Project description

ForskEL- call 2017
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Program der ansøges: *(angiv andre søgte programmer):*	ForskEL
Ansøgning nr.:	12533
Projekttitel:	**Cryogenic Carbon Capture and Use (C3U)**
Ansøger:	AAU-ET
Dato:	08-09-2016

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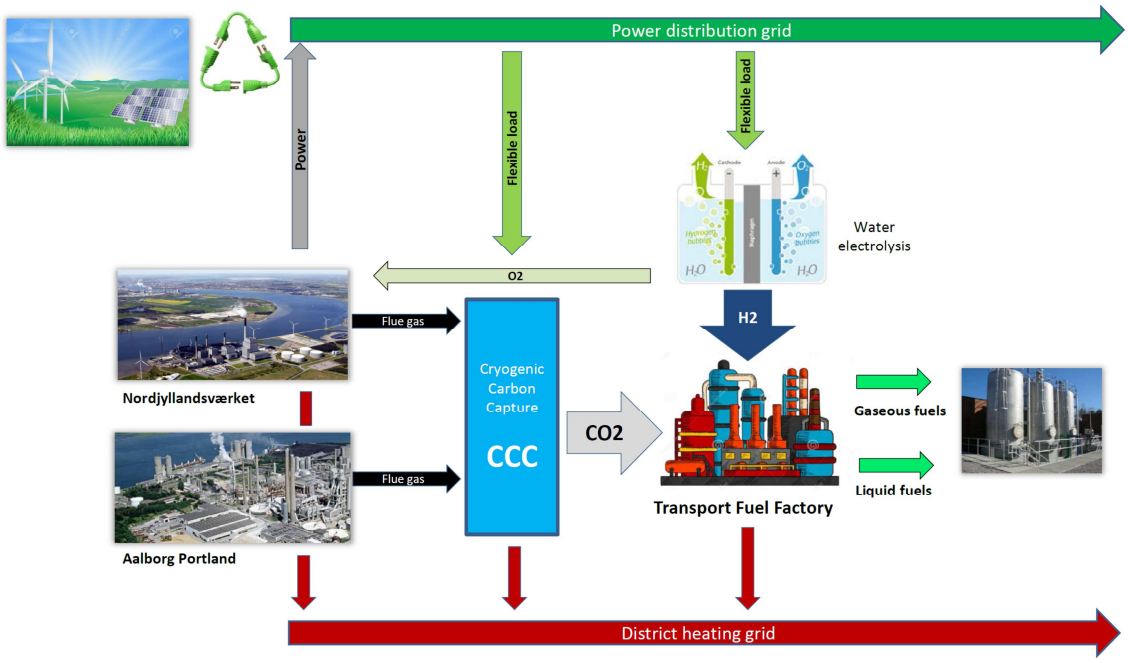
1. General description of the technology/project content

The objective of this project is to develop a highly innovative concept that offers multi-megawatt balancing power to the grid through cost efficient cryogenic carbon capture (CCC) technology coupled with biomass fired processes. Further processing of the captured carbon dioxide to high value transportation fuels with hydrogen from water electrolysis will provide long term energy storage and secure green fuels for heavy duty vehicles. Implementation of carbon capture on biomass fired facilities will activate a very large balancing capacity that was not previously given much attention. This is perfectly aligned with the ForskEL program's target area: Energy storage and coherent energy systems.



In this project only the two major carbon dioxide emitters in Northern Jutland, Aalborg Portland (AP) and Nordjyllandsværket (NJV), are considered but still the balancing potential is huge. Together they represent an annual CO_2-emission of about 3,0 mio tons which completely upgraded to methane represents an annual potential of 1,1 mio. tons - equivalent to 55 PJ. If all biogas is upgraded to methane the potential in Denmark is about 65 PJ[1]. Hence, the potential from these two concentrated sources alone is comparable to the total biogas potential. For reference, the total consumption of natural gas in Denmark was 145 PJ in 2012 showing a need for additional synthetic natural gas to become independent from import.

One large CCC installation, as opposed to many smaller biogas upgrading facilities, will benefit from the economy of scale. The balancing potential of the cryogenic carbon capture concept exceeds that of biogas upgrading as the cryogenic capture system in itself will offer significant balancing power and for the two sites considered it will exceed 150 MW. As such the CCC will provide significant balancing capacity even without conversion of the CO_2 to fuel. If included, the electrolyzer providing hydrogen for the methanation or liquid fuel production will require around 1500 MW assuming an energy consumption of 4 kWh/Nm^3 of hydrogen. Altogether, we are confident the system can play a significant and cost-efficient

[1] Technology assessment, Biogas and biogas upgrading, Danish Department of Energy, No. 2, 2014

role in the green transition of the energy system. The next phase is envisioned to be MW-scale demonstration in Denmark.

Currently the cryogenic carbon capture technology supplied by sustainable energy solutions in the US is in the demonstration phase and was proven at several combustion facilities and a cement factory (http://sesinnovation.com). The next step in the development will be a system capable of capturing the CO_2 from a 10 MWe-equivalent power plant slip stream. The technology has proven to offer higher efficiency, by at least a factor of two, than other known carbon capture technologies at a lower cost[2] . The technology to catalytically upgrade the CO_2 with hydrogen to hydrocarbons also exists although there is still a need for further improvements. New technologies are under development that will offer potentially more efficient routes from CO_2 to transportation fuels. One is co-electrolysis of steam and CO_2 in a solid oxide electrolysis cell another is photo-chemical reduction of CO_2 to CO using sunlight. Each of these will be analyzed and included in the scenarios.

