Solid Oxide Fuel Cells Systems Development

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Summary and conclusion

The main objective in this project has been to develop a generic and dynamic tool for SOFC systems simulation and development. Developing integrated fuel cell systems is very expensive and therefore having the right tools to reduce the development cost and time to market for products becomes an important feature. The tools developed in this project cover a wide range of needs in Dantherm Power, R&D, and can be divided into 3 categories:

1. Component selection modeling; to define component specification requirements and selection of suppliers
2. Application simulation model built from scratch, which can simulate the interface between customer demand and system output and show operation behavior for different control settings
3. System operation strategy optimization with respect to operation cost and customer benefits
    a. Allows to see how system size, in terms of electricity and heat output, and operation strategy influences a specific business case
    b. Gives a clear overview of how a different property, in the system, affects the economics (e.g. lifetime, electrical and thermal efficiency, fuel cost sensitivity, country of deployment etc.)

The main idea behind the structure of the tool being separated into 3 layers is to be able to service different requirements, from changing stakeholders.

One of the major findings in this project has been related to thermal integration between the existing installation in a private household and the fuel cell system. For a normal family requiring 4500 kWh of electricity a year, along with the possibility of only running the system during the heating season (winter), the heat storage demand is only 210kWh of heat with an approximate value of Dkr 160,- in extra gas consumption. In this case, it would be much more cost effective to dump the heat, in the house, and save the expense of adding heat storage to the system. This operation strategy is only valid in Denmark for the time being, since the feed-In-Tariff allows for a yearly-zero-net billing of electricity, meaning that the consumer could produce heat during winter when heat is always needed and turn off the system during summer to improve operation efficiency.

The development tools have already been tested and used for fuel cell system integration at Dantherm Power, R&D and have proved its worth in savings on components in the order of several thousand Danish kroner.

An area where a future project could contribute to the tools capabilities is to build an intelligent optimization algorithm into the tool and get the software to find the optimal solution automatically.

List of publications

During this project the publications listed below were produced.

PhD Thesis

Designing and control of a SOFC micro-CHP system (2012) *Vincenzo Liso.* Dept of Energy Technology. Aalborg University

Conference Paper

Reforming processes for micro combined heat and power system based on solid oxide fuel cell
Liso, Vincenzo; Nielsen, Mads Pagh; Kær, Søren Knudsen.
In Proceedings of ”SIMS 50 Scandinavian Simulation Society” Conference; (2009)

Journal papers

Performance comparison between Partial Oxidation and Methane Steam for SOFC micro-CHP systems
Liso, Vincenzo; Olesen, Anders Christian; Nielsen, Mads Pagh; Kær, Søren Knudsen.
In Energy Volume 36, Issue 7, July 2011, Pages 4216-4226.

Operation strategy for solid oxide fuel cell systems for small-scale stationary applications
Liso, Vincenzo; Nielsen, Mads Pagh; Kær, Søren Knudsen.
In International Journal of Green Energy, 6(6), 583-593 December 2009.

Analysis of the impact of Heat-to-Power Ratio for a SOFC-based mCHP system for residential application under different climate regions in Europe
Liso, Vincenzo*; Zhao, Yingru; Brandon, Nigel; Nielsen, Mads Pagh; Kær, Søren Knudsen.*
In International Journal of Hydrogen Energy Volume 36, Issue 21, October 2011, Pages 13715-13726.

Ejector design for recirculation of anode gas in a micro Combined Heat and Power system based on Solid Oxide Fuel Cell
Liso, Vincenzo; Nielsen, Mads Pagh; Kær, Søren Knudsen.
Accepted in Applied Thermal Energy.

Influence of anodic gas recirculation on Solid Oxide Fuel Cells in a micro Combined Heat and Power system
Liso, Vincenzo; Nielsen, Mads Pagh; Kær, Søren Knudsen.
Accepted in International Journal of Energy Research.

Project description

The project is a joint venture between Dantherm Power and Aalborg University.

The main goal of SOFC systems development is to make a generic software tool for assisting Dantherm Power R&D in optimizing systems and speedup the time to market.

The starting point is to develop a general tool; that combine technical experience from system integrators with customer and market requirements. The output of the software is the optimal system configuration with respect to: Customer requirement, economics both capital cost and operation cost and market potential.

