nano memc^2

NanoMaterials Enhanced Membranes for Carbon Capture

Enjoy reading the NANOMEMC^2 newsletter!

The NANOMEMC^2 project started in October 2016 and is a research and innovation action of Horizon 2020 funded under the topic LCE-24-2016 “International cooperation with South Korea on new generation high-efficiency capture processes”.

Within the current environmental concerns about global warming, Carbon Capture, Utilisation and Storage (CCUS) is seen as a necessary medium-term technology to reduce greenhouse gas emissions into the atmosphere while waiting for a complete transition towards a more sustainable energy system. Currently, the main downside to the application of carbon capture (CC) technologies is the high implementation cost; therefore, strong research efforts are required to optimize current capture processes and make CC an economically viable solution for the decarbonisation of industry.

The NANOMEMC^2 project aimed to overcome such limitations through the development of CO_2 capture innovative materials, membranes and processes which can achieve a substantial cost reduction, and help achieve the reduction of CO_2 emissions.

To that aim NANOMEMC^2 applied new membranes to both Pre- and Post-combustion capture stages in order to increase the flexibility of the proposed solutions and maximize the resulting technologies’ chances of success. NANOMEMC^2 also addressed the development of new, high efficiency capture processes, which are selected through techno-economic and environmental analysis, to obtain solutions tailored for a competitive implementation of membrane-based capture applications in relevant industrial plants.

NANOMEMC^2 has obtained a broad range of promising results for the development of membrane-based CC solutions. Most of the materials investigated showed properties in line or above the current permeability/selectivity trade off limit for CO_2 separation membranes and were successfully tested in relevant industrial environments. In addition, techno-economic analysis on optimized integrated processes showed that such membranes can be competitive with other CC technology in reducing the overall cost of the capture stage in different industrial applications. Three business cases were built as basis for the future deployment of membrane-based carbon capture solutions in industry.

Finally, NANOMEMC^2 sought strong collaboration with the Republic of Korea in the field of CCS to exploit complementary expertise and synergies in the development of new capture solutions.

NANOMEMC^2 is now at its end. This newsletter wants to give an overview of the achievements reached during the project.

CONTENTS

WP2 - Nanomaterials and Membranes Production

AIM

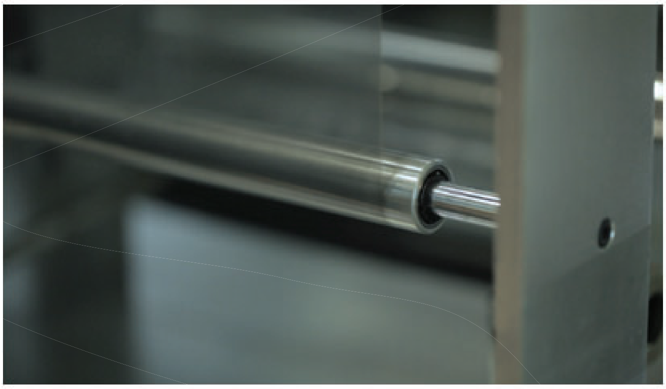
The aim of this WP is to fabricate and optimize hybrid polymer-based **membranes** for CO_2 capture.

RESULTS

During the project, different types of nanofillers based on cellulose nanofibers or graphene and graphene oxide have been analised to understand their ability to boost the separation performance of conventional membranes materials with interesting CO_2 capture capabilities. Two main families of membranes were investigated, the so-called Facilitated Transport Hybrid Membranes (FTHM) which separate the CO_2 through a selective carrier mediated transport mechanism, and the Continuous Phase Hybrid Membranes, which mainly exploit the molecular sieve mechanism to separate CO_2 from other gases. Durig the project three different generation of materials were considered **producing and testing more than 100 different membranes materials**. Different experimental techniques were used such as FTIR spectroscopy, SEM, AFM and X-ray scattering were considered to define the structure and the chemistry of the different sample while TGA, sorption tests and mechanical analysis were conducted to understand their response to thermal, chemical and mechanical stresses. The most promising materials were sent to WP3 partners for the analysis of permeation and separation performance and to WP6 partners for the scale up of the production to produce membrane modules suitable for industrial tests in the Colacem cement production facility in Gubbio (Italy) and in the Pilot-scale Advanced CO_2 Capture Technology (PACT) at the University of Sheffield (UK). Most of the materials resulted close or above the Robeson's upper bound which is usually applied to compare membranes separation performances

In the last year, WP2 partners focused mainly on the production and testing of innovative membrane materials produced by using modified nanofiller, based on both nanocellulose, graphene derived materials. Even if the project time span was not sufficient to test bring all the different innovative materials to a prototype scale for industrial testing, the consortium decided to continue the research trying to further improve the different membranes materials in view of further optimization of the membrane based carbon capture processes.

To test a more scalable option, a test on a roll-to-roll pilot plant has been made to apply graphene on a membrane. A very thin (10-20 nm) graphene coating deposition, even and uniform has been applied confirming the possibility to quickly scale-up the production to continuous production plant.



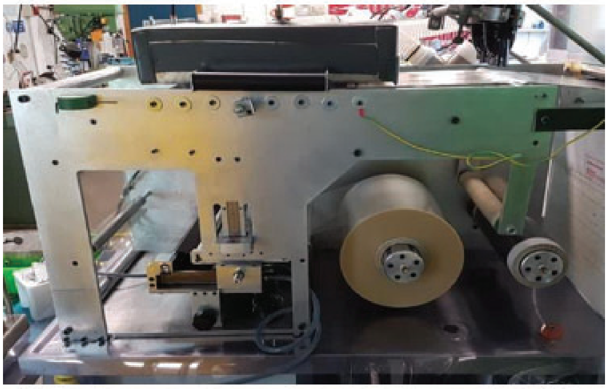


Figure 1 Pilot coating line applying graphene on polymer film

FTHM a flavour of results.

The 3rd generation materials for FTHM were developing following two different lines:

• The production of membrane based on modified nanocellulose grafted with CCO_2 -philic functional groups (PPG, PEG as shown in Figure 1 and different aminosilanes APTMS, AEAPTMS and AEAPDMS) to be coupled with an aminated polymers (polyvinylamine PVAm or sterically hindered polyallylamine, SHPAA) and possibly some aminoacid to be used as mobile carrier (UNIBO-NTNU-INOFIB).

