# PROJECT FINAL REPORT

**Grant Agreement number:** 241342

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## *Executive summary*

CACHET-II is a European Commission funded project that aims to develop innovative technologies to lower the cost of low-carbon power generation from fossil fuels. The project comprises of 8 partners, from industries, academia and institutions: BP (UK), Technip (France), SINTEF (Norway), ECN (the Netherlands), the National Technical University of Athens (Greece), Politecnico di Milano (Italy), the Dalian Institute of Chemical Physics (China) and the Shenyang Institute of Materials Research (China). Benefiting from such collective efforts of a European-Chinese consortium, the project focuses on advancing palladium membrane technology to increase the energy efficiency of gas- and coal-fired power plants fitted with pre-combustion $CO_2$ capture.

The CACHET-II project has been driving forward pure palladium membrane technology, developed in FP6 CACHET project and suitable for natural gas applications. The readiness level of the pure palladium membrane technology has upgraded progressively since the project started in January 2010: the membrane production process has been scaled up to 1m length, long term stability tests up to 150 days have been performed, a scaled-down version of a commercial membrane module have also been developed, and been tested at close to industrial conditions for approximately 1000 hours. The project recognizes a ceramic-to-metal seal that is able to endure high pressure high temperature conditions is critical for successful exploitation of palladium membrane. Hence, novel ceramic-to-metal seals are also developed, scaled up and tested for long term stability and in the scaled-down membrane module within the project. A 2-dimensional membrane simulation tool has been developed and validated against experimental data of pure Pd membrane. This simulation tool has been instrumental in guiding the selection of process integration concepts and the detailed design of membrane module. Integrating $H_2$ membrane into a NGCC-CCS process will reduce capture energy penalty by 15% and cost of $CO_2$ avoided by 7% in comparison to the state-of-the-art technology of MDEA.

Integration of $H_2$ membranes into solid fuel based process requires sulphur resistant membrane material. Hence, the project has also performed fundamental research to develop novel Pd-alloy $H_2$ membrane materials of higher sulphur tolerance and a high temperature sorbent-based sulphur removal technology of low exergy loss. These technologies will enable palladium membrane to advance into the broader coal pre-combustion $CO_2$ capture applications, with an outlook to reduce capture energy penalty by nearly 40% and cost of $CO_2$ avoided by 12% in comparison to the state-of-the-art technology of Selexol.

Via CACHET-II, the Pd membrane technology has moved a significant step forward. The valuable foregrounds and knowledge generated by the project have been sufficiently disseminated and shared with interested parties and potential end-users.

## *1. Project Context and Objectives*

Pd membrane is permeable to hydrogen only. When applied to pre-combustion capture processes, hydrogen can be selectively separated from other syngas molecules and used as a fuel for clean power generation. The remaining stream contains mainly $CO_2$ and unrecovered $H_2$ and steam. Subsequent condensation of the steam leaves concentrated $CO_2$ at high pressure, significantly reducing the compression energy for transport and storage.

Pd membrane can be either applied as a separator on its own, or integrated with water gas shift (WGS) reactors to achieve CO to $CO_2$ conversion and $H_2/CO_2$ separation efficiently in one single step. The European Commission FP6 CACHET project evaluated several advanced $CO_2$ capture technologies and concluded that WGS-Pd membrane reactors provide the highest energy efficiency and most promising cost reduction potential for the pre-combustion capture route of natural gas to low carbon power. Studies conducted by NETL concluded that by integrating $H_2$-permeable Pd membrane into IGCC-CCS (Integrated Gasification Combined Cycle with $CO_2$ Capture and Storage) plant, the cost of electricity can be reduced by 12%, higher than any other technology currently under development. Both credible studies, together with many other literatures, suggest that Pd membrane has great potential to reduce the cost of low-carbon electricity generation from fossil fuels.

The CACHET-II project was set up in January 2010 to advance the Pd membrane technology for its prospective application in natural gas- and coal-fired power plants fitted with pre-combustion capture. The project lasts for 3 years, till December 2012, and is budgeted at €5.7 million. The project is highly collaborative and comprises of 8 partners, from industries, research institutions and university academia in Europe and China: BP (UK), Technip (France), SINTEF (Norway), ECN (the Netherlands), the Dalian Institute of Chemical Physics (China) and the Shenyang Institute of Metal Research (China), the National Technical University of Athens (Greece), Politecnico di Milano (Italy).

In the European FP6 CACHET project, pure Pd membrane technology produced by the electroless plating method of Dalian Institute of Chemistry and Physics (DICP) was successfully demonstrated at a tubular membrane length of 50 cm. The technology is highly regarded to be suitable for natural gas-derived low carbon power applications, i.e. in NGCC-CCS (Natural Gas Combined Cycle with $CO_2$ Capture and Storage) plants. The CACHET-II project aims to drive forward the development of pure Pd membrane by scaling up DICP's technology, test it for long-term stability, develop a scaled-down version of a commercial membrane module and measure its performance in simulated industrial conditions. DICP's technique deposits Pd membrane layer onto ceramic tubing support. In order to install the resultant Pd membrane tubes in a metal vessel, the project recognizes that a ceramic-to-metal seal which is able to endure high pressure high temperature conditions is critical for successful exploitation of Pd membrane.

