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Demonstrating a Refinery-Adapted Cluster-Integrated Strategy to Enable Full-Chain CCUS Implementation – REALISE

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Abstract

The new H2020 project REALISE, started in May 2020, would demonstrate at pilot scale a CO_2 capture technology based on an advanced low-energy solvent, quantify emissions, solvent degradation, and quality of the liquified CO_2 when impurities from flue gases from an operating refinery are introduced to the pilot. Several innovative concepts will be demonstrated in the project (some directly at Irving Oil refinery in Cork, Ireland) allowing realization of the target objectives set in the project resulting in at least 30% reduction in the cost of CO_2 capture compared to the reference case based on 30% monoethanolamine (MEA).

Techno-economic analysis will be done for integration of a multi-absorber concept for at least 3 refineries. The results will be implemented in an open-access simulation tool to evaluate the cost of CO_2 capture and to decide carbon capture strategy at other refineries.

Assessment of transport, utilization and storage options will be performed for the studied cases and societal impact and CCS readiness index estimated for cases in Europe, China and S. Korea.

Keywords: CCS; CO_2 capture; absorption, CO_2 transport and storage; Refinery

1. Background

The refining sector contributes to around 4% of the total anthropogenic CO_2 emissions, globally, close to 1 billion metric tonnes per year, and ranks third among stationary CO_2 producers after the power sector and the cement industry[1]. Although significant achievements have been made in implementing successful energy reduction schemes at refineries since the 1990's, the energy intensive nature of refinery processes still cause production of large amounts of CO_2. To further reduce these emissions, carbon capture, utilisation and storage (CCUS) is a crucial technology solution for an important industrial sector at least in a short to medium term perspective [2].

A factor specific to refineries is a large number or relatively small sources with various levels of CO_2 concentration

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and flue gas impurities. The conventional conceptual strategy has been to capture CO_2 only from the major emission points, excluding stacks in which the emissions are below a given threshold. This leads to relatively low overall capture rates of about 50% [3]-[4]. REALISE proposes to capture up to 90% CO_2 from operating refineries by integrating a multi-absorber concept for capturing CO_2 from different stacks.

The REALISE project is driven by a strong industrial consortium, including 7 R&D institutions and 10 industrial partners, among which major refineries in EU, China and S. Korea, along with the complete technology value-chain.

2. Project concept

The cost reduction potential will be demonstrated in REALISE onsite operating refinery-centered cluster at Cork, Ireland, by using a novel low energy solvent (30% lower energy consumption, 70 times lower corrosion and 3 times lower thermal degradation), innovative concepts for reducing oxidative degradation of the solvent (80% lower active component loss), cheaper construction materials (15% reduction in CAPEX), intelligent Nonlinear Model Predictive Control (10% lower OPEX compared to operation without NMPC), and optimal integration with the available heat sources (Fig.1).

