depleted hydrocarbon field and other subsurface locations characterized by deep saline aquifers (> 800 m). A moderate capacity of < 1 Mt of CO_2 at each site is considered potentially feasible in multiple locations. This suggests that decentralised storage solutions aimed at the amount of emissions from medium scale CO_2 point sources (i.e. incinerators, cement plants) should be explored further. Some of these sites, especially the depleted gas field, show potential for an integrated CO_2 storage and CPG.

B2: Ranking of potential sites by Multi-Criteria Decision Analysis (PSI). B1 focused on the geological conditions and the risk of not finding an appropriate site. However, other factors, like the distance to the CO_2 emitter, the connection to roads, railways, pipelines, the presence of natural parks, biospheres, etc., the distance to populated areas, economic factors, e.g. taxes to the companies, etc., could have an impact on the site selection. Trade-offs have to be considered for an informed decision-making process, and to guide the public debate and participatory processes.

B3: CO_2 plume geothermal (CPG, ETHZ). CO_2 sequestered into the porous subsurface may be recirculated to generate electricity in a so-called CO_2 plume geothermal (CPG) system. A CPG model was built to show the dependence of power generation on depth and transmissivity. Thus, we can now say that CPG electricity may be generated in a reservoir as shallow as 1000 m, which is much shallower than for a brine system.

C1: Business case framework (First Climate). WP3 developed a publicly available business case framework to identify and select suitable business models for H_2-CCS projects. The application of the framework to the conditions of the Swiss case study indicates a clear need for targeted carbon pricing instruments to alleviate investment barriers for H_2-CCS chains and to support in ramping up viable business cases.

C2: Public and community acceptance (ETHZ). An online survey (D5.3.5) studied public perception of different options regarding CCS combined with H_2 production, different sources (natural gas and biogas) and different end-use options (electricity for the grid, H_2 for transport). In general, biogas was preferred over natural gas as source but there was no difference between electricity and H_2 as end-use.

UK case study

The UK case study research and application of the tools developed within the ELEGANCY project are tailored to complement assessments by industry led projects and appraisals. The case study research informs the planned UK implementation of large-scale production of H_2 for domestic and commercial heating with CCS as a technology to substantially reduce CO_2 emissions. The H21 projects have planned conversion of natural gas provision to 100% H_2 for large cities in the north of England.

Emissions reduction from energy intensive industries is also considered in the UK case study. The Grangemouth refinery and petrochemicals site is assessed for the implementation of CCS from existing sources and the implementation of hydrogen from methane reformation as a fuel for heating to drive industrial processes.

The case study reviewed publicly available and published industry plans and concepts for the capture of CO_2 from industrial sources and methane reformation of hydrogen for Teesside and Grangemouth. The ELEGANCY case study has assessed the supply of CO_2 and required geological storage capacity anticipated by the H21 project from large-scale reformation and other industrial sources at Teesside. Three variants of supply were distinguished based on low, intermediate and high rates of planned CCS project deployment (D5.1.4a). Increased UK ambitions for H_2 and CCS during the progress of the ELEGANCY project have been reflected in an update of the assessment in 2020 (D5.4.1c). The research found that the volume of CO_2 for storage captured from existing sources by planned CCS projects was less than five million tonnes per year to 2055 and thereafter. Implementation of hydrogen reformation for heating generated a very marked increase in the rate of CO_2 emissions capture and storage. The planned rate of supply in the projects growth scenario rapidly rising to 20 million tonnes per year by 2030 and 35 million tonnes per year by 2035 and thereafter remaining fairly constant. This rate of storage for the two UK east coast industrial clusters considered in ELEGANCY would exceed the UK storage target rate of 30 million tonnes per year by 2035. Planned CO_2 capture and storage rates are predicted to decline after 2050 in both the growth and mature projects scenario owing to a change in the process of hydrogen production from methane reformation to electrolysis powered by wind turbines.

The annual rates of supply and the cumulative total CO_2 supplied for storage were used to identify storage options of sufficient capacity and timing of availability emissions captured at the Teesside industrial cluster. Possible storage options were proposed for the three variants of low, intermediate and high rates of CCS project deployment (D5.4.1b), CO_2 injection has been simulated and injection scenarios presented to securely contain the CO_2 supplied by each variant (D5.4.1d). The H21 North of England and Net Zero Teesside projects both plan to store CO_2 offshore Teesside. Modelling of the geomechanical responses indicates the storage strata have the capacity to contain the simultaneous supply of CO_2 at the rate and volumes planned (D5.4.1f).

An appraisal of CO_2 supply from a petrochemicals and refinery has been achieved by assessment of processes and options for CCS and use of H_2 for heating at the INEOS Grangemouth site. An end-member assessment of CO_2 for storage by application of either CCS or H_2 and CCS from the petrochemicals and refinery site at Grangemouth has been completed and shared with the ALIGN-CCUS project. Intermediate options, between the two end members, will be evaluated by application of the H_2-CCS chain tool.

The H_2-CCS chain tool, in development by WP4 of ELEGANCY, has been applied to the UK case study for H21 Leeds City Gate and the Grangemouth site. Output from the chain tool has indicated options for a least-cost network by input of quantitative data to inform H_2 infrastructure development. Additional factors have been added to the chain tool and also the constraints for integration of UK CO_2 storage site operation. Existing infrastructure and the availability of subsurface H_2 storage capacity were found to be important factors for development of a UK H_2 and CCS network. The case study presented first provision of a national-scale theoretical hydrogen storage capacity estimate for the UK (D5.4.1e).

UK input to the business model selection and risk assessment tools, in development by ELEGANCY WP3, has been by individual contact with UK stakeholder organisations and at ELEGANCY/ZEP/ALIGN-CCUS external stakeholder events. A stakeholder workshop was held earlier than scheduled in Brussels on 14 March 2019. The workshop was attended by round 24 participants from industry, government, researchers, NGOs and the EC. Input was very positive. Representatives of BEIS also the Scottish Futures Trust participated in person and by telephone. Participation and discussion between private and public organisations was regarded as very valuable to inform risk allocation and business models.

Interaction between the research activities in Task 5.4 and resultant integration of the research findings has been a strength of the ELEGANCY UK case study. There has been close collaboration between the technical, business and commercial and industry contributors throughout the project.

German case study

The German case study aims at enabling the accelerated (partial) decarbonization of the German infrastructure through H_2-CCS chains by creating structures for the transport and export of CO_2 and adapting the gas grid to increasing amounts of decarbonized H_2. For this purpose, an interdisciplinary assessment of risks and potentials of different infrastructure options was performed that identifies the creation of a dedicate H_2 transmission system that is largely based on repurposed natural gas pipelines as the most feasible option.

Technical modelling: In the Carbon Capture and Transport (CCT) option, it was shown that the pure CO_2 sources (H_2 production) can be captured very cost-effectively, often below 20€/tCO_2. Most waste incineration plants, as well as paper and steel mills, are in the midfield below 50€/tCO_2. For the total transported amount of 50.7 Mt/a, the pipeline costs are around 6€/t CO_2, with additional 1.4€/tCO_2 for transport to the Netherlands.

Compared to this, the shipping option results in twice as high costs. In the second option, by blending of 25% H_2 into the natural gas grid, emissions can be reduced by 23 $MtCO_2$/a. Additional costs for retrofitting the transport network to 25% H_2 and the distribution network to 50% H_2 are estimated to cost around €14 billion by 2035. In the third option, the separate H_2 infrastructure, a regionalised assessment of demands for the target year 2035 was carried out in the mobility, heating and industrial sectors on the NUTS3 level. The analysis revealed total demands of 140 TWh/a by 2035. This results in CO_2 savings for 56.5 $MtCO_2$/a and pipeline transport costs of 11.2 ct/kgH_2. A technical best case out of the three options results in over 100 $MtCO_2$/a being avoided.

To identify fostering and hindering factors for a successful implementation of gas infrastructure modifications in Germany, a qualitative scenario analysis was applied and the following socio-technical scenarios were developed: (1) Fossil revival instead of green progress, (2) Technology-open green transformation, (3) Green transformation with hydrogen, (4) Incremental green transformation, (5) top-down effort & conflicting interests, (6) Bottom-up effort & political inactions. The level of transformation reveals to be most characterising as it mainly determines the feasibility of this case study's infrastructure options. The higher the overall level of a country's low-carbon transformation, the more feasible extensive infrastructure modifications are. The scenarios also show that availability of technologies plays a minor role, whereas subsidies for and the use of low-carbon technologies are crucial. For the investment in infrastructure, planning security is important, which can be increased through long-term national and international strategies on renewables gases, CO_2 price and legal requirements concerning H_2 and carbon storage.

To assess the feasibility of the different infrastructure options from a **legal perspective**, relevant legal issues were selected (D5.5.1), the specific legal landscapes were mapped (D5.5.2) as well as legal hurdles and possible remedies – both immediate and at a later stage – were identified (D5.5.3). Regarding CO_2 pipelines, there is a lack of operational and clear rules, that are specifically aimed at pipelines and networks, while the legal landscape for H_2 transportation is dominated by inappropriate provisions and legal uncertainty. An analysis of the existing EU law in regard to infrastructure harmonisation shows the need for further harmonisation in regard to CCS pipeline networks and to H_2 injection: Currently, the EU provisions on CCS pipelines rather hinder the necessary coordination of CO_2 streams in a transportation network than facilitate it; in an integrated natural gas transmission network, a substantial raise of H_2 admixture will need a coordination on EU level, for which there is no legal mechanism in place.

To examine **social acceptance** of H_2-CCS chains in Germany, relevant stakeholders from politics, economy, civil society and science were interviewed and a quantitative online survey with people living in Germany was conducted. Consensual perceptions among the stakeholders in evaluating H_2-CCS chains are a general openness to technologies in the context of the energy transition and a positive perception of H_2 technology, because it represents a link to the expansion of renewable energies. Albeit to varying degrees, all stakeholders acknowledged the general potential of reducing CO_2 emissions as opportunity of CCS. The consensus must, however, be limited to the decarbonisation of industry-induced or bioenergy-induced emissions via CCS. Within the chain, CCS technology – in particular CO_2 storage – is the biggest hurdle in terms of acceptance. CCS is evaluated more positive if the technology is located outside Germany (capture and storage in Norway) than if the technology is located in/close to Germany (CO_2 capture and transport in Germany and storage in the Netherlands). Combining CCS with hydrogen technology seems to raise the acceptance of CCS technology. Furthermore, transparency of information and citizen participation during the implementation process need to be considered to achieve broad acceptance.

Norwegian case study

The Norwegian case aims to identify and develop a business case for a Norwegian H_2 value chain based primarily on natural gas. It also aims to evaluate the benefit of converting Norway's large natural gas resources to H_2 with CCS, primarily to satisfy the expected growth in worldwide demand of H_2 as an energy carrier and additionally to mitigate emissions in offshore platforms and the transport sector. For Norway, a key question is whether it is optimal to convert natural gas to H_2 in Norway and export this via new (or converted existing) pipelines, or to export natural gas in existing pipelines for distributed H_2 conversion in Europe and then import the produced CO_2 for storage in the North Sea via a new pipeline for this purpose. This case study also tries to understand the possible synergies of large-scale H_2 production from natural gas with the development of a large-scale CCS infrastructure and in particular the Norwegian full-scale CCS project.

Using the tools developed in WP4 of the project, the Norwegian case study has developed an optimal strategy and infrastructure investment scenario for Norwegian H_2 export and utilization, including the location of H_2 production, CO_2 storage and transport of both gases to/from continental Europe in synergy with the Norwegian full-scale CCS project (D5.6.3).

While the main potential for H_2 from the Norwegian perspective is the export, understanding the potential national demand for H_2 in Norway is also important. To do so, a consistent set of potential H_2 utilisation numbers for Norwegian transportation and industrial use was established (D5.6.1).

Based on these data, optimal strategies for H_2 production from Norwegian natural gas CCS to deliver H_2 for both the national and European markets was investigated. On the European side, the focus was set on delivering 1.5 million tonnes of H_2 per annum to Germany through close collaboration with the German case study. The results showed that producing H_2 in Norway and exporting it to Germany through reuse of the Europipe pipeline and a new built H_2 pipeline was the best strategy from the cost perspective compared to production of H_2 in Germany or H_2 production in Norway with export in new H_2 pipelines. From the Norwegian perspective, the location of H_2 production within Norway is governed mostly by the export possibilities, since the domestic demand is relatively low. Furthermore, the results show that large-scale H_2 production for export and national demand can help establishing significant economies of scale in the development of a Norwegian CCS infrastructure.

Finally, the possibility of converting natural to H_2 with CCS offshore to meet the H_2 demand to decarbonise of the offshore oil and gas industry was investigated. As compactness is a key aspect for offshore application, the potential of a compact technology called protonic membrane reforming was investigated. The results showed that even with such a compact technology producing H_2 offshore was expensive, and transport of H_2 from shore would most likely be a better option.

1.7.3 HSE issues

None.

1.8 WP6 – Project management and dissemination

1.8.1 Objectives

The objective is to manage and coordinate the project efficiently and according to best practices and be responsible for the implementation of the strategic dissemination and networking activities.

1.8.2 Activities and results

ELEGANCY has been managed with the intention of establishing efficient and non-bureaucratic collaboration. The project-management team has had 47 meetings via GotoMeeting or Teams. The frequency has varied, with up to weekly meetings in busy periods. The collaboration has worked well, both in form and content. In order to get a project-wide progress overview, a bi-annual cost-reporting system was implemented.