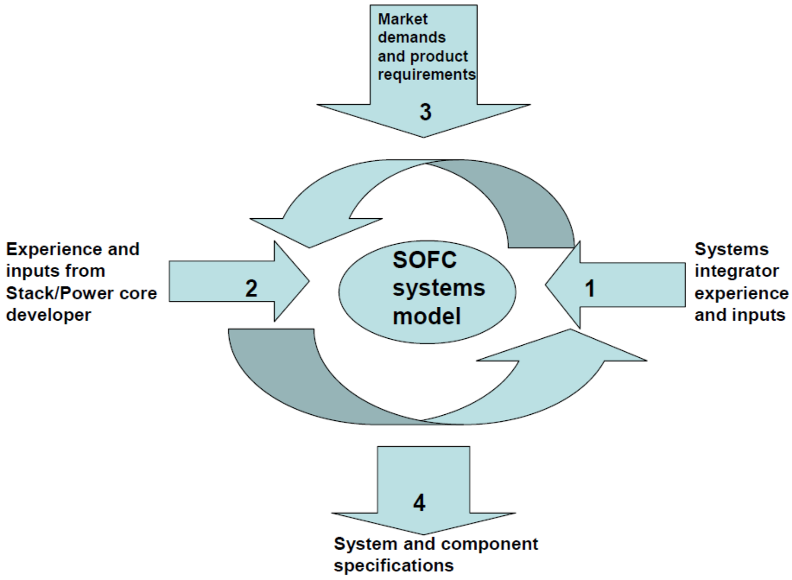


Figure 1: Schematic overview of project Input/Output

The project is divided into smaller work packages to be able to share the workload between Dantherm Power and Aalborg University.

Work package 1: A detailed simulation tool for modeling system at component level and thereby see consequences of selecting different pumps, blowers or heat exchangers with respect to performance and ultimately system cost.

Work package 2: An application simulation tool for modeling the interaction between customer demand and Dantherm SOFC micro combined heat and power system with respect to energy coverage for the customer and operation economics. Goal is to size system to match customer demand while minimizing system cost. The simulation tool will show whether the system fulfills customer demand to a satisfying degree. It will also be possible to set up different load scenarios for the system and optimize system control for best operation economics versus performance.

Work package 3: This work package deals with the need for user requirement data, i.e. gathering user requirements with regard to energy supply and availability.

Work package 4: New concepts/intelligent controls.

Work package 5: Economic & Environmental consequences. This work package determines the economic and environmental effect of the setup simulated with the data from the previous work packages.

Work package 6: Implementation of software at Dantherm Power R&D.

Schematic overview of development tool

This schematic overview of how the different layers of modeling /simulation interact. The economic model and supply/demand model has been implemented into the same software and can be used as one united tool. System component model is however separated because of licensing issues and choice of software tool.