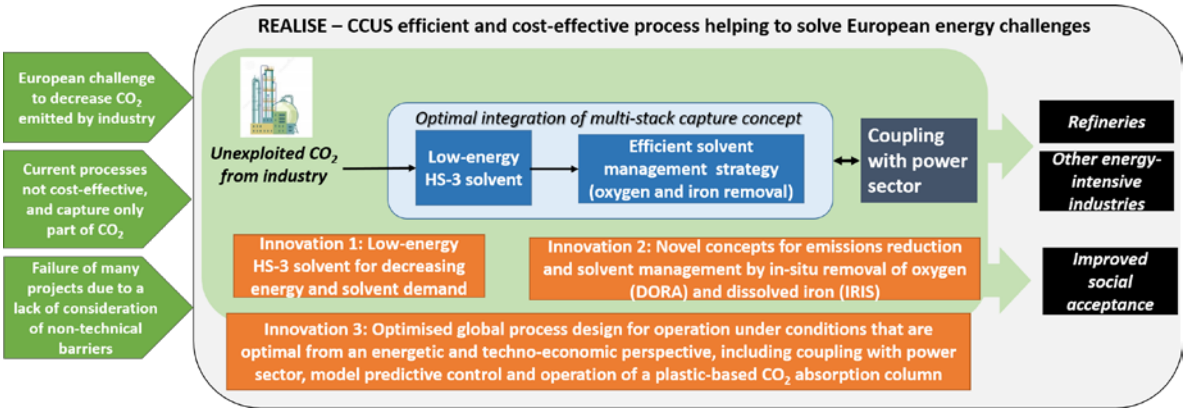

Fig. 1. REALISE project concept

The combined effects of the cost reduction strategies targeted in REALISE are represented in Fig. 2 and Table 1. The case presented is a refinery with an intermediary process complexity, with a nominal capacity of 200,000 bbl/d, with CO_2 capture integrated to the fluid catalytic cracker, crude and vacuum distillation units. This multi absorber case has previously been studied in the RECAP project [5] and can be used to illustrate for the cost reduction potential to be explored within REALISE.

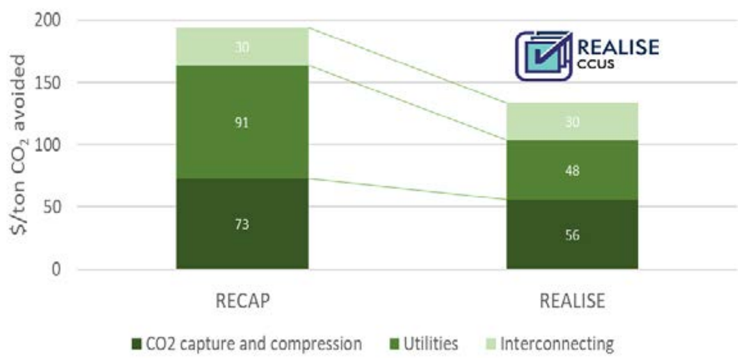

Fig. 2. Reducing the costs of retrofitting CO_2 capture to refineries ("Utilities" include steam demand in the capture plant; "Interconnecting" means integration of capture plant with both refinery and power plant)

Table 1. Cost reduction potential from implementation of REALISE concept and technologies.

REALISE Innovation	Type of reduction	Reduction in capture costs	
		$ / ton $_{CO2\ avoided}$	%
Use of plastic as construction material in the absorber	CAPEX	8	4
Reduced degradation by using DORA and IRIS	OPEX	8	4
Sector coupling and optimal integration and operation	CAPEX and OPEX	24	12
Novel free-to-operate solvent with low energy requirement	OPEX	20	10
TOTAL		**60**	**30**

3. REALISE objectives

The overall objective of REALISE is to develop a refinery-centred sector-coupling strategy to enable full-chain CCUS implementation, by demonstrating technologies to lower the cost of CO_2 capture by at least 30% and increase the overall rate of CO_2 capture to 90% by solving technical barriers, as well as developing recommendations for policy and regulatory changes to overcome societal, political and socio-economic barriers. This will be achieved through the following objectives and sub-objectives:

Objective 1: Establish use cases and identify prime sites based on energy-efficient, economically viable, environmentally friendly and socially acceptable process for CCUS in refineries:

- Assess key societal & environmental challenges: increase the social acceptance level of the public in general for such a CCUS process and improve the perception of the refinery sector. An education and public engagement (EPE) programme will be trialled at Cork. REALISE will contribute to improve willingness to accept a somewhat higher cost for a greener product.
- Assess the market potential for this technology in the next decades by establishing a transnational Industry Club, involving potential end-users to evaluate and increase their ability and interest to use the technology, as well as inform them about possible risks and threats.
- For policy makers, provide a clear and concise view over current CO_2 emissions in the sector and conversion issues as well as the available opportunities herein by applying the CCS-readiness index (RI) concept allowing to identify and propose ways of addressing policy-, law and regulation- and storage resource development barriers and serving as a basis for evaluation of alternative chains and enabling identification of the refineries best placed to deploy CCUS across Europe.

Objective 2: Demonstrate in a relevant environment an innovative cost-effective absorption technology for CO_2 capture based on a low-energy solvent including determination of emissions and quality of produced CO_2.