Six consortium meetings were arranged, in Brussels (2), Petten, London and Trondheim – and one in the form of a webinar series. These consortium meetings have been a combination of plenary sessions, where the key developments have been presented, and workshop-style meetings for discussion and planning on a more technical level. The project put emphasis of outward-reaching activities, and two of the consortium meetings were open for all, namely the ELEGANCY Conference (November 2018) and the ELEGANCY Webinar Series (June 2020).

In October 2018, we hosted a side event at GHGT-14 in Melbourne. The event attracted internal and external representatives from industry, funding agencies and research. Further, we put effort into organizing a Luncheon discussion meeting at the European Parliament in January 2020. A detailed description of the various ELEGANCY can be found in Section 4.1.

2 Project impact

Since the start-up of ELEGANCY, we have experienced an increased acceptance of H_2 as an important enabler for a decarbonized Europe, notably with the recent H_2 strategies issued by the EU Commission, the governments in Germany, the Netherlands and in Norway, and in the inclusion of H_2 in the UK Ten Point Plan. The Horizon Europe programme also lists H_2 as a partnership area. H_2 and CCS are highlighted as important elements in the long-term European strategy ‘A clean planet for all’, and several EU member states include CCS in their plans to reach the 2030 CO_2-emissions targets. In the 31st Madrid Forum, it was concluded that the role of natural gas in Europe is dependent on CC(U)S technologies. Further, H21 North of England illustrates the emerging H_2-CCS deployment. This has spurred interest for H_2 with CCS in European industry. For example, a pilot hydrogen-powered ferry is being designed for operation in Orkney, Scotland, and in Norway, *Teknisk Ukeblad* reports that Equinor envisages H_2-powered fast coastal passenger ships. Thus, ELEGANCY is expected to have an important impact on the future European energy system and the emergence of CCS.

ELEGANCY research is highly relevant for all aspects of future H_2-CCS chains – from closing basic science knowledge gaps critical for H_2-CCS development, to enabling major TRL advancements for key elements of the chain. It is also taking a truly holistic approach, incorporating the business case, legal and social acceptance aspects necessary for successful deployment and proposing solutions to issues in these fields. All these aspects are being integrated into an open-source, chain-analysis tool which industry, governmental organizations or policy makers can utilize. As an example, an early version of the Task 5.4 results was demonstrated to BEIS (UK Energy Ministry); these results were generated by the WP4 chain design tool. ELEGANCY applied the sum of this knowledge, using the chain tool, to specific scenarios in each participating country in order to fast-track H_2-CCS deployment. The impact of ELEGANCY on each of these components will be considerable, but the tight link between the work packages, together with strong industry involvement and the immediate applicability of results, will ensure cross-disciplinary fertilization of ideas. In short, the overall ELEGANCY impact will be significantly greater than that of each individual part.

2.1 Main ELEGANCY results and their impact

With the ELEGANCY deliverables completed and outreach activities performed, significant impact has already been achieved. Still, the full effect of the actions undertaken as part of ELEGANCY is expected to materialize later. The main expected results and their impact are described in Table 4 and can be summarized as follows:

- Realizing the H_2-CCS chain, where H_2 as an energy carrier is an integral part of the CCS system, will be a key enabler for CCS deployment due to the new economic and technical opportunities this opens. This is the ELEGANCY concept, which has been be promoted in all ELEGANCY outreach and dissemination.
- Closing knowledge gaps on the production of H_2 at different scales will enable the use of H_2 in different industrial sectors and countries – at an economically viable cost.
- Scientific results, methodology and models from ELEGANCY will de-risk CO_2 injection and storage, thus reducing a major hurdle to CCS deployment.
- The development of business models and business-case templates will facilitate economically viable deployment of CCS; it will also identify any requirements for regulatory and policy development.
- The new open-source evaluation tool for H_2-CCS integrated chains facilitates a transparent and consistent evaluation of CCS development options including uncertainty analysis of key parameters: first in the ELEGANCY case studies and later in other projects and by other actors. This is a necessary condition for optimal future decisions on CCS.
- The five national case studies have promoted CCS development by taking national considerations into account, while at the same time providing insights across borders. The inclusion of industry partners that operate across many of the ELEGANCY nations has strengthened pan-European insights.
- All case studies lead to concrete policy recommendations on the bold decisions that must be taken to rapidly deploy large-scale CCS, on both a national and European level.
- Studies of societal acceptance of CCS have given insight into public opinion boundary conditions that must be considered when developing CCS and enable future project developments to anticipate and mitigate these risks.

Table 4: Main ELEGANCY results and their impact.

	ELEGANCY results	Impact
Experimental data	**TRL 5 VPSA**/PSA cycle demonstration	Preparing the ground for adopting **single cycle adsorption processes for sharp H_2/CO_2 separation** in industrial-relevant plants.
	Petrophysical analyses of reservoir samples incorporating geochemistry, multiphase flow and elastic properties.	**De-risking storage** – reservoir characterization that incorporate the impact of heterogeneity at various scales (including those below seismic resolution) on flow and trapping
	Data on **microbial and geochemical reservoir responses to H_2**	Mitigation of risks of **loss of injectivity**
	Studies of **fibre optic monitoring** equipment degradation and protection	Ensuring **reservoirs can be monitored efficiently and reliably** during and after CO_2 storage operations
	Densities and speeds of sound for mixtures of CO_2-CO-H_2. **Phase equilibria** in CO_2-H_2-brine systems.	**Database for validation** and improvement of thermodynamic property models for these crucial systems
	Pipeline **depressurization data** and **vertical-flow data**	Reduced risk and cost of project through **safe and efficient design and operation** using validated transport and injection simulation tool.
Technical demos	**TRL 5 SEWGS** demonstration for carbon-rich gases	Accelerated demonstration activities and final industrial **uptake of capture technology in the iron and steel industries**.

Tools	**Open-source multiscale modelling**-based design and simulation tool for **technical, economic and environmental evaluation of H_2-CCS-chains**	Establish open source platform to ensure wider use. Thermodynamically and technically consistent and transparent chain evaluations. Added value to ELEGANCY case studies and for future decision makers. Dissemination of the outputs from the use of the tool to regional and national cases are already underway.
	Open-source model for economic response of the H_2-CCS chain to downstream customer market dynamics.	Enable robust design of the H_2-CCS chains to ensure they can absorb downstream customer market fluctuations without directly creating economic losses. The tools can assess the integration potential between H_2 and post-combustion CO_2 capture infrastructure for the decarbonisation of industrially relevant applications.
	Validated **transport and injection** simulation tool	Studies **quantifying uncertainties** and operational procedures and parameters. Possible tool commercialization.
	VPSA modelling tool	Facilitation of rigorous **process optimization** for adsorption-based CO_2 separation.
	Complex **thermodynamic property models** as standard for system engineering	Property models will become available as **open source package** with Cape-Open link to commonly used simulation and design tools, allowing improved estimation of physical properties in the scientific and industrial communities.
Business case development	**Market analysis** for H_2-CCS integrated chains	Provides the knowledge base regarding external risks, uncertainties, and gaps (regulatory, macro-economic, fiscal), as well as the **H_2-CO_2 business opportunities** essential for business case development within the ELEGANCY project and for use in other H_2-CCS initiatives in Europe.
	Guidance to policymakers on public measures required to support H_2-CCS integrated chains	Establishes **prioritization of public measures** for policy makers that can deliver risk reduction, overcome market failures, create acceptable risk allocation between public and private sources of capital, and result in lowering the cost of capital – thereby facilitating the development of H_2 production and CCS networks in Europe.
	Framework consisting of business models, assessment methodology, and business case templates	Supports stakeholders both within ELEGANCY case studies and elsewhere in Europe in **selecting business models and developing business cases** that reflect the prevailing performance obligations, liability interdependencies and complexities of an integrated H_2-CCS chain driven by market demand (H_2) and public sector support (CCS).
Case studies	Decarbonizing the **Dutch** economy	Enabling the integration of a multi-feed / multi product clean hydrogen generator in the Rotterdam industry. Establishment of the H-vision industry consortium.
	Efficient generation of renewable H_2 from biomass, while harvesting geothermal heat and enabling negative CO_2 emissions (**Switzerland**)	Enabling the decarbonization of heavy road transport, preparing the ground for a CO_2 storage site, and enabling negative CO_2 emissions.
	Establishing a balanced, multidisciplinary knowledge-based recommendation for the adaptation of gas infrastructure and processes to H_2 in **Germany** and CO_2 transport for export	Multidisciplinary, multi-objective knowledge basis for investments in CO_2 transport, in mixed H_2 / natural gas-grids, and in a separate H_2 grid, established. The results have strong emphasis on social and legal aspects and are used to inform industry partners and other key actors in workshops and direct contact. The results of the study have e.g. been communicated as background information to the recent German hydrogen strategy.
	Supporting planning for large-scale decarbonization of heating for **UK** cities and associated industrial clusters	ELEGANCY UK case study findings were presented to the UK Climate Change Committee, at their request, to present project objectives and emerging research findings. The findings of the UK business case were presented to National Grid and The Cabinet Office generating strong interest and follow-up actions for further use of the findings. The techno-economic modelling of UK hydrogen and CO_2 infrastructure network development and theoretical capacity for hydrogen salt cavern storage was included in a Royal Society report on future energy. Advice was sought and given to National Grid on capacities, by region for inter-day and inter-seasonal, energy storage and also sought by BEIS (Analysis Directorate).
	The **Norwegian** full-scale CCS chain and synergies with H_2 production	Providing Norwegian industry and policy makers insight into the possibilities for value addition of Norwegian natural gas through developing a suitable business case for combined H_2 production and CO_2 storage in Norway. The business case optimization is performed for size, location and investment planning.

2.2 Specific impact

H_2 supply chain and H_2-CO_2 separation

- The new VPSA process developed:
    - strengthens European competitiveness: demonstrated by patent application filed with Swiss Casale SA, and the established collaboration with core industries fast-tracking higher TRL
    - contributes to the facilitation of emergence of CCS by simplification of H_2-production-with-CCS technologies, allowing for adaptation of technology well-known in H_2-production facilities
- Work on basic oxygen furnace gas (BOFG):
    - has contributed to the decarbonization and valorisation of steel-work gases by extending the SEWGS functionality from blast furnace gas to BOF gas
    - will help facilitate the realization of CCS in Europe by the prepared multi-column demonstration in Luleå with BOFG – finalizing demonstration (TRL 7) on steel work gases which is the final step towards commercial roll-out
- De-risking the design and operation of CCS processes by
    - more accurate mixture-properties predictions with new thermodynamic models and tools
    - advanced experimental and modelling work enhancing our understanding of mixtures under relevant process conditions
- Contribution to business -model selection and -case development by:
    - Making a rigorous methodology and set of decision-support tools
    - Direct application in the ELEGANCY case studies – providing structured understanding

CO_2 transport, injection and storage

- ELEGANCY results facilitate the engineering of transport and storage systems for CO_2 stemming from hydrogen production by
    - Improved prediction of the properties of CO_2 mixed with hydrogen
    - Providing a realistic description of CO_2 pipeline and injection operations including startup and shutdown
    - Validated experimental and modelling approach to allow safe and effective CO_2 storage in underground rocks
    - Understanding the hydrogen-stimulated microbial response to CO_2 injection in underground rocks
    - Combined laboratory and field experiments with advanced modelling

- The facility installed for the ELEGANCY experiment at Mont Terri is a semi-permanent in-situ of multi-disciplinary and multi-institutional research unit, ideal for studying CO_2 storage/safety related aspects and should be continued to be used in the future. The first results at the experimental site shows so far that the Opalinus shale is a suitable cap-rock, with self-sealing properties.
- A new version of the thermophysical properties package TREND has been released. The pressure- and density-dependent combination of Gibbs and Helmholtz equations was carried out for the first time. Furthermore, this gives the possibility to calculate the whole CCS-chain consistently. TREND has more than 100 users in research institutions and companies all over the world.

Business case development for H_2-CCS integrated chains

- Development of a rigorous methodology and set of decision-support tools facilitating business model selection and business case development for hydrogen-CCS value chains. The tools are available on the ELEGANCY project website to enable improved investability of CCUS.
    - Direct application to ELEGANCY case studies, providing a structured understanding of how to deliver the UK's H21 Roadmap for phased investment in H_2-CCS infrastructure for cost effective decarbonisation of residential heating in the north of England, and providing an assessment of decarbonising Switzerland's transport sector.
    - Input to the policy discussions and legislative processes at EU level focussed on sustainable finance, CCUS projects of common interest, industrial decarbonisation, large scale use of hydrogen in the energy transition, sector coupling and revision of the EU gas legislation.

