LiquidPower-I

»Development & proof-of-concept of core methanol reformer for stationary & motive fuel cell systems & hydrogen refuelling stations«

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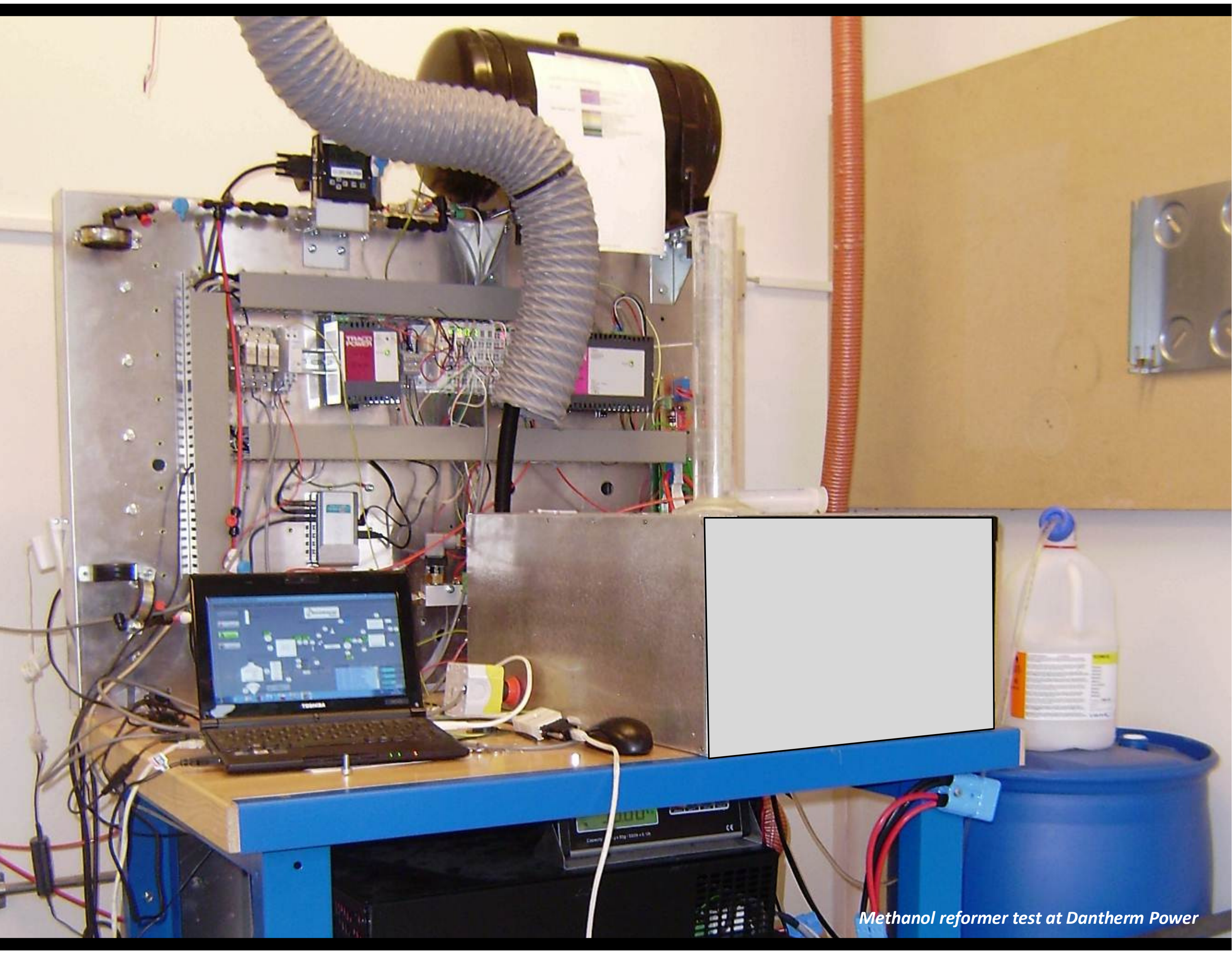

Methanol reformer test at Dantherm Power

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Executive summary

LiquidPower-1 has been the first phase of a strategic and joint R&D effort of Dantherm Power and H2 Logic on enabling use of methanol as fuel in fuel cell systems for back-up power and for onsite production of hydrogen to refuelling stations.