• The production of membranes by adding to the above mentioned polymers (PVAm and SHPAA) modified graphene or porous graphene oxide (PGO) in order to increase their, mechanical resistance in humid conditions as well as their selectivity thanks to size sieving ability of PGO (UNIBO – NTNU – Graphene XT)

CPHM a flavour of results.

The 3rd generation materials for CPHM were once again developed by considering different strategies, in this case mainly related to the use of Graphene oxide as a filler. In particular, both CO_2 selective membrane for post combustion application and hydrogen selective membranes for precombustion capture, were considered in this line of development.

- CO_2 selective membranes were on one side based on the UNIBO work initiated during an STSM in Hanyang university incollaboration with Prof. Park the NANOMEMC^2 Korean partner. In this case Pebax 2533 was added with different type of GO (Figure 2) and also chemical modification was considered to improve the polymer permselectivity as well as its affinity with GO. In parallel, at NTNU a study on the influence of casting solvent on the structure of midblock-sulfonated block polymer membranes, was also considered to understand if these materials could represent a viable more resistant alternatives to the other polymers investigated for CPHMs.

- For hydrogen selective membranes Fujifilm worked on the improvement of their membrane materials focusing mainly on the reduction of the support resistance without affecting the properties of the selective layer. Reduction of gutter layer thickness below 500 nm while maintaining the selective layer continuous and defect free.

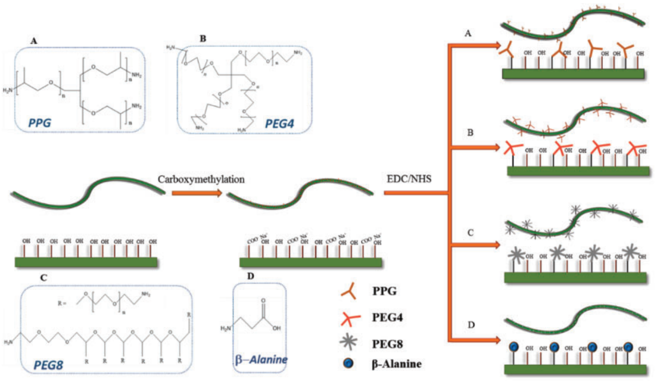


Figure 1 Example of Nanocellulose fibril surface modification performed within NANOMEMC^2.

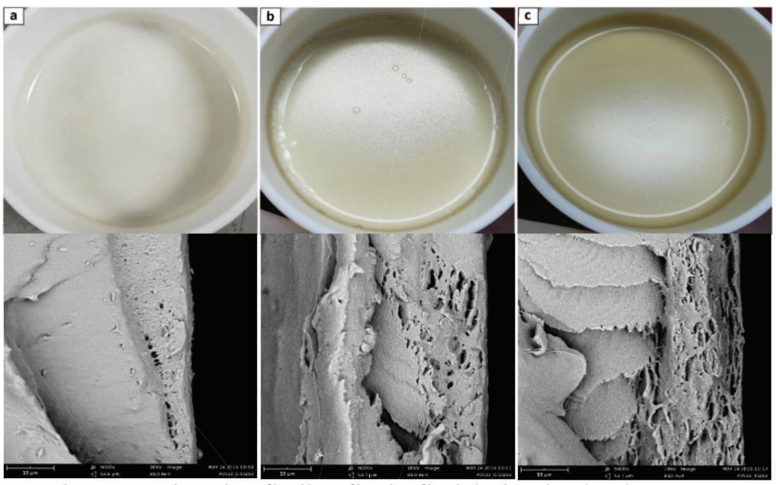


Figure 2: Pebax2533 + GO membranes, a) 0,1 wt% GO b) 0,5 wt% GO c) 1 wt% GO (Up) ; Below each membrane the respective SEM picture is shown.

WP3 - Membranes characterization and Testing

AIM

WP3 focuses on the performance testing of the different membranes produced in WP2.

RESULTS

Gas permeation properties of the membranes fabricated in WP2 has been tested using different gas pairs. Generally, the gas permeation tests were carried out at relatively mild conditions (e.g., temperature in the range of 25 ~ 65 °C and pressure in the range of 1~2 bar).

CO_2 transport through midblock-sulfonated block membranes prepared from four different solvents is investigated. The results presented here establish that membrane morphology and accompanying gas transport properties are sensitive to casting solvent and relative humidity. We likewise report an intriguing observation: submersion of these thermoplastic elastomeric membranes in liquid water, followed by drying prior to analysis, promotes not only a substantial change in membrane morphology, but also a significant improvement in both CO_2 permeability and CO_2 /N_2 selectivity. Measured CO_2 permeability and CO_2 /N_2 selectivity values of 482 Barrer and 57, respectively, surpass the Robeson upper bound, indicating that these nanostructured membranes constitute promising candidates for gas separation technologies aimed at CO_2 capture.

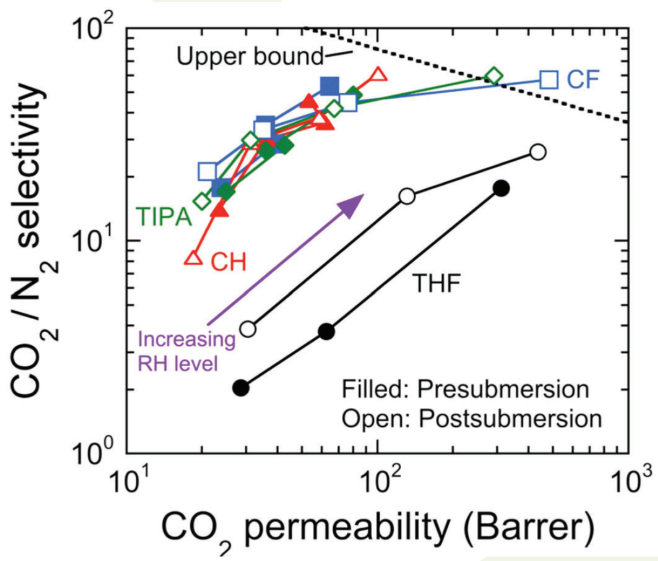


Figure 3 CO2 separation performance of TESET membranes cast from different solvents (labeled and color-coded) before and after submersion in liquid water (filled and open symbols, respectively).