H_2-CCS chain tool and evaluation methodologies for integrated chains

- Design tool and operation-simulation tool for H_2+CCS chains

- The potential regional roll-out of H_2 and CO_2 infrastructure to support the decarbonisation of heat across the UK has been studied. The findings have been disseminated with HMG's Department of Business, Energy & Industrial Strategy, Committee on Climate Change, National Grid and other stakeholders.
    - INEOS has applied the design tool to key refining and petrochemical sites in the UK, France and Belgium, and the results have informed their carbon and energy strategy, strengthening their positioning and competitiveness. INEOS employees dedicated to using the tools are analysing the deployment potential of infrastructure under various commercial models. Throughout the various applications, the tool has demonstrated its capability to model industrial scenarios.
    - The design tool has been applied to study the decarbonisation of several industrial clusters (with industrial partners such as Vitol) in the UK, where the findings from the studies have been presented as a roadmap to facilitate the transition towards net-zero greenhouse gas emissions.
    - The chain tool was applied by TNO to investigate future deployment scenarios of both blue and green H_2 pathways in Rotterdam, and more broadly in the Netherlands.
- It has helped to identify optimal investment regions, rollout of gas/ power infrastructure, deployment rates of production, transportation and storage technologies, technology mix and scale, value of storage technologies, resource efficiency, capital investment analysis, business model analysis, impact of upstream supply chain operation, etc.
- The operational modelling tool-kit has provided insight into several aspects of the H_2 + CCS distribution network. These include sizing storage facilities, determining control strategies, and analysing how well a given infrastructure can cope with fluctuations in demand.
- Life Cycle Impact Assessment (LCIA) Indicators developed in the project can help characterize different scenarios of H_2-CCS infrastructure evolution from an environmental perspective. This can help optimize future H_2-CCS infrastructure to have a low environmental impact.
- The ELEGANCY tool Consumet is freely available and can be used to replace computationally expensive models, in the H_2+CCS sphere, and beyond.

National case studies

- The Swiss case study in ELEGANCY has resulted in a clear message given to the Swiss Federal Office of Energy, namely that H_2 and CCS will play a key role for the energy transition because they allow to decarbonize critical sectors, and to generate the negative emissions needed to reach the climate goals.
    - ELEGANCY has studied the possibility to realize the necessary amount of annual storage in the Swiss underground. Preliminary findings point towards challenging characteristics of the Swiss geology, but the understanding of the Swiss subsurface is still insufficient. Therefore, an alternative will most likely be needed, i.e. the export of CO_2 to storage sites as it is being planned by the Northern Lights consortium.
    - Our results (LCA and energy system modelling) suggest focussing the deployment of H_2 in the sector which is hardest to de-carbonize, namely the road-based freight transport. Furthermore, we see the different H_2 production pathways – including electrolysis – to be complementary, a distinction of the various shades of blue and green hydrogen is therefore not useful, as long as rigid GHG accounting is generally applied
- The close integration of the UK case study has enabled very effective presentation of emerging findings to a range of audiences, including researchers, industry and government, to promote the interest and use of the ELEGANCY research.
    - The successful application of the H_2-CCS chain tool to the UK case study INEOS Grangemouth petrochemical and refinery site was followed up by wider application to the company's non-UK sites.
    - An initial presentation of the planned UK case study research to the UK Climate Change Committee staff interested them sufficiently for a request for a follow-up in-person meeting. Their interest in the emerging findings on UK H_2 storage volumes supported additional specific research, since this parameter was found to be very influential in the outcome of network modelling.
    - The findings of the resultant UK case study report on H_2 storage has been sought by the Royal Society to inform their long-term strategy and time-line for UK energy.

    - Task 5.4 have been introduced to National Grid, operator of the UK gas transmission network, via the Climate Change Committee.
    - ELEGANCY researchers have briefed their Director of Hydrogen Transportation, UK Policy Manager and Long-term gas business strategy manager on the UK case study research. Subsequently advice has also been given on the H_2 storage capacity from the ELEGANCY research.
- The results of the German case study inform decision makers by showing feasible ways of developing a decarbonized infrastructure and identifying issues that have to be taken into account. The German case study also provides concrete policy recommendations to enable viable pathways to integrate H_2-CCS chains into the infrastructure. Thus, it facilitates the smooth integration of new projects and business models in the field.
    - Additionally, the dissemination and discussion of intermediary results and approaches contributed to the overall debate on H_2-CCS chains and connected issues.
    - For a future planning of infrastructures, the results from the German case study can be used to locate the hot spots of hydrogen demands as well as feasible CCS sites. The transport modelling shows ways to use the existing gas infrastructure and possible alternatives like ship transport for CO_2.
    - The research on the legal background of H_2-CCS infrastructure options highlights the need for further political and legal discussions and establishes starting points for these. The work helped to shape the current discussion on legal aspects of H_2 and CCS transportation networks.
    - Developing socio-technical qualitative scenarios that show possible future pathways of developments in the energy sector that are relevant for a German future H_2-CCS chain has an impact on different levels. Within academia it raises the awareness for political feasibility as an alternative criterion to cost-effectiveness to increase the success of infrastructure modification. The work also showed the need to establish a common narrative about a possible energy system transformation and initiated further collaborations with e.g. Open Grid Europe.
    - Social acceptance is a key aspect for the successful implementation of H_2-CCS chains in Germany as new energy technology and infrastructure have often led to protests in the past. The work identified central relevant. They serve as a blueprint for further decisions on infrastructure planning for politicians, project planners, companies and associations.
- The Norwegian case study has demonstrated that producing H_2 in Norway and reusing existing natural gas pipeline is attractive compared to exporting natural gas to Germany and producing hydrogen there. This information is of importance to support Norwegian strategy on delivery low-carbon energy from its natural gas resources.
    - The benefits of large-scale hydrogen production for the development of a Norwegian CCS infrastructure have been shown, thus contributing to making Norway attractive as large-scale CO_2 storage for European CO_2 emissions.
    - The results enable Aker Solution to understand what technological solutions are the most suited to deliver H_2 to support the reduction of CO_2 emissions of the Norwegian oil and gas industry.
- ELEGANCY work led to the ‘Hydrogen for Europe’ pre-project funded by a European industry consortium to give input to the development of the EU Commission’s fourth gas package.

2.3 Industrial relevance

ELEGANCY has strong industry participation, which indicates that the subject of ELEGANCY is considered to contribute to the competitiveness of the companies. ELEGANCY aims at providing technical solutions, a base for investment decisions and policy recommendations to enhance the overall business environment with respect to H_2-CCS chains and their infrastructure. This coincides with growing interest of the industry and especially gas infrastructure business in H_2 and CCS technologies to mitigate the climate impact of business activities while retaining existing assets and infrastructure. The research by ELEGANCY on important aspects on H_2-CCS chains and their feasibility may be crucial for informed business investment decisions.

Some statements from the companies are given in the following.

ELEGANCY is contributing to *Aker Solutions'* technology monitoring and preparedness to consider emerging low-carbon technology markets.

Total wants to build competence within the area of ELEGANCY in order to make the right decisions with respect to future development.

One of *Gassco's* strategic goals is to reduce climate impact by sustainable operation and business development, and export of clean H_2 from Norway to Europe is a potential solution to deliver emission-free energy to Europe. Gassco is currently building knowledge through R&D on value chain combinations with H_2 production from natural gas and CCS to understand how the gas pipeline system may be utilized in such a scenario. The value-chain model and case studies in ELEGANCY will provide valuable insight in how to find the optimal solution, based on different market situations.

Equinor highlights that ELEGANCY contributes to strengthening the competitiveness and growth of European companies by developing competence and technologies (CCS and H_2) that in the longer run will build new commercial value chains in a low carbon future e.g.

- CO_2 storage for third parties
- Clean H_2 for power
- Clean H_2 for industry (refining, steel,…)
- European companies can deliver goods (H_2) and services (CO_2 storage) to worldwide customers (e.g. Japan, Africa).

INEOS has extended the use of the H_2 / CCS chain tool, developed within ELEGANCY, beyond Grangemouth to several sites in other countries (for example the port of Antwerp). In each case, INEOS has found its application to be extremely useful in understanding the different options resulting from the different characteristics of each of these sites. This is enabling us to better understand the potential technical pathways towards net zero for these sites. The business case / policy framework requirements have also been tackled by Elegancy and the Business Case Development Toolbox is a particularly useful reference for structuring conversations with Governments and other policy makers.

OGE states that with ELEGANCY, the challenge – to enable a low-carbon economy by means of CCS and hydrogen – was addressed on many levels at an early stage. From the point of view of the OGE, ELEGANCY has been able to illuminate numerous blind spots that are significant for the actual implementation of a hydrogen-based economy. Especially the integration of the country studies has contributed significantly to the success of the project and the studies on Norway, the Netherlands and Germany offer great potential to implement a hydrogen industry that does not stop at national borders right from the start. In view of the recently presented German National Hydrogen Strategy and European Hydrogen Strategy as well as other ongoing studies and project partnerships ELEGANCY has contributed to the successful implementation of the strategies.

Uniper believes that both green and blue H_2 is needed to decarbonise Europe quickly and in a sustainable and cost efficient way. Uniper is also developing blue H_2 solutions and has found with ELEGANCY an excellent platform to shape the blue hydrogen market together with other important European stakeholders.

2.4 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

2.5 Dissemination

A crucial way of maximizing the project impact is to disseminate the results. This is described in Section 4.

3 Collaboration and coordination within the Consortium

3.1 Management structure

The project management structure is shown in Figure 4. The Executive Board (EB) is the ultimate decision-making body. All parties having signed the CA are full and equal members of the EB, having one representative each. The EB Chairperson is Dr Nils Røkke (SINTEF). The EB normally convenes on a biannual basis. Urgent decisions can be made via teleconference or e-mail between the ordinary meetings.

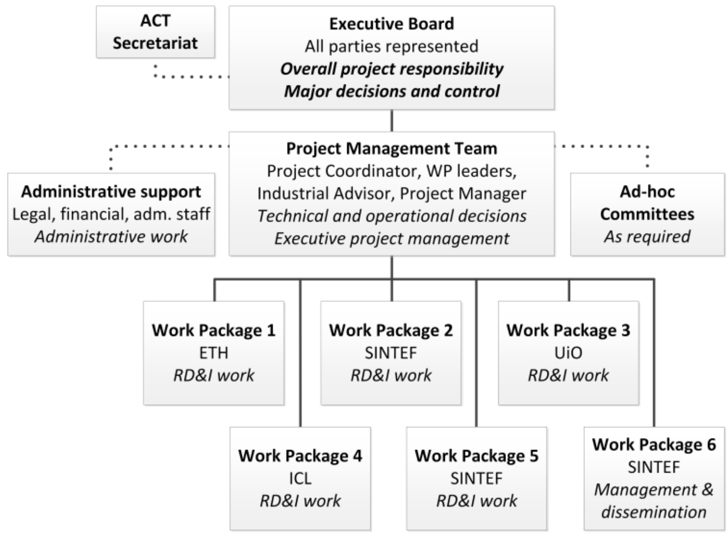


Figure 4. ELEGANCY management structure.

The Project Management Team (PMT) runs the project on behalf of the EB and is responsible for the quality and the progress of the work in the WPs and makes decisions on technical issues and project management. The PMT consists of the Project Coordinator, WP leaders and Project Manager (WP6 leader). The PMT has had web meetings (GotoMeeting or Teams) at intervals ranging six to one week, depending on the situation. Decisions in the project are delegated as extensively as possible to the lowest level, for ease of workflow and reducing bureaucracy. The WPs and national case studies have status and work meetings as needed and often at regular intervals.

3.2 Information and knowledge sharing

Documents, deliverables, software and reports are shared in a structured way between the project participants using an "e-room", which is a secure website. The main project-wide information-sharing, status and discussion arena is the biannual consortium meetings. Other workshops and meetings are arranged as needed. Dissemination and external knowledge sharing are emphasized in ELEGANCY; this is discussed in Section 4.

3.3 Transnational collaboration

Although the national subprojects have a value in their own right, the full potential of ELEGANCY could not be achieved if they were carried out in isolation. On the contrary, the international collaboration in ELEGANCY is the essence of the project, involving the exchange of experimental data, simulation results, software and ideas. This multi-faceted collaboration is also strengthened by the transnational industrial perspective taken by INEOS, Total and Equinor. The ELEGANCY partners are also international experts in their respective domains. The overall level of the work has been higher than what would have been the case if it were conducted solely at a national level. Some examples of the trans-national European collaboration are given in the following:

- Collaboration within WP1 between ETH-RUB-UU for the selection of gas mixtures of interest of the thermodynamic property model. Close collaboration, including researcher exchange, between UU and ETH on cycle development and optimization. ETH collaborated closely with UU for the development of new VPSA cycles. ETH collaborated intensively with ICL, including researcher exchange, on process modelling.
- Close collaboration between WP1, 4 and 5 on KPI definition and techno-economic framework and on the modelling of H_2 production pathways (participation in teleconferences and webinars, one-week visit of ETH PhD student at ICL, one-day workshop at ICL, for a three-month period, ETH-ICL had biweekly meetings on their modelling interfaces).
- Collaboration between WP1 (RUB), WP2 (ICL, RUB) and WP4 (ICL) to improve the thermodynamic property model software (TREND) and implementing this program into the supply chain tool (CAPE open interface). Transfer of experimental data (H_2 solubility in water and brine) from ICL to RUB (WP2).
- SINTEF (WP2) employs TREND from RUB for CFD calculations. This improves the CFD model predictions, while also submitting the thermophysical properties software to demanding robustness tests.