Hence, two different types of novel ceramic-to-metal seals are also developed, scaled up and tested for long term stability within the project.

Pure Pd material membranes are susceptible to poisoning by sulphur compounds present in coal-derived syngas. Integration of $H_2$ selective Pd membranes into solid fuel based processes therefore requires sulphur resistant membrane materials. Hence, the project has also performed fundamental research to develop novel Pd-alloy $H_2$ membrane materials of higher sulphur tolerance and a high temperature sorbent-based $H_2S$ removal technology which reduces the process exergy loss and unlocks the potential of Pd membranes in IGCC-CCS applications. These technologies in combination will enable Pd membrane to advance into the broader coal pre-combustion $CO_2$ capture applications, with an outlook to reduce capture energy penalty by nearly 40% in comparison to the state-of-the-art technology of Selexol.

Besides these endeavors in materials development of pure Pd membrane, Pd-alloy membrane and high temperature $H_2S$ sorbents, CACHET-II also devotes to advancing the engineering aspects of Pd membrane for decarbonised fossil fuel applications. Its development of a membrane simulation tool and membrane module mechanical design, the successful construction and demonstration of a 1m long scaled-down prototype, and the informative process optimisation and techno-economics evaluation results have all been instrumental for the significant advancement of Pd membrane technology achieved through CACHET-II.

CACHET-II carries out the abovementioned research activities through 4 technical work packages (see Fig. 1 for the project organization structure):

WP1 – Pd membrane engineering, development and testing: a work package focusing on pure Pd membrane scale-up. Its objective is to demonstrate the production of pure Pd membranes and sealing techniques at a scale of 1m length and prove their long-term stability (>1000 hours) at high temperature (up to 400 $^{o}C$) in a $H_2$ separation membrane module.

WP2 – High flux and high stability membrane development: a work package focusing on developing novel Pd-alloy material of improved permeability and tolerance against $H_2S$ and CO to suit coal-derived syngas $H_2$ separation. Its key objective is to research, evaluate and test the application of novel Pd-alloy membranes to solid fuels and achieve 100% higher $H_2$ permeability in the presence of up to 20 ppm $H_2S$ compared to the current state-of-the-art PdCu membrane. In addition, WP2 also develops advanced Pd-alloy membrane material for high temperature (approximately 650-750 $^{o}C$) stability to suit integrated membrane natural gas reforming application.

WP3 – High temperature sulphur compound removal: a work package focusing on developing novel high temperature $H_2S$ removal sorbents to enable economic integration of membranes into IGCC-CCS. Its objective is to research, evaluate and test the application of innovative high temperature sulphur compounds removal to reduce $H_2S$ concentration to <5-20 ppm in the cleaned gas and achieve 25-50% economic benefit over the state of the art technology.

WP4 – Module design, process integration, economics and HSE: a work package delivering the mechanical engineering, process engineering and process safety aspects of technologies developed in WP1, 2 and 3. Its objectives include: designing a full-scale membrane module with optimum use of membrane area; maximizing energy efficiency of NGCC-CCS and IGCC-CCS plants through innovative integration of the membrane and process optimisation; evaluating the lifecycle cost of $CO_2$ captured and avoided to quantify the benefits of Pd membrane in NGCC-CCS and IGCC-CCS applications, targeting for 25-50% avoided $CO_2$ cost reduction compared to the state-of-the-art $CO_2$ capture technologies.