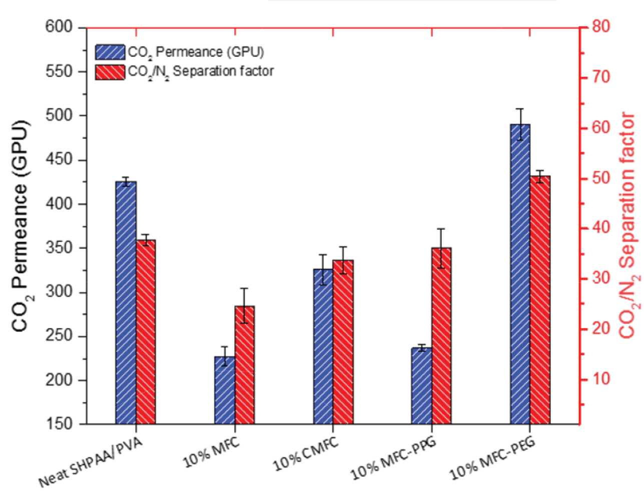


Figure 4 CO_2 separation performance of facilitated transport membranes containing modified nanocelluloses.

In another study, the effect of fillers' surface properties in hybrid facilitated transport properties were investigated (Figure 4). A facile surface modification procedure to introduce functional moieties of varying properties was developed as a "one-pot" process to manipulate the nanocellulose surface. The role of functionalized surfaces in hybrid membranes has been systematically investigated. Fillers functionalized with PEG groups were found to enhance separation. PEGlyation of MFC serves three purposes in the SHPAA-based membrane: firstly, the PEG chains increase the steric stability of the fibrils, as the charges are significantly lower after functionalization; secondly, the EO groups directly contribute to increased surface CO_2 sorption, creating enhanced surface diffusion pathways for CO_2 transport; thirdly, the high hydrophilicity of the PEG chains creates water reservoirs along the surface, enabling swelling of the hybrid matrix and enhancing the facilitated transport effect.

In hybrid facilitated transport membranes containing Graphene Oxide-based nanofillers, the separation performance was evidently dependent on physical and chemical properties of the 2D- fillers. High transmembrane flux of CO_2 with CO_2/N_2 selectivity of about 30 were obtained with most membranes. Furthermore, resistance to oxidation and other harmful components like NOx, SOx has also been observed. One such configuration with modified graphene oxide in facilitated transport membranes was chosen for scale up and further evaluation.

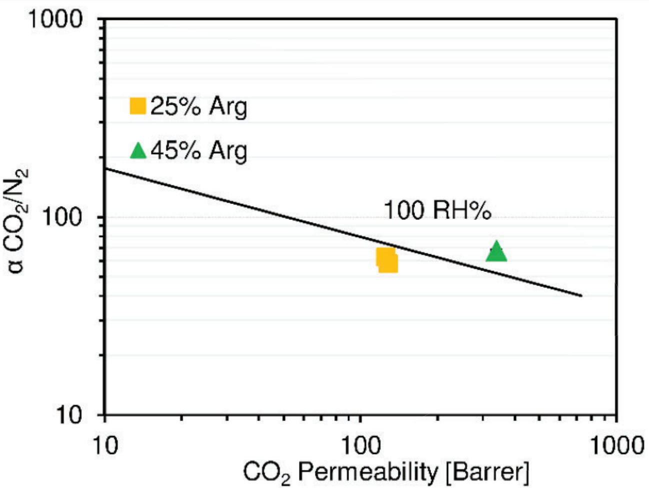


Figure 5 Robeson plot showing performance of PVAm/cmNFC membranes at different degrees of humidity and arginine loadings.

At UNIBO, novel FTHM materials based on PVAm, nanocellulose and arginine were fabricated and tested. It was found that humidity plays a major role in these membranes in addition to the amount of mobile carriers in the matrix. At high humidity of 100% RH, the 45 wt% Arginine loaded PVAm/Nanocellulsoe membrane exhibited a CO_2 permeability of 340 barrer with CO_2 /N_2 selectivity of 68 as seen in Figure 5.

UNIBO in collaboration with Graphene XT, also prepared PVAm/Graphene composite membrane on PDMS support by printing each layer resulting in composite membranes with CO_2 permeance as high as 646 GPU however with only a maximum CO_2 /N_2 selectivity of 20.5.

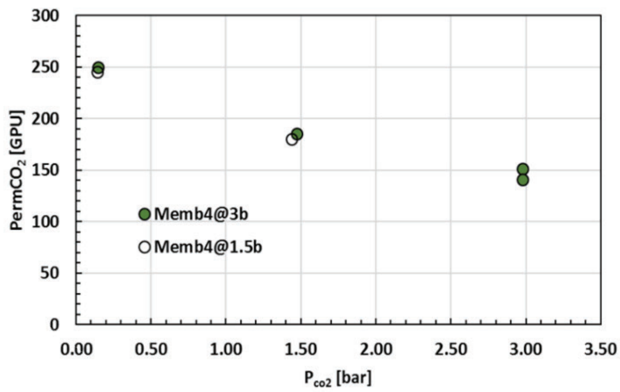


Figure 6 CO2 permeance at different total and partial pressures of feed gas stream in FTHM membranes.

PEBAX 2533 + GO composite membranes were made by UNIBO. However, contrary to expectations addition of modified Graphene Oxide was only able to increase the CO_2 permeability of PEBAX by 8% with no significant effect on CO_2 /N_2 selectivity.

UEDIN did an interesting study on FTHM materials supplied by NTNU and found that there is a pronounced carrier saturation phenomenon in the membranes which is the characteristic of fixed-site carrier membranes. It was found that the ultra thin selective layer has no significant response to high pressure highlighting the stability of the membrane to compaction phenomenon as seen in Figure 6.

FUJIFILM developed 3rd generation CPHM membranes for H_2/CO_2 separation application but tested with Helium instead of H_2 for safety reasons. The target He/CO_2 selectivity of 100 was achieved however the He permeance was still below the target permeance of 300 GPU. Increase in temperature was found to increase permeance however degraded the selectivity. Increase in pressure also resulted in similar trends.

AIM

The CO_2 facilitated transport mechanism in swollen poly-vinylamine is the object of the study in WP4. The main parameters affecting the transport, the diffusivity and the solubility, have been investigated via Molecular Dynamics and Equation of State approaches.

RESULTS

Different levels of hydration, temperatures and degrees of protonation, as well as the presence or the absence of chloride counter-ion, have been used to obtain very useful and detailed informations about material internal properties such as free fraction volume, density and polymer chains rearrangement; these mainly relates to the diffusion process.