- ICL and ETH/SCCER closely collaborate on the analysis of core samples from Mt Terri (WP2). This includes exchange visits both ways, Skype meetings, and joint experimental campaigns and joint manuscripts.
- SCCER and BGS collaborate on the effects of microbial impurities on CO_2-based geothermal (WP2).
- SDL and FC (WP3) have conducted knowledge transfer workshops for the Netherlands and German case studies.
- Close collaboration between ETH (CH), ICL (UK), SINTEF (NO), RUB (DE), TNO (NL) and PSI (CH) on KPI definition and techno-economic framework and on the modelling of H_2 production pathways.
- Knowledge sharing and model development work with TNO, ETH, RUB, SINTEF and ICL.
- ICL, RUB and SINTEF have undertaken joint work to produce abstractions of the thermodynamic models to use in the operational modelling tool.
- SDL (UK), BGS (UK), INEOS (UK), TNO, RUB, PSI and SINTEF have all been in contact with ICL to shape the development of the chain tool for broader use.
- Within WP4, integration of life cycle indicators into the chain-tool is based on intensive collaboration between ICL, PSI, and ETH: ICL designs the chain tool, PSI supplies life cycle indicators and ETHZ provides the technology modelling required for LCA of hydrogen production technologies. This collaboration and the resulting outputs represent a strong added value of ELEGANCY.
- The chain tool is used to undertake regional and national case studies by various project partners.
- Even though the case studies in WP5 are national, there are numerous transnational benefits. The experiences of the different partners are integrated, and the results placed in a European context to enable them to have a wider deployment potential. For example, the work on methane reforming in Switzerland is of direct use in the technology evaluation taking place in the Norwegian case study, the investigation and simulation of storage operations for CO_2 from natural gas reforming for H_2 production in the UK is applicable to such operations in the other European countries, while the work on public acceptance in Germany is relevant on a European level.
- German case study: The German WP5 team had ongoing contact with the WP5 teams, especially from Norway, which lead to a steady exchange on dependencies between the countries. The coordination of the case studies within WP5 and the Consortium allows to gather perspectives and experiences from other countries relevant for the German case study (e.g. insights into the UK H21 project, expert assessment of the Dutch CCS storage capacities). The sociological team collaborates with the Swiss social acceptance researchers to identify overlaps and to enhance understanding of acceptance beyond the German case study. The cooperation with WP3 regarding the risk assessments tools (including workshops) provides input regarding the overall European experience in respect of H_2-CCS chains. With the industrial partners OGE and UNIPER a collaboration in masters theses took place and an ongoing discussion on hydrogen topics was performed over the project time. The legal team of the German case study aligned its research with the legal team of WP3 to combine expertise and to avoid unnecessary duplication of work.
- Swiss case study: The assessment of thermochemical H_2 production pathways was executed in WP1 and is heavily used for the LCA and energy system modelling in WP5. The Mont Terri experiments and related lab measurements of WP2 provided important input for modelling and safety assessment. The business case framework applied to the Swiss case study was developed within WP3. There are also strong links between the modelling work and the H_2-CCS chain tool from WP4.
- UK case study: monthly meetings of the UK case study has enabled feedback from WP3 and WP4 to Task 5.4. Consortium collaboration to demonstrate the business case tools and the benefit of their application to the Netherlands case study via an ELEGANCY WP3 and WP5 webinar/Skype meeting has been coordination enabled via Task 5.4. Expertise on facilitation of risk assessment for site selection of UK partners has been applied to the Swiss case study.
- The Norwegian case study had close collaboration and exchange of data with the German case study, as the best strategy to deliver H_2 to Germany from Norwegian natural gas was a key focus for the Norwegian case study. The Norwegian case study has been following the tool development and have provided valuable feedback to facilitate future modelling of the case studies. The Norwegian case studies has also been in discussions with international actors to identify the potential of H_2 from Norway to Europe.

3.4 Covid-19 situation

The corona virus pandemic affected the project execution from March 2020. The final events could not be carried out as physical meetings, so they were held as webinars instead. Some deliverables were delayed, as laboratories closed down partially or fully, and collaboration planned as physical meetings had to be done differently. Some key personnel were directly affected by Covid-19. The ELEGANCY PMT mapped the situation, reported to the EB and ACT, and the finalization of the project was adapted in a pragmatic way. With a delay of three months, the project output is deemed to be of full quality.

4 Dissemination activities and list of publications

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.

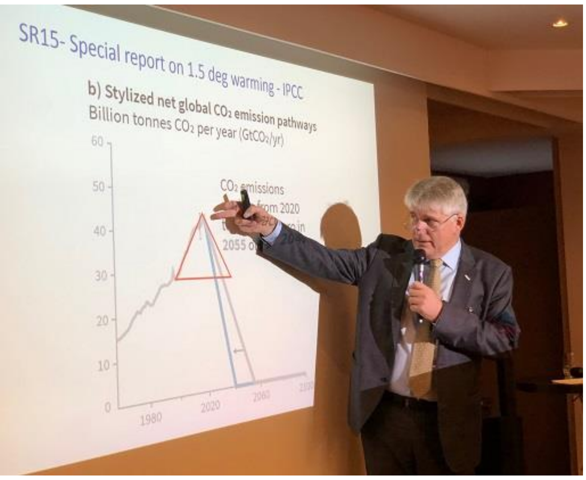
4.1 Major ELEGANCY events

ELEGANCY Conference

On 8 November 2018, we hosted the ELEGANCY Conference in Brussels. This was an open event aimed at bringing scientists, industry and policymakers together, and it achieved a total of 85 participants. The programme encompassed ELEGANCY results and external points of view:

09:00	Registration
09:30	• *Welcome, HSE and introduction* Nils A. Røkke, SINTEF/EERA
09:50	• *ELEGANCY overview* Svend T. Munkejord, SINTEF • *Low carbon solutions* Steinar Eikaas, Equinor
10:40	Coffee break & Poster session
11:00	• *H21* Dan Sadler, Northern Gas Networks • *ELEGANCY case studies* Gunhild A. Reigstad, SINTEF • *Climate effects of various CCU and CCS measures* Ana Serdoner, Bellona
12:30 – 13:30	Lunch
13:30	• *H_2@Scale* Bryan Pivovar, National Renewable Energy Laboratory • *Laboratory studies to understand the controls on flow and transport for subsurface CO_2 storage* Ronny Pini, Imperial College London Anne Obermann, ETH Zürich
14:30	Coffee break & Poster session
15:00	• Accelerating the energy transition – EU perspective Vassilios Kougionas, European Comission • *Economic and legal barriers and opportunities* Catherine Banet, University of Oslo • *Can we produce "green steel" with "blue hydrogen"?* Jorgo Chatzimarkakis, Hydrogen Europe
16:30	End of session

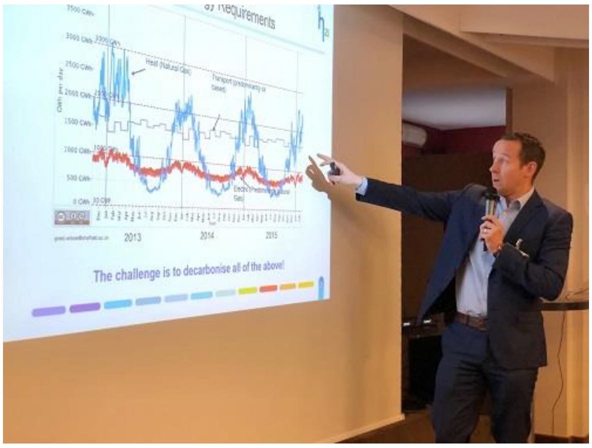
We received positive feedback during and after the conference. Some photographic glimpses are shown in the following. The ELEGANCY website (see next section) features the presentations, videos from the conference and more.



Nils Røkke (SINTEF)


Svend Tollak Munkejord (SINTEF)

Steinar Eikaas (Equinor)



Dan Sadler (Northern Gas Networks)


Ana Serdoner (Bellona)

Bryan Pivovar (National Renewable Energy Laboratory)

Ronny Pini (ICL)

Anne Obermann (ETH)

Catherine Banet (UiO)

Vassilios Kougionas (European Commission)

Jorgo Chatzimarkakis (Hydrogen Europe)

Consortium meeting in GERG headquarters, 9 November 2018

Luncheon discussion in the EU Parliament

More than 50 energy researchers, European policymakers, MEPs and their staff, press and other interested parties gathered in the EU Parliament in January 2020 to hear the very latest news on hydrogen with CCS as a key element in Europe's energy transition.

Chris Davies MEP with SINTEF's Nils Røkke during the ELEGANCY meeting at the EU Parliament.

The event was hosted by Chris Davies MEP, who began by outlining what he called some of the "blind spots" in the European Parliament over climate change:

"It's often said that there's no silver bullets in fighting climate change. That's true, because we need every available technology to make a difference. But policymakers sometimes have blind spots and one of those is the generation of Hydrogen from natural gas with CCS as distinct from generation through electrolysis from renewable electricity. If we want to use hydrogen at the scale that is going to be required to reach the net zero CO_2 emission goals by 2050 then we are going to need a lot of it, which means we need both methods."

The presenters during the two-hour event included:

Nils Røkke, SINTEF: "Clean Hydrogen: Unleashing production and infrastructure for a net zero emission Europe"

Baktash Nasiri, Uniper Energy Storage: "Hydrogen from the industrial perspective: Transformation of German gas infrastructure to decarbonise energy systems using Hydrogen as a clean energy carrier"

Catherine Banet, University of Oslo: "Fast-tracking pathways for clean Hydrogen – Legal and policy frameworks for redesigning gas markets"


ELEGANCY project members discuss hydrogen with CCS solutions with representatives from the EU Parliament.

A more detailed account of the meeting, including the slides of the presentations, can be found at the project website.

ELEGANCY Webinar Series

The project had planned to host a second ELEGANCY Conference towards the end of the project. However, the corona virus pandemic made it impossible to arrange physical meetings. Therefore, the final dissemination event was run in the form of a webinar series. Such a digital event precludes small talk at lunch and making new contacts, but, on the other hand, made it possible to reach a larger external audience. Indeed, we had 498 unique registrants for the webinar series. There were 255 participants for the main webinar, and between 109 and 160 for the rest of the webinars. The slides have been published and recordings have been distributed to ELEGANCY consortium participants and the registrants – numerous participants have shown interest for this.

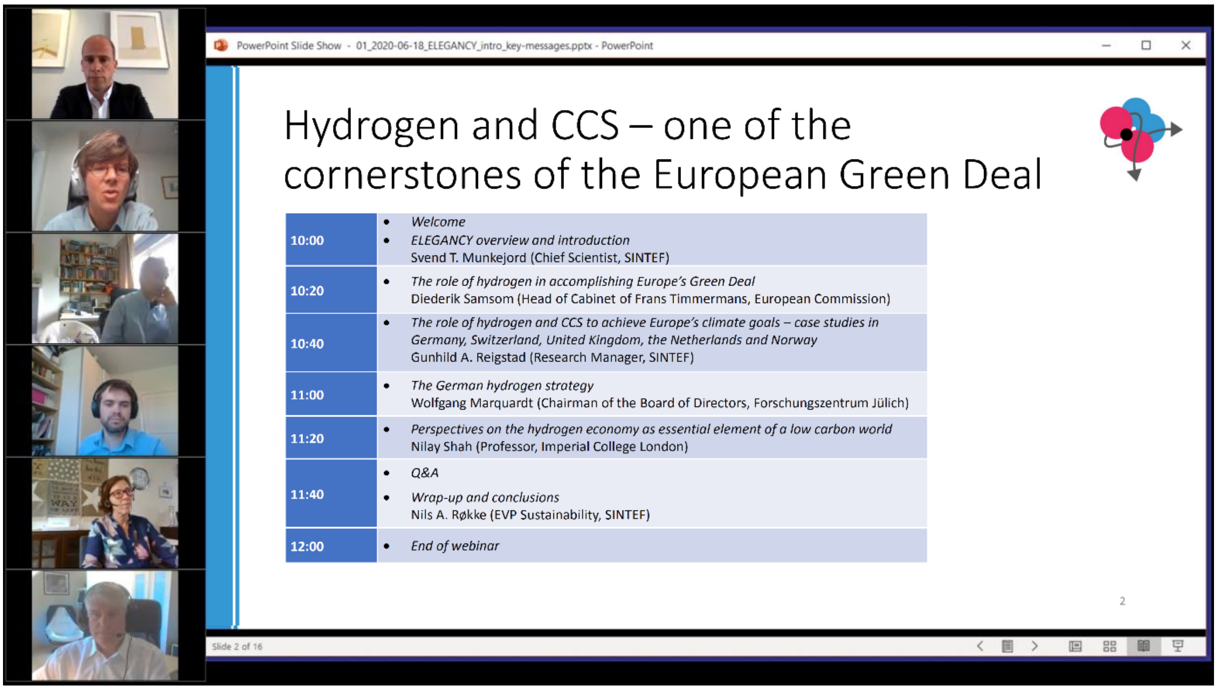


Figure 5. Svend T. Munkejord opens the ELEGANCY Webinar Series. From the top: D. Samsom, S.T. Munkejord, N. Shah, H.L. Skarsvåg, A. Hilmo, N.A. Røkke.