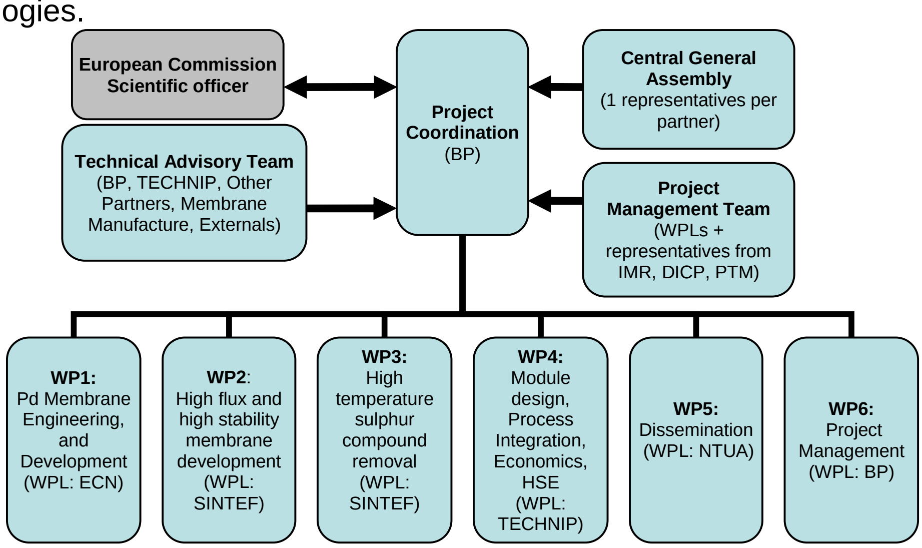


Fig. 1. Project organization structure of CACHET-II

## 2. Main S&T Results

*Pure Pd membrane and seals production scale-up and their stability*

CACHET-II inherited DICP's proprietary electroless plating technique for pure Pd membrane production from the European FP6 CACHET project which demonstrated DICP's technique up to 50cm long membrane production. In order to scale up DICP's technique to 1m membrane length, ECN has been preparing 1m long ceramic alumina supports with additional surface treatment to facilitate the deposition of the Pd-film by electroless plating at DICP. DICP has scaled up its membrane preparation and permeation test facilities including a furnace that is employed for the heat treatment of 1m long membranes during preparation. The manufacturing of such long membranes with 4-7 m thick Pd-films has been successfully demonstrated. The initial leak tightness of these membranes is good, showing a maximum $N_2$ leak rate smaller than 0.1 ml/min at a pressure difference of 100 kPa at room temperature.

A ceramic-to-metal mechanical sealing is critical for fixing the membranes in a commercially exploitable module assembly. Two development lines have been adopted by CACHET-II: (1) the further development of the already established ECN compression seal aiming at lower slip or sliding freedom of the seal over the membrane; (2) the development of an innovative sealing technology at Shenyang Institute of Metal Research (IMR) based on the already available knowledge on direct connection of ceramic membranes with stainless steel tubes. Both types of seal have successfully developed within the CACHET-II project, and have demonstrated their scalability to suit 1m length membrane. Fig. 2 shows the 1m long DICP pure Pd membranes equipped with ECN and IMR seals that were manufactured in CACHET-II. The two seals have also been fixed onto 5-10 cm long pure Pd membranes, 20-40 $cm^2$ in effective membrane area, and tested for the membrane-seal combined stability under simulated NGCC syngas conditions: temperature 673 K, syngas feed pressure 2.6 MPa, molar composition 51.2% $H_2$, 29.7% $H_2O$, 17.3% O, 1.2% CO and 0.6% $CH_4$, $H_2$ permeate pressure 0.6-0.8 MPa, $N_2$ sweep used to create 50:50 $H_2$:$N_2$ permeate product for hydrogen turbine specification. 120-150 day stability have been successfully demonstrated by the membrane-seal combinations. Fig. 3 presents results of a 150 day test with the displayed membrane which had a 4-5  m thick Pd layer. The $H_2$ permeation rate was very stable after some initial adjustments to limit $H_2$ recovery around 98% while $H_2$ purity fluctuated narrowly around 99% throughout the whole experiment. Thus 98% of the carbon content was held back on the feed side. This is more than sufficient with regard to the 90% CACHET-II carbon capture target and demonstrates the technological feasibility of pre-combustion carbon capture with Pd membranes.

Fig. 2. Picture of 1m long pure Pd membrane tubes equipped with IMR seals (on the top) and ECN seals (on the bottom).

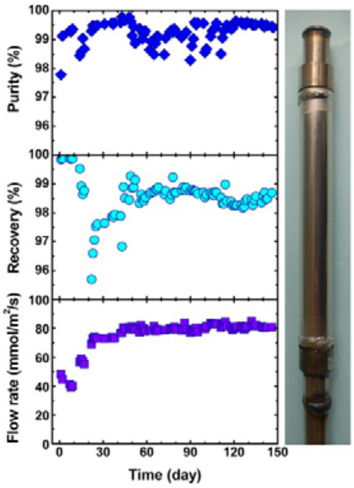


Fig.3. Performance of a Pd membrane during long-term testing in NGCC syngas at 400 °C, 26 bar feed and 8 bar permeate pressure.

*Novel Pd-alloy membrane material for IGCC-CCS application*

Magnetron sputtering is an alternative membrane manufacturing technique and was applied in CACHET by SINTEF. The CACHET-II project has adopted this technique for lab-scale Pd-alloy membrane production and screening in its WP2. >50 Pd-alloy membrane specimens have been manufactured by magnetron sputtering, including binary alloy materials such as Pd-Cu, Pd-Au and Pd-Ag, and ternary alloy materials such as Pd-Cu-TM and Pd-Ag-TM (TM = transition metal). Prepared membrane films have been characterized using SEM-EDS, XRD and XPS, and the gas permeation tests have been performed between 300 and 500 °C investigating the effect of CO and $H_2S$ inhibition on the various Pd-alloys. It has been shown that a $H_2S$ concentration of around 20 ppm saturates the Pd-alloy surface, thereby reducing the obtained $H_2$ flux by up to 90%. The $H_2$ flux through the Pd-Ag and Pd-Y alloy membranes are largely affected by CO poisoning. For these alloys, a reduction of up to 50% is obtained at a CO concentration of 5 vol%. For ternary Pd-Cu and Pd-Au alloy membranes the CO inhibition has been found to be less than 10% at the same CO concentration.