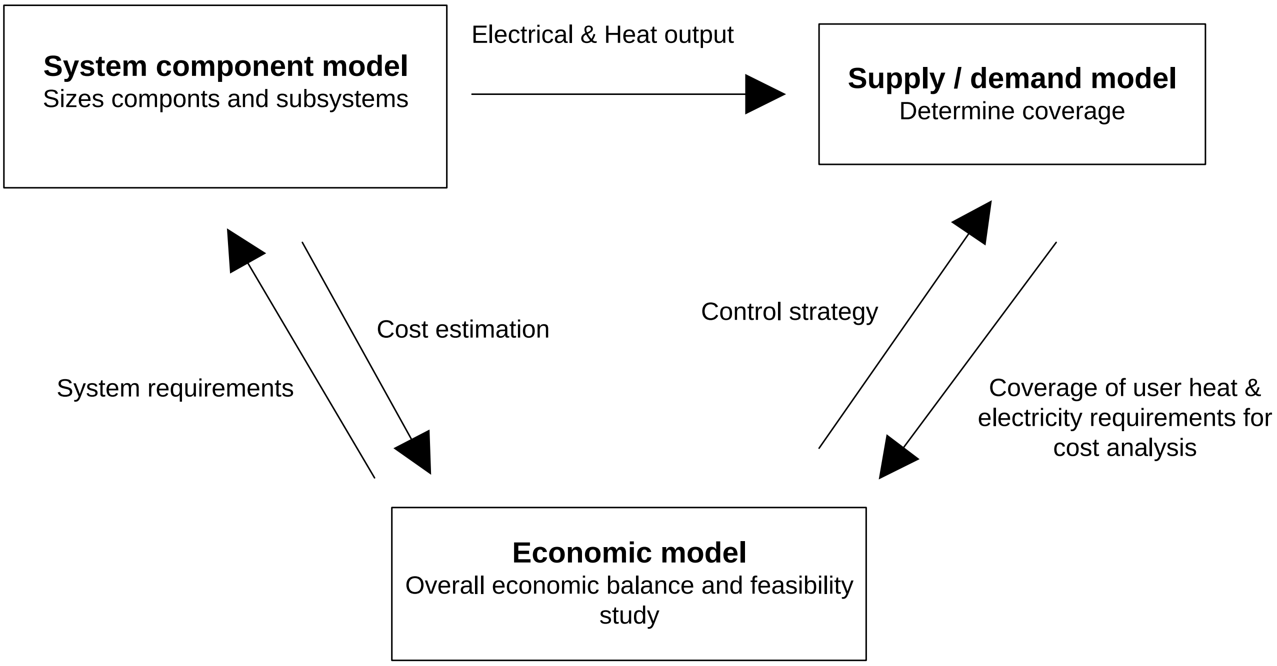


Figure 2: Schematic overview of how the different layers of modeling / simulation interact

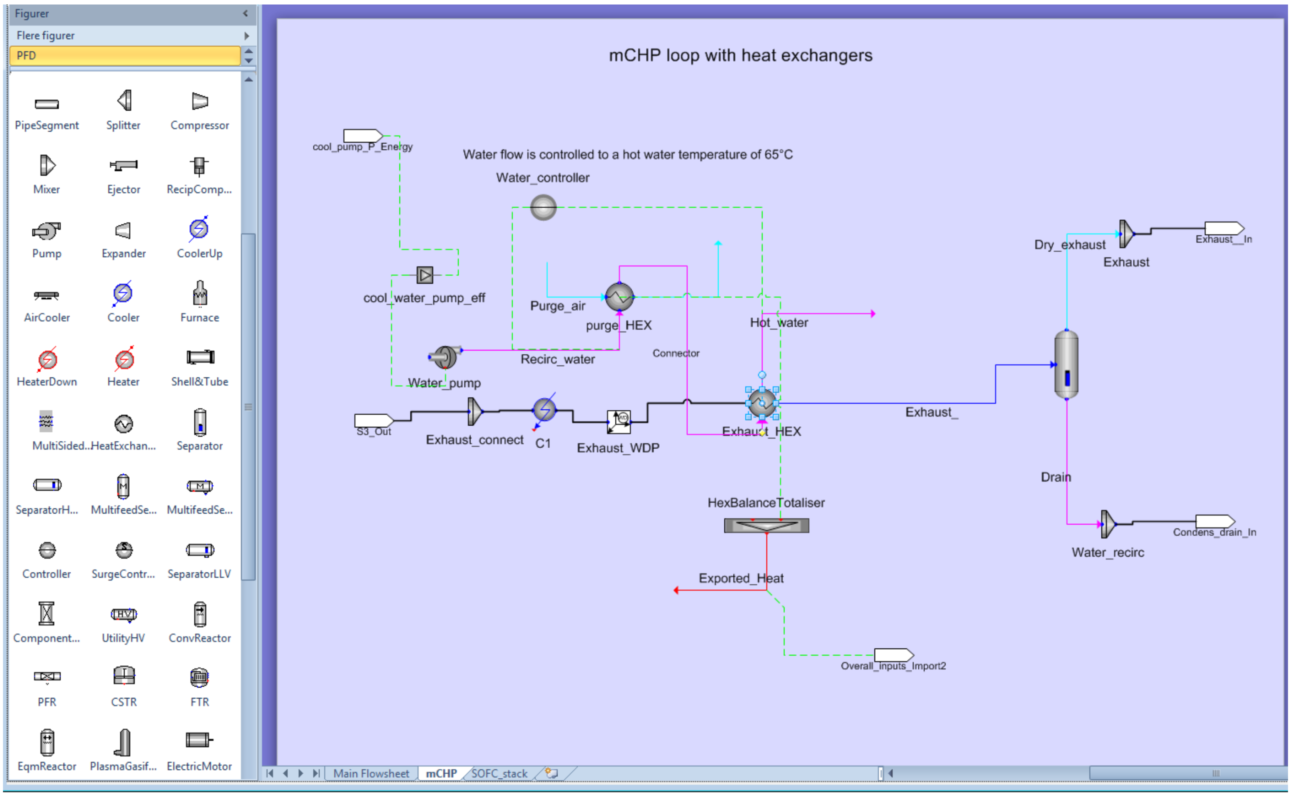
WP1: Fuel cells system component model

First generation mCHP concept

The objective for this work package is to have a starting point in the initial phase of specifying and building a prototype, fuel cell mCHP system, for testing and validation. The developed model for this work package is written with the software package VirtualMaterials which is basically a thermodynamic library and mathematically solver.