This document provides a detailed reporting of the activities and results in the core project work packages WP2, WP3, WP4 and WP5. The WP1 and WP6 work packages covered the standard administrative and dissemination related activities.

Tasks & results of WP2
The objective of WP2 was to specify Core Reformer requirements, components & subsystems across the targeted market segments and select a range of reformer suppliers for evaluation testing in WP3.

Specific results of WP2 are:

- A detailed core reformer technical specification for each markets
- System design & P&ID for laboratory reformer systems
- Identification & selection of four reformer suppliers for evaluation tests

Task & results of WP3
Objective of WP3 was to develop the laboratory reformer system set-up and conduct initial test of core reformers from the identified suppliers in WP2. Purpose of the initial tests was to select at least 2 reformers for the continued and more detailed tests in WP4.

Dantherm Power and H2 Logic each developed a laboratory test set-up for reformers from two suppliers.

The results of the test showed that only two of the four reformers were suitable for continued tests in WP4, thus these were selected.

Task & results of WP4
WP4 efforts included extensive laboratory tests at H2 Logic and Dantherm of the selected reformers from WP3, with the aim to verify reaching of the specifications from WP2. Potential improvement opportunities identified based on the testing's was also mapped and documented as input for WP5.

Reformer test results at Dantherm
The tests went as planned with the system delivering sufficient hydrogen for the fuel cell, although after about 500 hours the reformer performance dropped significantly and tests were stopped. System was not repaired during the project due to high cost. The reformer efficiency was as expected, but still needs improvement. If the reformer is to be used as backup power the start-up time has to be improved. There could be a potential use as a continuous run mode, to substitute a diesel generator.

Reformer test results at H2 Logic

The reformer only achieved a limited number of operation hours before it was sent for component repairs. The efficiency of the reformer seemed to be good and the flow, pressure and temperature was quite constant during the test period. The main problem was components failing already after few hours which required maintenance from the manufacturer. The manufacturer has stated that the next generation of reformer should be design so these failures are removed. Despite of the rather short test period the base technology seems stable. The new reformer generation is expected in summer 2013, where it is planned to undergo long term testing at H2 Logic (outside the project).

Task & results of WP5

WP5 efforts involved an update of technical & TCO targets based on project test results and an update of the LiquidPower R&D Roadmap and planning of future activities.

Reformer TCO targets (Total Cost of Operation) for each of the markets have been calculated including updated targets for efficiency and cost. These targets also serve as the main ones to be pursued as part of the continued R&D roadmap execution.

Based on both the project test results and updated TCO targets, the existing LiquidPower roadmap has been updated. Several changes have been made to the roadmap. Number of phases is the same but the content and timing have changed. Whereas the project results confirmed that methanol reforming technology is working it also revealed that stability and lifetime needs to be addressed and solved before commencing commercialisation.

Dansk sammendrag

LiquidPower-1 har været første fase af et strategisk og fælles F&U samarbejde mellem Dantherm Power og H2 Logic, med henblik på at muliggøre brug af metanol i brændselsceller til back-up power og brintproduktion ved tankstationer.

Dette dokument giver en detaljeret rapportering for aktiviteterne i arbejdspakkerne WP2, WP3, WP4 og WP5. Arbejdspakkerne WP1 og WP6 har indeholdt standard administrations- og formidlingsaktiviteter.

Opgaver og resultater WP2

Formålet med WP2 har været specifikation af reformer krav, komponenter og undersystemer på tværs af de adresserede markeder samt valg af reformer leverandører til evalueringstest i WP3.

Specifikke resultater fra WP2:

- En detaljeret teknisk reformer specifikation for hvert marked
- System design og P&ID for laboratorie reformer systemer
- Identifikation og valg af fire reformer leverandører til evalueringstest

Opgaver og resultater WP3

Formålet med WP3 har været udviklingen af laboratorie test opsætning og gennemførsel af evalueringstest af de valgte reformer leverandører fra WP2. Formålet med test har været at udvælge minimum to reformere til yderligere test i WP4.