Rigorous membrane preparation and characterization work has identified that the Pd-Ag-Au alloy membrane shows the best performance in relative $H_2$ flux in the presence of 20 ppm $H_2S$, compared to all binary and other ternary Pd-Cu-TM and Pd-Ag-TM alloy samples. For this alloy, an effective $H_2$ permeability equal to $1.0\times10^{-9}$ mol·m$^{-1}$·s$^{-1}$·Pa$^{-0.5}$ has been obtained in the presence of 20 ppm of $H_2S$. This value for the permeability is a 212% improvement compared to the state-of-the-art $Pd_{70}Cu_{30}$ membrane, thereby reaching the main objective of WP2: development of binary and ternary PdCuTM and PdAgTM alloy membranes aiming for 100% higher $H_2$ permeability in the presence of up to 20 ppm $H_2S$ than the current state-of-the-art membranes exhibit. In addition, only in the Pd-Ag-Au sample no sulphur is observed by XPS analysis. This indicates that the addition of small amounts of Au to the high-flux Pd-Ag alloy membrane has improved the sulphur tolerance of this alloy, and that this could thus be an interesting approach for future development of high-flux Pd-based alloy membranes with improved sulphur tolerance. This discovery has advanced Pd membrane technology a step closer to its application for solid fuel application.

*Novel sorbent material for high temperature $H_2S$ removal from coal-derived syngas*

New solid sorbents that can selectively capture $H_2S$ and be regenerated at high temperatures could circumvent the cooling and reheating of the syngas and thus avoid the cost and efficiency penalty related to conventional ambient sulphur removal technologies. To fully benefit from Pd membrane as the $CO_2$ capture technology, the targeted cleaning efficiency is 5-20 ppm $H_2S$ in the sweet gas upstream of the membrane. The CACHET-II project kicked off its $H_2S$ sorbent research by developing its performance criteria, and used that to guide the sorbent synthesis and selection work. In the sorbent criteria work the targeted $H_2S$ capacities of the sorbents have been estimated; and optimum temperature and pressure intervals for both pressure swing adsorption (PSA) and temperature swing adsorption (TSA) processes have been identified. The sorbent's sulphur selectivity over $CO_2$ and the sulphur purity in the regenerated off gas have also been considered. In addition, the likely integration of the sulphur removal unit into IGCC processes has been evaluated.

In the sorbent selection work, SINTEF has been focusing on development of Cu-based metal oxide material for TSA $H_2S$ removal process, while ECN has been leveraging their knowledge on hydrotalcite material for a PSA alternative. Both parties have identified novel sorbents satisfying the performance targets of sulphur capacity and slippage of $H_2S$. This discovery is highly encouraging that high temperature $H_2S$ removal through adsorption is plausible. The Cu-based material, developed by SINTEF, has the higher $H_2S$ removal efficiency from the syngas (<5ppm, at 375 C) and the higher capacity (1.2 wt%). For this compound, a very short efficient reduction after the oxidation gave a fast $SO_2$ release at the lowest temperatures at which $CuSO_4$ was formed during oxidation.

CACHET-II process evaluation by Politecnico di Milano (PTM) has shown that by replacing Selexol $H_2S$ removal with the Cu-based high temperature $H_2S$ sorbent process in the IGCC-CCS with Pd-alloy membrane flow-sheet, the net energy efficiency (on LHV basis) increases from 39.08% to 40.76%, equivalent to 25% reduction of energy consumption per tonne of $CO_2$ avoided. If such high temperature $H_2S$ removal technology becomes commercially available, it will significantly enhance the economic benefits and competitiveness of the Pd membrane in solid fuel applications.

*Membrane simulation tool, full-scale membrane module design and its scaled-down unit demonstration*

SINTEF has developed a 2-dimensional membrane module simulation tool within CACHET-II project. The simulation tool accounts for bulk-phase feed side mass transfer characteristics, permeability and mass transfer resistance associated with the membrane deposition layer, mass transfer characteristics through the ceramic support tubing and at the bulk-phase permeate side of the membrane. A water gas shift (WGS) reaction model has also been built in, enabling the simulation tool to model both integrated WGS-membrane reactor setup and non-integrated membrane separator setup. For both setups, this simulation tool has been validated using 0.5m long pure Pd membrane testing data by ECN.

The simulation tool has been instrumental to the design of the membrane module design in 2 perspectives: (1) at 90-95% hydrogen recovery factor, the integrated reactor encounters a lower rate of mass transfer on the feed side of the membrane, and does not necessarily reduce the required membrane surface area in comparison to the non-integrated separator; (2) with the simulation tool, the project was able to analyse the $H_2$ transport characteristics from the feed side to the permeate side, identify the rate-limiting step(s) on the $H_2$ flux and innovate on a membrane module design that controls the rate-limiting step(s) and diminishes the required membrane area. With such insights, Technip led the task of developing a module design for full-scale membrane application, incorporating the pure Pd membrane and sealing technologies that have been scaled up and demonstrated in CACHET-II. Fig.4 illustrates the look of a single membrane module as well as the layout of installing 20 modules at industrial scale. The CACHET-II module design is able to host 12 m$^2$ membrane per module and costs approximately 5800 €/m$^2$ of membrane.

