Final report

1. Project details

Project title	Power2Met
File no.	64018-0552
Name of the funding scheme	EUDP
Project managing company / institution	Green Hydrogen Systems A/S
CVR number (central business register)	30548701
Project partners	Green Hydrogen Systems Aalborg Universitet Reintegrate Process Engineering Hydrogen Valley Holtec Automatic-Nord Lillegården EL Drivkraft Danmark Rockwool NGF Nature Energy E.ON
Submission date	6. September 2018

2. Summary

- *English version*

The purpose of the Power2Met project is to develop, design and build a pilot plant for a complete, standardised, and modular power-to-methanol plant that can be offered to upgrading biogas plants, utilizing their CO2 and hydrogen in a synthetic process to produce green methanol and providing for a positive business case from day one.

Power2Met focuses on the development of the core technology and its validation in an industrial scale pilot plant. The project consortium has the required competencies to specify all technical details required for easy adoption of the technology from the biogas industry. In parallel, the business case is validated from the point

of view of technology providers and the end-users of the technology including their key costumers for the biomethanol, the oil and gas companies.

Efficient development and market introduction is secured by a strong project consortium that represents the full value chain from renewable electricity through technology development (GreenHydrogen, REintegrate, Aalborg University, Process Engineering, Holtec Automatic-Nord, Lillegården El) and end-users (E:ON and Nature Energy) to the biomethanol market (Drivkraft Danmark). Value creation from all product streams is a focus point and Rockwool is involved due to their interest in purchasing oxygen at later stages of the technology rollout.

- *Danish version*

Formålet med Power2Met-projektet er at udvikle, designe og bygge et pilotanlæg til et komplet, standardiseret og modulært power-to-methanol-anlæg, der kan tilbyde opgradering af biogasanlæg ved at udnytte deres CO2 og brint i en syntetisk proces at producere grøn methanol og sørge for en positiv business case fra dag ét.

Power2Met fokuserer på udviklingen af kerneteknologien og dens validering i et pilotanlæg i industriel skala. Projektkonsortiet har de nødvendige kompetencer til at specificere alle tekniske detaljer, der kræves for let anvendelse af teknologien fra biogasindustrien. Parallelt hermed valideres business case ud fra teknologileverandørers synspunkt og teknologiens slutbrugere, herunder deres vigtigste kunder til biomethanol, olie- og gasselskaberne.

Effektiv udvikling og markedsintroduktion sikres af et stærkt projektkonsortium, der repræsenterer hele værdikæden fra vedvarende elektricitet gennem teknologiudvikling (GreenHydrogen, REintegrate, Aalborg Universitet, Process Engineering, Holtec Automatic-Nord, Lillegården El) og slutbrugere (E: ON og Nature Energy) til biomethanolmarkedet (Drivkraft Danmark). Værdiskabelse fra alle produktstrømme er et fokuspunkt, og Rockwool er involveret på grund af deres interesse i at købe ilt på senere stadier af teknologiudrulningen.

3. Project objectives

- *What was the objective of the project?*

Power2Met builds on Danish technological strongholds in biogas, hydrogen technology and system integration where the applicants have completed several research and development projects. The technology consists of two main building blocks; the GreenHydrogen high-pressure alkaline electrolyzer and a novel small-scale methanol synthesis plant developed by REintegrate, Process Engineering and Aalborg University.

GreenHydrogen developed and progressed the HyProvide™ alkaline electrolyzer technology to be in the international forefront with respect to key technical data and total cost of ownership. The system level power consumption on the current HyProvide™ A60 is 4.63 kW/Nm3 hydrogen at a pressure of 35 bars and the expected lifetime exceeds 10 years. Altogether, these performance metrics provide a solid foundation for the business case of the total Power2Met solution.

Since the autumn of 2016, GreenHydrogen has focused on increasing the current density on the electrodes of the stack and thereby achieving a significant cost reduction for our electrolyzers on both CAPEX and OPEX throughout the project H2Cost2. In the Power2Met project, GreenHydrogen will further develop the concept and implement the enhancements from H2Cost2 in the final product and as a part of the project test the system placed at AAU.

This work will further progress and mature the electrolyzer technology towards roadmap targets of higher operating temperature (100 °C) and higher current density (600 mA/cm2) resulting in efficiency improvements – objective is 4.4 kW/Nm3 - and cost reduction. Through further optimization of the complete supply chain and from increased production (economy of scale) the system cost is decreased from 30.000 DKK/Nm3 /h to 20.000 DKK/Nm3 /h (2020 roadmap target) corresponding to a cost target of 650.000 EUR/MW

GreenHydrogen's market activities have identified a need for fully integrated and proven turnkey hydrogen-based solutions. The lack of turnkey solutions utilizing hydrogen is a risk to the market acceptance and growth in the use of hydrogen. End-user customers – and even large energy companies - are not ready to take the technical and economic risk of engaging in the system integration of the electrolyzer with either a fueling station or a power-to-gas or power-to-liquid (Power2Met) process. This conclusion probed GreenHydrogen to participate in the MeGa-stoRE project using hydrogen to produce methane from biogas CO2. GreenHydrogen also later teamed up with an international supplier of hydrogen fueling stations (HRS) to create a turnkey HRS solution including on-site hydrogen generation. In Power2Met GreenHydrogen teams up with a turnkey supplier (REintegrate) to secure a new near future sales channel to the biogas market which is validated during the project through E.ON and Nature Energy. GreenHydrogen also sees a large international market for the Power2Met technology that can be reached via GreenHydrogen's network of existing trusted partners such as for example Engie (www.engie.com).

Power2Met is divided in two phases to reduce the technical and economic risks. This application concerns the first phase.

Power2Met, Phase 1 (2019-2020):

- The objective of the first phase is to develop the core technology and demonstrate the Power2Met technology in a pilot plant at Aalborg University. E.ON and NGF Nature Energy set the technical specifications that must be proven after phase 1 and Drivkraft Danmark endorse the produced advanced biomethanol for use in the Danish transport sector. This validates the complete business case and paves the way for phase 2 and quick market introduction.

Power2Met, Phase 2 (2020-2021):

- The objective is to develop the final turnkey solution by scaling the pilot plant to the standard 1MW turnkey module tailored to biogas plants. Phase 2 also develops the required interface technology towards the biogas plant and demonstrates advanced biomethanol blending at Danish gasoline terminal(s). When the complete standardized module is introduced to the market in 2020/2021 it will have a unique value proposition.

- *Which energy technology has been developed and demonstrated?*

The fundamental principle of the Power2Met plant is catalytic reaction of biogas CO2 with hydrogen using an existing commercial catalyst.

Through Power2Met a joint effort by REintegrate, Process Engineering and Aalborg University has progressed into a state-of-the-art of small-scale power-to-methanol plant that enables dynamic operation against electricity cost variations with the focus on developing a standard turnkey solution.