Dantherm Power og H2 Logic har begge udviklet et laboratorie testopsætning og hver udført test af to reformere. Resultaterne viste at kun to af de fire reformere var egnede til fortsatte test i WP4.

Opgaver og resultater WP4

WP4 har udført laboratorie test hos H2 Logic og Dantherm af de udvalgte reformere fra WP3. Målet har været at verificere opfyldelsen af de ønskede specifikationer fra WP2. Potentialet for forbedringer også blevet identificeret og anvendt som input til roadmap opdateringen i WP5.

Reformer test resultater fra Dantherm

Test forløb som planlagt og reformer systemet leverede tilstrækkelig brint til drift af et brændselscelle system. Efter 500 timer faldt reformerens performance betydelig og test blev stoppet. Reparation af reformeren blev vurderet for dyrt. Reformer effektiviteten var som forventet dog er forbedringer nødvendige for at nå målsætninger. Hvis reformeren skal anvendes til back-up power skal opstartstid reduceres betydeligt. Der kan være et potentiale for brug ved kontinuerlig drift og erstatning af diesel generatorer.

Reformer test resultater fra H2 Logic
Der blev kun opnået et beskedent antal timers drift hvorefter det var nødvendigt at sende reformeren til reparation. Effektiviteten under driften var tilfredsstillende og flow samt og tryk nogenlunde stabilt i løbet af testperioden. De største vanskeligheder var fejl på sekundære komponenter som krævede reparation af leverandøren. En ny reformer generation er under forberedelse hos leverandøren hvor fejl forventes at være rettet. På trods af den korte testperiode synes basis reformeren at være stabil. Den nye reformer forventes klar i sommeren 2013 hvor H2 Logic vil fortsætte tests efter projektets afslutning.

Opgaver og resultater WP5
WP5 har omhandlet opdatering af tekniske og TCO målsætninger baseret på projektets test resultater, samt en opdatering af LiquidPower F&U Roadmappen.

Reformer TCO (Total Cost of Operation) målsætninger er blevet beregnet for hvert marked og mål for effektivitet og priser er blevet opdateret. Disse målsætninger fungerer også som de primære der skal forfølges i udførelsen af F&U Roadmappen.

Baseret på resultaterne og de nye målsætninger er F&U roadmappen blevet opdateret hvor adskillige ændringer er blevet foretaget. Antallet af faser er det samme som tidligere men indhold og tidspunkter er blevet ændret. Selvom projektet har bekræftet at metanol reformering virker har det også afdækket at stabilitet og levetid skal adresseres og løses førend en kommercialisering kan påbegyndes.

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WP2 – Specification & planning of work

The objective of WP2 was to specify Core Reformer requirements, components & subsystems across the targeted market segments and select a range of reformer suppliers for evaluation testing in WP3.

In total WP2 involved the following R&D activities:

- Task 2.1 Identification of marked specific system requirements
- Task 2.2 Formulation of Core Reformer specification
- Task 2.3 Outlined components and subsystem specification
- Task 2.4 Identification & selection of suppliers for key components

Task 2.1 & 2.2 Market & core reformer specifications

Both Dantherm and H2 Logic targets use of methanol reformers for different market applications. Dantherm targets integration of the reformer in fuel cell system for back-up power supply (BP-FC) and H2 Logic for integration in hydrogen refuelling stations (HRS) for material handling vehicles and road vehicles.

The initial specification exercises revealed several main observations with regards to the easiness of achieving a core reformer that is useable across the markets.

The integration requirements and operation environment for the two markets are very similar as they are both stationary applications. In both applications the reformer will be part of an integrated and packaged system, with similar operation temperature ranges.

With regards to reformer dimensions and footprint the back-up fuel cell requires a standardised cabinet (as used in back-up-power systems today). For the hydrogen refuelling stations the cabinet approach is sufficient for today's capacity levels. In future as capacity required at refuelling stations will increase the reformer packaging design will most likely change and be tailored towards each market.

The main differences for the two markets are the outlet pressure needed and the future capacity required. The HRS requires at high outlet pressure (preferably above 7 bar) from the reformer as possible in order for the HRS to continue compression up to the refuelling pressure. The BC-FC only requires an outlet pressure minimum 3,5 bar, preferably 7bar. Concerning capacity BC-FC requires up to 320slpm whereas the HRS in short term will only require <160slpm (<20kg/day) but in future up to than 1.600 slpm. In the short to medium term both markets are within the same capacity range. In long term a flexible modularity of the core reformer (several systems in parallel) may extend the capacity synergy across the two markets.