Webinar 1: Hydrogen and CCS – one of the cornerstones of the European Green Deal

18 June 2020 at 10:00—12:00 CEST

Programme

- ELEGANCY overview and key messages (Svend T. Munkejord, Chief Scientist, SINTEF)
- The role of hydrogen in accomplishing Europe's Green Deal (Diederik Samsom, Head of Cabinet of Frans Timmermans, European Commission)
- The role of hydrogen and CCS to achieve Europe's climate goals – case studies in Germany, Switzerland, United Kingdom, Netherlands and Norway (Gunhild A. Reigstad, Research Manager, SINTEF)
- The German hydrogen strategy (Wolfgang Marquardt, Chairman of the Board of Directors, Forschungszentrum Jülich)
- Perspectives on the hydrogen economy as essential element of a low carbon world (Nilay Shah, Professor, Imperial College London)
- Q&A
- Wrap-up and conclusions (Nils A. Røkke, Executive Vice President, SINTEF)

Webinar 2: ELEGANCY – Unlocking opportunities and addressing challenges for large-scale hydrogen provision in Germany, Switzerland, United Kingdom, the Netherlands and Norway

19 June 2020 at 10:30—12:15 and 13:30—14:45 CEST

Programme

- Welcome and introduction (Gunhild A. Reigstad, SINTEF, and Nilay Shah, ICL)
- A Roadmap for the introduction of a low carbon industry in the Rotterdam Region and the Dutch H_2 backbone (Floris van de Beek, TNO, and Lukas Weimann, UU)
- Business case and opportunities for a Norwegian hydrogen and value chain synergies with the Norwegian large-scale CCS deployment (Simon Roussanaly, SINTEF)

- Hydrogen and CCS to reduce emissions from domestic heating and industrial clusters, H21 North of England and Grangemouth case studies, UK (Maxine Akhurst, BGS, and Ward Goldthorpe, SDL)
- A multi-disciplinary approach of assessing strategic infrastructure development for natural gas, CO_2 and hydrogen in Germany (Stefan Flamme, RUB)
- Identifying the role of hydrogen and CCS for reaching the Swiss climate targets (Marco Mazzotti, ETH)
- Summary of impacts for the Netherlands, Norway, UK, Germany and Switzerland (Gunhild A. Reigstad and Nilay Shah)

Webinar 3: Hydrogen supply and CO_2 injection and storage

22 June 2020 at 10:00—11:30 and 12:30—14:00 CEST

Low-carbon hydrogen supply with CCS

- Advanced Property Models for Processing, Transport and Storage of Gas Mixtures Containing H_2 (Roland Span, RUB)
- Optimization of Sorption Enhanced WGS for use with Basic Oxygen Furnace Gas from the steel plant (Jean Pierre Pieterse, TNO)
- Biomass to hydrogen with CCS: can we go negative? (Cristina Antonini, ETH)
- Demonstration of VPSA for CO_2-H_2 co-production (Anne Streb, ETH)
- Life Cycle Analysis of low-carbon H_2 supply with CCS (Karin Treyer, PSI)

ELEGANCY – CO_2 transport, injection and storage

- The influence of thermodynamic properties on CO_2 storage in saline aquifers (Martin Trusler, ICL)
- Towards an accurate and consistent description of thermodynamic properties of mixtures of CO_2 with brines (Roland Span, RUB)
- Depressurization of CO_2-N_2 and CO_2-He in a tube (Svend T. Munkejord, SINTEF)
- Laboratory studies to understand the controls on flow and transport for CO_2 storage (Sam Krevor and Ronny Pini, ICL)
- Mt. Terri experiment: Fault trapping (Antonio Pio Rinaldi and Alba Zappone, SCCER)
- Microbial activity in response to H_2 in a CO_2-rich stream (Simon Gregory, BGS)

Webinar 4: Business case development and hydrogen-CCS chain tool

23 June 2020 at 10:00—11:30 and 12:30—14:00 CEST

ELEGANCY – Business case development for H_2-CCS integrated chains

Ward Goldthorpe (SDL), Jonathan Schwieger (FC), Catherine Banet (UiO):

- Introduction and objectives (Ward Goldthorpe, SDL)
- Business context assessment (Ward Goldthorpe, SDL, Jonathan Schwieger, FC, and Catherine Banet, UiO)
- Business risk identification and mitigation (Ward Goldthorpe)
- Business models development, and business case development and assessment (Lionel Avignon, SDL)

H_2-CCS chain tool and evaluation methodologies for integrated chains

- Overview and rationale of the work package; modelling framework (Nilay Shah, ICL)
- Model reduction approach and rationale (Julian Straus, SINTEF)
- Integrated design optimisation and LCA – method development and application study (Nixon Sunny, ICL and Karin Treyer, PSI)
- Overview of operational modelling, including local thermodynamic models (Edward Graham, ICL)

4.2 Digital communication

A project website has been established using SINTEF's project website tools and templates. Since ELEGANCY is a multi-partner project, we have made www.elegancy.no as an easy-to-use pointer. The website 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 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).

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. In Table 5, an overview of the most recent blogposts and their outreach is presented.

Table 5: Overview of ELEGANCY news items / blog posts and their reading statistics as of 2020-12-04.

Title	**Author**	**Date**	**Views**	**Avg reading time**
Unveiling the Dynamics of CO_2 Injection into Underground Storage	Svend Tollak Munkejord	2020-11-09	186	3:17
Hydrogen: The Future Is Green, But the Path There Is Multicoloured	Stefania Gardarsdottir	2020-06-30	730	3:55
Hydrogen economy: Too good to be true for Norway?	Nils A. Røkke	2020-06-24	428	3:09
Webinar: Hydrogen from Norwegian Natural Gas to Decarbonise Europe & Norway	Simon Roussanaly, Catherine Banet	2020-06-15	913	3:42
ELEGANCY Webinar Series on CCS and Hydrogen	Svend Tollak Munkejord	2020-05-11	2154	4:22
Taking the Hydrogen & CCS debate to the Heart of Europe	David Nikel	2020-02-20	566	4:00
ELEGANCY –- progress meeting in London	Svend Tollak Munkejord	2019-12-05	153	3:18
H_2/CCS chains in Germany – Social Perception and Acceptance	Sabrina Glanz, Anna-Lena Schönauer	2019-12-05	177	2:45
Consumet: Constructor of surrogate models and metamodels	Julian Status, Jabir Ali Ouassou, Rahul Anantharaman	2019-11-04	159	2:44
A framework for interdisciplinary collaboration and evaluation of infrastructure transformation in Germany	Daniel Benrath, Stefan Flamme, Sabrina Glanz, Franziska M. Hoffart	2019-10-09	103	1:36
ELEGANCY: From Helmholtz-type Equations of State to Legal Conditions	Svend Tollak Munkejord	2019-09-05	364	2:49
ELEGANCY Dutch Case Study: TNO initiates industrial participation with H-Vision project	Octavian Partenie, Rajat Bhardwaj, Robert de Kler, Erwin Giling	2019-05-23	848	4:11
ELEGANCY WP3: Joint workshop on CCS risk sharing and business model selection	Ward Goldthorpe	2019-04-03	124	0:57
ELEGANCY Consortium meeting in a historic setting	Hans L. Skarsvåg	2018-12-12	248	2:09
ELEGANCY Conference 2018	Svend Tollak Munkejord	2018-12-12	476	3:21
ELEGANCY researcher, Marco Mazzotti, chairs Gordon Research Conference on CCUS	SINTEF	2018-10-23	63	1:07
Updates from the Mont Terri experiment: Studying Caprock and Fault Sealing Integrity	Alba Zappone, Michèle Marti, Melchior Grab, Quinn Wenning	2018-10-17	125	2:17
Joint workshop on CCS risk and liability sharing	Catherine Banet	2018-09-25	227	2:13

ELEGANCY collaboration with ALIGN-CCUS ‘sister’ Accelerating CCS Technologies (ACT) project	Maxine Akhurst	2018-08-25	134	1:37
ELEGANCY – progress meeting in Petten	Svend Tollak Munkejord	2018-05-28	259	2:27
Future Business Models for CCS: Hydrogen from natural gas	Mona J. Mølnvik	2018-03-21	2303	5:17
Part 2: Presenting ELEGANCY at the ZEP Network Technology meeting in Brussels	Gunhild A. Reigstad	2018-03-14	81	2:02
Part 1: Presenting ELEGANCY at the ZEP Network Technology meeting in Brussels	Gunhild A. Reigstad	2018-03-13	313	2:02
Mont Terri Experiment: Studying Caprock and Fault Sealing Integrity	Alba Zappone, Michèle Marti	2018-03-07	185	2:41
ELEGANCY – accelerating CCS deployment by combining CCS and hydrogen	Svend Tollak Munkejord	2017-11-07	446	3:24
Hydrogen is on a mission to decarbonise the world	Nils A. Røkke	2017-10-03	259	3:18

4.3 Dissemination at Mt Terri

The experiment site in the Mont Terri Lab stimulated the interests of the press. The experiment was described in the context of CCS in many articles on local, national and international newspapers. Some interviews and clips were shown as part of television broadcasts both in Switzerland and in some European countries. The site of the experiment is regularly visited by a large audience of non-experts, schoolchildren and researchers interested in storage.

4.4 List of publications, presentations, and other dissemination activities

4.4.1 Popular science presentations

- S. T. Munkejord, November 2018, Enabling a Low-Carbon Economy via Hydrogen and CCS, ELEGANCY Conference, Brussels, Belgium.
- S. Eikaas, November 2018, Low Carbon Solutions (Equinor), ELEGANCY Conference, Brussels, Belgium.
- G. A. Reigstad, November 2018, ELEGANCY Case Studies, ELEGANCY Conference, Brussels, Belgium.
- R. Span, November 2018, Perth: R&D Needs for Hydrogen Utilization – German Perspective and Experience, H_2-Workshop Australian Centre of LNG Futures, Perth, Australia.
- J. Pearce, M. Akhurst, September 2019, How much CO_2 storage capacity will the UK need for a low-carbon industry cluster to meet future carbon budgets?, STEMM-CCS CO_2 Storage Research Showcase, Brussels, Belgium.
- M. Akhurst, 2019, November, Reducing atmospheric CO_2 emissions from industrial sources, domestic and commercial heating in Scotland, SAGES conference on ‘Global Climate Challenges to a Blue Green Economy’.
- C. Banet, October 2019, Sector-coupling in the North Sea: decarbonising and creating new value by coupling the energy systems. Seizing a window of opportunity, Beyond Oil 2019, Bergen, Norway.
- G. A. Reigstad, November 2019, Enabling a low-carbon economy via hydrogen and CCS – the ELEGANCY project, EGATEC 2019, Groningen, Netherlands.
- C. Banet, November 2019, Decarbonising the European energy industry. Opportunities in the business area of carbon capture and storage., European Utility Week 2019, POWERGEN Europe, Paris, France.
- C. Banet, January 2020, Sector-coupling: EU law and energy policy strategy, Let's Talk about Energy, UiO:Energy, Oslo, Norway.

- N. A. Røkke, January 2020, Clean hydrogen: Unleashing production and infrastructure for a net zero emission Europe, Zero Emissions with Hydrogen NOW!, European Parliament, Brussels, Belgium.
- B. Nasiri, January 2020, Transformation of German gas infrastructure to decarbonise energy systems using hydrogen as a clean energy carrier, Zero Emissions with Hydrogen NOW!, European Parliament, Brussels, Belgium.
- C. Banet, January 2020, Fast-tracking pathways for clean hydrogen - Legal and policy frameworks for redesigning gas markets, Zero Emissions with Hydrogen NOW!, European Parliament, Brussels, Belgium.

4.4.2 Scientific presentations

Oral presentations

- A. Streb, February 2018, H_2 purification with integrated CO_2 separation by (V)PSA, Process-Net Adsorption, Kiel, Germany.
- A. Maurer, June 2018, Sound speed measurements in binary gas mixtures containing hydrogen using an acoustical spherical resonator, Twentieth Symposium on Thermophysical Properties, Boulder, CO, USA.
- C. Antonini, October 2018, Low Carbon Hydrogen Production with VPSA for H_2/CO_2 Purification, GHGT-14, Melbourne, Australia.
- S. T. Munkejord, October 2018, Dynamic simulation of CO_2 injection wells, GHGT-14, Melbourne, Australia.
- R. Pini, November 2018, Laboratory Studies to Understand the Controls on Flow and Transport for CO_2 Storage, ELEGANCY Conference, Brussels, Belgium.
- C. Banet, November 2018, Enabling the H_2-CCS value chain: Business models, risk mitigation, incentives and legal framework, ELEGANCY Conference, Brussels, Belgium.
- J. Pearce, M. Akhurst and J. Booth, November 2018, UK profiles of CO_2 supply for H_2 and CCS, present day to 2100, Green and Blue Hydrogen Seminar, Scottish Hydrogen and Fuel Cell Association, ECCI, Edinburgh, Scotland.
- C. Bauer, November 2018, An environmental assessment of road freight transport, SCCER Workshop ETHZ, Zurich, Switzerland.
- F. Hoffart, S. Glanz, November 2018, Energy infrastructure transformation in Germany - a stakeholder-based economic and sociological approach, Sustainable Urban Energy Systems Conference, Delft, Netherlands.
- F. Hoffart, S. Glanz, February 2019, Energy infrastructure transformation in Germany - a stakeholder-based economic and sociological approach, International Conference for Clean and Green Energy, Milano, Italy.
- D. Benrath, March 2019, Blind Spots in the Harmonisation for an H_2-CCS chain, Harmonisation in Environmental and Energy Law. Hasselt University, Belgium.
- A. Streb, M. Hefti, M. Gazzani, M. Mazzotti, May 2019, On how adsorption enables the simultaneous production of H_2 and CO_2 from a multicomponent feed, Fundamental of Adsorption, Cairns, Australia.
- A. Streb, May 2019, On the potential of adsorption processes for low-carbon hydrogen production with carbon capture, Gordon Research Seminar on CCUS, Les Diablerets, Switzerland.
- A. Zappone, June 2019, ELEGANCY CS-D at Mont Terri in Switzerland: an in-situ experiment to monitor caprock and fault sealing integrity, ECCSEL Workshop, Switzerland.
- S. Glanz, A.-L. Schönauer, June 2019, Public acceptance of H_2/CCS chains in Germany, TCCS-10, Trondheim, Norway.
- S. T. Munkejord, June 2019, Dynamic simulation of CO_2 injection wells taking the near-well reservoir into account, TCCS-10, Trondheim, Norway.
- G. A. Reigstad, June 2019, Accelerated decarbonization of Europe's energy system – how case studies are applied in the ELEGANCY project to secure adaption of improved technologies, knowledge and tools to national and regional business case opportunities for hydrogen - CCS chains, TCCS-10, Trondheim, Norway.