The result is a dynamic tool, where Microsoft Visio is the component selector with a wide range of built-in components that are fast to change and resize.

All vital components for the system have been fully implemented in the software model and as shown below. the final model is quite complex. Heat integration and Stack model is separate models to simplify the main flow sheet in an attempt to have an easy overview, see Figure 3 and Figure 4.



mCHP loop with heat exchangers

Water flow is controlled to a hot water temperature of 65°C

Figure 3: Software interface (VMGsim), on the left the component selector is shows. To add a component the user clicks and drags the component into the PFD.

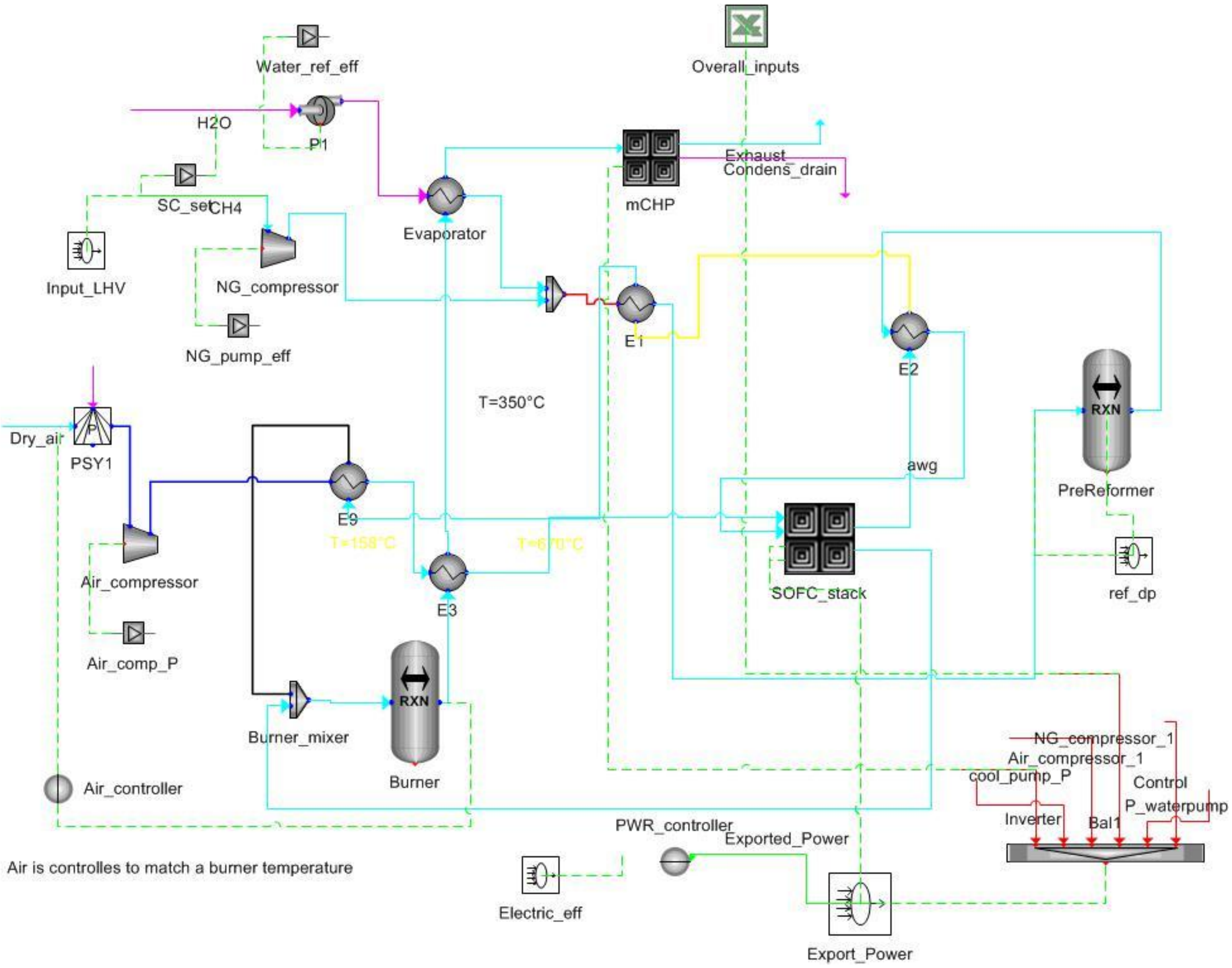
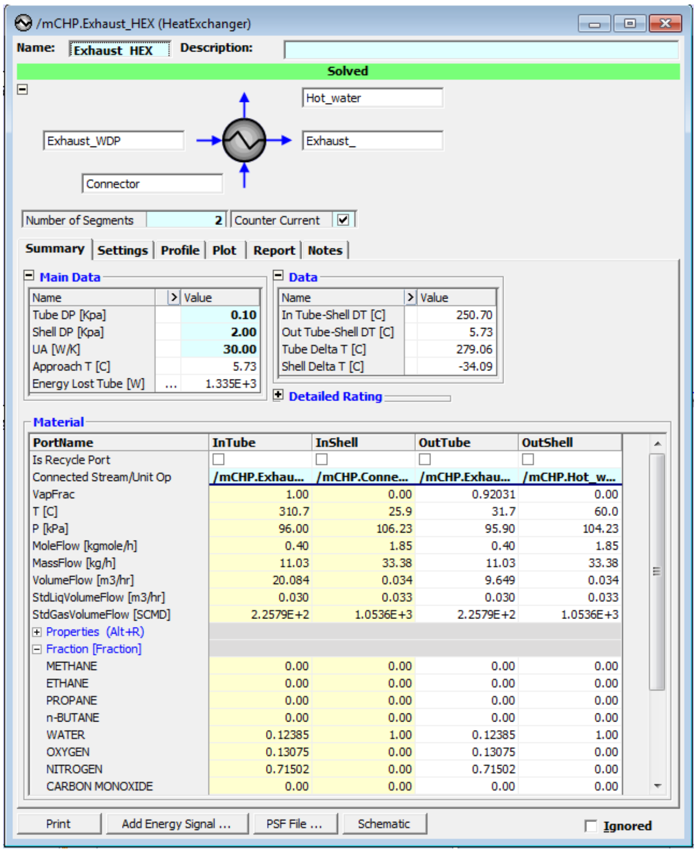


