Deliverable 5.4

Study of scaling the methanol fuelled CHP system to 50-100 kW

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Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
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CO	Confidential, only for members of the consortium (including the Commission Services)	
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Nomenclature

A	cell active area [cm^2]
F	Faradic constant [C mol^{-1}]
g	acceleration of gravity [m s^{-2}]
H	enthalpy [J]
h	differential head [m]
I	current [A]
j	current density [A cm^{-2}]
$\dot{m}$	mass flow [kg s^{-1}]
N	number of units [-]
$\dot{n}$	molar flow [mol s^{-1}]
P	power [W]
p	pressure [Pa, bar]
Q	heat [J]
$\dot{Q}$	rate of heat flow [J s^{-1}]
R	Gas constant [J mol^{-1} K^{-1}]
T	temperature [K, °C]
U	voltage [V]
X	conversion rate [-, %]
x	molar fraction [-, %]
γ	heat capacity ratio [-]
η	efficiency [-, %]

Background and objectives

Summary of the project scope

The objective of the project is to develop and demonstrate a compact and highly efficient micro combined heat and power (CHP) system based on high-temperature proton exchange membrane fuel cell (HT-PEMFC) technology and a methanol steam reformer. The developed micro-CHP system is intended as a back-up solution for sequential or simultaneous cogeneration of electricity and thermal energy in rural areas with unstable or zero grid availability. A core focus on thermal integration and waste-heat recovery enables high fuel utilization, high electrical- and CHP efficiency, and dynamic load response and fast start-up for flexible integration with intermittent renewable energy sources.

Purpose of the document

This deliverable aims to demonstrate the scalability of the 5 kW mini-CHP system to a 50 kW configuration. A mathematical model taking into account the physical and chemical aspects of the methanol-fueled HT-PEMFC CHP system is developed. Additionally, cost estimations for the upscaled system are executed to study its market potential.

Scale-up study for 50 kW system

Fundamentals of system model

In principle, the modelled system for the upscaled HT-PEMFC CHP system aligned with the developed 5 kW CHP system. Nonetheless, certain enhancements were incorporated into the system. This included considering the pressurization of the air side, accounting for its impact on stack output power improvement, and harnessing pressure energy from exhaust air using an expander. The benefits of pressurization and the recovery of pressure energy through the expander were investigated in Deliverable 4.4, and the favourable outcomes prompted their integration into this model. In following figure, the modelled system is visualised.