The core development activities in Power2Met was centered on system integration of the complete sector coupling solution enabling dynamic operation. Towards achieving this objective, the methanol synthesis process represents the area requiring technical development and innovation. Existing methanol production technology that is commercially available from Haldor Topsøe, Johnson Matthey, Casale and other global players

is a solid starting point with several similarities as well as a deep understanding of the fundamental process and equipment design. However, Power2Met also differ in some important aspects related to technology and market approach. Technically, Power2Met converts CO2 and wind energy into methanol via reaction with hydrogen produced from water electrolysis whereas large-scale methanol plants typically use natural gas or gasified coal. Whereas the large-scale plants operate continuously, only interrupted by service or maintenance, the small-scale Power2Met plants will operate intermittent to follow electricity prices and the needs from the power regulation market. On the market side, Power2Met targets a niche of standardized small-scale modules as opposed to the large-scale plants engineered to each individual location. Whereas the large-scale plants produce fossil methanol the small-scale plants target advanced biomethanol production that has approximately twice the market value of fossil methanol. The focus on a standard module al lows the module to be optimized with respect to cost, efficiency and engineering solutions since the associated cost is shared between a large number of modules. Based on engineering work and careful cost analysis conducted by Reintegrate and Process Engineering, the consortium behind the Power2Met is confident a viable business case for the end-user can be validated through the Power2Met project. Substantial development and innovation is required to reach the required technical targets on turndown ratio and dynamics of the complete Power2Met module. Aalborg University, Process Engineering, GreenHydrogen, Reintegrate, Holtec Automatic-Nord and Hydrogen Valley bring the required key competencies and experience to the project. Aalborg University has a long track record of successful R&D in system level process simulation and optimization related to hydrogen technology. Their knowledge builds on projects supported by EUDP and Innovation Fund Denmark (COBRA-I and COBRA-II, AddPower, C3U, BoP-OP, REST, SYNFUEL etc.). Process Engineering brings experience in product engineering to the consortium ensuring manufacturability of the final product. GreenHydrogen contributes with key knowledge in electrolysis and from the MeGastoRE project. Reintegrate has developed a deep understanding of the methanol synthesis plant and its dynamic operation and system integration. Holtec Automatic-Nord has experience in industrial automation and will develop the control system and use interface. Hydrogen Valley has key knowledge in grid balancing with electrolysis from the HyBalance project.

The required key system components and sub-systems (electrolyzer and methanol reactor) are individually relatively mature (TRL 8-9) and available either commercially or as mature prototypes. When integrated, the complete, integrated Power2Met solution is relatively less mature (TRL 5-6) - main reason being new complexities arising from the required ability to provide multiple services simultaneously (the sector coupling). More specifically, the two individual systems and auxiliaries will need to be further developed and adapted on technology level, interface level, in operation and in total system management/control to obtain a level of integration that makes it possible to deliver a coherent, turnkey power-to-methanol solution. At the same time, the HyProvide™ electrolyzer requires its' own further development to reach increased output, higher efficiency and lower cost (CAPEX and OPEX). The same goes for the methanol reactor where the general concept – based on technology from a larger scale methanol reactor - will need further adaptation and development – specifically with regards to the requirements for dynamic operation and cost reductions

Power2Met has progressed the power-to-methanol technology to TRL 6 through focused efforts at the system integration level with a total system level efficiency of around 77%. The outcome is a proven pilot scale technology ready for scale up and market introduction.

4. Project implementation

- *How did the project evolve?*

The project started by looking into the methanol production process to consider and determine the principles of the operation of the plant. The initial work concluded with a workshop and a report which establish the

working principles of the plant and its integrations. The control and monitoring systems followed, and the design of the overall process meant that sub-suppliers could begin the construction of the reactor. In parallel the regulative frameworks of producing renewable fuels were investigated including the value of biogenic CO2. The consortium developed 3D layout based on flowsheets with material and mass flow balances for the methanol synthesis loop as well as the piping and instrument diagrams. This concluded in the identification of critical components, which were specified and ordered.

The construction of the physical plant began as planned, and the development of control and data registration systems was done while the different components were delivered by the sub-suppliers. The construction was established at the outdoor testing facility at Aalborg University, while the methanol synthesis was developed and tested on a lab scale with focus on catalyst performance and system operation. The electrolysis system completed its construction and was ready for testing, with focus on function, performance and safety. That concluded in the delivery of the container with the electrolyzer being delivered to the plant site at Aalborg. Meanwhile the plant was waiting for acceptance by the Danish Emergency Management Agency.

The scientific work in this phase focused on the chemical process modelling of the system and the investigation of integration of heat as well as the possible optimization of the plant operation. This work was from the start meant to be used in the communication and dissemination strategy.

After the delivery of the electrolysis plant, and the further installation of the methanol synthesis components, the safety and fire technical approval was completed. This was around the time when the Covid-19 pandemic was becoming a global concern. Therefore, the project had to work under uncertainties, and the official inauguration had to be postponed. A workshop with the consortium took place, where the actions of accommodating the challenges of Covid-19 was the main point.

The inauguration was postponed to the fall, and the dissemination of the project results so far was made into a video showcasing the plant and the different processes. This work was followed by PR actions and resulted in a lot of positive attention to the project.

The plant was proven to operate successfully, and different testing and optimization was done, still under the restrictions of the pandemic. This meant that the project partners could not visit the plant, as external visitors were limited. Furthermore, the delivery of certain components was delayed and the operation and testing in longer periods was hindered by these factors. Therefore, the consortium decided to postpone the project, and in the meantime discussed the plan for the final testing and operation of the plant, which was decided and accepted as the objective in the last phase of the project, with focus on gathering data on the overall system performance. When the plant has been operated for a long period of time, it was agreed in the project group that data is collected along the way, to gain insights about start-up, process outcomes and general operation of the plant. This workshop also concluded that the Phase 2 of the Power2Met project did not have support.

The final event will be held after the project has been terminated, and the sharing of the data collection between the partners will conclude the project.

- *Describe the risks associated with conducting the project.*

The following risk dimensions was identified in the project: organization, technology, market- and framework conditions.

Organizational Risk
The organizational risk in the project was considered minimal as GreenHydrogen and the partners have

demonstrated their ability to manage project execution risk in previous projects. A professional project management team, competent key personnel, and proven experience in delivering technology demonstration projects serves as a good foundation for the successful execution of the project. The organisation managed to navigate in the uncertainty of the Covid-19 pandemic, and due to the measures implemented by the partners, the pandemic did not have a great effect on the organisation of the project, only the timeframes and certain deliverables.