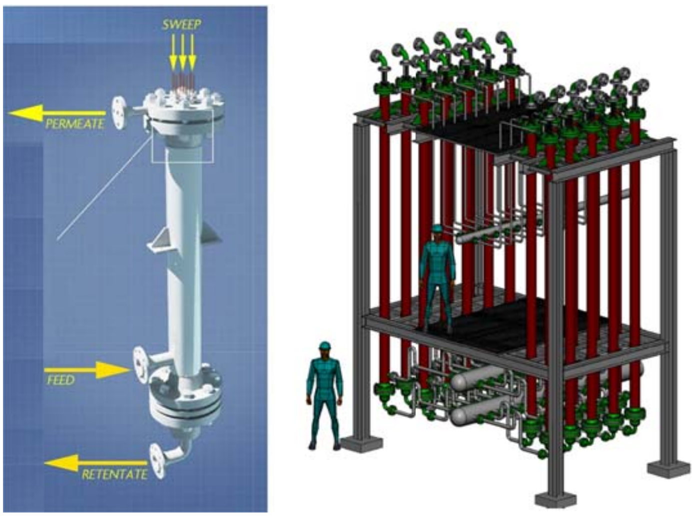


Fig.4. A 3D picture of the membrane module (left) and arrangement of 20 industrial size membrane modules (right).

ECN worked from the full-scale membrane module design and constructed a scaled-down membrane unit, equipped with three 1m long DICP pure Pd membranes (0.12 $m^2$ total membrane area), ECN's and IMR's ceramic-to-metal seals. This scaled-down membrane module has been tested under simulated NGCC-CCS conditions at ECN, aiming for >1000 hours of stable operation. The module has been able to generate about 19 $Nm^3/m^2$.hr of hydrogen at an operating temperature of 400$^oC$ under 30 bar of NGCC-gas composition and 6 bar $N_2$ sweep pressure at a $H_2$-recovery of approximately 90%. The retentate composition results in dry $CO_2$-levels well above 80% balanced by remaining CO and $H_2$. The presence of non-condensables in the retentate is lower than 1%, which fulfills the $CO_2$-storage requirements. It has been demonstrated that the module can survive 1000 hours of operation under constant hydrogen permeance and a hydrogen purity higher than 95%. Fig. 5 also shows that the hydrogen purity remained well above 99% for 800 hours. However during the last 200 hours, the $H_2$ purity dropped to a purity level slightly above the minimum purity target of 95%. This drop in hydrogen purity certainly requires further attention for follow-up activities of this project.

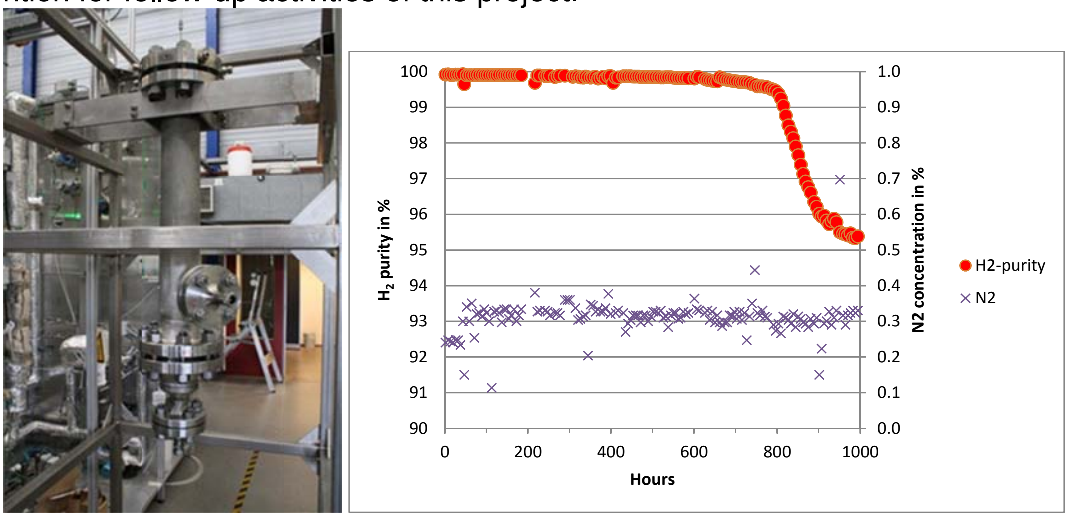


Fig. 5. Picture of the scaled-down membrane module and one set of its test results

*Energy efficiency and process economics advantages of Pd membrane for NGCC-CCS and IGCC-CCS applications*

For both NGCC-CCS and IGCC-CCS applications, the energy efficiency and process economics advantages of Pd membrane over the state-of-the-art solvent-based technologies are evident.