2. Project description

a. Objective of the project

The main scope of this project is to establish well documented and quantified techno-economic scenarios for grid balancing by cryogenic carbon capture coupled with synthesis of transportation fuels. The project will leverage a recent break-through in the cryogenic carbon capture technology that has proven superior to any other capture technology in terms of energy efficiency and cost. In addition it offers an inherent low cost ability to provide energy storage services to the grid. This portion of the project alone makes a major contribution to the Forskel objectives. Integration of the cryogenic process with transportation fuel production based on the captured CO_2 and hydrogen from electrolysis will add further to the balancing capacity and contribute with an important value stream to the system.

The scope of the project will be addressed through the following activities:

- Detailed mapping of the plant data and CO_2 sources at the two sites in Norhern Jutland including future development scenarios.
- Further development and optimization of the cryogenic capture technology towards the specific Danish energy systems and the considered plants
- Theoretical and experimental investigation of synthetic fuel production routes from the captured CO_2. Future development scenarios.
- Detailed studies of the balancing potential of the investigated plant concepts and techno-economic assessments. Feasibility study of large-scale demonstration.

The project was initiated to explore a unique opportunity to develop, jointly with the US partner, a technology that will ensure maximum benefit from the biomass utilized in the process and combined heat and power plants. It will simultaneously address the following key elements:

- Substantial contribution to grid balancing that these plants would otherwise not take part in
- Secure a large carbon resource for the production of green transportation fuels

[2] Prediction and validation of external cooling loop cryogenic carbon capture (CCC-ECL) for full-scale coal-fired power plant retrofit, International Journal of Greenhouse Gas Control, 2015, Vol 42, pp. 200–212

- Contribute significantly to the reduction of CO_2 emission and the achievement of the Kyoto targets.

In the US research into the CCC technology started several years ago and it has now reached the demonstration phase. A major 6 mio. USD research program funded by the US Department of Energy (DOE) is about to start. With this project Denmark has a unique opportunity to join the activities and evaluate the technology in a Danish energy system context. This new project is one in a continued series of development projects thus far. The sum of the development efforts to date, excluding the new funding, exceeds $20M to date when cost share is included, although there is some double-counting of cost share.

b. Description of content of the project

The project consists of a detailed feasibility study backed by experimental validation of key figures related to the cryogenic carbon capture (CCC) system and the fuel synthesis processes. The work is divided into five work packages with a number of tasks, deliverables and milestones. The resources allocated for each work package and for each partner are summarized in Table 1.

Table 1 Resource (hours) allocation on work package level

	AAU	CEMTEC	BYU	AP	NJV	EMD
WP1	250		50	100	**100**	
WP2	750		**1300**	15	15	250
WP3	**3000**		250	15	15	250
WP4	1250	**500**	250	20	20	1000
WP5	**500**	250	25		50	

The first work package consists of a detailed mapping of all relevant plant data including the carbon dioxide emitting processes at Aalborg Portland and Nordjyllandsværket. The current situation as well as scenarios for future development will be addressed. Aalborg Portland and Nordjyllandsværket will be the main responsible for this work. Brigham Young University (BYU) and SES Innovation (SES) will support with input on the required plant data in relation to the cryogenics capture technology. The outcome will be a report with technical data that will form the basis for subsequent detailed plant simulations and optimization.

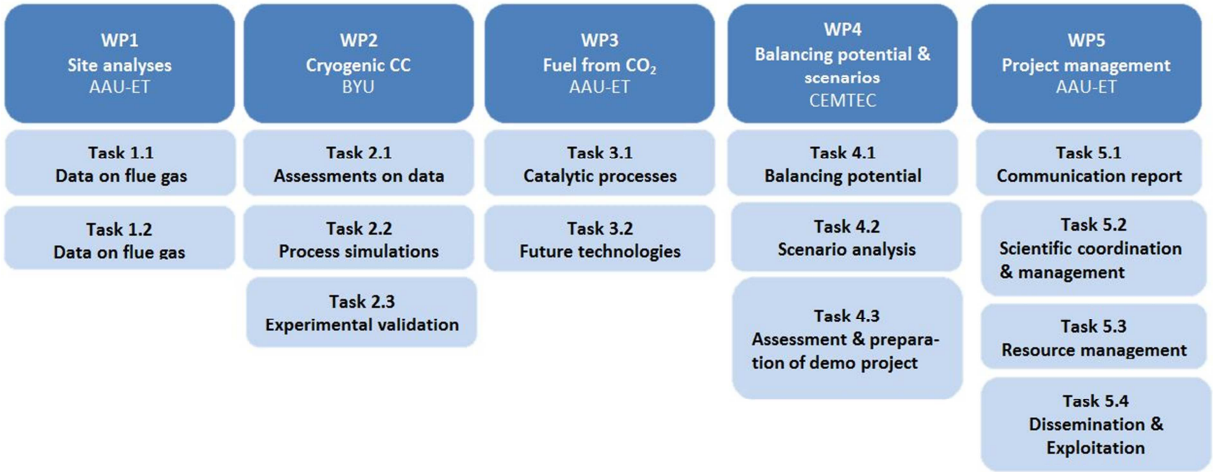
The second work package will focus on the cryogenic carbon capture technology seen from a grid balancing perspective. Process optimization particularly focused on the two Danish sites will be performed by BYU supported by AP and NJV. At least two features will differentiate the Danish system from previously studied cases; the supply of district heating and the integration with CO_2 upgrading to produce transportation fuels and boost the balancing potential via water electrolysis. The work will be a combination of computer simulations and test campaign on existing CCC pilot plant. The outcome will be detailed data on a complete integrated capture system for the two sites including its balancing and district heating potential.

The third work package is a theoretical and experimental feasibility study of using the captured CO_2 as a carbon source in transportation fuel synthesis. Optimization and heat integration of the involved processes will be addressed. Aalborg University (AAU) will be responsible for this work supported by BYU. The outcome will be a detailed mapping of the possible process pathways from CO_2 and H_2 to hydrocarbons including the grid balancing potential associated with the processes.