Technological Risk
The risk of developing the two main technologies in the project was overall considered to be medium/low. The two technologies to be further developed in the project were the pressurized alkaline electrolyser and the methanol synthesis process.
Due to the progress in previous projects and the stage of the technology at the time of entering the project, the technical risk related to the electrolyzer development was deemed low. There were however some critical steps related to the development of the methanol synthesis unit.
The process used CO2 and hydrogen as feedstock and especially hydrogen is less reactive than the normally used syngas and the whole unit had to support an operation with intermittent hydrogen supply.
Even so, the technical risk was considered medium to low as there was a very deep and preliminary understanding of the methanol synthesis process available in the consortium.

Market-Related Risks & Framework Conditions
To reduce the risk of building an expensive full-scale plant which cannot be operated economically, Power2Met was divided in two phases. The decision whether or not to proceed with a Phase 2 was determined in WP6 and was not supported by the consortium. The main reason was that the economically feasible conditions was identified and pursued in GreenLab Skive, and the main demonstration of the technology in a larger scale was planned instead of a Phase 2 in the Power2Met project.
The extensive knowledge gathered by REintegrate about the market related risks concluded in an assessment that deemed the market risks to be low, as the knowledge of price estimates and market assumptions provided a foundation to make informed decisions about the market.

- *Did the project implementation develop as foreseen and according to milestones agreed upon?*

The project did develop as planned, even when challenges of the Covid-19 pandemic shut down most of the world. The following milestones and Work Packages have been concluded and delivered as expected from all partners.

It is still the intention of Aalborg University to keep the pilot plant operational after the duration of the project through further investments in refurbishing or modifying the equipment. In this way it can continue to be a valuable collaboration platform for the consortium. By investing in the maintenance of the plant further analysis of for example operating modes, control algorithms, degradation mechanisms are envisioned. The plant can also be used as a test bench for new reactor designs, to optimize the balance of plant components or to investigate new and improved electrolyzers. In all cases, we expect this will require additional investments to be made in order to keep the plant operational.

The following Work Packages and their milestones are delivered and the main objectives of each has been achieved.

WP1 Technical Specifications (GH)

- Gathered technical input from all stakeholders

- Delivered a complete technical specification for the complete Power2Met solution
- Organized a workshop to consolidate the technical specification

Work Package Deliverables		Delivery month
D1.1	Report on technical specification from workshop	M2
Work Package Milestones		**Delivery month**
M1.1	Technical specification workshop	M1
M1.2	All technical specifications frozen	M3

WP2 System development and optimization (REI/GH)

- Developed the complete technical integration concepts for the two sub-systems (WP3 and WP4) into one system, in compliance with the specifications from WP1.
- Developed both steady state and dynamic process simulation models
- Optimized the overall system heat integration and process control concepts using the developed models
- Deliver design input/output specifications and critical interfaces of the complete solution

Work Package Deliverables		Delivery month
D2.1	A technical specification of the Power2Met pilot plant assembly	M10
D2.2	Specification of overall control concept and operating modes	M10
D2.3	Technical report of validated steady state and dynamic process simulation models	M18
Work Package Milestones		**Delivery month**
M2.1	A complete technical solution meeting the specification from WP1	M10
M2.2	Process simulation models completed and validated	M16

WP3 Electrolysis (GH)

- Assessed and mitigated all potential technological risks in the electrolysis unit
- Ensured technical development towards the specification from task 1.3
- Tested the unit against the specifications delivered in WP2
- Building of production module
- Ensured smooth delivery to the integration WP2 and assembly of WP5

Work Package Deliverables		Delivery month
D3.1	Report describing the system architecture and PID	M5
D3.2	Cost analysis regarding upgrade of stack from 80 to 100 degrees	M6
D3.3	Test protocol for Initial test and long terms test in WP 5	M8
D3.4	Test report for Initial test at GH	M12
Work Package Milestones		**Delivery month**
M3.1	Production platform ready for test at GH	M8
M3.2	Initial test done at GH and production platform ready for installation at AAU	M12
CM1	HyProvide™ A90 platform ready for integration (Generic value added)	M12

WP4 Methanol Synthesis (REI/PE)

- Assessed and mitigated all potential technological risks in the methanol synthesis unit
- Optimized the synthesis reactor according to WP1 specifications
- Developed the methanol synthesis control principle and algorithms
- Developed the final methanol synthesis process flow sheet and P&ID
- Developed an advanced reactor simulation model

Work Package Deliverables		Delivery month
D4.1	Final process flow chart and P&ID	M6
D4.2	A report describing reactor design and manufacturing procedures	M8
D4.3	A technical report describing the CFD model	M10
D4.4	A report describing novel reactor designs and their limitations	M12
Work Package Milestones		**Delivery month**
M4.1	CFD-model development completed	M6
M4.2	Methanol reactor and synthesis process design frozen	M8
M4.3	Control concepts developed to support specified operation modes	M10
CM2	Methanol Synthesis platform ready for integration (Generic value added)	M12

WP5 Prototype-scale (250 kW) construction and testing (AAU)

- Constructed the integrated pilot plant according to the developed design from WP2, WP3 and WP4.
- Demonstrated the performance of the Power2Met system under different operating conditions
- Validated the grid balancing capabilities

Work Package Deliverables		Delivery month
D5.1	Test plan	M8
D5.2	Final test report	M20
Work Package Milestones		**Delivery month**
M5.1	Pilot plant commissioning	M12
M5.2	Test campaign completed according to D5.1	M18

WP6 Evaluation and next steps towards market introduction

- Assessed the future potential of Power2Met, based on the pilot-scale demonstration and innovation efforts
- Ensured that further steps towards market introduction was planned
- Provided the market basis of the business model, including end user and customer requirements

Work Package Deliverables		Delivery month
D6.1	Report on technical aspects of using biomethanol by Danish gasoline companies.	12
D6.2	Report on regulatory framework for biomethanol production and use	12
D6.3	Summary from workshop	18
D6.4	Evaluation report to be included in final report (D7.4)	24
Work Package Milestones		**Delivery month**
M6.1	Workshop held and next steps approved by steering committee	18
CM3	Technology validated in pilot scale	18

WP7 Project Management, Dissemination and Stakeholder involvement (HV/GH)

- Ensured effective communication and management of the project
- Ensured good flow of information, knowledge and results between the participants
- Enabled robust transfer of expertise and knowledge to each of the consortium members

- Ensured timely and correct delivery of all milestones and deliverables
- Provided objective mediation of conflicts
- Ensured that all project results were formulated and compiled into a protectable form
- Prepared and sent the financial and status reports to EUDP
- Ensured the continuous evaluation and quality management of the project

Work Package Deliverables		Delivery month
D7.1	Minutes from consortium meetings (task 1.1) are transformed into a set of to-dos, that are delivered to the responsible parties from each partner organization	M1-M24
D7.2	Annual progress report	M12
D7.3	Press release concerning main conclusion from WP6	M18
D7.4	Final Report	M24
Work Package Milestones		**Delivery month**
M7.1	Annual and final report approved by Steering Committee and EUDP	M24

- *Did the project experience problems not expected?*

The project did encounter problems mainly due to the direct effects of the Covid-19 pandemic. The restrictions led to logistic challenges in the delivery of components, and the limits to external visitors at Aalborg University. The disruptions happened in the latter part of the project period exclusively and had no direct influence on the physical part of the project.

5. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*

The goal of the Power2Met project was to execute the development of a 250-kW pilot plant to serve as the technological platform to further develop a 1 MW hybrid Electrolyzer/biomethanol unit to the biogas-plant market and to rapidly expand the market for electrolysis in a Phase 2 of the project.

The main objective of the technological development was achieved, and the advancement of the electrolyser and the methanol synthesis was a success. The decision of continuing the project in a Phase 2 was however not decided amongst the partners, as the demonstration of the technologies in a larger scale was planned to be established in another project.

- *Describe the obtained technological results. Did the project produce results not expected?*

A 250-kW pilot plant was developed including all critical subcomponents as well as the entire system integration. The plant will be used to optimize the technology towards the market introduction and to validate technical

as well as business case aspects of the technology. The pilot plant will be located at Aalborg University as a central R&D partner and serve as reference plant for future development and optimization. In this first phase the complete up- and downstream value chains are validated as a desktop-study. Key manufacturing partners are involved to prepare the market introduction. Several Danish oil and gas companies are involved to validate the value of the produced methanol and the feasibility of using biomethanol as a renewable fuel directly at the oil and gas terminals.

The outcome of the project has been:

• A pilot plant demonstrating the developed technology

• An integrated balance of plant for a hybrid-system of electrolyzer and methanol synthesis plant

• Optimization of the GreenHydrogen Electrolyzer; HyProvide A90

• Road map for Danish biomethanol blended in gasoline on the Danish gasoline market

• Validation that CO2 can be turned to an income for biogas-plants

• Validation that Danish production of advanced biofuel is feasible

• A concept supporting the transition from fossil energy to renewable energy

• A concept for integration of electricity and liquid transportation fuel

• Increased revenues and new jobs in Denmark

Based on the technological feats from the pilot plant, a large demonstration plant will be developed and demonstrated at GreenLab Skive.

- *Describe the obtained commercial results. Did the project produce results not expected?*

The main commercial partners in the Power2Met project are GreenHydrogen and REintegrate. REintegrate will supply the methanol synthesis plant and GreenHydrogen supplies the electrolyzer in a hybrid solution with REintegrate as the responsible partner. The partners will together create a common sales plan for bringing the hybrid solution to the market. In the early stage and for the Danish market REintegrate is the responsible partner signing contracts with customers and for delivering/commissioning the complete solution, provide project management and after-sales service.

Two significant commercial results have been obtained in the project, besides the creation of a sales-framework. The first being the offtake of methanol from the plant to Circle K, who has ordered 50 million liters of methanol based on the developed technology.

The other milestone is the establishment of a large 10MW demonstration plant in GreenLab Skive, with GreenHydrogen and REintegrate as partners. This demonstration has also attracted commercial interests as Maersk has ordered methanol based on the demonstration plant as well.

- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*

The Power2Met project and its solutions are directed mainly at two target groups. Biogas plant owners and the transport sector.

Biogas facilities
The primary target market segment for the hybrid technology is biogas facilities currently upgrading their biogas to synthetic natural gas quality through the separation of biomethane and CO2. Today CO2 from the process is a waste product emitted to the atmosphere. Using the new hybrid technology from Power2Met, the owners of the biogas-facilities can create an additional source of income through the conversion of CO2, which is re-used in the upgrading process of producing methanol. The hybrid solution provides a positive business case for the biogas plant – even with a small-scale production (1 MW methanol plant).

Besides the additional income from upgrading the CO2, the technology will also help mitigate the CO2 emissions of the agricultural sector. Furthermore, it enables the biogas plants to convert CO2 from a waste-product into a new source of income, it will at the same time save the biogas facility of significant operational costs for purchased heat.
Today there are more than 450 upgrading biomethane plants in Europe according to IEA. In Denmark upgrading biogas facilities are mostly owned by two stakeholders: E.ON and NGF Nature Energy which are both partners in the Power2Met project.

As the customer base is well defined and manageable it is considered realistic that the project partners GreenHydrogen and REintegrate will be able to sell the solution to – initially - these two potential customers who operate a number of biogas plants in Denmark and Europe.

Biogas Denmark has a very strong position as supplier and market leader in biogas technology. Biogas plays a central role in sustainable agriculture and waste management but has been claimed to receive too high subsidies compared to its contribution to renewable energy. With the Power2Met technology this is better justified as biogas will take a new role unlocking the sector coupling – biogas and electricity - and providing services to the energy system that are required towards becoming fossil free in 2050. The sustainability merits will be further improved by the carbon utilization. The renewable energy provided from the biogas plants will increase by 50% and could be based on energy from wind turbines that would otherwise be curtailed.

Transport
According to reports from OECD, CO2 emissions from transport is a critical problem. While the CO2 emitted from all other sectors has decreased in recent years, the transport sector continues to emit increasing amounts of CO2. This trend is also the case from Denmark. Biofuels constitute the large majority of the CO2 reduction that was achieved in Denmark and continues to appear as the only feasible solution with significant impact in the near term. Key drivers are RED, RED II and the Danish legislation from 2016 “Lov om avancerede biobrændstoffer”. These directives and legislation imposing the gasoline industry to blend biofuels into normal gasoline. This creates a demand for biofuels that create a premium on the price for biomethanol compared to black methanol. The key reason behind this is the fact that it uses the same infrastructure and car fleet, hence it is much less cost intensive than alternative technologies. We see biomethanol as a potential key component in the short to medium term facilitating de-carbonization of the transport sector while battery and fuel cell technology is matured. In the medium to long term, the biomethanol can be used in heavy transport, shipping and aviation, made possible by further upgrading the methanol to synthetic gasoline, diesel or jet-fuel.

- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

The Power2Met project and its results has been disseminated according to the dissemination plan which the project consortium produced and agreed upon during the initial stages of the project. The full dissemination plan has throughout the project been utilized for initiating dissemination actions. In the following sections, we highlight some of the core activities that have been implemented in Power2Met's project period.