Fig. 6 shows the optimum process layout for NGCC-membrane plant, developed by NTUA in CACHET-II. This integrated 900 MW NGCC-membrane system has a close to 100% $CO_2$ capture rate and a net efficiency of 50.8% LHV. Its gain on SPECCA (Specific Primary Energy Consumption for $CO_2$ Avoided) compared to the methyl diethanolamine (MDEA) $CO_2$ capture base case reaches 15%. The NGCC-membrane system is associated with 61.5€/$t_{CO2}$ $CO_2$ avoidance cost, 7.4% lower than the MDEA base case 67€/$t_{CO2}$.

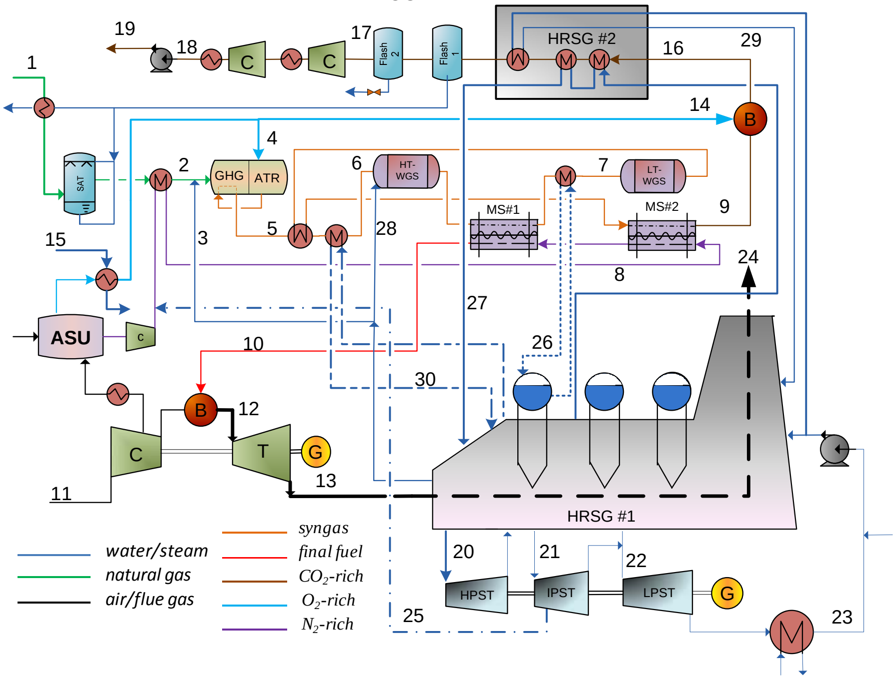


Fig. 6. Process Flow Diagram of NGCC-membrane plant exploiting pure Pd membrane and oxy-combustion $CO_2$ purification technologies.

CACHET-II's techno-economics evaluations of IGCC-membrane systems have been conducted by PTM, who have focused on IGCC-CCS plants exploiting Shell dry feed gasifier technology. Due to the amount of nitrogen used in gasifier dry feeding, the resultant syngas has a very high $N_2$ content and the process was initially not able to achieve the $CO_2$ purity required for storage. PTM has investigated two different options to satisfy the minimum $CO_2$ purity of 96%, the adoption of a $CO_2$ cryogenic separation system and $CO_2$ coal feeding, and concluded that the former option is more beneficial. Economic assessment has shown that the calculated membrane area for the initially selected 37 bar gasifier feed pressure is too large and penalising the overall process economics. PTM thus investigated alternative studies: membrane feed pressure as well as Hydrogen Recovery Factor (HRF) were varied in order to minimize the membrane surface area. In any case though, it is to be noted that the membrane is the most costly element of the plant. For this reason, close to the end of the project, an innovative lay-out where part of the hydrogen permeated is used to post-fire the HRSG was proposed. This lay-out allows a significant membrane surface area and cost reduction with negligible impact on the efficiency.

As a result, the combination of Shell gasifier, non-sulphur tolerant pure Pd membrane, Rectisol sulphur removal, HRSG $H_2$ post-firing, HRF 90% and 54 bar feed pressure, is concluded to be the most efficient and promising IGCC-membrane process, offering 39.1% LHV efficiency, SPECCA of 2.51 MJ/kg$_{CO2}$, and cost of $CO_2$ avoided 31.5 €/t$_{CO2.}$ The Process Flow Diagram of this optimum process is included in Fig. 7. The IGCC-CCS base case using Shell gasifier and Selexol pre-combustion capture technology has the following performance: efficiency 36.4%, SPECCA 3.67 MJ/kg$_{CO2}$, cost of $CO_2$ avoided 36.0 €/t$_{CO2}$. That is, the IGCC-membrane system is approximately 32% lower in energy penalty and 12% lower in cost of $CO_2$ avoided comparing to the state-of-the-art IGCC-CCS technology of Selexol. As the sulphur tolerant Pd-alloy membrane and high temperature sulphur sorbent technologies continue to advance post CACHET-II, their prospective exploitation in the IGCC-membrane system, to substitute the pure Pd membrane and Rectisol sulphur removal, will further increase the energy efficiency by 1% point reaching close to 40% energy penalty reduction and reduce the cost of $CO_2$ avoided.