To ensure reflection of the reformer state-of-the-art level in the specification an initial dialogue was conducted with a range of suppliers. This revealed that there is a limited flexibility in redesigning of the core reformer reactor to fit various market needs. This reason is that the reactor design is very much linked chemical/mechanical properties. To ensure future flexibility in selection of reformer suppliers the specification efforts instead focused on defining the overall capacity and interface specification, allowing for flexibility on the reformer reactor & subsystem.

The efforts lead to the shown specifications below that provides detailed specifications for the methanol reformer when applied in the BC-FC and HRS markets.

Concerning specification of efficiency, lifetime and CAPEX this was decided to be handled as part of WP5. The initial dialogue with the reformer suppliers showed that an alignment on these parameters would require continued and future activities. Instead alignment and test on the technical requirements should be prioritized.

Based on the above considerations a detailed reformer specification has been developed for each market. (not disclosed).

Task 2.3 Outlined components and subsystem specification

Based on the Core Reformer specification (task 2.2) the 2.3 focused on identifying and specifying required components and subsystems for the reformer system.

Whereas several of the external components to the reformer would differ across the markets, the defining of the actual physical interfaces to the core reformer was important. As concluded in task 2.2 the available reformers on market can only to some extent be modified to various market needs. So the main effort was to ensure an interface that would enable a flexible use, not only of various reformers but also in each of the market applications.

Five main subsystem of the reformer system were defined:

1) **Methanol supply (inlet)**
   The configuration of the actual methanol supply system is independent of the market application, however the pipeline interface and methanol mixture inlet to the reformer are to be the same. As capacity and in particular utilization (run-time) will differ from each market application, the methanol supply set-up may differ. Also the location may require various set-ups, e.g. back-up power potentially at remote locations, whereas HRS's are located in populated areas.

2) **Reformer (core system)**
   The reformer is the core subsystem to be provided by sub-suppliers. The clear defined inlet and outlet interfaces as well as similar packaging/footprint requirements should enable both supply from a range of suppliers and across the markets.

3) **Power supply/control (inlet)**
   The power supply and in particular control inlet to the reformer enables ex-

ternal control of the operation. The exact interfaces may vary depending on supplier and also the market application (different standby voltage, control protocols etc). As methanol reformer technology is matured and standardized during the coming years, a more specified control interface may be come possible. Experiences from electrolysers (more mature and standardized) have shown that it is possible to specify a control interface in detail across various suppliers and applications.

4) **Exhaust (outlet)**
Exact design and configuration of the exhaust may differ across the markets, due to different overall housing of the entire system. However pipeline interface and flow capacities from the reformer side are to be the same.

5) **Hydrogen outlet / application use**
The "hydrogen outlet" subsystem is a wide definition of the use of the hydrogen outlet from the reformer. For the BC-FC this includes the entire fuel cell system and thus the hydrogen pipeline interface and supply from the reformer. For the HRS this includes compressing and dispensing of the hydrogen, thus also the pipeline interface to the reformer.

Based on the definition of sub-systems detailed P&ID of a "running" reformer system for each market were developed (not disclosed).

Task 2.4 Identification & selection of suppliers for key components

With basis in the P&ID for each market systems (task 2.3) suppliers of key components has been identified and selected for provision of these to WP3 activities.

Main efforts were spent on identifying potential suppliers for the core former. The other components were either existing ones (e.g. used on the FC and HRS system) or standard available components.

In total four reformer suppliers were selected (names not disclosed).

The selection was made based on a screening among several international manufacturers, where the above proved to be among the most mature ones. Also the reformers' physical size and integration packaging were closest to the specifications.

WP3 – Laboratory reformer development & initial test

Objective of WP3 has been to develop the laboratory reformer system set-up and conduct initial test of core reformers from the identified suppliers in task 2.4.

Purpose of the initial tests has been to select at least 2 reformers for the continued and more detailed tests in WP4.

Initial test of the four selected reformers was allocated between Dantherm Power and H2 Logic to reduce the scope of the laboratory system development efforts.