- Optimize further develop the environmentally sustainable HS-3 solvent, an advanced absorbent developed in the HiPerCap project (FP7-Energy, project 608555 [6]).
- Demonstrate in a pilot plant that this solvent lowers the solvent regeneration energy demand and minimises possible emission of solvent and solvent degradation products.
- Demonstrate reliable operation and additional energy savings by applying NMPC for intelligent process control. This includes demonstrating short-term solvent caching, which is key to accommodate process intermittence when coupling to the load changing power generation units, thus opening for dynamically interconnecting the energy producing sector with the refinery sector the purpose of saving energy.
- Assess the quality of the produced CO_2 for different application areas (chemical conversion, enhanced oil recovery, transport and storage)

Objective 3: Demonstrate in operational environment an economically viable and environmentally friendly process for carbon capture integrated with solvent management technologies.

- Show that the CAPEX for the capture plant can be reduced by using plastic as construction material in the absorber and other process units.
- Demonstrate prototypes of the two novel concepts for in-situ removal of oxygen and dissolved iron in operational refinery environment (TRL7).

- Demonstrate solvent reclaiming for recovery of HS-3 active components from the used solvent from the demonstration campaigns.

Objective 4: Real world assessment of the potential of the carbon capture technology integrated at an oil refinery through development of full CCUS chain business cases.

- Perform techno-economic analysis (TEA) of the integrated capture process for a realistic estimation of the CO_2 capture cost at least 3 refineries of different complexity including NMPC based operating strategies to reduce energy, number of operators and maintenance costs.
- Identify storage and use scenarios for the three selected business cases, estimate requirements, maturity and implementation lead time.
- Develop an extended and strong network with Mission Innovation (MI) countries, such as Canada, China, and South Korea.
- Develop an open-access simulation tool for evaluating different CO_2 capture scenarios from a techno-economic perspective.
- Show that the cross-chain risks can be lowered by connecting the refinery cases studied within REALISE with on-going projects on CO_2 transport and storage, such a Northern Lights (Norway).

4. REALISE concept

Within REALISE, technologies for CO_2 capture and solvent management will be demonstrated at the Irving Whitegate refinery, which has capacity to process up to 75.000 barrels of crude oil per day (bbl/d). Located in Cork, Ireland, it is the country's only refinery supplying about 40% of the countries transport and heating fuels. To trigger CO_2 transport and storage from a single location, the amount of CO_2 should be significant (millions of tons per year). The Irving refinery is located next to the Whitegate and the Aghada CCGT power plants. Together, these three locations constitute the **Cork industrial cluster**. Total CO_2 emissions from the Irving Whitegate refinery is about 240,000 tonne CO_2 per year. The combined cycle power plants (CCGT) of Whitegate and Aghada have nominal capacities of 430 MW each. Considering a load factor of 100%, each plant could emit about 1,7 $Mton_{CO2}$/year. However, the loads are projected to be 25-40% in 2030, and 16-20% in 2050, so that by 2050, the refinery is expected to contribute to 28% of the CO_2 emissions from the cluster.

The sector-coupling concept as suggested within REALISE proposes that the steam necessary for the CO_2 capture in the refinery comes from nearby heat sources (power plant or waste heat). In the case of the Cork industrial cluster, the Whitegate power plant is the immediate choice of steam provider, given that it is adjacent to the refinery. This can be observed in Fig. 3(left).