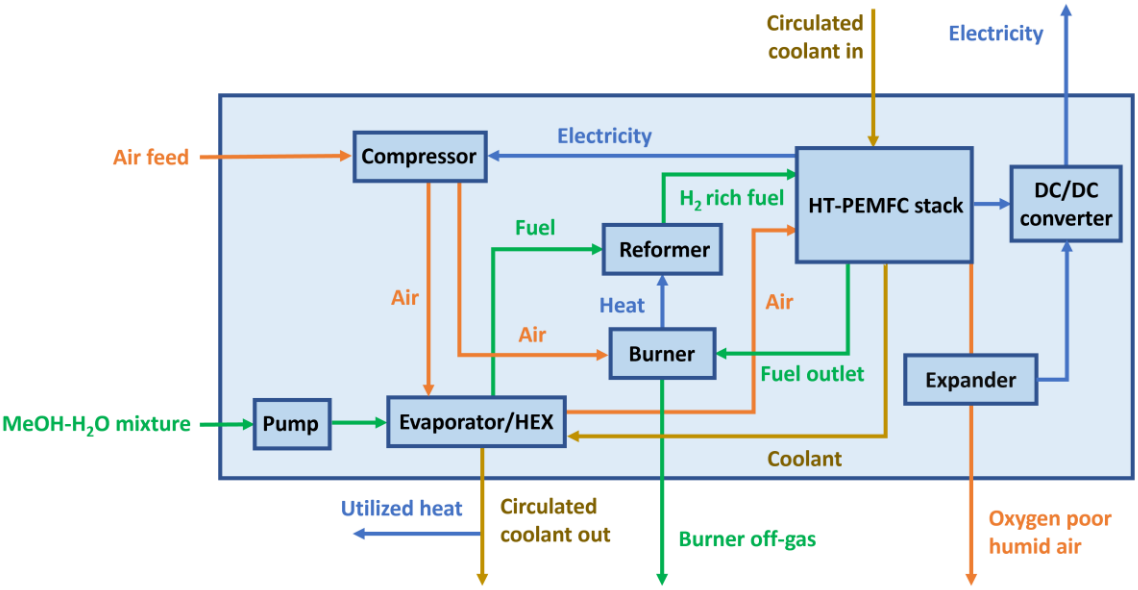

Figure 1. Visualisation for modelled system.

The model was constructed utilizing MATLAB and Simulink. Simulink played a crucial role in visualizing simulation scenarios intelligently during the development phase and when examining actual cases. The Simulink model contained straightforward mathematical operations and MATLAB Function blocks, where the physical and chemical phenomena of system components were represented. Consequently, the primary effort was directed towards implementing mathematical functions in the form of MATLAB functions. Furthermore, meticulous attention was dedicated to thoroughly examining the relationships between all the model blocks. The relationships between model blocks are illustrated in the figure on the following page.

In supplement to literature data and correlations, additional input data was incorporated into the analysis. For the assessment of fuel cell performance, authentic performance data supplied by Blue World Technologies was employed. Additionally, in the context of methanol-water pre-mixture evaporation, a model previously developed in the project using the Aspen Plus process simulator tool was leveraged.