Project Webinar
The partners behind the Power2Met project held a webinar in which the projects results and next steps were in focus. The full webinar recording can be found at the following link:
https://www.youtube.com/watch?v=6MTJngl6vPI

Site-tour video
Power2Met has produced a site-tour video of the pilot methanol plant located at Aalborg University. In the video, Founder and CTO Søren Knudsen Kær from Reintegrate takes the viewer on a tour of the facility and explains the process. The site-tour video can be found on the following link:
https://www.youtube.com/watch?v=3EL7b2Q_yw8&t=205s

Project video
On 23. jun. 2020, Power2Met released a project video on Youtube with the purpose of providing stakeholders and the public with a short introduction to the Power2Met project, its purpose, and objectives. The video can be found on the following link:
https://www.youtube.com/watch?v=_r6Q1ElwLoI&t=66s

Press – articles and features in News
Links to the articles listed below can be found on Power2Met's project site on the following link:
https://hydrogenvalley.dk/power2met/

Date	Title	Media
01.07.2020:	Fra PtX-idé til virkelighed: Danmarks første eMethanolanlæg producerer flydende el,	Energy Supply
Juni 2020:	Nu producerer Danmarks første PtX-anlæg methanol	Biopress
25.06.2020:	Danmarks første eMethanolanlæg producerer flydende el,	Gridtech
25.06.2020:	Fra PtX-idé til virkelighed: Danmarks første eMethanolanlæg producerer flydende el,	Fjordavisen
24.06.2020:	Fra PtX-idé til virkelighed: Danmarks første eMethanolanlæg producerer flydende el,	Energiforum Danmark
24.06.2020:	Nyt anlæg er et skridt i den danske PTX-satsning,	EnergiWatch
23.06.2020:	Fra PtX-idé til virkelighed: Danmarks første eMethanolanlæg producerer flydende el,	Pressemedelelse
19.06.2020:	Milliardaftale om grøn energi	(9 minutter inde i udsendelsen) DR nyhederne
19.06.2020:	Hvis det skal blive grønt at flyve, har vi brug for Power-to-X, men hvad er det overhovedet,	DR.dk

21.12.2019:	Brinteventyret i Hobro bliver til virkelighed,	Nordjyske
20.12.2019:	: Først i verden til banebrydende grønt projekt: Tre nordjyske selskaber er med,	Nordjyske
22.11.2019:	Brint er byggeklodsen i fremtidens energisystem,	Energiforum Danmark
05.11.2019:	Fra grøn el til flydende brændstoffer: Danmark er langt med 'Power-to-X',	Ingeniøren
04.02.2019:	Nordjysk projekt baner vej for flydende el,	Nordjyske
04.02.2019:	Nordjysk projekt baner vej for flydende el,	Energy Supply
01.02.2019:	Nordjysk anlæg skal konvertere brint og CO2 til metanol,	Biopress
23.01.2019:	Nyt anlæg skal bane vejen for grøn transport,	Energiwatch

Press Coverage

The partners in the Power2Met project have in multiple occasions disseminated the potentials of Power-to-Methanol to national media such as DR News and Børsen. Below is a few examples.

Date	Title	Media
22.08.2019:	Brint-boss: "Hvis Danmark vil det, ligger der et kæmpe eksporteventyr og venter. Vi har alle esserne på hånden"	Børsen
23.04.2019:	Teknologien rykker: Snart sætter flere anlæg sol og vind på flaske	DR

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

The technological results and experience obtained for the project partners through the Power2Met project has led to various exploitable results that the following section will point out based on each project partner.

Green Hydrogen Systems

The results in the Power2Met project represents a new business area for GreenHydrogen that will help reach new markets for their electrolyzers.

GreenHydrogen has developed, tested and demonstrated their HyProvide™ A90 electrolysis module as a part of the integrated and hybrid solution for production of green methanol. This will enable GreenHydrogen to faster introduce the HyProvide™ A90 electrolyzer to the market. Furthermore, the integration work required to have the electrolyzer and methanol reactor work seamlessly in a coherent system solution - delivering methanol under variable production load and conditions - is a major undertaking. However, the market requires coherent hydrogen solutions, and GreenHydrogen needs to constantly develop the technology and auxiliaries to facilitate close integration with other technologies and electricity sources of the hydrogen value chain.

The results of the project comprise resource intensive and highly challenging technological development activities that has fostered a close collaboration between GreenHydrogen, AAU, Process Engineering and Reintegrate. The technology platform of the HyProvide system will now be demonstrated on an even larger scale, and this is due to the results from the Power2Met project.

Reintegrate
Reintegrate now holds key knowledge related to the Power2Met technology, the market and the regulatory framework surrounding the technology including the certification of the produced methanol for target markets in the biogas and transport sectors. The results in the project allowed Reintegrate to further develop the technology that enables biogas plants to turn the waste CO2 into renewable methanol, and together with key-partners such as GreenHydrogen they aim to bring the hybrid technology to the market through new demonstration projects. The results showed that it was feasible to scale the process down, and now the next step is to demonstrate that it can be scaled up in a plant 40 times larger than the pilot plant.

Reintegrate will be able to develop and demonstrate their power-to-methanol plant through the Power2Met project as the company now has a very strong collaboration platform and network. Without this collaboration platform and the experience learned in the porject, Reintegrate would not have been able to bring its technology to the market. By participating in Power2Met, Reintegrate has proved the technology and has been acquired by European Energy, who will help develop the technology platform and put further focus on the realization and commercialization of the Power2Met technology together with GreenHydrogen.

Aalborg University
Aalborg University, Department of Energy Technology, has obtained a significant technological experience from the Power2Met project which adds to the existing knowledge within the field of hydrogen technologies. The department has started a research program in electro-fuels and the Power2Met project allowed Aalborg University to allocate one fulltime postdoc and two faculty members to the project that would otherwise not have been able to work in this area. In addition, the result from the project provides an opportunity to further strengthen the already very strong international position in renewable energy as the work has fostered several innovative ideas some of which may be patentable.

Process Engineering
The role of Process Engineering A/S in the Power2Met project was to support Reintegrate concerning the detailed technical specifications and design, the process development in relation to the methanol synthesis reactor and the complete plant. Process Engineering also monitored the construction phase and took part in the commissioning.

The result from these activities builds upon the already extensive knowledge of plant design that has been acquired in other projects and allows Process Engineering to further develop their expertise in Power2X. These engineering results is an important foundation that helps the project partners and other companies to continue to bring both the power-to-methanol and other technologies to the market. Process Engineering A/S now has a deeper knowledge of these technologies, which can be utilized in future developments of new technologies in Power2X.

Hydrogen Valley
Hydrogen Valley is a non-profit organization with the purpose of nurturing regional business development in renewable energy and hydrogen technologies. Hydrogen Valley has seen the Power2Met project as a natural continuation of the HyBalance project that focuses on using water electrolysis for grid balancing. The project is also well aligned with the overall scope to facilitate the transition of the energy supply from one based on fossil fuels to one based on renewables. Hydrogen Valley has been vital in the regions focus on hydrogen technology for producing other valuable products builds on the experience of facilitating pilot plants and lighthouse projects such as HyBalance. The technological results have provided more knowledge for Hydrogen Valley that can be used in technical management, administration and dissemination to further determine and help develop projects and technologies in the future.