- N. Sunny, June 2019, A systematic assessment of low-carbon hydrogen and CCS options for the de-carbonisation of heat, TCCS-10, Trondheim, Norway.
- K. Treyer, June 2019, Biogas reforming with CCS and DACCS: A life cycle assessment of carbon dioxide removal from the atmosphere, TCCS-10, Trondheim, Norway.
- B. Semrau, June 2019, Implementation of a Gibbs energy explicit seawater equation in Helmholtz mixture models to represent the interaction of brines with CCS-relevant fluids, TCCS-10, Trondheim, Norway.
- C. Antonini, June 2019, Optimal process design of MDEA CO_2 capture plant for low-carbon hydrogen production, TCCS-10, Trondheim, Norway.
- C. Bauer, June 2019, Road transport decarbonization via reforming based H_2 with CCS – a Life Cycle Assessment, TCCS-10, Trondheim, Norway.
- A. Zappone, August 2019, Imaging the long-term loss of faulted hos-rock or cap-rock integrity, IEAGHG Monitoring Network and Environmental Research Workshop, Calgary, Canada.
- C. Antonini, September 2019, Analysis of Hydrogen Supply Chains for Swiss Mobility, 12th European Congress of Chemical Engineering, Florence, Italy.
- D. I. Ferrer, September 2019, H_2-CCS chain tool and evaluation methodologies for integrated chains, 12th European Congress of Chemical Engineering, Florence, Italy.
- A. Streb, September 2019, On the potential of adsorption processes for low-carbon hydrogen production with carbon capture, 12th European Congress of Chemical Engineering, Florence, Italy.
- Q. C. Wenning, Madonna, R. Pini, A. Zappone, September 2019, Fracture aperture and flow evolution due to confined shear displacement using X-ray computerized tomography on crystalline and clay-rich rocks, 13th EURO-Conference on Rock Physics and Geomechanics, Potsdam, Germany.
- R. Span, September 2019, Process Simulation - The Need for Accurate Thermodynamic Property Models, Hydrogen Liquefaction & Storage Symposion, Perth, Australia.
- N. Sunny, N. MacDowell, N. Shah, September 2019, ELEGANCY project: UK case outcomes, UK CCS Research Centre, Programme Meeting, Edinburgh, Scotland.
- N. Sunny, N. Mac Dowell, N. Shah, 2019, November. Large Scale Deployment of Low Carbon Hydrogen and CCS Value Chains for the Decarbonisation of Heat: Novel Methods and Insights. 2019 AIChE Annual Meeting. AIChE.
- J. Straus, B.R. Knudsen, R. Anantharaman, 2019, November. Sampling Domain Reduction for Surrogate Model Generation–Applied to Hydrogen Production with Carbon Capture. In 2019 AIChE Annual Meeting, AIChE.
- N. Sunny, N. Mac Dowell, N. Shah, 2020, February. Design of low-carbon hydrogen and CCS infrastructure for the decarbonisation of heat in the UK, H_2FC Supergen Research Conference, Nottingham, UK.
- B. Semrau et al., October 2019, Representation of the Interaction of Brines with CCS-Relevant Fluids by a Gibbs-Energy Explicit Seawater Equation and Helmholtz Mixture Models, 12th ATPC Conference, Xi'an China.
- F. Hoffart, October 2019, Gas Infrastructure Modification in Germany – Developing Scenarios for an Economic Evaluation, 14th SDEWES Conference, Dubrovnik, Croatia.
- S. Glanz and A.-L. Schönauer, October 2019, Towards a low-carbon society – chances and risks from a stakeholder perspective, 14th SDEWES Conference, Dubrovnik, Croatia.
- Q. C. Wenning, October 2019, Progress of a faulted caprock integrity experiment at the Mont Terri Rock Laboratory, 2nd Pre-ACT Stakeholder Meeting, Freiburg, Switzerland.
- J. Vente, October 2019, Valorisation of steel off-gases to enable economic viable CO_2 storage and utilization, Baltic Carbon Forum, Tallinn, Estonia.
- D. Benrath, October 2019, The legal contribution to the German Case Study: Legal hurdles for CCS and hydrogen pipelines, Institute for Mining and Energy Law, Bochum, Germany.
- A. Rinaldi, A. Zappone, November 2019, The CS-D experiment at the Mont Terri Laboratory: site-characterization and preliminary results of long-term injection, 17th Swiss Geoscience Meeting, Freiburg, Germany.

- A.Rinaldi, November 2019, Coupled processes in clay during fault injections, Decovalex Coupled Processes Symposium, Brugg, Switzerland.
- L. Weimann, June 2019, On the role of H_2 storage and conversion for wind power production in the Netherlands, 29th European Symposium on Computer Aided Process Engineering, Eindhoven, The Netherlands.
- L. Weimann, August 2019, Modeling gas turbines in multi-energy systems: a linear model accounting for part-load operation, fuel, temperature, and sizing effects, International Conference on Applied Energy, Västerås, Sweden.
- L. Weimann, October 2019, Planning and design the decarbonization of large industrial clusters, The Netherlands Process Technology Symposium, Eindhoven, The Netherlands.
- R. Span, January 2020, The German Hydrogen Strategy and the Status of the Description of Thermodynamic Properties of Hydrogen and Hydrogen-Rich Mixtures, HYDROGENIUS and I2CNER Joint Research Symposium, Fukuoka, Japan.
- R. Span, February 2020, The German Hydrogen Strategy and the Status of the Description of Thermodynamic Properties of Hydrogen and Hydrogen-Rich Mixtures, Chemical Engineering Seminar, Tokushima University, Japan.
- Q.Wenning, February 2020, Swelling effects on fluid flow in shale fractures, Event hosted by Prof. Suzanne Hangx, Utrecht University, Netherlands.
- Q. C. Wenning, February 2020, Shale properties, Shell Technology Centre, Amsterdam, Netherlands.
- S. Gregory, March 2020, Microbiology of subsurface gas storage, Department of Civil Engineering and Geoscienses, Delft University of Technology, Netherlands.
- D. Benrath, March 2020, The European perspective on hydrogen regulation, IBE-Jahrestagung: Die Gaswirtschaft in der Energiewende, Ruhr-Universität Bochum, Germany.
- L. Weimann, March 2020, Design and optimization of multi-energy systems, RESILIENT Island project workshop, University of Curacao, Curacao.
- M. Grab, A. Zappone et al., May 2020, Active seismic monitoring of CO_2-saturated brine injection into a fault (CS-D experiment in the Mont Terri Rock Laboratory), online presentation, EGU2020-21588 doi:10.5194/egusphere-egu2020-21588, EGU2020, Online.
- Q. C. Wenning et al., May 2020, Fault hydromechanical characterization and CO_2-saturated water injection at the CS-D experiment (Mont Terri Rock Laboratory), online presentation, EGU2020-19243, doi:10.5194/egusphere-egu2020-19243, EGU2020, Online.
- A. Rinaldi et al., May 2020, Coupled processes in clay during tunnel excavation, online presentation, EGU2020-18041, doi:10.5194/egusphere-egu2020-18041, EGU2020, Online.
- D. Benrath, July 2020, CCS und H_2 Pipelines: Rechtswissenschaftliche und rechtliche Herausforderungen, Dissemination Online Workshop CCS- und H_2-Pipelineinfrastrukturen, Online.
- D. Benrath, July 2020, Key Findings, Dissemination Online Workshop CCS- und H_2-Pipelineinfrastrukturen, Online.
- S. Glanz, July 2020, Social Acceptance of H_2 and CCS technologies, Dissemination Online Workshop CCS- und H_2-Pipelineinfrastrukturen, Online.
- L. Weimann, September 2020, Energy system design for the production of synthetic carbon-neutral fuels from air-captured CO2, 30th European Symposium on Computer Aided Process Engineering, Online.
- A. Streb, March 2021, Adsorption in the context of clean hydrogen production: process intensification by integrating H_2 purification and CO_2 capture, GHGT-15.
- M. Akhurst, March 2021, Tools and options for hydrogen and CCS cluster development and acceleration – UK case study, ELEGANCY project, GHGT-15 abstract accepted.
- F. Sebastiani et al, April 2021, Modelling of CO_2 and H_2O interaction during adsorption cycles on hydrotalcite for SEWGS applications, GHGT-15.
- C. Bauer, March 2021, Need for carbon removal technologies to meet stringent climate targets in Switzerland – an energy system model based analysis, GHGT-15, Abu Dhabi.

- C. Bauer, March 2021, Hydrogen production from natural gas and biomethane with carbon capture and storage – a techno-environmental analysis, GHGT-15, Abu Dhabi.

Poster presentations

- L. Weimann, June 2018, Decarbonization of the Dutch industry by integrated design of multi-energy systems with carbon capture, IEAGHG CCS Summer School, Trondheim, Norway.
- R. Span, August 2018, The Interdisciplinary Approach of the German Case Study to Enable a Low Carbon Economy by Hydrogen and CCS, International Conference on Applied Energy, Hong Kong, China.
- F. Hoffart, August 2018, Macroeconomic Considerations on Transforming the Energy, International School on Energy Systems, Kloster Seeon, Germany.
- A. Streb, October 2018, Hydrogen Purification with Integrated CO_2 Separation by vacuum pressure swing adsorption (VPSA), GHGT-14, Melbourne, Australia.
- J. Boon and J. F. Vente, October 2018, Valorisation of residual streams for economically effective CO_2 sequestration, GHGT-14, Melbourne, Australia.
- A. Streb, November 2018, Hydrogen purification with integrated CO_2 separation by vacuum pressure swing adsorption (VPSA), ELEGANCY Conference, Brussels, Belgium.
- S. T. Munkejord, November 2018, CO_2 Transport, Injection and Storage, ELEGANCY Conference, Brussels, Belgium.
- C. Banet, November 2018, Business case development for H_2-CCS integrated chains, ELEGANCY Conference, Brussels, Belgium.
- R. Bhardwaj, November 2018, Decarbonization of Rotterdam Port Area, ELEGANCY Conference, Brussels, Belgium.
- A. Guidolin, November 2018, The Swiss case study: Exemplary research highlights, ELEGANCY Conference, Brussels, Belgium.
- F. Hoffart, November 2018, The German Case Study: Macroeconomic Considerations, ELEGANCY Conference, Brussels, Belgium.
- G. A. Reigstad, November 2018, The ELEGANCY Case Studies, ELEGANCY Conference, Brussels, Belgium.
- M. Akhurst, November 2018, Accelerating CCUS: A Global Conference to Progress CCUS, ERA-Net ACT stand, IEA/BEIS, International Ministrial Conference, Edinburgh, Scotland.
- M. Akhurst, November 2018, Enabling a Low-Carbon Economy via H_2 and CCS, UK CCS RC Network Conference, Edinburgh, Scotland.
- M. Akhurst, February 2019, Reducing your carbon footprint at home and your travel by private and public transport: Hydrogen and Carbon Capture & Storage (H_2 and CCS), Decarbonisation and Resource Management Workshop BGS, Keyworth, England.
- R. Pini, S. Rabha, March 2019, Impact of subcore-scale permeability heterogeneity on solute mixing in a microporous limestone: experiments and numerical simulations, 11th Interpore Annual Meeting, Valencia, Spain.
- A. Zappone, A. P. Rinaldi, M. Grab, April 2019, Mont Terri CS-D: Mont Terri CS-D: Mont Terri CS-D:an in-situ experiment to monitor for caprock and fault sealing, European Geoscience Union general Assembly 2019, Wien, Austria.
- A. Streb, M. Hefti, M. Gazzani, M. Mazzotti, May 2019, On how adsorption enables the simultaneous production of H_2 and CO_2 from a multicomponent feed, Fundamental of Adsorption, Cairns, Australia.
- Petrini, Madonna, Zappone, May 2019, Continuum Based Seismo-Hydro-Thermomechanical Poro-Visco-Elasto-Plastic Approach for Modelling Earthquake Cycle and Induced Seismicity, Geomechanics and Mitigation of geohazards, Spring Meeting, Caltec, CA, USA.
- C. Antonini, May 2019, Analysis of Hydrogen Supply Chains for Swiss Mobility, Gordon Research Seminar on CCUS, Les Diablerets, Switzerland.
- A. Streb, May 2019, On the Potential of Adsorption Processes for Low-Carbon Hydrogen Production with Carbon Capture, Gordon Research Seminar on CCUS, Les Diablerets, Switzerland.
- A. Zappone, June 2019, The support of an underground laboratory to low carbon economy: CS-D experiment at Mont Terri, TCCS-10, Trondheim, Norway.