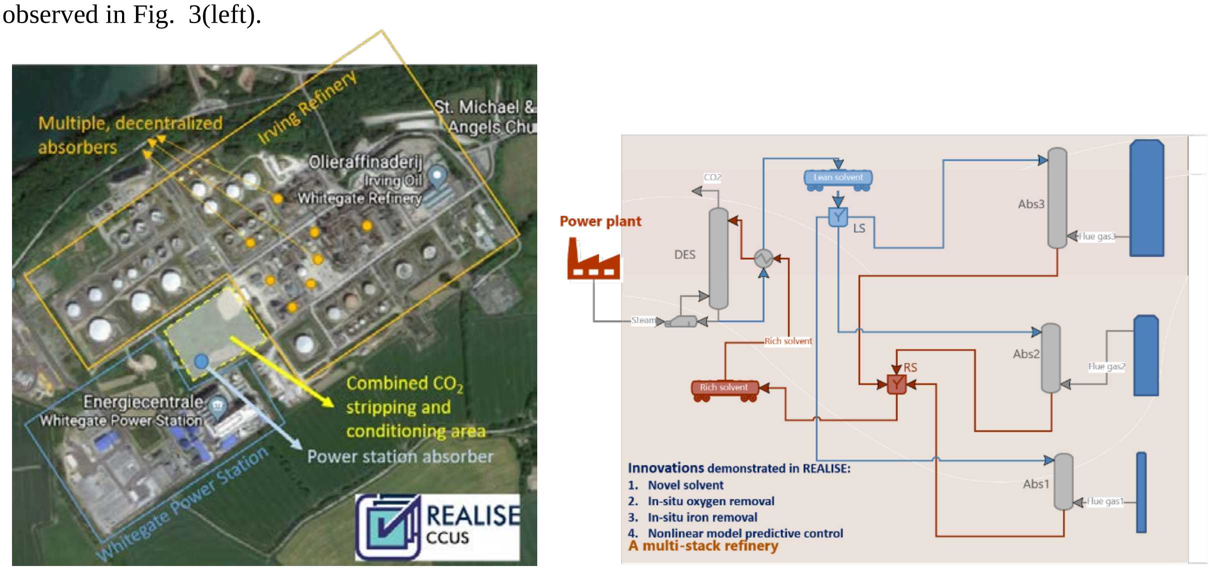

Fig. 3. Left: REALISE sector-coupling concept for CO_2 capture. Right: Multi-absorber concept example

While the CO_2 is absorbed in multiple columns arranged near to the refinery stacks and one column next to the power plant stack, the desorption operation is centralised (Fig. 3 right). The CO_2 stripping and conditioning equipment can be installed in a common area between the refinery and the power plant. This area concentrates the necessary solvent and CO_2 buffering tanks. While CO_2 is captured continuously from the refinery stacks, it is only stripped out from the solvent for example when the electricity cost is low (varies during the day), and therefore steam is available at lower price. This innovative concept for shared assets avoids that a dedicated steam generation or CHP unit is built within the refinery, thus significantly lowering the CO_2 capture costs.

Such work has been performed earlier on retrofitting CO_2 capture units to power plants, e.g., Adams and Mac Dowell [4] have performed a case study for a 420 MW CCGT power plant in which a CO_2 capture unit is retrofitted. Their work shows that the percentage of steam extraction is proportional to the plant load factor, according to the model given in Fig. 4. Fig. 4 shows projections of the steam demand of the Whitegate power plant and the Irving refinery as a function of the refinery load. These projections, covering a load range of 10-30% are representative of the 2030-2050 period. While the refinery steam demand is significant, the steam combined extraction demand to allow for 90% capture rate in both the refinery and the power plant remains between 58 and 76%. This is the same range of steam extraction required for a power plant operating at loads between 50% and 70% according to the model of Adams and Mac Dowell. Therefore, Fig. 4 indicates that the proposed concept is technically feasible. Moreover, at this range, the energy penalty is expected to be between 7,5 and 8,0 % points.

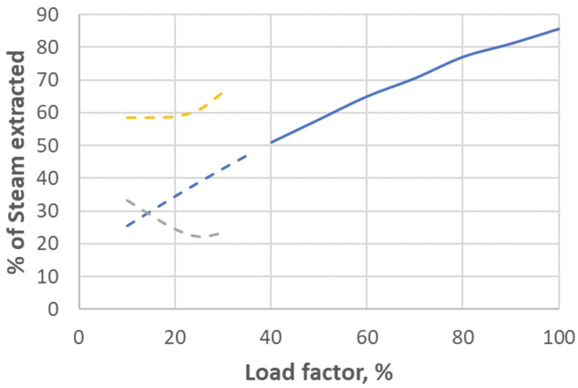

Fig. 4. Steam extraction as a function of load factor. Model adapted from Adams and Mac Dowell and projections for the power plant (PP) and refinery at lower load ranges: — model (PP); - - projected (PP); - - projected (refinery);); - - projected (refinery + PP)