Regarding the solubility of carbon dioxide, related to both physical and chemical interactions with the humidified polymer, the polyelectrolyte PC-SAFT, coupled with a chemical reaction scheme, revealed how the process parameters such as temperature, relative humidity (RH) and carbon dioxide partial pressure (P_{CO2}) influence the CO_2 uptake in PVAm water swollen membranes. In this framework, together with dispersion, hydrogen bonds formation and hard-sphere chain contributions, also the ion-ion interactions as well as the so called 'counter-ion condensation' effect were considered. The approach based on pePC-SAFT EoS does not require additional parameters respect to the ones already used in the classical PC-SAFT. This means that, to model the polyelectrolyte behaviour arising due the chemical reaction, the parameter set retrieved (in previous investigations) for the non-charged PVAm can be used without further modifications. Moreover, the knowledge of the equilibrium ionic species concentrations, allows determining the protonation degree of the polyelectrolyte without experimentally measurements. In this sense the tool developed is fully predictive. The two figures below show the main results in terms of constant carbon dioxide uptake, expressed as grams of total sorbed CO_2 (physical and chemical) per grams of PVAm, as function of P_{CO2} and RH in the gas/vapour phase.

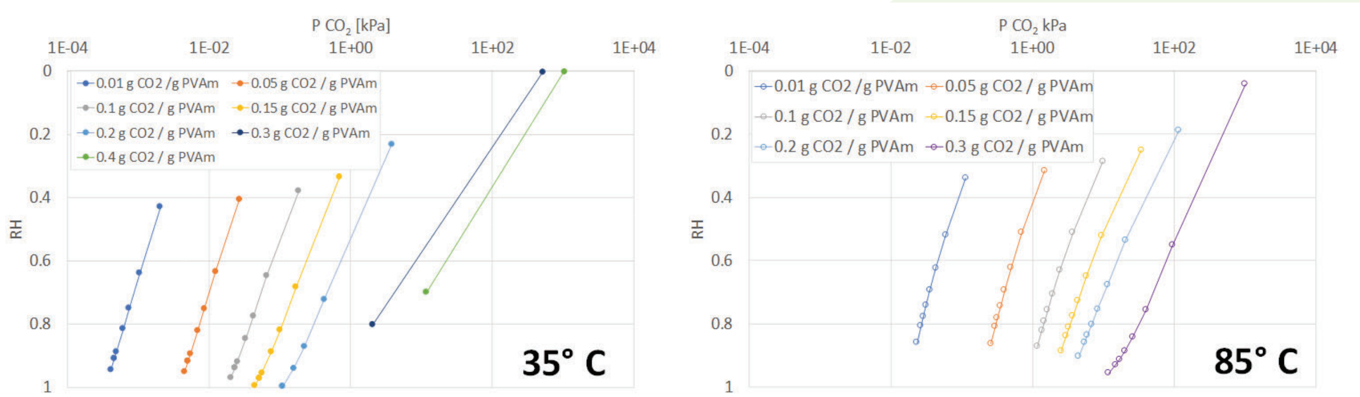


Figure 7. Total Carbon Dioxide uptake in water swollen PVAm as function of partial pressure of CO2 and Relative Humidity in the gas/vapour phase. Temperature equal to 35 °C and 85 °C in the left and right plot respectively.

Two temperatures were investigated, 35°C and 85°C, show in the left and right panel respectively. Independently from these values, in this range, an obvious positive effect of the relative humidity is elucidated on the carbon dioxide uptake. It is possible to see that, for all the constant concentration lines, if an increase in relative humidity happens, a lower value of P_{CO2} is needed. Moreover, the approach can describe the exothermic nature of the sorption process: in the same conditions of RH and P_{CO2} the sorption uptake decrease by increasing temperature.

WP5 - Process Design, Optimization and Assessment

AIM

The activities of the work package "Process Design, Optimization and Assessment" aimed at implementing the novel NANOMEMC^2 membrane materials into industrial test cases. By a benchmark against conventional process alternatives that, respectively, apply no carbon capture (BAU) or explore state-of-the-art technology for carbon capture (BC), their capabilities were evaluated in terms of economic and environmental aspects. In addition to the consideration of the novel process designs from economic perspective, a Life Cycle Assessment (LCA) was performed to analyse the environmental impacts of the proposed innovations.

RESULTS

The LCA analysis regarded four Industrial Production Scenarios for the implementation of the novel NANOMEMC^2 membrane materials. These processes originated from three industrial sectors:

- Hydrogen production via steam methane reforming - Oil&Gas (SMR)
- Integrated coal gasification combined cycle power plants - Power Generation (IGCC)
- Clinker production process (Cement)
- Natural gas-based power production - Power Generation (NGCC)

LCA study – Assessing the process from an environmental perspective

Life cycle assessment is a methodological framework for assessing the environmental impacts attributable to the life cycle of a product, including climate change, human toxicity, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, water depletion and fossil fuel depletion. According to the ISO 14040 and 14044 standards (ISO 14040 defines the principles and framework of the LCA, while ISO 14044 provides requirements and guidelines), an LCA represents a four-step procedure: **goal and scope definition, inventory analysis, impact assessment, and interpretation.**

The scope definition sets out the framework of the study and identifies the objectives of the assessment under consideration of the recipients' concerns. In that context, the analysis includes technical details such as the description of the system boundaries. The Life Cycle Inventory (LCI) analysis summarizes the inventory of the process with regard to materials and energy flows within the whole life cycle. The Life Cycle Impact Assessment (LCIA) represents the calculation of the environmental impacts associated with the identified inventory of the process (LCI). Finally, the results interpretation allows drawing conclusions and providing recommendations.

Approach and methodology

The LCA performed within the NANOMEMC^2 project pursued the objective of assessing the environmental and health benefits obtainable thanks to the use of the innovative NANOMEMC^2 membranes, in respect to state-of-the-art technologies. In the course of the current study, the novel NANOMEMC^2 developments are exploited to perform the energy-efficient capture and sequestration of carbon dioxide to reduce the environmental footprint of the products hydrogen, cement and electricity.

Accordingly, a focus is set to impact category of "Climate Change". Being characterized by the mid-point indicator "Global Warming Potential (GWP)", reported in CO_2-equivalent emissions (CO2eq), all CO_2-emission-related impacts connected to the generation of the target product, such as the use of raw materials, utilities etc. are summarized. In addition, to deepen the understanding of a particular capture application, three endpoint indicators have been considered, too: damage to human health, to ecosystems, and resource availability.