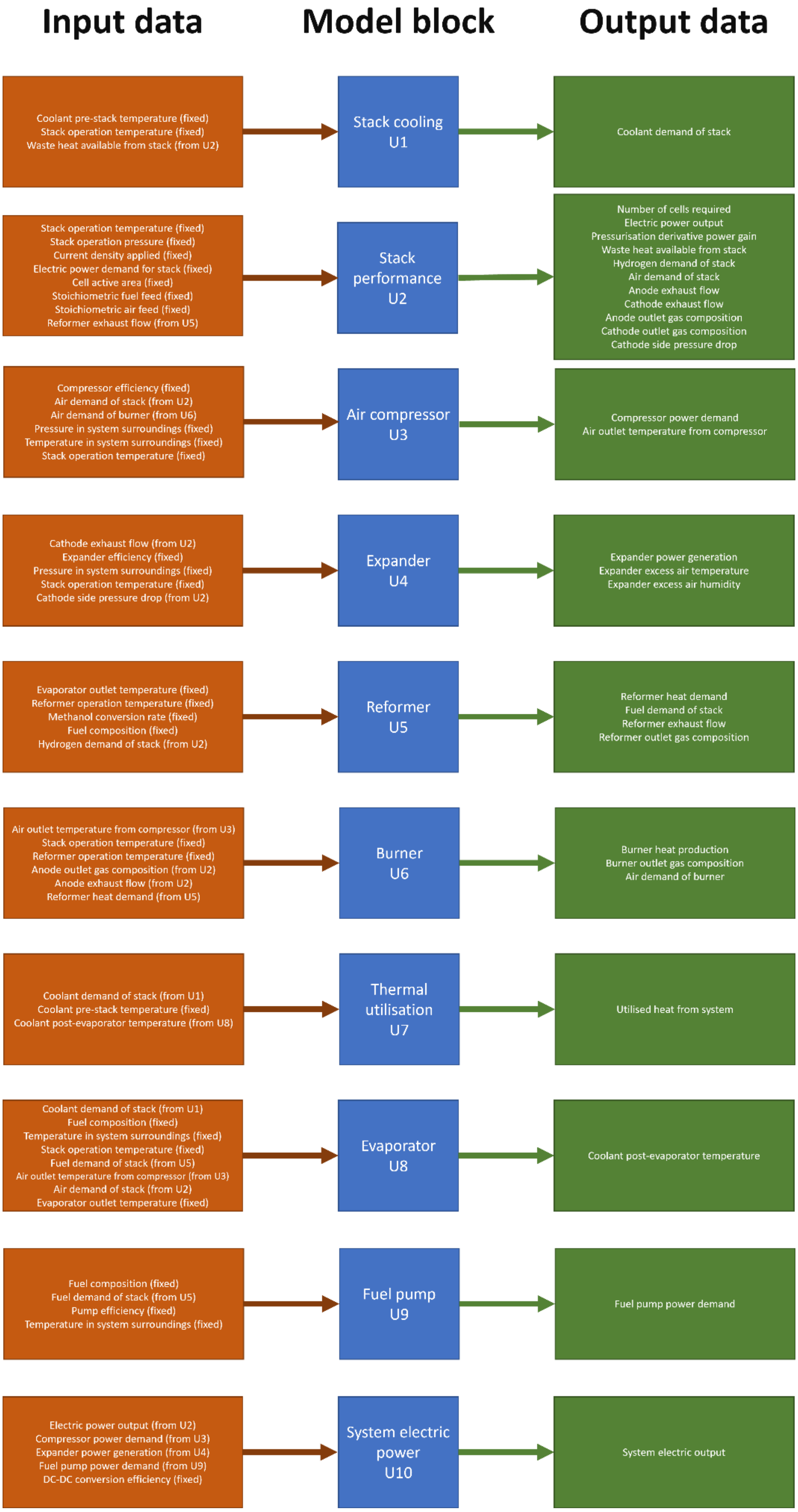

Figure 2. Simplified visualisation for developed up-scaling tool and relations between model blocks.

From a system simulation perspective, the model incorporated various fixed constraints. Nevertheless, certain parameters were allowed to vary between simulation cases. These included, for instance, the efficiencies of the compressor and expander, cathode side overpressure, power demand of the stack, and methanol conversion rate in the reformer. On the other hand, specific parameters were intentionally kept constant and were not subject to variation between cases. Examples of such fixed parameters include stoichiometric fuel and air feeds, cell active area, and fuel composition.

Individual component models

As outlined earlier in this document, the developed system model comprises a total of ten model blocks. Each block encompasses numerous mathematical operations and optimization tools. This subsection clarifies the underlying mathematics of each component, presenting key equations that describe power consumption or production for each unit.

Stack

To calculate the power generation of the pressurized stack, the following equation was used.

$$P_{\text{stack}} = N_{\text{cells}} \cdot j_{\text{stack}} \cdot A_{\text{cell}} \cdot \left(U_{cell} + \frac{R \cdot T_{\text{stack}}}{4 \cdot F \cdot \log\left(\frac{p_{\text{out comp}}}{p_{\text{atm}}}\right)} \right)$$

Air compressor

To calculate the power consumption of the compressor, the following equation was used.

$$P_{\text{comp}} = C_{\text{P}} \cdot \frac{T_{\text{in comp}}}{\eta_{\text{comp}}} \cdot \left(\left(\frac{p_{\text{out comp}}}{p_{\text{in comp}}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \cdot \dot{m}_{\text{air in sys}}$$

Expander

To calculate the power generation of the expander, the following equation was used.

$$P_{\text{turb}} = C_{\text{P}} \cdot \eta_{\text{turb}} \cdot T_{\text{out stack}} \cdot \left(\left(\frac{p_{\text{out turb}}}{p_{\text{in turb}}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \cdot \dot{m}_{\text{air out stack}}$$

Reformer

To calculate the heat demand of the reforming reaction, the following equation was used.

$$\dot{Q}_{\text{ref}} = \sum_i H_i(T) \cdot x_{i\text{ out ref}} \cdot \dot{n}_{\text{tot out ref}} - \sum_i H_i(T) \cdot x_{i\text{ in ref}} \cdot \dot{n}_{\text{tot in ref}}$$

Burner

To calculate the heat demand of the reforming reaction, the following equation was used.