Holtec Automatic-Nord
The role of Holtec Automatic-Nord in the Power2Met project was to develop the automation system for the plant including the user interface and monitoring system. Holtec Automatic-Nord's are specialized in developing software, construction and installation assignments. As such, the results from the Power2Met project builds upon the company ability to provide solutions in the field of control technology and automation solutions tailored to match customer needs and requirements. The capabilities to provide control systems for Power2X plants has now been further proven and Holtec Automatic-Nord sees the Power2Met technology as a potential future business area where they supply the control system and technical support related to the process control.

For the first time Holtec Automatic-Nord will now be able to provide a software solution that will be targeted for a mass market. Until now Holtec Automatic-Nord has produced and sold specific solutions for specific customers. Participating in Power2Met Holtec Automatic-Nord has allowed the company to produce a software solution enabling the electrolysis/Biomethanol solution to be controlled by this software. The company will now bring a product to the market, that will be replicated based on a software service contract. After Power2Met Holtec Automatic-Nord will start to build up a service organization supporting this new business.

Lillegården EL
Lillegården EL have over 30 years of experience in providing electrical installations to industry, agriculture and housing. The role of Lillegården EL in the Power2Met project was to build the methanol producing reactor in close corporation with Aalborg University, Holtec Automatic-Nord and Process Engineering.

Lillegården EL has now through its participation in the project developed new skills and demonstrated its electrical installations and services in the energy business area. Hence, this is a natural development for Lillegården EL, as Lillegården EL has participated in several previous projects as subcontractor. Latest HyBalance in Hobro, where Lillegården EL did all the cabling in an ATEX environment. After Power2Met, Lillegården EL will be a leading supplier of services within electrical installations in the Danish hydrogen world.

Drivkraft Danmark
Drivkraft Danmark is an independent business association for the Danish petroleum & gas companies based in Copenhagen. Drivkraft Danmark ensures favorable conditions for the business activities of its members through proactive and professional interest management aimed at political and administrative authorities, the public and the press. Their participation in the Power2Met project was driven by a strategic interest in securing Danish production of advanced biofuels for use in the affiliated companies. The role of Drivkraft Danmark

and its members was to lead the technical studies on how advanced biomethanol can be used in the Danish transport sector and contribute towards the national CO2 reduction targets.

Drivkraft Danmark's main focus in the Power2Met project was in direct line with the interest of its members in the form of gasoline companies. These gasoline companies are faced with a future with higher requirements for the use of advanced biofuels in the gasoline mix. This is due to the EU's Renewable Energy Directive which establishes that a minimum of 10% biofuels or other renewable fuels for transport shall be used in every Member State by 2020. As such Drivkraft Danmark's participation in the Power2Met project has ensured a perspective of the usage of methanol in the transportation sector. The project's investigations of using methanol as a blend-in fuel, has led to the conclusions that there are obstacles that hinder the uptake of renewable produced methanol in direct usage in traditional engines and in the blending of gasoline. There needs to be changes in specifications of gasoline and the configurations of engines before methanol can be used as a fuel for road transport.

Rockwool

Rockwool is one of the world's leading producers of rock wool-based products mainly used in the construction sector for isolation, acoustic ceilings, and facade boards. The role of Rockwool in the project was a member of the advisory board. The Power2Met project provided Rockwools with information about sustainability pathways through Power2X products, based on their framework "Rising to the challenge" which sets out to assist in delivering against the UN's Sustainable Development Goals (SDGs). Specifically, the Power2Met technology has proven that it can provide green oxygen (by-product from production of hydrogen by water electrolysis) to the Rockwool production facilities. The technical specifications of oxygen as a by-product and the potential economic value have been concluded in the project.

NGF Nature Energy

NGF Nature Energy is the largest biogas producer in Denmark. This makes NGF Nature Energy the potential largest customer and an important part of the value chain for the methanol plant which has been developed in the Power2Met project. NGF Nature Energy had a strategic interest in observing and learning from the technology development that can secure economically viable CO2 utilization. The role of NGF Nature Energy in the project was as a member of the steering committee and they provided specialist knowledge to the project concerning biogas technology and the use of CO2 in biomethanol production.

E.ON

E.ON builds, own and operate biogas plants. E.ON produce approximately 20% of the upgraded biogas in Denmark. This makes E.ON the second largest potential customer and an important part of the value chain for the methanol plant which is to be devolved in the Power2Met project. E.ON also own and operate biogas in other countries. E.ON had a strategic interest in observing the technology development that can secure economically viable CO2 utilization, and thus the role of E.ON in the project was as a member of the steering committee and they provided specialist knowledge concerning biogas technology and the use of CO2 in biomethanol production. The main interest of the two biogas companies was to help the project partners in bringing a new technology to the market. This in turn can help both companies in increasing the profitability of running biogas-plants and having a better CO2 footprint.

- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*

The two main commercial partners in the project, GreenHydrogen and Reintegrate have both achieved commercial results based on the Power2Met project.

The project results add to the already commercialized technology platform for GreenHydrogen, and the conclusions made from the investigations and tests of a flexible operation adds to the tested features of the pressurized alkaline electrolysers. Furthermore, the listing of GreenHydrogen on the stock market enables a higher production capacity of the HyProvide systems through new production facilities, as well as scaling up the technology platform.

The Power2Met demonstration results has proven to be a significant step towards commercialization of e-methanol as it has laid the foundation for the initial validation of the product value-chain and business case. The project results have been of key importance in regard to achieving the first commercial offtake agreement for green methanol for shipping fuel. The commercializing and offtake of the produced methanol has proved to be a success, as Reintegrate and European Energy has engaged into an off-take agreement with Maersk looking to buy significant shares of the methanol that will be produced from the planned larger demonstration plants.

For more details on the Maersk offtake agreement, see the following link:
https://www.maersk.com/news/articles/2021/08/18/maersk-secures-green-e-methanol

The other partners in the project will use the results and learnings in new projects and services, as the experience of building the pilot plant and investigating the required commercial context for power-to-x production has led to the identification of new business areas, partners and products.

- *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*

Since the project started, both Green Hydrogen Systems and Reintegrate have both obtained additional private investments and progression in terms of employment.

To scale up activities to meet market demands, such as the Maersk agreement, Reintegrate has obtained private investments of 20.000.000 and has recently been acquired by European Energy. In the process of integrating Reintegrate into European Energy, a new Power-to-X department has been established and a significant increase in employment will be a result of this. Building upon the Power2Met project results as a steppingstone, scaling up and commercializing will lead to increased turnover and exports within the next 2 years following the project.