A short interpretation of the outcome: *Steam methane reforming (SMR)*

The application of the innovative NANOMEMC² membranes to a process that generates hydrogen from natural gas via steam methane reforming has been simulated and the related impacts on the environment have been assessed with a particular reference to the GWP. Compared to the process alternative that does not apply means of carbon capture, the CO2eq emissions are reduced up to 80%, thanks to the application of decarbonization measures by either using conventional or innovative technology. Concerning the reduction of the total environmental impacts (right-hand set of columns of Figure 8, weighted cumulative of ecosystem quality, human health and resources) by 20 to 30%, a lower, but nonetheless important effect is observed. It becomes obvious that the reduction of the total environmental impacts is less significant as it is for the GWP: this is mainly dedicated to the elevated use of resources (natural gas and electricity) related to the application of carbon capture technologies. From the data presented, it is concluded that the environmental performance of NANOMEMC² membrane materials is fully in line with best available capture technologies (Figure 8).

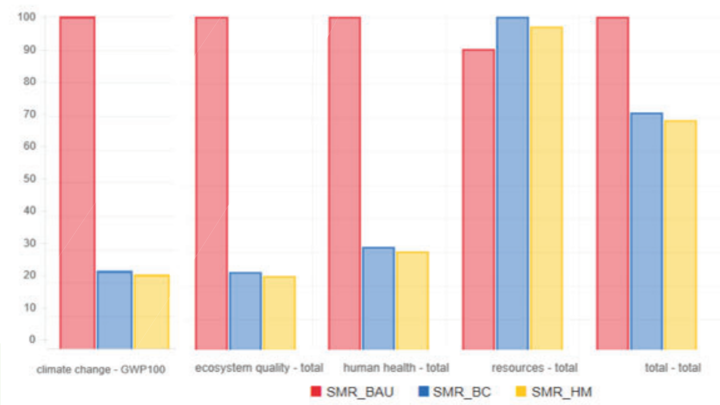


Figure 8 SMR – GWP, selected endpoint indicators and total environmental impacts

Integrated Gasification Combined Cycle (IGCC)

Considering the impacts in terms of GWP, the reduction of the CO_2 eq emissions in respect to the no-capture case is similar for the use of both technologies, innovative as well as conventional. It equals to about 70%. Along with that, a decrease of the total environmental impact of the processes with CO_2 capture of 40% is evident. This mainly connects to the restrictions of the GWP, while the increased use of resources (coal and water) resists to further reductions of adverse impacts (Figure 9).

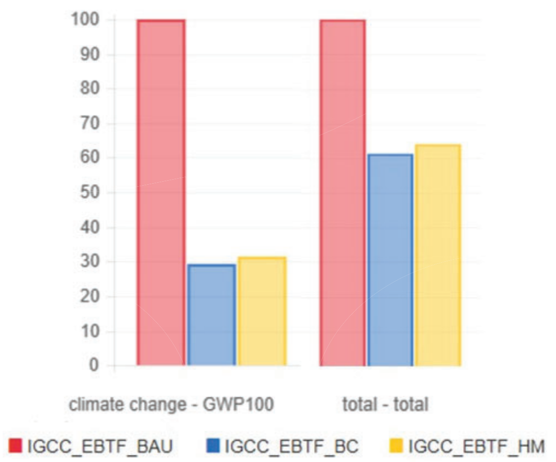


Figure 9 IGCC – GWP and total environmental impacts

Clinker production

The impacts of carbon capture on clinker production plants has been assessed considering the facility operated by the project partner COLACEM. Here, NANOMEMC² membrane technology has been implemented successfully into a real-life industrial process. By the use of the new technology, the CO2eq emissions are reduced by 25%, accompanied by the decrease of overall impacts associated with clinker production by about 20%. Care needs to be taken while interpreting the results: while the GWP is diminished by 25% only in view of a cradle-to-grave approach, a reduction of about 90% is disclosed considering the gate-to-gate boundaries (i.e. excluding CaCO3 mining): in fact, the impact of raw materials on the GWP is very strong (more than 50%) and is independent from CO_2 capture, which affects only the part of the GWP linked to direct emissions of CO_2 into the atmosphere. The environmental performance of NANOMEMC² membranes is almost the same as it is for the state-of-the-art membranes, as shown in Figure 10.

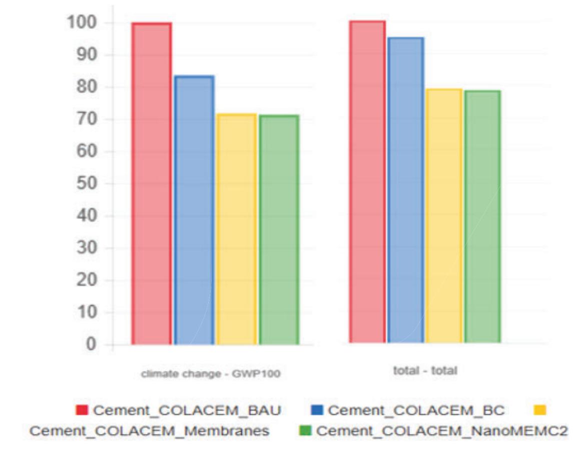


Figure 10 Clinker production – GWP and total env. impacts

Natural Gas Combined Cycle (NGCC)

Figure 11 provides a typical result of the Life Cycle Assessment with regard to the power production by the use of natural gas. From a direct comparison, it becomes evident that the application of both, conventional capture technology (NGCC_BC) and NANOMEMC^2 membranes (NGCC_HM), shows a positive impact on the eco-balance of the process. However, comparing the new NANOMEMC^2 membranes against state-of-the-art capture systems, it needs to be stated that membrane applications for carbon capture have their limits: in reference to the use of conventional capture technology, the membrane-based processes exhibit an enhanced total environmental impact.

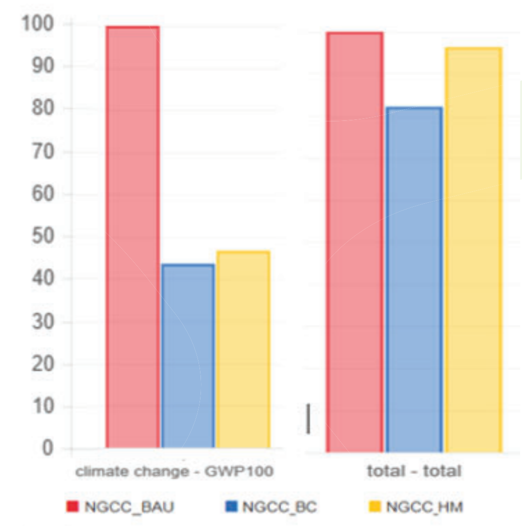


Figure 11 NGCC – GWP and total env. impacts

Conclusions

From an environmental point of view, the application of the membranes in the course of CCS is very promising. Considering the whole process, the LCA has demonstrated that the application of the novel NANOMEMC^2 membranes enables a strong reduction of the GWP (from 25% to 80% depending on the specific process considered). Concerning the total environmental impacts, a restricted effect is evident (40%), due to the presence of other contributors such as the use of resources (natural gas, water, etc.).