$$\dot{Q}_{\text{bur}} = \sum_i H_i(T) \cdot x_{i\ \text{out bur}} \cdot \dot{n}_{\text{tot out bur}} - \sum_i H_i(T) \cdot x_{i\ \text{in bur}} \cdot \dot{n}_{\text{tot in bur}}$$

Evaporator

To calculate the heat demand of the evaporator, the following equation was used.

$$H_{\text{tot evap}} = \dot{n}_{\text{tot in evap}} \cdot \sum_i x_i \left[\left(T_{\text{out evap}} - T_{\text{vap}} \right) \cdot c_{p,i\ \text{gas}} + \Delta h_{i,\text{vap}}(T) + \left(T_{\text{vap}} - T_{\text{in evap}} \right) \cdot c_{p,i\ \text{liq}} \right]$$

Fuel pump

To calculate the power consumption of the fuel pump, the following equation was used.

$$P_{\text{pump}} = \frac{\dot{m}_{\text{fuel in ref}} \cdot g \cdot h}{\eta_{\text{pump}}}$$

Results

For the review of the model, a relevant scenario for the upscaled system was chosen. In this particular scenario, the fixed values for the most significant variables were as follows:

- Power demand for stacks: 50 kW
- Current density for stacks: 0.2 A/cm^2
- Stack operation temperature: 160 °C
- Fuel conversion in reformer: 90 %
- Stack pressurization: 0.5 bar(g)
- Compressor efficiency: 80 %
- Expander efficiency: 65 %

Some of these constraints exceed the values adopted in the developed systems. However, these presented constraints were carefully reviewed to ensure their realism in the context of the upscaled mini-CHP product.

After scenario the main outputs of the system were the following:

- Number of stacks (with increased cell number): 3
- Electrical efficiency of stack: 58.7 %
- Compressor capacity: 4.7 kg$_{\text{air}}$/min
- Total fuel consumption: 655 g/min

Results generated by the selected scenario, were utilized for cost-analysis for up-scaled systems presented in the following section of the document.

Cost analysis for up-scaled system

The initial manufacturing cost analysis for the developed 5 kW mini-CHP system was outlined in Deliverable 4.2 (Selection and Characterization of all BoP components).

A comprehensive breakdown of the capital expenditures (CAPEX) for the 5 kW system met the predefined target of 3,000 €/kW when the production scale reached 20,000 units per year. For the upscaled system, the target was set more ambitiously at 1,000 €/kW. Due to the confidential nature of Deliverable 4.2, the impact of each component in the 5 kW system scenario is not explicitly presented in this report. Therefore, costs are presented in component type groups.

Cost estimations for up-scaled system

Based on an analysis of component price developments, the impact of the demand for the upscaled system, and additional practical estimations, cost estimates were formulated for an upscaled 50 kW system with an annual production of 20,000 units. It's important to note that since such an upscaled product is not currently in production and hasn't even been built for demonstration purposes, these estimations involve numerous assumptions and uncertainties.

Component type groups (all component costs estimated individually:

- Fuel supply system: fuel tank, level indicators, fuel pumps, sensors, and valves
- Reformer system: air blower, and methanol reformer
- Fuel cell stack(s): only stacks
- Balance of Plant components: DC/DC converter, coolant pump, piping, connectors, compressor, valves, sensors, control unit, and expander (expander only in case of 50-kW system)
- Electrical system: battery, DC/AC convertor, high-level control module, sensors, wiring, and connections
- Heat management: radiator, piping, and insulation
- System assembly: rack, and labour

According to the cost estimation, the overall pre-markup cost of the total system amounted to 51,889 €, resulting in a cost per kW of 1,038 €. This outcome is favourable, as the price is very close to the target of 1,000 €/kW for upscaled systems.