Also, the model of Adams and Mac Dowel [4] predicts a relatively flat relationship between the cost of CO_2 avoided and the load factor. By extrapolating the central natural gas (NG) price curve presented in their work to the load region of 10-30%, one can expect that cost remains around 45 pounds/t_{CO2} avoided in the power plant. However, the total amount of CO_2 avoided within the cluster increases significantly, thus lowering the total cost of CO_2 capture.

Flexible operation of a multi-stack absorber-single stack stripper with or without intermittent stripping capacities as indicated above will require a sophisticated control system to ensure energy efficient operation whilst the capture rate target of at least 90% is maintained over a certain time horizon. In REALISE we will focus on non-linear model predictive control (NMPC), which is widely used in the process industry [7]. So far, the use of such advanced control system in capture plants has been implemented and successfully tested in previous projects in SINTEF's pilot plant facility at Tiller as well as at the TCM facility [8]. In REALISE we will further test this application at the Tiller pilot facility and explore the potential in process simulations.

Within REALISE, the concept of sector-coupling will be evaluated for at least 3 case studies to cover large spectrum of processing capacity and refining complexity. That will allow proposing integrated flexible solutions that would fit all refineries, thus maximising the project impacts.

5. Technologies demonstration in REALISE

During the project lifetime of 36 months, the cost-efficient and sustainable CO_2 capture technology will be optimised and demonstrated at pilot scale (TRL 6 and 7). The starting point for developing the integrated full chain CCUS solutions will be existing experimental methods, test rigs and simulation tools developed by expert partners within CCS in an earlier project.

Demonstration of the carbon capture technology at refinery is complicated due to requirements to the systems intended for use in potentially explosive atmospheres (ATEX directive). Typically, the demonstration of carbon capture technology with real flue gases mainly aims at testing durability of the materials and chemicals exposed to real impurities in the flue gases. While large scale pilot analysis is important for understanding scale-up issues and larger equipment performance, energetic optimisation of the process for maximum solvent performance can be investigated in a smaller pilot plant as long as the pilot replicates the representative gas and liquid flows ratios and residence times in the actual sized plant (full-height absorber, desorber). This stepwise research approach saves resources and greatly increases flexibility. A smaller plant can also be used for researching solvent degradation. At the same time, impurities and degradation products in the solvent will affect amine emissions from the capture plant. REALISE will use a combined approach to **minimise the cost and risks associated with the technology demonstration** at an operating refinery at the same time providing realistic results (Fig. 5):

1. A mini-pilot (20L solvent, 3 Nm^3/hr flue gas) will be connected to sampling lines (up to 6 different stacks) *at an operating refinery* at Irving Oil (Cork, Ireland), and CO_2 will be captured from the real flue gases using the HS-3 solvent. The degradation mitigation technologies, DORA and IRIS will be connected to the pilot. These tests will allow validation of mitigation options for solvent degradation and emissions (*the scale is sufficient for the validation*). At the end of the demonstration campaign at Irving refinery, the minipilot will run without DORA and IRIS to allow for maximum accumulation of impurities from the flue gases and maximum degradation of the solvent. This solvent will be sent for testing at SINTEF's Tiller CO_2 plant.
2. The partly degraded solvent from the minipilot tests will be mixed-up with a fresh solvent and used for testing in a larger, full-height, pilot (600L solvent, 250 Nm^3/hr flue gas) at Tiller. The composition will then be quite similar to a solvent that has been partly reclaimed. Real impurities and degradation products from the refinery will ensure realistic solvent composition although a mimicked flue gas will be used at SINTEF's pilot. Optimal operation conditions and OPEX estimates will be done based on these tests (*the scale is important*).
3. The pilot plant at SINTEF will be modified in the project with a bench scale (about 10 m^3/hr) CO_2 compression/liquefaction unit (CCLU) to allow sampling and analysis of the produced CO_2. This information is rarely available [9], although impurities in CO_2 may have an impact on downstream applications (CO_2 conversion, transport, storage).