Dantherm Power and H2 Logic each developed a laboratory test set-up for reformers from two suppliers.

The results of the test showed that only two of the four reformers were suitable for continued tests in WP4, thus these were selected.

Below further elaborated on the various WP3 activities at respectively Dantherm Power and H2 Logic and the reasoning for selection of the mentioned reformers.

3.1 Dantherm Power laboratory reformer system set-up & initial tests

A laboratory reformer test system was developed and installed at Dantherm Power. The table below provides a description of the test results for each reformer. Name of reformer suppliers not disclosed.

Reformer	Results description & recommendation
X	The system was set up as described earlier, provided with electricity and methanol, the system delivered hydrogen, to the low temperature PEM stack, and the system ran on it for approximately three month, then slowly the performance on the reformer was reduced to 12 slpm, this drop in performance resulted in the system could only run in half power, we tried changing the pump, but with no better results. Furthermore we recorded some results measuring formaldehyde in the preheat period. After the system is fully running, the formaldehyde also drops, and is concentrated in the exhaust. The system should be put up, in highly ventilated places.
Y	The unit is supplied with a 48V power supply and a power meter is used to show the consumption during heat up and operation. The pressure switch is adjusted to approximately (1070mbar(off) 880mbar(on))= Supply pressure for H2 outlet is coupled to 20 litre buffer tank. The valve block is modified with bypassed pressure switch(new 0,1-1 bar will be mounted instead) pressure Fuel mix according to manual 63wt% MeOH 37wt%H2O

	The reformer did not deliver any Hydrogen, the methanol flowed right through the unit, and was sent back for repair, Dantherm Power never saw the unit again.

As can be seen from the test results only one reformer was suitable for the continued tests in WP4.

3.2 H2 Logic laboratory reformer system set-up & initial tests

A laboratory reformer test system was developed and installed at H2 Logic.

The table below provides a description of the test results for each reformer.
Name of reformer suppliers not disclosed.

Reformer	Results description & recommendation
X	The reformer was setup as described by the manufacturer and the system around the reformer was set up to be able to measure and log flows, pressure and temperatures. Already during the first start up it was noticed that there was liquid coming out together with the hydrogen. After consulting the manufacturer and conducting further measurements it was found that the palladium membrane was defect and thus sending fluegas out together with the hydrogen. As this failed on delivery it was not possible to make any tests on the reformer. The reformer had been tested before freight and the results delivered by the manufacture looked fine. A conclusion is that the system should be rigid enough to withstand freight. The defect palladium membrane is a big concern as this could result in sending contaminations, such as CO and liquids, into the fuelling station. It is a requirement that the palladium membrane technology delivered by supplier has been proven to be leak tight and the system is able to run without problems for many thousands of hours. Because it had failed and without any data obtained the conclusion was that the reformer could not be used for the WP4 testing.
Y	The reformer was setup in the test setup with a minimum of changes to the first test (reformer X). After installation supplier send 2 persons to help with the initial start up. A couple of safety hazards were identified and the system had to be modified, but otherwise it started and operated perfectly. After the smaller modifications the system was started again and it was found that it was delivering hydrogen as expected at a correct

	temperature, pressure and flow. The reformer seemed to have a reasonable efficiency and it was decided to continue with some longer tests to find any problems when running the reformer for longer periods. This resulted in moving the reformer to an outside location and setup of a more sophisticated controlling system (as part of WP4).

As can be seen from the test results only one reformer was suitable for the continued tests in WP4.

WP4 – Continued reformer integration & test

WP4 efforts have included extensive laboratory tests at H2 Logic and Dantherm of the selected reformers from WP3.

The tests have been conducted with the aim to verify reaching of the specifications from WP2 and included analysis of system performance mapping and stability clearances. Potential improvement opportunities identified based on the testing's was also mapped and documented as input for WP5.

Total Cost of Operation calculations was conducted in WP5 (see later section).

4.1 Dantherm reformer integration & test

The tests went as planned, the system delivered hydrogen to the fuel cell, and the fuel cell ran very good on it, although after about 500 hours the reformer performance dropped to 12, 75 slpm, this was not enough for the fuel cell to deliver 1600 w and therefore the system was set to only deliver 600w. The system ran steady on 12,75 w, so we suspect the membrane was contaminated somehow. The system did not get repaired, because it needed a new costly membrane.