In work package four the main focus will be on the grid balancing potential associated with each of the identified possible plant layouts. This work package will also establish the basis to perform an economic feasibility study and compare the overall concept with related technologies such as biogas upgrading. All partners will contribute to this work with CEMTEC as main responsible. CEMTEC brings to this work package experience from the Power2Hydrogen project. The outcome will be a report addressing the balancing potential and economic feasibility assessment. The work package will also initiate the work towards a demonstration phase if the concept is found feasible.

Work package five deals with the project administration. AAU will be responsible for this work with input from all partners. The deliverables will be financial reports, technical progress reports, dissemination activities and monitoring of the project progress.

c. Description of work packages



WP 1. Site analyses

Time frame: *M1 – M6*
WP Leader: *AAU-ET*
Other Partners: *AP, NJV, BYU*
Main Objectives:

- *Mapping of CO_2 capture potential at the two sites*
- *To perform a detailed process analysis of the capture sites*
- *Identify future development scenarios*

Deliverables:

D1.1: Report with key process data for CCC process integration analysis
D1.2: Report describing future scenarios in relation to CCC implementation

<u>Task 1.1: Aalborg Portland</u>
Aalborg Portland will establish the data required to perform a detailed analysis of the CO_2 capture potential in their cement manufacturing process. To assess the heat integration potential for the cryogenic capture process a map of the heating and cooling demands will be made. The analysis will also assess possible future developments as input for the scenarios investigated in work package 4. The implementation of large scale electrolysis as part of synthetic fuel production will create a large source of oxygen. This work package will also

investigate possible use of this oxygen in oxygen enriched combustion processes as a means to concentrate the CO_2 stream.

Task 1.2 Nordjyllandsværket

Nordjyllandsværket will collect and make available the data required to perform a detailed analysis of cryogenic carbon capture at the plant. This will include the needs for hot and cold utility which will be used to design a heat integrated capture system in work package 2. As part of the task detailed plant simulations may be performed based on existing simulation tools available at Nordjyllandsværket.

Nordjyllandsværket is planned to undergo major changes within a 10-15 year time horizon. This task will establish information about possible future scenarios and make this information available to the activities under work packages 2 and 4. As for the cement factory investigated in task 1.1, the potential benefits from utilizing oxygen from water electrolysis will be taken in to account.

WP 2. Cryogenic carbon capture

***Time frame**: M1 – M18*
***WP Leader**: BYU*
***Other Partners**: AAU, EMD, AP, NJV*
***Main Objectives**:*

- *To assess CCC implementation based on existing information*
- *Experimentally validate operation tailored to the two sites*
- *To perform a detailed process analysis of the capture sites*
- *Provide input for future development scenarios*

***Deliverables**:*

D2.1: Report with key process data for CCC process integration analysis
D2.2: Report describing future scenarios in relation to CCC implementation
D2.3: Experimental data to support the modeling of the Danish sites

Task 2.1: Assessments based on existing data

BYU and Sustainable Energy Solutions have accumulated experience from laboratory and pilot scale test of cryogenic carbon capture in both power plant processes and cement manufacturing. This task will make the experience available to the project for further assessments and to direct the development direction. A comparison will also be made with data available from Nordic and European research activities on carbon capture. Most of these are based on amine capture.

Task 2.2: Detailed process simulations

This task comprises a key activity at BYU that aims to investigate and design an optimal carbon capture system for the two sites studied in the project. The activity will build on existing models and knowledge that is adapted based on the input from work package 1. The district heating system in Aalborg receives the majority of heat from AP and NJV. It is thus essential to address the potential for district heating supply from the integrated system. Simulations will use Aspen Plus process simulation software and will include stream tables and equipment specifications, complete with capital and operating cost estimates. These estimates will be reviewed by competent Danish experts and adjusted to local market conditions accordingly.

The task will also address the quite significant synergetic effect in relation to simultaneous capture of particulates, NOx and SOx. This information is essential for the techno-economic assessment in work package 4. The availability of a clean CO_2 stream is also important for the downstream catalytic fuel synthesis reactions as impurities may poison the involved catalysts.

Task 2.3: Experimental validation
Based on the detailed simulations from task 2.2 selected key process steps will be verified in the laboratory using existing setups at BYU and/or SES. The collected data will further substantiate the theoretical analyses and the decision making in work package 4 related to large-scale demonstration of technology.

WP 3. Transportation fuel from CO_2

Time frame: *M1 – M21*
WP Leader: *AAU-ET*
Other Partners: *BYU, EMD, AP, NJV*
Main Objectives:

- *Mapping of pathways from CO_2 to fuels*
- *Detailed study of most promising pathways*
- *Experimental validation of selected synthesis steps*
- *Thermodynamic process integration modeling*
- *Future scenario analysis*

Deliverables:

D3.1: Report on fuel synthesis pathway tailored to the two sites
D3.2: Article on experimental and modeling study of synthesis processes
D3.3: Article on thermal integration of processes at the two sites

Task 3.1: Traditional catalytic processes
Catalytic chemical conversion processes to produce synthetic fuels from CO_2 and hydrogen will be investigated in this task. The work will use a new synfuel laboratory that is currently being established at Aalborg University with support from Det Obelske Familiefond. A detailed literature study will be conducted first to pinpoint the most promising processes and catalysts for the subsequent detailed investigation.

A key challenge is efficient reduction of CO_2 to CO or other chemically reactive species that makes the carbon available for further synthesis. Conventional methods include the reverse water gas shift reaction and dry reforming of CO_2 with CH_4 to produce CO and hydrogen. Selected catalysts for these reactions will be purchased and thoroughly characterized to provide information for process simulations. The data will also be useful if detailed reactor simulations are to be made in the next phase of the project.