WP6 - Module development and prototype testing

AIM

WP6 is devoted to scale up of the most promising membranes developed in WP2 and to test them under operating conditions identified in WP5 as the most suitable for high efficiency industrial capture.

RESULTS

In the preparation to the final pilot-scale tests the test-rigs were engineered and integrated at the Colacem cement plant located in Gubbio, Italy (Figure 12) and at the PACT (Pilot-Scale Advanced Capture Technology) centre located in Sheffield, United Kingdom (Figure 13).

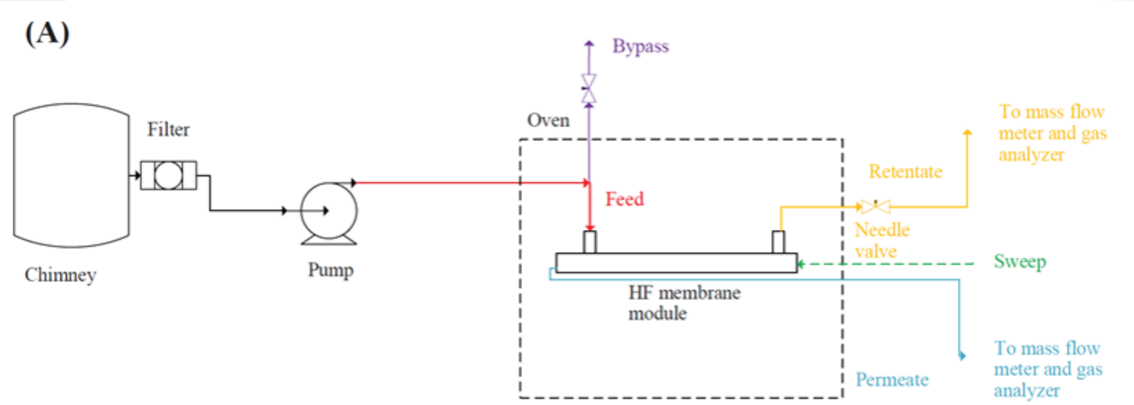


Figure 12 Membrane integration at Colacem cement plant (Gubbio, Italy).

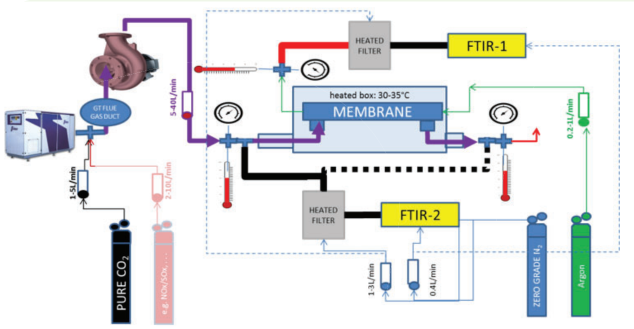


Figure 13 Membrane integration at PACT (Sheffield, United Kingdom).

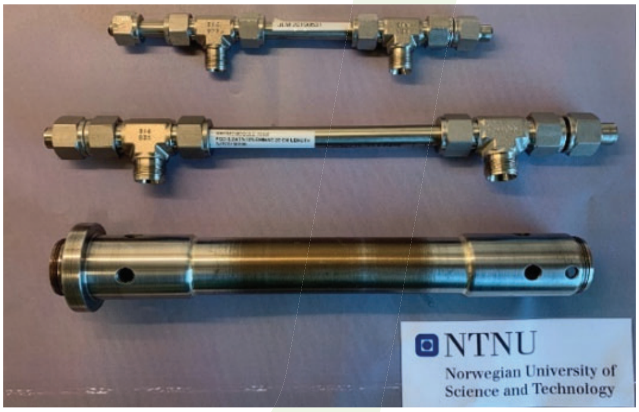


Figure 14 Membrane modules for the second prototype testing

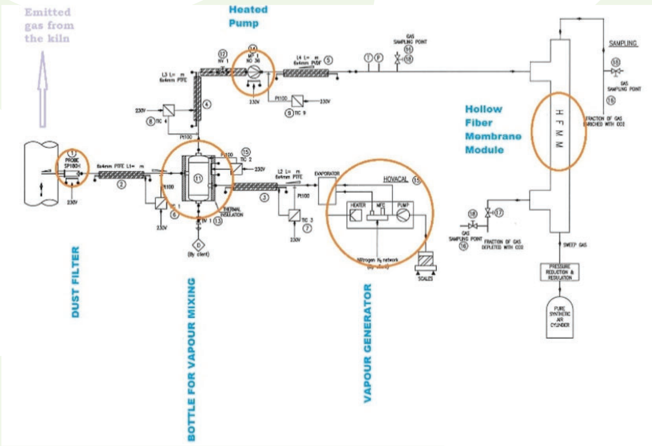


Figure 15 Process schematic showcasing in-house design of membrane testing rig with additional vapour generator

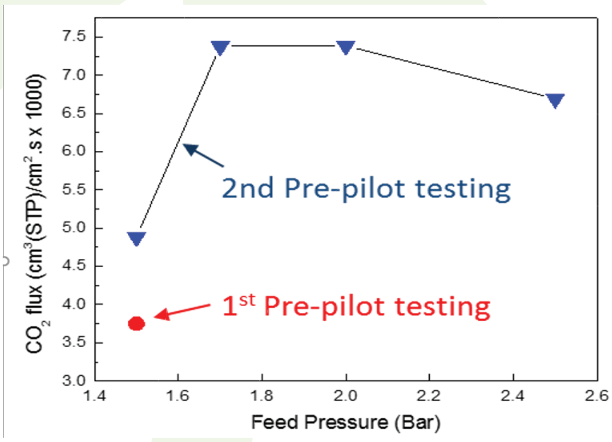


Figure 16 Comparison of separation performances of engineered pre-pilot prototypes.