- *Describe the competitive situation in the market you expect to enter.*
  - *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*

When discussing competition, it is relevant to address this at two levels that influence the overall viability of the business case. At the first level, there are competing technologies that offer to turn biogas CO2 into a value stream for the biogas plant owners. These technologies are in direct competition with the Power2Met technology. At the second level are those technologies challenging the business case at the customer side.

Direct competition from similar technology
To our knowledge, only one supplier of similar technology exists worldwide that has already built an operational plant. Carbon Recycling International operates an existing 4-5MW production unit in Iceland based on CO2 from geothermal energy production and hydrogen from water electrolysis. This is still a demonstration site for the technology.
Liquid Wind from Sweden (https://www.liquidwind.se/) has plans to develop a similar technology, using carbon dioxide and renewable electricity to produce methanol. This is a similar technology with a large scope, and is thus considered a competitor.

Competing technologies
BioMCN in Holland is a company that converts biomethane into biomethanol (www.biomcn.eu). This is a similar product to the end user, but the feedstock is not CO2 but the upgraded biogas.

In a Danish context the best business-case for a biogas-plant owner is to upgrade the raw biogas by removing/scrubbing the CO2 from it, sell the upgraded biogas to the national gas-grid, and turn the CO2 into biomethanol. As long as there is an upgrade fee paid to feed-in the upgraded biogas to the gas pipeline, this combination provides for the best business case.

We identified two main competing technologies that offer to turn biogas CO2 into value: methanation and CO2 purification and liquefaction.

Methanation uses a process similar to the Power2Met technology but the end product is methane rather that biomethanol. We identified the following pros and cons of this technology.

CO2 purification and liquefaction, requires that the biogas CO2 is cleaned and liquefied. The end-use can be greenhouse gas for agriculture, fire extinguishers, carbonated soft drinks, as refrigerant, for dry ice or as liquid solvent for many organic compounds.

Bioethanol
Competition for the biomethanol is mainly bioethanol on the gasoline market. However, this is not a direct competitor to the technology, but is mentioned here because it is in competition with the methanol produced on the hybrid Electrolysis/Biomethanol solution developed in Power2Met.

Biomethanol
There are only two competing plants in operation in Europa today. One is operated by CRI on Island Iceland and is still a small demonstration-plant. The other is at BioMCN in Holland that turn biomethane into biomethanol. There are a few competing technologies in the world that can also produce biomethanol at small scale. There are at least two technologies:

1. Biomethane steam reforming followed by methanol synthesis. Several suppliers of this technology exist mainly in the US where they target flare gas and other unused methane sources. Production of biomethanol at a cost competitive price requires access to low-cost biogas. In Denmark, the government's subsidies for biogas upgrading, makes the biomethane much too expensive for biomethanol production. Lower cost biomethane in other countries is a potential competitor.

2. Biomass gasification with or without addition of hydrogen from electrolysis. This technology was the subject of the GreenSynFuel project sponsored by the EUDP program. This technology can potentially produce biomethanol at a cost comparable to the Power2Met technology, but key technologies are not yet available. The required pressurized gasification technology does not exist and neither does a large-scale pressurized SOEC.

Based on the initial analysis and by following the market and competition closely throughout the project, it can be concluded that the main potential competition in the advanced 2nd generation biofuel market is biomethanol from biomethane and not from bioethanol.

- *Describe entry or sales barriers and how these are expected to be overcome.*

"Biobrændstofsloven" was amended in 2019, so that the blend-in requirement of 5.75% (the target as energy) was increased to 7.6% in 2020. This happened as part of Denmark's compliance with the RE Directive's requirement of 10% RE in transport in 2020. To live up to the requirement of 7.6% bio blend-in, the fuel suppliers in Denmark introduced the so-called E10 petrol (petrol with 10% bioethanol) as a standard in Denmark.

The possibility of blending methanol into E10 petrol has therefore been investigated and discussed in the working group. It is the working group's conclusion that in practice it is not possible to mix e-methanol in E10 petrol. The challenge is that for each unit volume of methanol blended in E10 gasoline, a larger volume of ethanol must be removed in order for the final mixture to continue to meet the specification (EN228). In other words, the total amount of RE (bio-blend) in the gasoline decreases. For the individual fuel supplier, this will therefore mean that it will be more difficult to comply with the Biofuels Act's total requirement of 7.6% bio blend-in - measured as energy.

It was also investigated, together with the bio-diesel manufacturers, whether e-methanol could replace fossil methanol in the production of biodiesel (FAME). The conclusion of these studies is that the current requirements for bio- / RE blending do not reward the use of biodiesel with higher CO2 displacement than the minimum requirements. The producers of biodiesel therefore also do not have sufficient incentives to use e-methanol instead of fossil methanol in the production of biodiesel.

It is the overall conclusion that it is technically possible to mix e-methanol in petrol within the applicable specifications. However, the specification contains a number of fuel technical requirements, which means that blending of e-methanol will at the same time reduce the possibility of blending bioethanol in petrol, so that the total blending of renewable energy is reduced compared to the pure blending of 10% bioethanol, which gives the maximum share of RE within the specification.

It will require a change in the specification for petrol at European level in order for direct blending of e-methanol into petrol to become an option in practice. It is assumed that such a change will have to be seen in the context of the requirements for CO2 emissions that car manufacturers in Europe must comply with. Because the cars CO2 emissions are measured in the exhaust, the incorporation of biofuels and, for example, e-methanol does not count towards the car factories' targets. Therefore, they have no incentive to produce cars that can run on higher blends of methanol than what the current specification for petrol allows.

Finally, the project partners investigated the use of methanol in production of biodiesel, and if e-methanol is to become widespread as a feedstock for the production of biodiesel, the current requirements for bio-blending in "Biobrændstodsloven" must be changed to a general CO2 displacement requirement in a cradle to grave perspective. This will mean that the individual producer of biodiesel will have a clear incentive to ensure such a high CO2 displacement from the produced biodiesel. An obvious part of that effort will be to replace the current use of fossil methanol in the production of biodiesel with e-methanol.

The analyses and investigations have led to the conclusions that the expectance of using methanol and targeting market segments in the transportation sector is limited. There is however a growing interest of methanol as a fuel in the shipping industry, and this could be the primary target for renewable methanol until the regulations and specifications in road transport is changed.

- *How does the project results contribute to realise energy policy objectives?*

The Power2Met technology has the potential to contribute substantially to the security of supply in several ways:

• It can potentially ensure an increased supply of advanced biofuels in transportation applications, produced from domestic resources, waste and wind energy. However, there are still regulatory challenges in specifications of gasoline and configurations of engines, before methanol can be used either as a blend-in fuel or solely as a fuel in common passenger cars.