At least three synthesis fuels will be included in the analysis: Methane, methanol and Fischer-Tropsch diesel. The processes will be mapped and investigated with respect to reaction kinetics and heat integration potential. Catalysts will be procured from industrial suppliers and characterized in the laboratory to provide input for the model simulations in Aspen or

similar software package. Recent work indicate that methanol may be the preferred product having CO_2 as the starting point due to more favorable reaction rates and overall efficiency[3][4],

Task 3.2: Future technologies

Co-electrolysis of steam and CO_2 in a solid oxide electrolysis cell to produce a syngas consisting of CO and hydrogen is a potentially very interesting emerging technology. It will have very strong synergies with the proposed CCC process supplying a clean CO_2 stream. In this task key information will be extracted from the literature and ongoing projects such as the SYNFUEL project to provide input for the scenario analysis in work package 4. The reduction of CO_2 in CO may also be achieved in the future using a molten carbonate electrolysis cell[5]. This possibility is treated similarly to the SOEC technology using information from literature and included in the scenario analysis.

Another emerging technology with potentially disruptive impact on the overall concept of the C3U project is photo-catalysis. In recent years much attention was directed to photo-catalytic processes capable of converting CO_2 to a syngas containing CO using sunlight. Research into this topic is beyond the scope of this work. However, this task will address the potential of such a technology in relation to the proposed carbon capture and use plant concept.

WP 4. balancing potential and scenarios

Time frame*: M9 – M24*
WP Leader*: CEMTEC*
Other Partners*: EMD, AAU, BYU, AP, NJV*
Main Objectives*:*

- *Detailed assessment of the grid balancing potential with energyPRO*
- *Technical report on future scenarios related to the sites*
- *To establish a decision base for the GO/NO-GO on a phase 2 demo project*

Deliverables*:*

D4.1: Report on balancing potential at the two sites
D4.2: Future scenario analysis report
D4.3: Market analysis and basis for GO/NO-GO decision

Task 4.1: Balancing potential

The cryogenic carbon capture system has a substantial balancing potential as the flue gas cooling circuit can be operated independently from the capture system. A major portion of the parasitic energy consumption of the cryogenic process is related to the liquefaction of natural gas used to cool the flue gas to the CO_2 sublimation temperature. This cryogenic natural gas can be generated and stored in periods of excess electricity. In periods of peak electricity demand and/or low production from wind the liquefaction system can be shut down and the capture system supplied from the tank. This potential has been documented in

[3] An Introduction of CO2 Conversion by Dry Reforming with Methane and New Route of Low-Temperature Methanol Synthesis, ACCOUNTS OF CHEMICAL RESEARCH, 2013, Vol 46 No 8.

[4] Highly active copper-ceria and copper-ceria-titania catalysts for methanol synthesis from CO2, SCIENCE, AUGUST 2014, Vol 345 No 6196.

[5] Thermodynamic and experimental approach of electrochemical reduction of CO2 in molten carbonates, International Journal of Hydrogen Energy, 2014, Vol 39

several recent journal articles[6]. The inherently transient nature of some portions of the CCC process during energy storage gives rise to several process complications that are addressed by patented dynamic heat exchangers and other technologies[7] [8]. This task will further quantify this grid balancing potential when implemented on the cement factory and CHP plant, respectively. The field tests of the CCC process completed to date include biomass-fired facilities, a commercial cement plant, and a heating plant. The balancing potential of the fuel production steps is largely governed by the electrolysis providing hydrogen for the process. In this area results from the power2hydrogen project will be used as input for the assessment of balancing potential. The potential of using induction heating in a reverse water gas shift reactor and in a dry reforming process will also be assessed as part of this task.

The work will also address the electrical connection points to the main grid which is essential for multi-megawatt balancing. At NJV two 500 MW transformer stations are available as potential connection points to the backbone of the grid.

The EMD energyPRO model will be further developed to simulate the Aalborg district heating system and account for the implementation of the C3U plant.

Task 4.2: Scenario analysis
This task will collect all the information from work packages 2 and 3 and draw scenarios for the future development of CCC at the sites. The potential related to further processing of the CO_2 to transportation fuels will also be considered. The outcome will be techno-economic assessments of selected scenarios including consideration on the maturity of the technology.

The long term development of the processes at the two sites will be addressed to evaluate the future feasibility of the conclusions and the sensitivity towards changes in operation strategy and overall plant layout. In particular Nordjyllandsværket will undergo major changes during the next 10 years as the main furnace is expected to be decommissioned hence an assessment of the long term.

Task 4.3: Assessment and preparation of demonstration project
Preparation of detailed market analysis and economic assessment related to the implementation of the technology. This will be an essential element in the GO/NO-GO decision related to a phase 2 demonstration project.

WP 5. Project Management
***Time frame**: M1 – M36*
***WP Leader**: AAU-ET*
***Other Partners**: CEMTEC, BYU, AP, NJV*
***Main Objectives**:*

- *Administrative, financial, and resource management of the project*
- *To ensure an efficient communication between project partners and between project partners and funding committee;*
- *To monitor progress of the project activities and to ensure technical quality;*

[6] Dynamic optimization of a hybrid system of energy-storing cryogenic carbon capture and a baseline power generation unit, Applied Energy, 2016, Vol 172, pp. 66-79

[7] Transient natural gas liquefaction and its application to CCC-ES (energy storage with cryogenic carbon capture (TM)), Energy, 2016, Vol 103, pp. 369-384

[8] Theoretical and Experimental Analysis of Dynamic Heat Exchanger: Retrofit Configuration, Energy, 2016, Vol 96, pp. 545-560

- *To create a website of the project, which will be used to present the most important achievements and increase project visibility and impact;*
- *To stimulate and ensure project dissemination and exploitation activities;*

***Deliverables**:*

D5.1: C3U project website;
D5.2: Annual scientific and financial reports.