If the reformer is to be used as backup power the start-up time has to be improved. It is not advisable to use this reformer as backup power, due to the long start-up time, the amount of power used in heated standby and the fault conditions when restarting from heated standby.

There could be a potential use as a continuous run mode, to substitute a diesel generator. Therefore the setup for a reformer used to continuous-run has been prepared to run in very cold climates.

4.2 H2 Logic reformer integration & test

The reformer only achieved a limited number of operation hours before it was sent for component repairs. The efficiency of the reformer seemed to be good and the flow, pressure and temperature was quite constant during the test period

The main problem was components failing already after few hours which required maintenance from the manufacturer. The manufacturer has stated that the next generation of reformer should be design so these failures are removed.

Despite of the rather short test period the base technology seems stable. The faults was on secondary components, thus not the core reformer reactor. The mind-set and speediness of the manufacturer and service level indicates good chances that the next reformer generation will be much improved.

The new reformer generation is expected in summer 2013, where it planned to undergo long term testing at H2 Logic (outside the project).

WP5 – Planning R&D and commercialization

WP5 efforts have involved the following sub-tasks:

- Update of technical & TCO targets based on project test results
- Update of Liquid Power R&D Roadmap and planning future activities

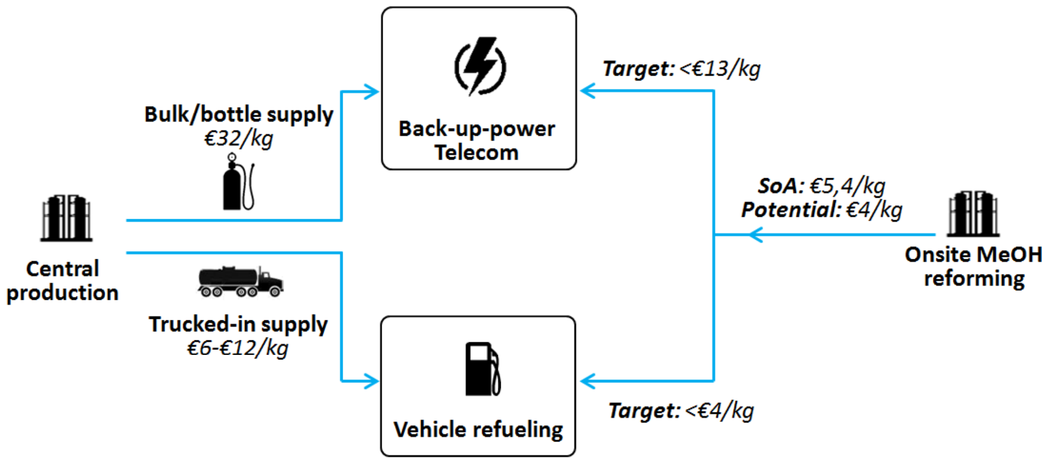
The update of technical and TCO (Total Cost of Operation) targets has been done based on the tests results from the project. Based on this the Liquid Power Road-map has been updated and planning and securing of future activities conducted.

5.1 Update of technical / TCO targets

The main driver for all technical reformer targets is the achievable hydrogen price in the specific market applications. This price is determined by the Total Cost of Op-eration of the reformer, thus the TCO is also the hydrogen outlet price from the reformer when all CAPEX and OPEX costs are covered. The outlet price is what the market application has to "pay" for hydrogen from the reformer and this figure can then be used in the TCO calculations within each market.

The figure below shows an illustrative calculation of the hydrogen outlet price with state-of-the-art reformer technology and what technical targets are needed to achieve the target price for each market application.

Central hydrogen production vs. MeOH reforming



SoA = State-of-the-Art

Onsite MeOH reforming	*SoA*	*Commercial target*	*Note*
System CAPEX	€3.000	€1.000	*Per Nm3 H2/hour capacity for complete reformer system*
100% Methanol consumption (Efficiency LHV H2 / MeOH consumed)	0,99 liter (65%)	0,86 liter (75%)	*Per Nm3 H2 production*
Methanol cost	€0,35/liter		*100% methanol*
H2 outlet price from reformer	€5,4/kg	€4/kg	*@ 5 year simple payback*

The two addressed markets have different targets for the "inlet" hydrogen price to the application. The "inlet" price equals the "outlet" price from the reformer, defined as CAPEX and OPEX for the reformer with a 5 year simple payback. Maintenance cost of 4-8% of CAPEX per year included, but not including reformer degradation or cost for refurbishment.