- M. van der Spek, C. Antonini, T. Otgonbayar, A. Streb, M. Mazzotti, June 2019, Optimal Standalone Low-Carbon Hydrogen Production with Autothermal Reforming and Vacuum Pressure Swing Adsorption, TCCS-10, Trondheim, Norway.
- A. Streb, July 2019, On the potential of adsorption processes for low-carbon hydrogen production with carbon capture, IEAGHG Summer Schoo.l, Regina, Canada.
- A. Zappone, M. Grab, A.C. Obermann, C. Madonna, C. Nussbaum, A. P. Rinaldi, Q. C. Wenning, S. Wiemer, September 2019, Tracing the CO_2 pathway in a faulted caprock: the Mont Terri Experiment, IEAGHG Monitoring network and environmental research Workshop, Calgary, Canada.

4.4.3 Scientific publications

- A. A. Assadi, Numerical simulations of underground carbon dioxide storage with hydrogen impurities, Institut für Wasser- und Umweltsystemmodellierung, Master thesis (Collaboration) (2018).
- A. Maurer, M. Richter, J.P.M. Trusler, R. Span, Speed-of-sound measurements in (hydrogen + carbon dioxide) over the temperature range from (250 to 350) K at pressures up to 10 MPa, Submitted (2019).
- A. Minardi, E. Stavropoulou, T. Kim, A. Ferrari, L. Laloui, Experimental investigation of the sealing capacity on Opalinus Clay for CO2 sequestration, Submitted to International Journal of Gas Control (2020).
- A. Streb and M. Mazzotti, Supporting information to: A metal-organic framework, Cu-TDPAT, offers high performance in single-cycle hydrogen purification and CO2separation from synthesis gas, Submitted.
- A. Streb and M. Mazzotti, Adsorption for efficient low carbon hydrogen production – part2: cyclic experiments and model predictions, Submitted.
- A. Streb, M. Asgari, M. v. d. Spek, W. Queen, M. Mazzotti, A metal-organic framework, Cu-TDPAT, offers high performance in single-cycle hydrogen purification and CO2separation from synthesis gas, Submitted.
- A. Streb, M. Hefti, M. Gazzani, M. Mazzotti, Novel Adsorption Process for Co-Production of Hydrogen and CO2 from a Multicomponent Stream, Industrial & Engineering Chemistry Research, 58(37), 17489-17506 (2019). DOI: 10.1021/acs.iecr.9b02817.
- A. Streb, M. Mazzotti, Novel Adsorption Process for Co-Production of Hydrogen and CO2 from a Multicomponent Stream—Part 2: Application to Steam Methane Reforming and Autothermal Reforming Gases., Industrial & Engineering Chemistry Research, 59(21), 10093-10109 (2020). DOI: 10.1021/acs.iecr.9b06953.
- A. Zappone, A. P. Rinaldi, M. Grab, A. Obermann, C. Madonna, C. Nussbaum and S. Wiemer, Sequestration: Studying Caprock And Fault Sealing Integrity, The CS-D Experiment In Mont Terri, First Break - Fifth CO2 Geological Storage Workshop, EAGE proceedings (2019). DOI: 10.3997/2214-4609.201803002.
- A. Zappone, A.P. Rinaldi, M. Grab, Q. Wenning, C. Roques, C. Madonna, A. Obermann, S. M. Bernasconi, F. Soom, P. Cook, Y. Guglielmi, C. Nussbaum, D. Giardini, M. Mazzotti, S. Wiemer, Fault sealing and caprock integrity for CO2 storage: an in-situ injection experiment, Submitted to Solid Earth (2020).
- Adams, B.M., Bielicki, J.M., Ogland-Hand, J.D., & Saar, M.O., Using geologically sequestered CO_2 to generate and store geothermal electricity: CO_2 Plume Geothermal (CPG), Proceedings of MIT A+B Applied Energy Symposium, 12-14 Aug, 2020. DOI: 10.3929/ethz-b-000444911.
- B. Cox, C. Bauer, A. M. Beltran, D. P. van Vuuren, C. L. Mutel, Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios, Applied Energy, 269, 115021 (2020). DOI: 10.1016/j.apenergy.2020.115021.
- C. Antonini, A. Streb, M. van der Spek, M. Gazzani, D. Sutter, M. Mazzotti, Low Carbon Hydrogen Production with (V) PSA for H2/CO2 Purification, In 14th Greenhouse Gas Control Technologies Conference Melbourne (pp. 21-26) (2018). DOI: 10.2139/ssrn.3365807.
- C. Antonini, K. Treyer, A. Streb, M. van der Spek, C. Bauer, M. Mazzotti, Hydrogen production from natural gas and biomethane with carbon capture and storage–A techno-environmental analysis, Sustainable Energy & Fuels (2020). DOI: 10.1039/D0SE00222D.
- C. Antonini, K. Treyer, E. Mojoli, C. Bauer, M. Mazzotti, Hydrogen from wood gasification with CCS – a techno-environmental analysis of production and use as transport fuel, Submitted to Sustain. Energy Fuels (2020).

- C. Zahasky, S. J. Jackson, Q. Lin, S. Krevor, Pore network model predictions of Darcy-scale multiphase flow heterogeneity validated by experiments, Water Resources Research, 56(6) (2020). DOI: 10.1029/2019WR026708.
- D. Benrath, Applicable law to hydrogen pipelines for energy purposes in Germany, Journal of Energy & Natural Resources Law 38.1 (2020). DOI: 10.1080/02646811.2019.1696519.
- D. Benrath, Die Verbesserung der Wasserstofftauglichkeit des Erdgasfernleitungsnetzes, Recht der Energiewirtschaft (2020).
- F. M. Hoffart, E.-J. Schmitt, M. W. M. Roos, Rethinking Economic Energy Policy Research – Developing Qualitative Scenarios to Identify Feasible Energy Policies, Journal of Sustainable Development of Energy Water and Environment Systems (in press) (2020). DOI: 10.13044/j.sdewes.d8.0331.
- F. M. Hoffart, S. Glanz, R. Span, A.-L. Schönauer, F. M. Hoffart, S. Glanz, R. Span, A.-L. Schönauer, Transition towards a low-carbon economy through gas infrastructure modification–economic and sociological interdisciplinary insights, International Conference on Applied Energy, International Conference on Applied Energy, Energy Proceedings (2019).
- G. A. Torrin-Ollarves and J. P. M. Trusler, Solubility of Hydrogen in Sodium Chloride Brine at High Pressures, Submitted to Fluid Phase Equilibria.
- J. Von Rothkirch, O. Ejderyan, Anticipating the social fit of CCS projects by looking at place factors, Resubmitted after major revisions to International Journal for Greenhouse Gas Control (2020).
- L. Hämmerli, M. Stauffacher, The neglected role of public perception of risk mitigation in the risk governance of underground technologies – the example of induced seismicity, International Journal of Disaster Risk Science (2020). DOI: 10.1007/s13753-020-00298-3.
- L. Weimann, M. Ellerker, G. J. Kramer, M. Gazzani, Modeling gas turbines in multi-energy systems: a linear model accounting for part-load operation, fuel, temperature, and sizing effects, International Conference on Applied Energy, Energy Proceedings (2019).
- L. Weimann, P. Gabrielli, A. Boldrini, G. Jan Kramer and M. Gazzani, On the role of H2 storage and conversion for wind power production in the Netherlands, Computer Aided Chemical Engineering, proceedings of ESCAPE29 (2019). DOI: 10.1016/B978-0-12-818634-3.50272-1.
- L. Weimann, P. Gabrielli, A. Boldrini, G. J. Kramer and M. Gazzani, Optimal hydrogen production in a wind-dominated, zero-emission energy system, submitted to Applied Energy (2020).
- L. Weimann, G. Dubbink, L. van der Ham, G. J. Kramer and M. Gazzani, An MILP model of post-combustion carbon capture based on detailed process simulation, submitted to Computer Aided Chemical Engineering, proceedings of ESCAPE31 (2021).
- M. Hammer, H. Deng, L. Liu, M. Langsholt and S. T. Munkejord, Upward and downward two-phase flow of CO2 in a pipe: Comparison between experimental data and model predictions, Submitted to International Journal of Multiphase Flow (2020).
- N. Sunny, N. Mac Dowell and N. Shah, What is needed to deliver carbon-neutral heat using hydrogen and CCS? Energy & Environmental Science, 13, 4204–4224 (2020). DOI: 10.1039/D0EE02016H.
- P. Gabrielli, A. Poluzzi, G. J. Kramer, C. Spiers, M. Mazzotti, M. Gazzani, Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage, Renewable and Sustainable Energy Reviews, 121, 109629 (2020). DOI: 10.1016/j.rser.2019.109629.
- Q. C. Wenning, C. Madonna, A. Zappone, M. Grab, A P. Rinaldi, M. Plötze, C. Nussbaum, D. Giardini, S. Wiemer, Shale fault zone structure and stress dependent anisotropic permeability and seismic velocity properties (Opalinus Clay, Switzerland), Submitted to Journal of Structural Geology (2020).
- Q. C. Wenning, C. Madonna, T. Kurotori, C. Petrini, J. Hwang, A. Zappone, S. Wiemer, D. Giardini, and R. Pini, Chemo-mechanical coupling in fractured shale with water and hydrocarbon flow, Submitted.
- Q. C. Wenning, C. Madonna, T. Kurotori, R. Pini, Spatial mapping of fracture aperture changes with shear displacement using X-ray computerized tomography, JGR Solid Earth, 124, 7 (2019). DOI: 10.1029/2019jb017301.
- R. Beckmüller, M. Thol, I. H. Bell, E. W. Lemmon and R. Span, New Equations of State for Binary Hydrogen Mixtures Containing Methane, Nitrogen, Carbon Monoxide, and Carbon Dioxide, Submitted.
- R. Sacchi, B. Cox, C. Bauer, Does size matter? The influence of size, load factor, range autonomy and application type on the Life Cycle Assessment of current and future trucks, Submitted to Environ. Sci. Technol. (2020).

- R. Sacchi, C. Bauer, B. Cox, C. Mutel, Carculator: an open-source tool for prospective environmental and economic life cycle assessment of vehicle. When, Where and How can battery-electric vehicles help reduce greenhouse gas emissions? Submitted to Renewable and sustainable Energy Reviews (2020).
- S. Flamme, D. Benrath, S. Glanz, F. Hoffart, C. Pielow, M. Roos, R. Span, H.-J. Wagnera, A.-L. Schönauer, The Interdisciplinary Approach of the German Case Study to Enable a Low Carbon Economy by Hydrogen and CCS, Energy Procedia 158, 3709–3014 (2019). DOI: 10.1016/j.egypro.2019.01.887.
- S. Glanz, A.-L. Schönauer, Towards a Low-Carbon Society via Hydrogen and Carbon Capture and Storage: Social Acceptance from a Stakeholder Perspective, Journal of Sustainable Development of Energy Water and Environment Systems,9(1) (2020). DOI: 10.13044/j.sdewes.d8.0322.
- S. P. Gregory, M. J. Barnett, L. P. Field and A. E. Milodowski, Subsurface microbial hydrogen cycling: natural occurrence and implications for industry, Microorganisms 7(2), 53 (2019). DOI: 10.3390/microorganisms7020053.
- S. T. Munkejord, H. Deng, A. Austegard, M. Hammer, A. Aasen, H. L. Skarsvåg, Depressurization of CO_2-N_2 and CO_2-He in a pipe: Experiments- and modelling of pressure and temperature dynamics, Submitted to International Journal of Greenhouse Gas Control (2020).
- S. T. Munkejord, M. Hammer, Å. Ervik, H. Lund, L. Odsæter, Coupled CO_2-well-reservoir simulation using a partitioned approach: Effect of reservoir properties on well dynamics, Greenhouse Gases: Science and Technology, In press (2020). DOI: 10.1002/ghg.2035.
- A. O'Brien and C. Banet, De-risking the hydrogen-CCS supply chain through law. Submitted to Journal of Energy and Natural Resources Law (2020).
- C. Banet, Hydrogen and CCUS compatible gas networks: Hydrogen and CCUS compatible gas networks: identifying legal principles for gas market re-design. Submitted to European Energy and Environmental Law Review (2020).

4.4.4 ELEGANCY tools

Tools developed in ELEGANCY are important project results. By making them publicly available the work can reach a large audience thus increasing the potential impact of ELEGANCY. A list of the tools and their applications can be found in Table 6.

Table 6: ELEGANCY publicly available tools.

Tool	Application
H_2+CCS chain tool, https://github.com/act-elegancy/chain_tool	Open-source tool consisting of a chain design tool and a chain dynamic simulation tool.
Consumet, https://github.com/act-elegancy/consumet	Open-source tool 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. Potential use with a range of process systems beyond H_2-CCS
Carculator, https://carculator.psi.ch/	Carculator is an open-source, comprehensive and transparent life cycle assessment tool for passenger cars and other vehicles. It allows for an economic and environmental evaluation of different types of cars under several driving and energy supply scenarios.
Business case development toolbox, https://www.sintef.no/projectweb/elegancy/programme/wp3/business-case-development-toolbox/	Collection of spreadsheets to facilitate the identification of key issues and promote collaborations early-on in the project development process.