Task 5.1: Communication management
This task aims at assuring a high quality of the internal and external communication of the project results. This involves organization of project meetings and workshops on a regular basis (e.g., every six months). Moreover, the project's website, which will be updated on a monthly basis, will be the main channel for the external communication of the project results.

Task 5.2: Scientific coordination and management
The task of the work package leader will be to monitor, on a monthly basis, the project progress in order to ensure a high technical quality of the research and to assure a prompt submission of the deliverables according to the proposed Gantt chart. This task will also include continuous risk assessment and implementation of required mitigation measures.

Task 5.3: Resource management
This work task aims at monitoring the project budget and expenditures and taking decision related to any budget adjustments, if required.

Task 5.4: Dissemination and exploitation of project results
This task will involve planning and monitoring the dissemination activities (publications, meetings, workshops, etc.). Moreover, in this work task the identification, protection, and exploitation of the Intellectual Property Rights (IPRs) will be managed.

d. Risk assessment

As the project mainly consist of a feasibility assessment and focused experimental tests to generate input data for simulation models and validate key aspects of the technology no major technical risks exist. The core CCC technology was already demonstrated and the conventional catalytic processes required for the fuel synthesis also exist. So all together there is a relatively well proven path towards the objective.

The trans-Atlantic collaboration imposes challenges in relation to the coordination and management of activities. The fact that AAU and BYU have a long track record of successful collaboration in the field of biomass combustion gives the applicants great confidence that the collaboration will be efficient and smooth. Professor Larry Baxter frequently visited Denmark and has insights in the Danish energy system. Professor Søren Knudsen Kær was a visiting researcher at BYU for 13 months and visited the US many times. Both professors plan to visit each other's facilities as part of this project. In addition, an exchange of students working on the project will help ensure an efficient exchange of information.

3. The project relevance (ForskEL og andet)

Generally, an effective electrification of energy services is a key initiative to ensure cost-effectiveness of wind scenario. But a number of energy services will continue to require access to fuels. For example, heavy transport, air and maritime transport, certain types of high-temperature industrial process heat, peak load power plants etc. Power-to-Fuel technology can supply this demand through an extensive increase in wind power provided sufficient carbon is available (a CO_2 source)[9]

Biomass plays an important role in most scenarios towards a fossil free energy system in the process industry as well as in heating and combined heat and power plants. Denmark has relatively large amounts of biomass and bio-waste that may be included in energy production. The current biomass resources available for biofuel production cannot cover the demand for liquid fuels today. In addition, biomass is used for other purposes, including heat not related to fuel production.

Towards a restructuring and better utilization of biomass and waste, there is a great potential in the still large carbon emissions from industry processes and conventional energy production. The suggested technology is compatible with all these conversion processes and will recover a very large carbon sources and make it available for liquid fuel production. This is essential as shortness of biomass as a carbon source creates a critical limitation in several scenario analyses of a future fossil free energy system.

Related projects
Carbon capture from the cement industry was already given some attention internationally. The Nordic CCS competence center investigated the potential of four capture technologies but did not include cryogenic capture[10]. The European Cement Research Academy are also deeply involved in studying different pathways towards CO_2 reduction from the cement industry through carbon capture[11].

The pan-European BioCat Consortium has made large investments in a 1 MW P2G demonstration site at Avedøre. By converting electrical energy to chemical energy in the form of methane, through the use of hydrogen, P2G allows surplus energy to be injected into the existing natural gas infra-structure to a practically unlimited extent. Also noteworthy is the very successful MeGa-Store methanation project led by DTU Mechanics in collaboration with GreenHydrogen.dk, Elplatek and Lemvig Biogas.

The ForskEl project "Power2Hydrogen" project in Hobro will demonstrate dynamic operation of a 1.2 MW polymer electrolyte membrane (PEM) electrolyser for balancing the electric grid. The project will produce green hydrogen to fuel hydrogen cars, for industrial purposes and to upgrade biogas. The project is led by Air Liquide in collaboration with Cemtec. The project will leverage the results from the ForskEl project "Power2Hydrogen" in relation to large scale electrolysis. The experience from this project with respect to efficiency,

[9] Energikoncept 2030 – Sammenfatning, En analyse af koncepter og udviklingsveje, der kan understøtte et konkurrencedygtigt og robust VE-baseret energisystem, Energinet.dk, May 2015
[10] Industrial implementation of carbon capture in Nordic industry sectors, Nordiccs technical report D4.2.1501/D18, November 2015
[11] Technical Report TR-ECRA-119/2012 ECRA CCS Project – Report on Phase III

load changes for grid support and reliability will be used in the feasibility assessment of the CO2 utilization part of this project.

Experience from biogas upgrading in the ForskEL projects "MegaBalance" and "MegaBalance II" will be used in the analysis of methanation.

In the longer term SOEC co-electrolysis of steam and CO_2 may form a new pathway to transportation fuels. In this area the project will benefit from the Innovationsfonden project "SYNFUEL" where AAU is responsible for the system integration activities.