The industrial tests are split into two phases, the pre-pilot tests and the final pilot-tests phase. The membrane selected for the pre-pilot tests was a thin film composite hollow fibre membrane with an approximate 500nm thick selective layer made of the PVA/amino acid salt hybrid membrane with 40 wt% ProK. The support substrate was a PPO hollow fibre membrane. These membranes were developed by the Norwegian University of Science and Technology Trondheim, Norway and they performed a scale-up from lab-scale to pre-pilot scale. The second prototype chosen was also scaled up by Norwegian University of Science and Technology Trondheim, Norway (Figure 14) and tested at similar conditions in COLACEM cement plant facility. The differences in lab and pre-pilot scale testing conditions are highlighted in Table 1.

	Lab scale test at NTNU	*Pre-pilot scale test at Colacem*
Feed gas composition	*Synthetic gases* (10/90 vol CO_2/N_2)	*Real flue gas* ($CO_2/N_2/O_2$/NOx/SOx etc.)
Feed pressure	*1.7-2 bar*	*1.5 ~2 bar*
Operation temperature	*Room temperature*	*80 ~115 °C*
Permeate side	*Sweep gas used*	*Sweep gas/vacuum*
Humidity	*100 % (R.H.)*	*9 ~ 14 % (vol/vol)*
Membrane area	*~16 cm²*	*~ 200 - 2000 cm²*

Table 1 Differences in conditions of lab scale and pre-pilot scale tests.

Additionally, owing to the requirement of water in the feed stream, process changes were made in the feed gas line from the stack. An external vapor generator was connected in line to study the effect of water content to the performance of the modules as seen in Figure 15. The second prototype module contained FTHM membrane material which exhibited the maximum separation performance among the engineering membranes in WP2 and WP3. Although lab scale performances of both materials chosen for first and the second prototype were similar, the more predictable humidity profile and high temperature of the humid feed gas resulted in contrasting effects on different material configurations. An enhanced facilitated transport of CO_2 was observed with second prototype with much higher fluxes than the first prototype that was tested at considerably lower pressure of operation as seen in Figure 16. The CO_2 purity in a single stage module remained over 50% making it a viable technology for post-combustion CO_2 capture with optimized process design. Additionally, the membrane modules also exhibited commendable long-term stability with no significant drop in performances highlighting their resistance to impurities in the feed gas stream. Further tests on stability are on-going at PACT facility in USFD.

WP7 - Dissemination and exploitation of results

AIM

Several activities were performed to disseminate project concept, vision and results to the largest possible audience to engage every stakeholder at European and global scale. In particular, during the last six months:

Partners published several articles on magazines and peer-reviewed scientific papers. Have a look at section **Interested in knowing more? Download NANOMEMC² publications** of this newsletter to find out where you can read these publications;

> Partners attended several international conferences and events, including:

- TCCS19, 18th-19th of June 2019, Trondheim. TCCS19 is a globally leading scientific carbon capture and storage (CCS) technology conference, gathering annually 400 CCS experts and world leading speakers. The Conference is hosted jointly by SINTEF and NTNU, and is organized by the Norwegian CCS Research Centre.
- *H2020 Carbon Capture Storage/Use (CCS/CCU), alternative Fuels and Flexible Power Plants projects clustering workshop*, 17th September 2019. During this workshop, UNIBO and PNO had the opportunity to interact with 15 EU-funded projects focussed on CCUS: LEILAC, CHEERS, CLEANKER, GRAMOFON, ROLINCAP, FReSMe, MOF4Air, 3D, SUN-TO-LIQUID, eForFuel, KEROGREEN, C2Fuel, CO2FOKUS, COZMOS, eCOCO2. Partners from the different project discussed how to find synergies to better exploit and disseminate the project results, and how to align in methodologies to avoid duplication of results while making easier the comparison of project results (e.g. in performing life cycle assessment analysis).

> Several events have been also organised by partners:

- PNO together with BP organised the industrial workshop named *CO_2 selective membranes for carbon capture and decarbonised fuels*, on the 11th of April 2019 in Brussels. The industrial workshop had the aim of disseminating the learnings from the project and how the technology could contribute to decarbonisation for industrial stakeholders. The event brought together various stakeholders in the field of carbon capture and decarbonised fuels who made presentations on European policies and goals and industries' interests and efforts in this field. NANOMEMC² partners presented their views in this area and the advances made in the project. A panel discussion allowed for interaction between all stakeholders. Total number of attendees was around 40.
- NANOMEMC² final conference was organised in collaboration with GRAMOFON and ROLINCAP projects, all funded by EC in the framework of Topic LCE-24-2016 "International Cooperation with South Korea on new generation high-efficiency capture processes". Partners from all the three projects presented their views in carbon capture area and the advances made in the projects. Keynote speakers from European DG RTD and Korean KCRC presented current development in the field of CCUS in both South Korea and Europe. A poster session allowed for interaction between all stakeholders. Total number of attendees was around 50. Presentations used during this event can be found in the websites of the three projects.
- PNO organised the European Energy Days on the 26th of September 2019 in Brussels. The event gathered six successful Horizon2020 energy projects for a day of knowledge-sharing of energy research and innovation and exploitation of project results into new innovation and research action. The event contained four key elements:
    - o Knowledge-share with partners from six EU Horizon2020 energy projects through presentations;
    - o Four dedicated timeslots for networking;
    - o Keynote presentations from key players (the EU Commission, the R&D environment and industry);
    - o 1-to1 brokerage sessions with energy experts to discuss project ideas, proposals, interest in calls for follow up projects etc.

> Two videos have been realised:

- The first one was performed by PNO in occasion of the industrial workshop, held in Brussel on the 11th of April 2019. The video is available on the homepage of the project website;
- The second one, available from September 2019, was performed by UNIBO, to explain the main features of the project and is available on YouTube and on the project website.

Figure 17 Photos from the CO_2 selective membranes for carbon capture and decarbonised fuels event, held on the 11th of April 2019 in Brussels.

Exploitation of results: A Flavour of Results

Exploitation activity was based on active collaboration among partners to systematically define and monitor foreground and Key Exploitable results early and throughout in the project. Guided by PNO and FUJI, the consortium decided to define three types of exploitable results: Project KERs (The majority of the consortium contributes/ benefits from project KERs), Individual KERs (Only one partner contributes/ benefits from project KERs) and multi-partners KERs (a restricted portion of the consortium contributes/ benefits from project KERs). As main outcomes in the project we obtained 21 Individual KERs, 1 multi-partners KER and 3 Project KERs, one per each business case. Individual/multi-partners KERs includes products (e.g. materials for applications in packaging and industrial water treatment), new knowledge, consultancy services for direct and indirect use, inputs for new EU or national funded projects (6 applications have been submitted up to now). A full assessment of each of these KERs and its corresponding exploitation plan was run as part of the exploitation activities during the whole duration of the project to asset its value proposition, unique selling point-USP, target groups, exploitation channels, competitors, etc.