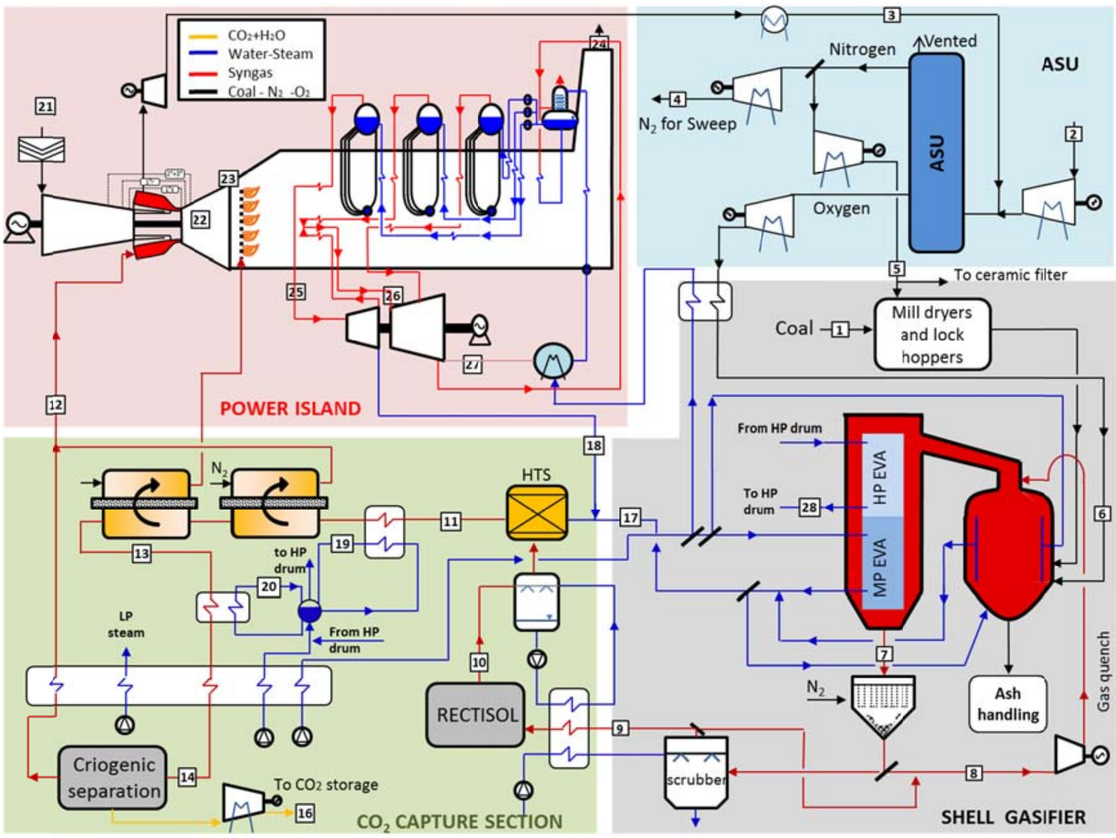


Fig. 7. Process Flow Diagram of IGCC-membrane plant exploiting Shell gasifier, Rectisol sulphur removal, pure Pd membrane, HRSG post-firing and cryogenic purification technologies.

## 3. *Dissemination Activities and Socio-Economic Impacts*

CACHET-II has made conscious efforts in effectively communicating the project's major outputs to decision-making organisations and other interested parties in the industry, research centres, academia, governmental organisations, NGO's and the general public. This initiative has been realised by a combination of scientific and more popular channels: a project website, press release, annual newsletters, publications in scientific journals, presentations at conferences to exchange information with other scientists in relevant fields, organisation of workshops to promote results to industry and end-users have all been exploited. One student at NTUA and one student at PTM have been funded by CACHET-II for part of their PhD studies. Lectures have also been given to NTUA and PTM undergraduate and master classes to raise awareness and interest of next generations on membrane technology and low carbon power generation.

Over its duration of 3 years, CACHET-II has published 7 papers with peer-reviewed journals, e.g. Journal of Membrane Science, Catalysis Today and Journal of Energy Conversion and Management. Another 5 papers are being currently prepared for 2013 Q1 submission. CACHET-II has also had significant presence at European and international conferences related to membrane development and CCS technologies. For example, the CACHET-II consortium contributed two podium presentations and two poster presentations on some of the final project results at the 11$^{th}$ International Conference on Greenhouse Gas Technologies (GHGT-11) that was held in Kyoto, Japan, 18-22 November 2012. Formed in 1997, the Greenhouse Gas Control Technologies (GHGT) conference series followed the merger of the earlier series of ICCDR and the Greenhouse Gas Mitigation Options conference. The GHGT conferences are held every two years in IEAGHG's member countries and have become a focal point for international research on $CO_2$ capture and storage. CACHET-II's significant presence at the GHGT-11 conference is a sign of recognition of the importance of the Pd membrane technology and the success of the project.