4. Communication plan and embeddedness

Dissemination
The results of the project will be disseminated at several levels:

- To students through lectures and project work (AAU PBL model)
- To heads of research at AAU through internal networks and cross-topical workshops (particularly to electrical research areas)
- To academics and industry professionals through peer reviewed publications and semi- professional journals, conferences and workshops and national networks (CLEEN, INBIOM, The Danish Hydrogen and Fuel Cell Partnership and others), online fora such as LinkedIn
- To policy makers through regional networks (eg House of Energy, Fuel Cell Cluster North) and national networks (eg CLEAN, INBIOM, The Danish Hydrogen and Fuel Cell Partnership, initiatives on aviation fuel etc), direct communication and work-shops, online fora such as LinkedIn

The target for peer reviewed journal manuscripts for this project is at least 7-10, to be published in high impact factor journals. If possible, Open Access journals will be preferred. As the project progresses, the partners will place non-specialist communiques in professional society periodicals such as Ingeniøren. The management team will identify ad hoc opportunities for dissemination and act accordingly to make use of them.

The PBL model of study at AAU will be a vehicle for student interaction, and project proposals for both thesis work and semester projects will be prepared at each semester start during the project. As engaged students generally perform very well, this will significantly boost available manpower and help exceed the targets.

As a bilateral effort between US and Denmark, co-publishing between the partners will be encouraged to show the collaborative nature of the project.

Exploitation and IPR
No immediate commercial exploitation activities are included in the project. However, the close collaboration between the project partners and relevant industrial players will obviously allow this avenue to be tested during the project. However, this will be done according to the collaboration agreement and IPR regulations stipulated herein. It is anticipated, though, that a successful or even partly successful outcome of the project will serve to create significant commercial interest in taking the next steps. Sustainable Energy Solutions (SES) owns the IP for the CCC process, including its energy storage capabilities. SES is very actively commercializing this technology and will cooperate to include this project in its commercialization activities.

5. Organization and competences for players

Project partners	Project contributions and benefits
Aalborg University **Project Manager** Project manager: Søren K. Kær	Process design of the CO2 source for the catalytic synthesis of the three sources; optimization and integration potential (thermal); experimental analysis of the synthesis processes, sensitivity to CO2 percentage contaminants, etc. The project will establish research activity on "solar fuels" area, the context of Smart Energy Systems, biofuels and storage. Ability to bring new experimental facilities into play in connection with up scaling
CEMTEC **Innovation partner** Contact: Steen B. Petersen	Project manager and responsible for the overall vision of a scaled-up carbon capture and use system for grid balancing and production of synthetic fuels (MeOH, HC). The project will provide establishment of scaled facilities in conjunction with existing activities. Creates jobs and business growth.
SES/BYU **Technology partner** Contact: Larry Baxter	Developer and supplier of CO2 capture technology on thermal base. The project will make a case for deployment / up scaling of the capture technology
Aalborg Portland **Industry partner** Contact: Jesper Damtoft	CO2 supplier, process data and integration with district heating. Minor role, steering committee / advisory board. The project will make future sustainability investments, but currently has no plans to install capture technology.
Nordjyllandsværket **Industry partner** Contact: Jan Wæhrens	CO2 supplier, process data and integration with district heating. The project will make future sustainability investments.
EMD **Industry partner** Contact: Anders N Andersen	Estimation of balancing potential and techno-economic assessment. The project will enhance the development of the energy pro software with the CCC technology

AAU

The fuel cell and battery systems research program was initiated in year 1999 and currently involves around 25 researchers with a total project portfolio of EUR 10.0 mio. The program is centered on fundamental and applied research in components, subsystems and complete systems related to fuel cells, electrolyzers and batteries. In relation to electrolysis, grid balancing and synthetic fuel production, the research group is running the e-STORE project and participates as a partner in the SYNFUEL project both with funding from Innovation Fund Denmark. The group is the major research partner the large demonstration project, Power2Hydrogen, funded by the ForskEL program.

The biomass research group counts approximately 15 researchers, with a current project portfolio of approx. EUR 5 mio. The program revolves around efficient use of biomass for energy and fuels, including biogas and hydrothermal liquefaction.

Key persons:
Søren Knudsen Kær, Professor, M.Sc. Eng., Ph.D. Head of the fuel cell and battery systems program that has expanded with significant activities on electrolysis and energy storage. He is a Board member of the Danish Hydrogen Association and CEMTEC. Dr. Kær is a Task leader on energy storage in the CLEAN network and a representative in the FCH-JU research grouping N.RGHY. He has 20 years of experience from the energy sector working with biomass conversion systems and electrochemical energy storage and conversion technologies. In 1999 he was a visiting researcher at Lawrence Livermore National Laboratories, California, USA and in 2001 he was a postdoctoral fellow at Brigham Young University, Provo, Utah, USA. His main research areas are in energy systems and the application of computational fluid dynamics modeling in advanced process simulations.
Lasse Rosendahl, Professor, M.Sc. MechEng, PhD. Head of the biomass research program and Danish representative to the Horizon2020 Program Committee on Energy. Has worked with aspects of combustion and other thermochemical conversion of biomass, notably hydrothermal liquefaction where he runs the InnovationFund Denmark supported research project Center for Biooil (C3BO). Recently, together with Søren Knudsen Kær, he received a 2.5 mio DKK grant from "Det Obelske Familiefond", matched by 2.5 mio DKK from AAU, to design and construct a power-to-fuel research facility, focusing on the use of hydrogen to valorize carbon dioxide and HTL biocrude to transport grade fuels.

BYU

Brigham Young University and Sustainable Energy Solutions own the intellectual property right to the cryogenic carbon capture technology. Professor Larry Baxter and his team at Brigham Young University have many years of experience in combustion processes and chemical engineering related to power plants and related processes. Sustainable Energy Solutions developed the technology and engineering concept to implement the cryogenic capture technology in large scale.

Key person:
Larry Baxter, Professor, M.Sc. Chem. Eng., Ph.D., Is responsible for the technical direction and vision of SES. He has spent his entire career working with sustainability issues and combustion and is well respected for his expertise in this area. He is also a Professor of Chemical Engineering at Brigham Young University. He holds B.S. and Ph.D. degrees in Chemical Engineering and his research focus has been sustainable energy systems. Prior to joining the faculty at BYU, Dr. Baxter worked for fourteen years at Sandia National Laboratories' Combustion Research Facility. He has written five chapters for books, edited four books, and authored over 70 archival journal publications.