For Dantherm below €13/kg is sufficient to match fuel costs of a diesel generator in back-up power application. For H2 Logic the price target is €4/kg in order for the hydrogen refuelling station to dispense hydrogen at a competitive price to diesel and gasoline (irrespectively of vehicle type).

State-of-the-Art (SoA) for MeOH reforming can theoretically reach €5,4/kg in "outlet" hydrogen price however this is at a very low guaranteed lifetime of a few thousand hours (at best). Thus in reality the SoA hydrogen "outlet" price would be significantly higher if cost for reformer/purifier refurbishment were to be included.

The stated SoA figures for CAPEX and efficiency are based on an approximate average of the reformers tested within the project as well as general market intelligence from H2 Logic and Dantherm. Generally the figures vary a lot depending on the actual reformer and manufacturer (both upwards and downwards).

A theoretical reformer system CAPEX and efficiency (methanol consumption) has been calculated in order to reach €4/kg – this also acts as the commercial target for the reformer technology.

As also can be seen from the figure SoA MeOH reforming theoretically can provide a hydrogen outlet price significantly below what is achievable today with trucked-in hydrogen solution. The main issue is the assurance on stability and lifetime of the reformer. Thus as long as this is not fully validated the reformers are not stable enough for actual commercial use in the field.

In order to reach a full commercial level for the hydrogen outlet price the MeOH technology has to be developed further with regards to price and efficiency. Theoretically an efficiency of 75% and a price of €1.000 Nm3 H2/hour are achievable, however it would require further R&D efforts and high unit volume production.

The main priority in the coming years of R&D efforts should however be to ensure and validate stability and a high lifetime before looking at cost and efficiency, as this the main unsolved or validated issue at present.

5.2 Update of Liquid Power R&D Roadmap & planning future activities

Based on the project results and update of targets in section 5.1 the LiquidPower R&D Roadmap has been updated.

Several changes have been made to the roadmap. Number of phases is the same but the content and timing have changed. Whereas the project results confirmed that methanol reforming technology is working it also revealed that stability and lifetime needs to be addressed and solved before commencing commercialisation.

Below are listed the new phases and overall content

- **Phase 1 – Proof-of-concept (2011-2013)**
  The LiquidPower-1 project has helped to determine the actual state-of-the-art level for methanol reforming. The lessons learned and SoA is also acting as the basis for the future phases and their content.
- **Phase 2 – Proof-of-Durability (2013-2015)**
  Phase 2 are to validate and confirm that sufficient stability and lifetime of the reformer can be achieved. In parallel R&D efforts should also enable a continued increase of efficiency and reduction of cost. Issues for integration and use in the two markets are also to be addressed, in particular increasing outlet pressure from the reformer. Phase 2 is a go/no decision gate, thus if stability and life-time is not confirmed, a Phase 3 will have to be changed to continued R&D of the reformer technology. The following main activities and targets are foreseen in phase 2:
    - Expand reformer supplier base – continued benchmark testing
    - Validate 10.000+ hours of operation with stable performance
    - Validate efficiency of 70% (average during lifetime)
    - Validate potential for €2.000/Nm3 H2 per hour
- **"Phase 3 – Proof-of-Targets" & "Phase 4 – Commercialisation" (2015+)**
  If phase 2 is successful a phase 3 are to validate the reformer targets in the field (demonstration). Also continued R&D efforts are to ensure potential for reaching full commercial targets for efficiency and cost. If phase 3 is successful a phase 4 is to initiate product maturating and commercial introduction and use of reformers in the two markets. The following main activities and targets are foreseen in phase 3:
    - Validate 20.000+ hours of operation in field
    - Validate efficiency of 75% (average during lifetime)
    - Validate potential for €1.000/Nm3 H2 per hour
    - Develop system integration design for the two markets