CACHET-II has organised 3 workshops to disseminate its S&T results and engage with other membrane researchers and potential end-users from industries to gather their feedbacks about the project. The first public CACHET-II Workshop was held on 11$^{th}$ April 2011 at the Dalian Institute of Chemical Physics (DICP), as part of the International Conference on Clean Energy Science (ICCES), organised by Royal Society of Chemistry (RSC) and Chinese Academy of Sciences (CAS). The Workshop was attended by approximately 30 delegates worldwide, comprising of 8 podium presentations and 4 posters that aimed at introducing the workscope and objectives of CACHET-II, disseminating the results and achievements from the first year of the project and disclosing its plan for the following 2 years. The second public workshop was held in London on 25$^{th}$ May 2011 as part of the CO2NET annual seminar, which attracted approximately 100 delegates worldwide. CACHET-II consortium contributed 4 podium presentations, which focused on disseminating its research results and positive technology outlook with CCS industry stakeholders who are the prospective end-users of CACHET-II technologies.

The third public workshop was one of its most important events of CACHET-II. As the project was approaching its completion, it was ready to disseminate a great deal of its results and achievements, as well as engaging with interested parties to discuss the way forward for Pd membrane technology. CACHET-II recognized that two other European FP7 projects, CARENA and CoMETHy, were also developing palladium membrane technology for two different applications. Due to the technology synergy and common interest, the three projects joined forces to organize a workshop together, focusing on discussing “palladium membrane scale-up challenges and solutions”. The workshop was held in Rome, Italy, on 12-14th of November 2012, including two days of presentations and interactive discussions in Rome, and a site visit to Tecnimont KT membrane reforming pilot plant at Chieti. The workshop brought together more than 70 participants from more than 45 different organizations worldwide, with a broad participation of industrial stakeholders besides representatives of research institutions and universities. In addition to the members of the three organizing projects, a good number of “external” participants and projects also presented and contributed to the interactive discussion. Therefore, the event proved to be a unique knowledge-sharing experience for the three projects and all participants, providing a clear picture of the status of palladium membrane technology in view of its commercialization. The workshop covered a good breadth of topics that are critical for palladium membrane technology scale-up: from the fundamentals of palladium membranes, support and seal manufacturing, mechanical design, to various concepts of membrane module design and system integration; from lab-scale long-term stability testing results to industrial pilot plant operational insights. The closing discussion session sketches a picture of the general opinion on the status of the Pd-technology and an overview of the critical issues to be addressed in the near future.

The workshop was such a success that the participants expressed interest to have more workshops like this on a regular basis. Thus a committee has been formed, who will take care of a follow-up of the current workshop. It is envisaged that a follow-up workshop will be organized approximately two years from now, which coincidently marks the final phase of the CARENA and CoMETHy EU-projects. In addition, following this successful workshop, the publication of a book on Palladium Membrane Technology and Applications has been undertaken. The book is expected to be published by Woodhead Publishing Ltd. in late 2013 and will combine knowledge gained from all three projects and further disseminate the results of the CACHET-II project.

CCS is a critical carbon abatement technique for the mankind to stabilize atmospheric $CO_2$ concentration and avoid the associated climatic impacts. Multiple studies, including the techno-economics assessments by CACHET-II, have indicated that Pd membrane has the potential to reduce the cost of carbon abatement via CCS. The diligent work performed by CACHET-II has moved the Pd membrane technology forward by a significant step and generated valuable foregrounds. If the world one day starts adopting CCS and exploiting the Pd membrane technology for that purpose, a supply chain of membrane associated production and services, including some of CACHET-II’s foregrounds, will begin to materialize: from manufacturing of ceramic tubular membrane supports, to modification of the supports (ECN technique practised in CACHET-II), to plating of palladium membrane layer onto ceramic tubes (DICP technique scaled up by CACHET-II), to sealing of membrane tubes (ECN and IMR techniques scaled up by CACHET-II), to manufacturing of commercial scale membrane modules (Technip engineering design developed by CACHET-II), to sizing and designing the membrane process (SINTEF membrane simulation tool developed by CACHET-II) and to provide operational guidance and performance assurance on the built-up and operation of membrane modules (joint knowledge from the CACHET-II consortium). In a word, a novel industry would emerge in correspondence to the commercial exploitation of CCS, and some of CACHET-II's foregrounds and partners could play a significant role in it. Although CCS is not expected to be commercially deployed across Europe until 2020-2030, foregrounds and knowledge developed in CACHET-II are yet transferrable to other applications of Pd membrane, e.g. niche markets of distributed $H_2$ production and $H_2$ purification for semiconductor industry.

## *4. Beneficiaries and Contacts*

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|---|---|---|---|---|
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