CEMTEC
Center for Energy and Materials Technology (CEMTEC) is a business developing foundation based in the city of Hobro, Mariagerfjord Municipality - a part of the Northern Jutland Region in Denmark. CEMTEC has for more than a decade been active in regional business development including the creation of more than 200 local jobs and the attraction of private and public investments for more than 150 MDKK through a focused effort in the hydrogen, fuel cell and green energy sector making the area a recognized international fuel-cell business cluster. CEMTEC has a widespread network in Denmark and Europe within the energy sector and CEMTEC's secretariat today serves as a recognized business project developer and manager contributing to the transition of the Danish energy sector becoming sustainable and fossil free.

Key persons:
Steen Børsting Petersen, Electrical engineer. Wide experience in international project management as well as design and supervision of electrical installations. 15 years of experience as international Project Manager within the wind energy business and industrial buildings covering preparation of tender documents for turnkey contracts as well as contracting according to FIDIC. Has also worked 18 months as Construction Manager on site in China. Furthermore, the background as electrical engineer covers experience in wind energy, electricity supply, large-scale industrial installations as well as lifts and machine installations, energy-saving measures, and design and testing of electrical systems for electrical trains.
Lars Udby, M.Sc., 30 years of experience as sales executive and sales manager in the computer business industry in Denmark. Owner and operator of several Danish Hotels. From 2006-08 CFO of CEMTEC Foundation, from 2008 to present CEO of CEMTEC Foundation. Responsible for among others the projects: Hydrogen Economy and Applied Technology(HEAT)2 (2008-13) and Fuel Cell Hydrogen Test Centre in co-operation with among others KIWA, Region North Jutland, Dantherm Power, Serenergy, H2Logic (ongoing).

Aalborg Portland
Aalborg Portland A/S is Denmark's only cement producer with production at the factory in Aalborg. The company is a market leader in the Danish market with a major export out of Aalborg. Aalborg Portland produces cement at technologically advanced production facilities and has intensive research in the area of cement, environment and energy with the objective to reduce the CO2 emission.

Nordjyllandsværket
North Jutland plant's production of electricity and heat is focused on the environment and efficient coal burning. North Jutland plant's production of electricity and district heating in two block plants. This has a capacity of 410 MW electricity and 490 MJ / s district heating. With an efficiency of up to 91% of combined production and 47% of electricity production utilizing block fuel is about 20% better than older coal-fired plants. District heating is supplied partly to Aalborg and partly to smaller towns in the region. Most of the district heating is supplied to Aalborg in large pipes under the fjord.

EMD
EMD international has competences with commercial software packages for the design and planning of renewable energy projects - windPRO and energyPRO. In addition EMD is offering consultancy and software solutions during the commercial operation of wind farms, cogeneration plants and other types of integrated energy plants.

EMD has taken part in different national and European projects related to renewables integration: Power2Hydrogen, where the energyPRO energy systems analysis tool is further developed with facilities to simulate hydrogen production plants participating in both wholesale markets and in the balancing markets; 4DH – where a research center is established for the coherent development of 4th Generation District Heating Technologies and Systems in which synergy is created between the energy; the EU project stoRE aiming to facilitate the realization of the ambitious objectives for renewable energy by unblocking the potential for energy storage infrastructure.

Key person:
Anders N Andersen has extensive experience from Projects in balancing the grid. He was involed in a large numbers og related projects:Power2Hydrogen, NEMO: The "Novel E-MObility Grid Model NEMO" project, part of the ERA-NET Plus programme electromobility+, 4DH: In this project is established a research centre for the coherent development of 4th Generation District Heating Technologies and Systems. CITIES: Center for IT based intelligent energy systems in cities. store: The EU project stoRE facilitate the realization of the ambitious objectives for renewable energy by unblocking the potential for energy storage infrastructure.

6. Financing and general comments to budget

A relatively large share of the budget will be spent at the universities in this first feasibility study phase and the own contribution is relatively small. Consequently, the support intensity will be relatively high. The Budget for each partner related to the individual work packages is summarized in Table 2 .

Table 2 Budget divided into partners and work packages. Numbers in 1.000 DKK

	AAU	CEMTEC	BYU	AP	NJV	EMD
WP1	130		30	100	**100**	
WP2	465		750	15	15	130
WP3	2230		141	15	15	130
WP4	660	240	141	20	20	520
WP5	243	120	14		50	
Total	**3728**	**360**	**1080**	**150**	**200**	**780**

BYU together with SES was granted a USD 6.0 mio. project to further develop and scale up the CCC technology towards multi-megawatt. The results from this and preceding projects will be made available as an in-kind contribution to this project.

7. Incentive effect

The technology is still in a relatively early stage of development and the main scope of the C3U project is a techno-economic feasibility study. Without the support from ForskEL the partners do not have the financial resource to carry out this study. Brigham Young University has unique and patented knowledge on the CCC technology through the spin-off company Sustainable Energy Solutions. Without support from ForskEL they do not have the capacity to support the project and undertake studies tailored to the Danish sites and energy system.

8. The market

a. Target group and added value for consumers

The technology will benefit the energy market in general. The cryogenic carbon capture technology is aimed for use by energy production companies and heavy industry that are obliged to reduce CO_2 emissions from production. A very significant added value for the end user (process industry or power plant) is the simultaneous removal of particulates, NOx and SOx in particular in new installations where the need for other flue gas cleaning equipment can be offset.