4.4.5 Events with external participants

- M. Akhurst and J. Pearce, February 2018, Geological Survey, in-person meeting with industry stakeholder on ELEGANCY and the UK case study, Northern Gas Networks, Leeds, England.
- M. Akhurst, J. Pearce, J. Williams, N. Sunny and D. Iruretagoyena, February 2018, In-person meeting with industry stakeholders on ELEGANCY and the UK case study, Wood Group and Tees Valley Combined Authority, Darlington, England.
- M. Akhurst, March 2018, ELEGANCY project and collaboration between UK ERA-Net ACT projects, UK CCS RC Meeting, Cambridge, England.
- M. Akhurst and J. Pearce, May 2018, ELEGANCY Project & UK case study, British Geological Survey, In-person meeting with UK Government Climate Change Committee staff, London, England.

- A. Streb, M. Asgari, M. van der Spek, W. Queen, M. Mazzotti, September 2018, SCCER networking meeting, Synergistic Material and Process Development for Efficient Adsorption Process Processes, Lucerne, Switzerland.
- October 2018, ELEGANCY Side event at GHGT-14 with presentations by S.T. Munkejord, M. Akhurst and M. van der Spek, GHGT-14, Melbourne, Australia.
- S. T. Munkejord, November 2018, Stakeholder dialogue on the role of Carbon Dioxide Removal (CDR) in Switzerland's decarbonization, Event organized by the Risk Dialogue Foundation, Zurich, Switzerland.
- November 2018, ELEGANCY Conference, Brussels, Belgium. See Section 4.1 for details.
- C. Banet, February 2019, Selected legal aspects of CCS, Joint seminar between the ELEGANCY and ALIGN-CCUS projects, University of Oslo, Norway.
- February 2019, Workshop: Scenarien zur Zukunft der deutschen Gasinfrastruktur 2035, Dissemination workshop with representatives from academia and business, Ruhr-University Bochum, Germany
- March 2019, A Framework for CCS Risk Sharing and Business Model Selection, Joint workshop with the Zero Emissions Platform, Brussels, Belgium.
- N. Shah, N. M. Dowell, M. Trusler, N. Sunny, March 2019, Meeting with BEIS on potential of ELEGANCY tools to support industrial decarbonization strategy, Imperial College London, England
- March 2019, Joint workshop with the Zero Emissions Platform, Brussels, Belgium.
- M. Akhurst, J. Pearce, N. Sunny, E. Graham, W. Goldthorpe, L. Avignon, November 2019, Meeting with UK Climate Change Committee, London UK.
- R. Span and colleagues, June 2019, side event to TCCS-10, Trondheim: Workshop on the Thermophysical Property Database software TREND. Participation from research and industry partners from ELEGANCY and NCCS.
- N. A. Røkke, B. Nasiri, C. Banet, January 2020, Zero emissions with Hydrogen NOW!, Luncheon discussion in the EU Parliament. See Section 4.1 for details.
- M. Akhurst, N. Sunny, W. Goldthorpe, L. Avignon, J. Pearce, March 2020, online meeting with National Grid Ventures.
- M. Akhurst, J. Pearce, May 2020, online meeting with National Grid Ventures.
- D. Benrath, S. Flamme, S. Glanz, F.M. Hoffart, July 2020, CCS- und H_2-Pipelineinfrastrukturen: Die deutsche Fallstudie der Ruhr-Universität Bochum zum ELEGANCY-Projekt.
- ELEGANCY Webinar series, June 2020. See Section 4.1 for details.
- CCS risk and liability sharing, Joint Workshop with Zero Emissions Platform and the ALIGN-CCUS Project, Brussels, Belgium.
- S. Roussanaly, C. Banet et al., June 2020, Hydrogen from Norwegian Natural Gas to Decarbonise Europe & Norway. Open Webinar.

4.5 List of ELEGANCY deliverables

The list includes hyperlinks to those deliverables that are public at the time of writing.

WP1	Title	Partners
D1.1.1	Report on new PSA and VPSA cycles for sharp separation of CO_2, H_2 and impurities	**ETH**
D1.1.2	Report on characterization of equilibria and transport phenomena in promising new absorbents for CO_2/H_2 separation	**ETH**
D1.1.3	Scientific paper on demonstration of novel PSA/VPSA cycles for CO_2/H_2 separation	**ETH**
D1.1.4	Scientific paper on optimization of novel PSA/VPSA cycles and their application to different case studies	**ETH,** UU
D1.2.1	Report on 1000 hour catalyst stability	**ECN**
D1.2.2	Report on demonstration of SEWGS performance under basic oxygen gas performance at TRL 5	**ECN**, MEFOS
D1.2.3	Scientific paper on modelling of SEWGS cycles and prediction of separation performance for high CO content syngas	**ECN**
D1.2.4	Report on preliminary design of a TRL7 demonstration platform for the SEWGS technology	**ECN**
D1.3.1	Report on optimal plants for production of low-carbon H_2 with state-of-the-art technologies	**ETH**, UU
D1.3.2	Scientific paper on optimal plants for production of zero-carbon H_2 with adsorption-based technologies	**ETH**, UU

D1.3.3	Scientific paper on optimal plants for production of zero-carbon H_2 with SEWGS	**ETH**, UU, ECN
D1.4.1	Scientific paper on measured densities and speeds of sound for mixtures of H_2 with CO_2, CO, and CH_4	**RUB**
D1.4.2	Scientific paper on improved Helmholtz energy model for mixtures of H_2 with CO_2, CO, and CH_4	**RUB**
WP2	**Title**	**Partners**
D2.1.1	Report and software on a property model for CO_2-rich mixtures in contact with brines with a sea-water like composition	**RUB**
D2.1.2	Report and software on a property model considering a broader range of brine comp.	**RUB**
D2.1.3	Report and software on the final property model implementing results from WP1 (improved description of CO_2/CO/H_2 mixtures) and WP2 (brine model), dissemination and implementation in WP4	**RUB**
D2.1.4	Report detailing experimental apparatus for measurement of H_2 solubility in brine and validation	**ICL**
D2.1.5	Document reporting results of solubility measurements for H_2 in pure water at reservoir conditions	**ICL**
D2.1.6	Document reporting results of solubility measurements for H_2 in brine at reservoir conditions	**ICL**
D2.2.1	Paper describing the inclusion of water phase and near-well model and performing relevant simulations	**SINTEF**
D2.2.2	Paper assessing the influence of CO and H_2 impurities on depressurization by analysing depressurization experiments and performing flow-model validation	**SINTEF**
D2.2.3	Report analysing vertical-flow experiments with respect to well-operational issues and performing model validation	**SINTEF**
D2.3.1	Report detailing rock and fluid samples to be used in the petrophysics studies	**ICL**
D2.3.2	Document summarising the results of routine core analysis on selected rock samples	**ICL**
D2.3.3	Report on single-phase core flooding experiments	**ICL**
D2.3.4	Document reporting results of equilibrium and dissolution multi-phase core-flooding experiments	**ICL**
D2.4.1	Preliminary report on characterization and design of the Mont Terri exp.	**SCCER**
D2.4.2	Report/paper on core characterization from related rock mechanics experiment and modelling of Mont Terri experiment	**SCCER**
D2.4.3	Report/paper on risk assessment and de-risking strategies for future scenarios and knowledge transfer to WP5	**SCCER**
D2.4.4	Final report execution and characterization of the Mont Terri Experiment	**SCCER**
D2.5.1	Review of literature of effect of H_2 in subsurface environments and response of microbes. Knowledge transfer to WP5	**BGS**
D2.5.2	Report on recommendations for operational practise and materials to minimize the degradation of installed downhole fibre-optic cable monitoring infrastructure. Knowledge transfer to WP5	**BGS**
D2.5.3	Report on impact of the geochemical response to H_2 as impurity on the Bunter or Captain sandstone	**BGS**
D2.5.4	Report on the response of microbial communities to H_2 and potential impacts on CCS	**BGS**
D2.5.5	Report/paper on the thermal-hydraulic-chemical (THC) simulations of CO_2-based geothermal energy systems	**SCCER**
ID	**Title**	**Partners**
D3.1.1	Legal input to the interim report detailing the regulatory, fiscal, and macro-economic background for each case study	**UiO**, FC
D3.2.1	Interim report detailing the regulatory, fiscal, and macro-economic background for each case study	**FC**, SDL, UiO
D3.3.1	A business risk matrix for application in Task 3.3	**SDL**
D3.3.2	Interim report detailing policy-issues, business risks, de-risking instruments, and incentive mechanisms relevant for case study countries.	**SDL**, UiO, FC
D3.3.3	Interim report detailing the development of business models and commercial structures	**SDL**, UiO, FC
D3.3.4	Interim report detailing the guidelines for the assessment and application of the business case templates in WP5	**SDL**, UiO, FC

D3.4.1	Publication of the findings and outcome from WP3 in article or report format	**FC**, SDL, UiO
WP4	**Title**	**Partners**
D4.1.1	Overall functional and architecture specification for toolkit including methodology and metrics, report: requirement spec., functional spec., technical spec.	**ICL**, SINTEF, PSI, RUB, TNO
D4.2.1	Definition of quantifiable environmental, economic and operability metrics for all H_2-CCS chain sections and model components, report	**PSI,** ICL, TNO, SINTEF
D4.3.1	Component models: H_2 production with integrated CSS, including software for property calculations, report and software uploaded to project eRoom	**ICL**, SINTEF, TNO, RUB
D4.4.1	Reduced order component models: H_2 production with integrated CCS, software and report	**SINTEF**, ICL, TNO, PSI
D4.5.1	First prototype of whole chain design and simulation tool, report including user manual and model documentation	**ICL**, SINTEF, RUB, TNO, PSI
D4.5.2	Overall design and operational toolkit – final version, scientific paper describing toolkit, including user manual and model documentation	**ICL**, SINTEF, TNO, PSI, RUB
WP5	**Title**	**Partners**
D5.1.1	Regional overview of requirements and potentials of H_2 markets	**SINTEF**, TNO, SDL, BGS, PSI, RUB
D5.1.2	Opportunities and challenges for H_2-CCS chains in Europe for accelerating deployment of CO_2 capture	**SINTEF**
D5.2.1	Report describing the current industrial cluster in Rotterdam with its socio-economic contribution, CO_2 emissions and target setting for emission reduction	**TNO**, UU
D5.2.2	Report describing the needed H_2 production facilities, integration in port infrastructure, possible ownership structures and OPEX and CAPEX estimates	**TNO**
D5.2.3	Report describing the needed offshore storage and transport facilities to meet the emission reduction requirements including OPEX and CAPEX estimates	**TNO**
D5.2.4	Report describing the foreseen zero emission H_2 utilization in industry, power generation and natural gas mixing, including limited market economics	**TNO**
D5.2.5	Scientific papers analysing the Rotterdam Industrial Cluster development with and without availability of CCUS	**UU**
D5.2.6	ROADMAP for the introduction of a low carbon industry in the Rotterdam Region	**TNO**, ECN, UU
D5.3.1	Scientific papers on H_2 production from biogas and bio-mass in Switzerland: technical evaluation, potential estimation and comparison with H_2 production from electrolysis, including focus on infrastructure for decarbonising transport	**ETH**, PSI
D5.3.2	Scientific papers on screening of underground sites in Switzerland for geothermal and CO_2 storage applications, with emphasis on de-risking storage	**SCCER**, ICL, BGS, PSI
D5.3.3	Scientific papers on scenario modelling for energy production via coupled CO_2 storage and geothermal in Switzerland, including quantification of Swiss H_2-CCS chain performance	**SCCER**, PSI
D5.3.4	Scientific papers on improved DACCS for accelerating CO_2 storage and geothermal applications, including life cycle analysis of DACCS compared to biomass-based H_2-CCS	**Climeworks**, PSI
D5.3.5	Scientific papers on the potential and role of clean H_2 for road transportation and DACCS as enabler of geothermal and CO_2 storage applications in the Swiss society	**SCCER**, PSI
D5.3.6	Report on energy model analysis of the role of H_2-CCS systems in Swiss energy supply and mobility with quantification of economic and environmental trade-offs, including market assessment and business case drafts	**PSI**, FC
D5.4.1	Report of the injection scenario and storage operation for H21 Roadmap	**BGS**
D5.4.2	Scientific paper on UK case modelling, including industrial decarbonization potential	**ICL**, INEOS
D5.4.3	Business case template and risk matrix H21 Leeds City Gate	**SDL**, SE
D5.5.1	First assessment of options for a decarbonized gas infrastructure	**RUB**
D5.5.2	Report on German case: first results, final design and methodology	**RUB**
D5.5.3	Final Report German Case Study	**RUB**, UES, OGE, GERG
D5.6.1	Potential for H_2 utilization and CO_2 storage	**SINTEF**, AKSO
D5.6.2	Scenarios for Norwegian H_2 value chain	**SINTEF**, AKSO
D5.6.3	Norwegian H_2 value chain from a European perspective	**SINTEF**, AKSO
D5.6.4	Norwegian H_2 value chain - business case and opportunities	**SINTEF**, AKSO