Graphs depicting cost distributions for both 5 kW and 50 kW systems, with an annual production of 20,000 units, are provided below. A significant difference lies in the magnitude of the fuel cell stack itself, constituting 22% of the cost in the case of the 5 kW system and 39% in the 50 kW system. Upon closer examination, this aligns with expectations, considering that the fuel cell is the single most expensive component, whereas other components are mostly commercial products with widespread availability. It is noteworthy that even with the inclusion of the expander exclusively in the upscaled system, the share of Balance of Plant (BoP) components does not increase. This highlights the attractiveness of incorporating them into upscaled systems.

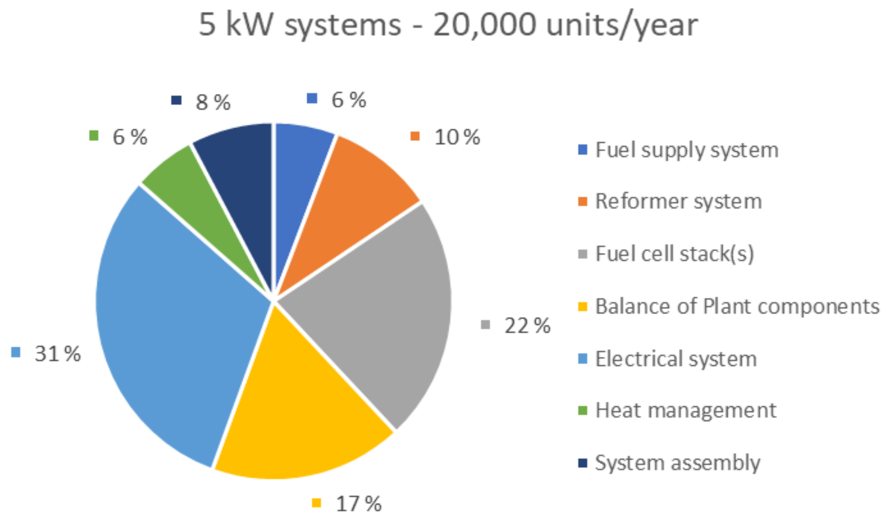

Figure 3. Cost estimations for 5 kW system, when APR was excluded.

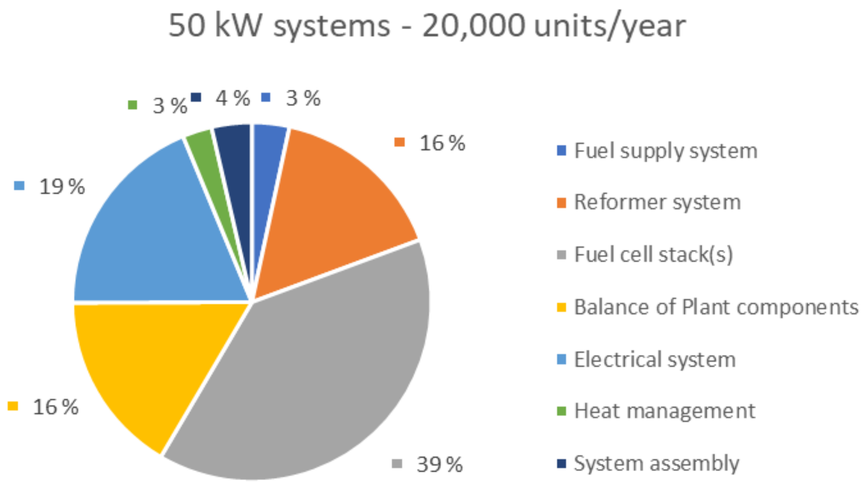

Figure 4. Cost estimations for 50 kW system.

Conclusions

In this deliverable, efforts were concentrated on developing a system model and conducting cost estimations for an upscaled mini-CHP system. Both tasks significantly contribute to affirming the scalability of the initially developed system. According to the cost estimation, the overall pre-markup cost of the total system amounted to 51,889 €, resulting in a cost per kW of 1,038 €, which was close to the target of 1,000 €/kW. It's crucial to note that, given the absence of current production and demonstration of such an upscaled product, these estimations carry inherent assumptions and uncertainties. To enhance the accuracy of these estimations, further demonstration work, product development, and market analyses are deemed essential.