• It will support high penetration of wind energy in the Danish smart energy system through large-scale energy storage and grid balance capabilities. In this way, Denmark can continue to have one of the most reliable electrical grids in the world. This is supported by the analysis in Systemperspektiv 2035 by Energinet.dk.

• It will decrease the dependence on international electricity grid connections that are very expensive to build and operate. In this way, Danish supply will not rely on the stability of these connections and the electricity grid in foreign countries.

The Power2Met technology will boost the carbon utilization of biogas plants from 60-65% to 100% by turning the biogas CO2 content into a high value transportation fuel using wind energy. The produced biomethane will continue to be injected in the national gas grid and contribute to its decarbonization. Together, this will maximize the contribution to fossil independence from these two important domestic resources, wind and biogas.

The participation of major Danish oil companies, through Drivkraft Danmark, has ensured the commercial perspective in the Power2Met project. Through thorough analyses, a description of the technical and legal framework using the produced biomethanol at Danish terminal(s) and its impact on decarbonizing the Danish transport sector has been conducted. It helped validate that this technology can make a significant, near-term contribution towards fossil independence in the Danish transport sector. The complete infrastructure is in place, however it is a requirement to replace or modify the existing car fleet before methanol can be used as an intended fuel.

The Power2Met technology facilitates large-scale energy storage and grid balancing by conversion of wind energy into a liquid energy carrier that is easy and inexpensive to store in large quantities. In this way, it enables the transition to a fossil free energy system largely based on electricity from wind and solar energy. Considering only the current 25 Danish biogas plants with upgrading technology installed to remove CO2 from biomethane, around 220 mio. liters of advanced biomethanol can be produced. This will require hydrogen from more than 200 MW of electrolysis capacity, which can make a substantial contribution to grid balancing already in the near future.

In the longer term, the biogas potential of around 60 PJ will support the production of 30 PJ of advanced biomethanol from CO2 and wind energy. This biomethanol can be used directly as transportation fuel or upgraded to synthetic gasoline or jet-fuel. This contribution is around 15% of the expected total energy consumption from the transport sector in 2030 representing a value of 20 bn. EUR.

The CO2 emission from the unregulated sectors is one of the key focus points in the ongoing climate discussions. In the Power2Met project, we address the agricultural and transport sectors by turning the waste CO2 from biogas into a valuable and CO2 neutral transport fuel using wind energy. This expands the already circular economy of biogas and its value for the future energy system becomes even more evident. Today, 25 Danish biogas plants upgrade the raw biogas to biomethane by removing around 250.000 tons of CO2. Currently, this CO2 is released to the atmosphere. The Power2Met project results in a technology to convert this CO2 into advanced biomethanol. As new biogas plants are built and existing modified to include upgrading to biomethane, the potential will further increase.

As CO2 emission associated with grid electricity is reduced towards 2050, the greenhouse gas emission reduction from advanced biomethanol produced via CO2 hydrogenation will approach 100% when hydrogen is produced by water electrolysis. At the same time, the Power2Met technology has very favourable sustainability merits in terms of being non-food based, requiring very little land area and having a low water consumption compared with other technologies for liquid fuel production.

From a climate and environmental perspective, the transport sector has experienced many initiates for decarbonisation while the project was running. The most significant being the projections of a Danish roll-out of battery electric vehicles in 2030 of 1 million cars of a car fleet totalling 3 million[1]. Hence to make a substantial impact on the CO2 reduction from the remaining car fleet, renewable liquid transport fuels could be a low cost and near-term opportunity if the challenges mentioned regarding specifications and modifications of engines are addressed. Adding biomethanol to Danish gasoline could not only reduce the CO2 emissions from transport but also improve other environmental aspects of fossil fuels in transport. Experience from other countries have shown that methanol addition to gasoline reduces emissions of unburned hydrocarbons, carbon monoxide and particulates in existing gasoline cars. Methanol addition to gasoline may also improve the overall efficiency of the combustion engine.

In the medium to long term, biomethanol can also play a significant role in the decarbonization of shipping and aviation. Ships can burn biomethanol with high efficiency in slightly modified diesel engines as shown by MAN Turbo & Diesel. Biomethanol leads to substantial reductions in harmful emissions such as NOx and particulates and does not suffer from the critical issue of high methane slip from gas engines. For aircrafts, the biomethanol can be upgraded to jet-fuel using the Haldor Topsøe TIGAS technology or the Exxon-Mobil Methanol-to-gasoline technology, both of which were already proven in large scale.

- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

No Ph.D.'s has been part of the project.

[1] https://cepos.dk/media/2902/udgiften-ved-1-mio-groenne-biler.pdf

7. Project conclusion and perspective

- *State the conclusions made in the project*

• Proof of technology (pilot plant) live in October 2020

• The plant is powered from the grid

• H2 from electrolysis has been produced

• Flexible production has been proven

• CO2 delivered from industry gas supplier and has been tested/used in the synthesis process

• Daily methanol production capacity: 1.000 L

• Objectives are reached and shows that green methanol production can be down scaled to match the CO2 output from biogas plants – with a positive business case

• Testing continues on pilot plant after official project end to gather important experience and collect data on performance

- *What are the next steps for the developed technology?*

In GreenLab Skive REIntegrate and Green Hydrogen Systems will deliver a complete 10 MW methanol plant in 2022 (project supported by funding from Danish Energy Agency)

• Modular electrolyser system of 12MW capacity delivered by Green Hydrogen Systems

• 10 MW for methanol production

• 2 MW for mobility applications

• Methanol reactor and distillation system from REintegrate

• CO2 delivered from E.On's biogas plant

• Power delivered by EuroWind based on windturbines and PV

• Off-take contract secured for full methanol capacity

- *Put into perspective how the project results may influence future development*

Both technological, commercial and regulatory developments may be influenced by the results achieved in the Power2Met project. As the project has investigated the conditions in connections to each other, the consortium has established some recommendations that the development of the technology and its surrounding context could focus on investigating more and further develop.

• The cost of producing hydrogen has to be reduced with at least 30%

• Confirmation of certification to secure high value methanol in RED II and IMPCA

• Mapping the market for green methanol

• Today there is a market for ”black” methanol priced at 350 €/ton (2018 price)

• The end-product from Power2Met competes against 2nd generation bio-ethanol also made from waste stream. Price for bio-ethanol is 1,000 € - 1,200 €

• Long term market certainty is key (RED II)

• Still some regulatory issues (free zones) to be solved, before a feasible BC can be achieved for the investors

• Future investment cost for the units must come down trough economy of scale and industrialization

8. Appendices

- Website: https://hydrogenvalley.dk/power2met/
- Video (webinar & site tour): https://www.youtube.com/watch?v=6MTJngl6vPI&t=733s