Business cases were developed for the 3 Project KERs, corresponding to the use of NANOMEMC^2 membranes for carbon capture from cement plants and from plants producing hydrogen by steam methane reforming (SMR), and for biogas upgrading to biomethane.

The business plan stems from the detailed identification of the markets (evaluation of the market size, competing technologies, possible clients), analysis of the insights gathered from the market interviews of key stakeholders, life cycle assessment (LCA) and techno-economic assessment carried out in WP5, definition of the value chains and of the actors within it, definition of the NANOMEMC^2 business models and value proposition, evaluation of costs, forecast of future revenues, definition of the exploitation strategies.

The membranes developed in NANOMEMC^2 proved to be potentially competitive in all the business cases considered. Biogas upgrading is particularly interesting since membrane technology is becoming the preferred upgrading technology in EU, number of biogas upgrading plants is rapidly growing in EU (33% increase in 2017 compared to 2014) and, by assuming the use of waste heat/ excess steam to generate steam, NANOMEMC^2 membranes show superior performances with respect to conventional membranes.

Regarding carbon capture applications, a coarse cost-benefit analysis was also performed by PNO to highlight NANOMEMC^2 potential economic value of generated welfare as mitigation of climate changes and pollution effects.

WP8 - Twinning activities with Hanyang University, South Korean partner of NANOMEMC^2 project

AIM

WP8 is dedicated to the organization and managements of all the twinning activities among the NANOMEMC^2 consortium partners and Prof. Ho Bum Park's group at Hanyang University.

The interactions are organised around 4 strands: Exchange of Information, Materials, Data and Researchers.

Results

The third EU-South Korea joint workshop on "New generation high-efficiency capture processes", held on the 2nd of July 2019 in Paris, represented the final opportunity within the project to discuss the twinning activities performed during the last 3 years as well as further collaborations between South Korea and European Countries in the field of carbon capture, storage and utilisation. The workshop was open only to NANOMEMC², GRAMOFON and ROLINCAP project partners and their South Korean partners (around 40 attendees).

The good results of the collaboration among the Korean and European partners was also recently presented at the ECCE 12 conference in Florence, Italy. The presentation, with title: "Pebax®2533 and Graphene Oxide-Based materials for Carbon Capture Membranes" (from Riccardo Casadei, Marco Giacinti Baschetti, Myung Jin Yoo, Ho Bum Park), focused in particular on the work carrier out during the 5 months visit of Riccardo Casadei, PhD student from the University of Bologna, to Prof Park's laboratory.

Figure 18 Photos from the NANOMEMC² final conference.

Interested in knowing more? Download NANOMEMC² publications

• Casadei, R.; Venturi, D.; Giacinti Baschetti, M.; Giorgini, L.; Maccaferri, E.; Ligi, S. Polyvinylamine Membranes Containing Graphene-Based Nanofillers for Carbon Capture Applications *Membranes* **2019**, 9, 119

• Dai, Z.; Aboukeila, H; Ansaloni, L; Deng, J; Giacinti Baschetti, M; Deng, L. Nafion/PEG hybrid membrane for CO_2 separation: Effect of PEG on membrane micro-structure and performance, *Separation and Purification Technology* **2019**, 214, 67-77

• Dai Z.; Ottesen V.; Deng J.; Lilleby Helberg R. M. and Deng L. A Brief Review of Nanocellulose Based Hybrid, *Fibers* **2019**, 7(5)

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• Ahmadi M.; Janakiram S.; Dai Z.; Ansaloni L.; Deng L. Performance of Mixed Matrix Membranes Containing Porous Two-Dimensional (2D) and Three-Dimensional (3D) Fillers for CO_2 Separation: A Review, *Membranes* , **2018**, 8(3), 50

• Dai Z.; , Løining V.; Deng J.; Ansaloni L.; Deng L Poly(1-trimethylsilyl-1-propyne)-Based Hybrid Membranes: Effects of Various Nanofillers and Feed Gas Humidity on CO_2 Permeation, *Membranes* **2018**, 8(3), 76

• Master thesis Enhancement of the Separation Performances of High Free Volume Polymers for CO_2 Capture

• Master thesis Novel CO_2 separation membranes with functionalized nanofillers

• "System to rid space station of astronaut exhalations inspires Earth-based CO_2 removal", Horizon, *The EU research & Innovation Magazine*, **2018**

• "NANOMEMC² Innovative membranes for Carbon Capture applications", *European Energy Innovation magazine*, Spring 2019 Edition, **2019**

How can you engage with the NANOMEMC² project?

If you want to learn more about the NANOMEMC² project, visit the website at www.nanomemc2.eu, or Follow the project on the social.

Follow our NanoMEMC² tweets on Innovation Place and CiaoTech

Follow our NanoMEMC² news on Innovation Place

Follow us on Facebook

Follow us on Research Gate

To get in touch with one of the NANOMEMC² partners, please e-mail the Co-ordinator Marco Giacinti Baschetti at Marco.Giacinti@unibo.it or the contact person for Dissemination and exploitation activities Ada Della Pia at A.Dellapia@ciaotech.com or visit the website contact page.

NANOMEMC² consortium

The NANOMEMC² consortium involves 11 partners and covers the whole value chain of the newly developed carbon capture solutions. More information about the involved organisations and their role in the project can be found in the first NANOMEMC² newsletter, which can be found here.

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www.carboncapture.eng.ed.ac.uk

THE UNIVERSITY OF SHEFFIELD
www.energy2050.ac.uk

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www.graphene-xt.com

INOFIB SAS
www.inofib.com

CIAOTECH SRL
www.pnoconsultants.it

About Horizon 2020

NANOMEMC² project has received funding from the European Union's Horizon 2020 research and innovation programme. The H2020 LCE-24-2016 project supports the development of high potential novel technologies or processes for post and/or pre-combustion CO2 capture. Horizon 2020 is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020). It promises more breakthroughs, discoveries and world-firsts by taking great ideas from the laboratory to the market. Coupling research and innovation, Horizon 2020 has its emphasis on excellent science, industrial leadership and tackling societal challenges. The goal is to ensure Europe produces world-class science, removes barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation.
For more information:
https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020