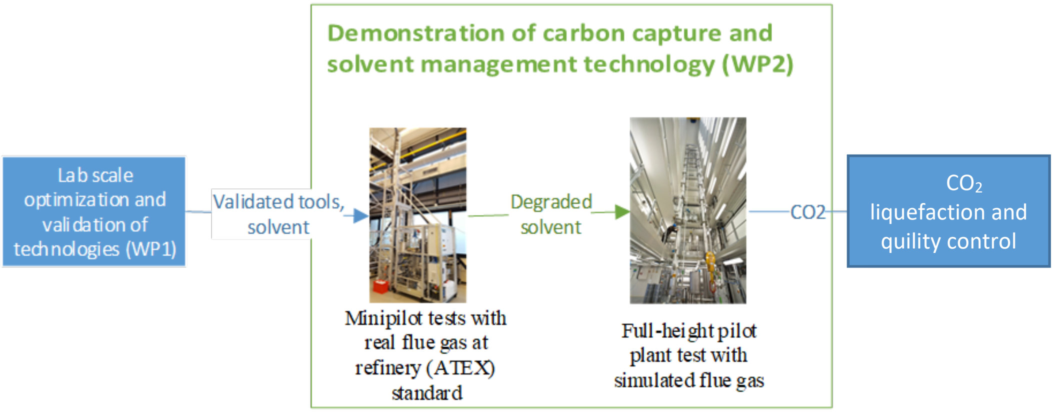

Fig. 5. REALISE methodology for scaling up and demonstration of carbon capture and solvent management technologies.

6. Project outcome

REALISE partnership includes major companies representing the entire value chain and well-known universities and research centres for solvent-based process development as well as end-users in major energy intensive industries in Europe and worldwide. For all business cases, an exploitation plan, including the full chain, will be developed. For the Cork cluster, CO_2 storage in a local well and connections to Northern Lights will be explored. CO_2 utilization and storage solutions relevant for the refineries in China and S. Korea will be proposed.

REALISE will demonstrate a **low-energy solvent**-based absorption process for CO_2 capture from multiple stacks at oil refinery and determine the **quality of the CO_2 produced**, as this is key for downstream processes (CO_2 utilisation, transportation and storage). The project will demonstrate the operability and effectiveness of the absorption-based process at site, focusing on **solvent management and emission aspects**. Furthermore, REALISE will demonstrate intelligent process control by applying **nonlinear model predictive control** (NMPC), allowing for dynamic and flexible operation of the integrated carbon capture process in a sector-coupling scenario.

Within REALISE, the concept of sector-coupling will be evaluated for at least **3 case studies**, chosen so to cover large spectrum of processing capacity and refining complexity. Besides the Cork cluster, the project partners will provide us with the necessary information on refineries in China (Dunhua Oil) and South Korea (SK Innovation). Applying the REALISE concept to these refineries is a key element for evaluating the replicability of the proposed approach. The business cases will be developed to identify the most economical ways of capture worldwide, thereby supporting rapid implementation of the technology. In addition, an **open-access, user-friendly simulation tool for evaluating CO_2 capture strategies for refineries** will be developed and offered to other refineries for preliminary assessment of CO_2 capture at their sites.

Assessment of the full CCUS chain from Emitter to Storage will be performed taking advantage of having consortium partner in common with transport and storage projects Northern Lights [10] and Ervia CCUS [11].

The adapted version of the **CCS Readiness Index,** developed by the Global CCS Institute [12], will be expanded to include wider work on socio-political consideration to support advocacy work for CCUS. Through the adaptation of the CCS readiness index, REALISE will identify which refineries across Europe are best positioned for CCS deployment. Using this information, REALISE will perform targeted advocacy; approaching refineries identified and local governments to explore deployment. Emphasis will be also placed on **increasing the level of public acceptance** by developing a programme for education and public engagement.

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