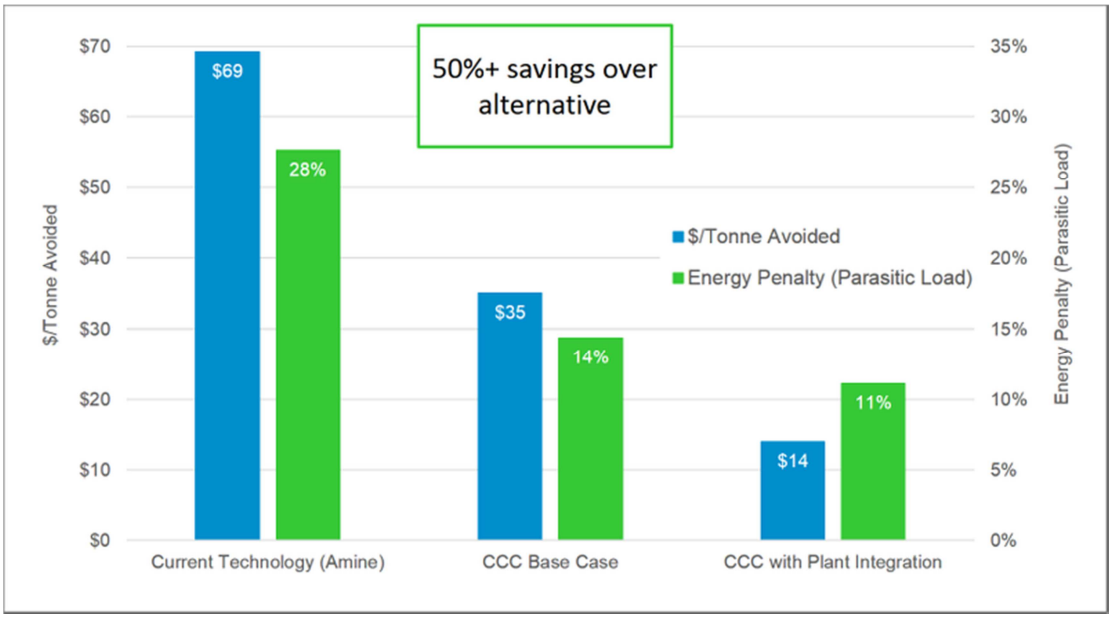
With respect to the electrolyzer operation and balancing potential results and market analysis and trading strategies from the power2hydrogen project will provide input for this project.

b. Competition analysis

In the market for grid balancing services the proposed technology will compete with a broad range of other technologies ranging from CHP over heat pumps to biogas upgrading facilities and electrolyzer installations. If focus only is directed towards technologies that can provide grid balancing services AND supply the transportation sector with renewable energy the main competitors are biogas plants coupled with upgrading facilities and thermal gasification plants with fuel synthesis. The C3U technology is unique in addressing a whole new carbon source with a potential that exceeds competing sources by a significant margin. Other technologies will require a complete shift in the entire biomass utilization away from the current and into liquid fuel production. The techno-economic feasibility of the C3U concept will be addressed in detail in this project to allow for a more quantitative comparison with for example biogas upgrading. Further to this point it is also important to note that carbon will be a limited resource in the future energy system and the proposed technology represent a promising concept to address this shortness of carbon.

Cryogenic Carbon Capture™ (CCC) is a post-combustion technology that has the potential to reduce carbon emissions from fossil-fueled power plants by 95–99%, at half the cost and energy of current state-of-the-art carbon capture processes. In addition, CCC also removes other pollutants, such as SOX, NOX, and mercury.

CCC can capture carbon for a fraction of the cost and energy of current methods. When considering the additional benefits of pollutant capture and steam cycle integration, the cost is even lower. The Energy Storing (CCC-ES) implementation also allows for very efficient grid-scale energy storage—enabling better use of renewable energy sources and virtually eliminating CCC's parasitic load during peak demand times. The figure below compares the CCC technology with today’s most frequently used Amine technology in terms of cost and energy efficiency.



In addition to capturing 95–99% of carbon, CCC also captures other pollutants such as NOX, SOX, and mercury (Hg). In greenfield installations, the pollutant capture capability of CCC can offset the cost of traditional pollutant removal systems.

The pollutants are captured using desublimation—the same mechanism used to capture CO2. At lower temperatures, higher quantities of the pollutants are captured. At low enough temperatures, the exhaust exiting the stack actually has less CO2 content than the surrounding air.

c. Market potential

With the Kyoto target on CO_2 emission reduction there is a global push towards technologies that can support this objective. If the techno-economic assessment proves the C3U technology is energy and cost efficient the world-wide market potential is enormous.

Moreover, there will be an increasing market for green transportation fuels to support the ambition to make the transport sector independent from fossil fuels. An increasing number of countries see this transition as an important part of their strategic plans for the country.

Over the years the very ambitious Danish goals in terms of energy efficiency and emission reduction has fostered the development of a number of innovative solutions and technologies. This has resulted in the creation of a number of big exporting companies in Denmark. The new market for grid balancing, liquid fuel product and CO_2 emission mitigation can very well result in very significant job and value creation in Denmark.

d. Marketing plan

The technology concept is still in an early phase in terms of addressing the Danish energy system needs. In the US Sustainable Energy Solutions have developed marketing plans and established a supply chain and manufacturing capability to bring the technology to the market.

With the C3U project, Denmark may become a spearhead for the introduction of the CCC technology in Europe. Several European countries face similar challenges as Denmark and a successful demonstration phase in Denmark will open a potentially very substantial market.

It is essential to have close research collaboration with industrial partners at this early stage to develop a model for integration of the carbon capture technology. Exploitation of project results will lead to a phase 2 project where the technology will be developed and demonstrated. In this phase, an important objective will be to analyze the market and prepare a detailed marketing plan.