Figure 4: Main flow sheet in the developed model (VMGsim), focus is here on Balance of plant components as compressors and pumps are parasitic losses in the system.

In Figure 5, a screen shot from the software that shows the requirements for the exhaust heat exchanger in the heat integration sub assembly is presented.

Pressure losses on both sides as well as thermal heat transfer properties are available and can be used when purchasing the component from a supplier. The tool itself will take condensation (phase change) into consideration. On each component it is possible to add user defined comments or get the tool to write out a report to be used for system documentation and specification.



Name: Exhaust HEX **Description:**

Solved

Number of Segments 2

Counter Current ☑

Main Data

Name	Value
Tube DP [Kpa]	**0.10**
Shell DP [Kpa]	**2.00**
UA [W/K]	**30.00**
Approach T [C]	5.73
Energy Lost Tube [W]	1.335E+3

Data

Name	Value
In Tube-Shell DT [C]	250.70
Out Tube-Shell DT [C]	5.73
Tube Delta T [C]	279.06
Shell Delta T [C]	-34.09

Material

PortName	InTube	InShell	OutTube	OutShell
Is Recycle Port	☐	☐	☐	☐
Connected Stream/Unit Op	/mCHP.Exhau...	/mCHP.Conne...	/mCHP.Exhau...	/mCHP.Hot_w...
VapFrac	1.00	0.00	0.92031	0.00
T [C]	310.7	25.9	31.7	60.0
P [kPa]	96.00	106.23	95.90	104.23
MoleFlow [kgmole/h]	0.40	1.85	0.40	1.85
MassFlow [kg/h]	11.03	33.38	11.03	33.38
VolumeFlow [m3/hr]	20.084	0.034	9.649	0.034
StdLiqVolumeFlow [m3/hr]	0.030	0.033	0.030	0.033
StdGasVolumeFlow [SCMD]	2.2579E+2	1.0536E+3	2.2579E+2	1.0536E+3
Properties (Alt+R)				
Fraction [Fraction]				
METHANE	0.00	0.00	0.00	0.00
ETHANE	0.00	0.00	0.00	0.00
PROPANE	0.00	0.00	0.00	0.00
n-BUTANE	0.00	0.00	0.00	0.00
WATER	0.12385	1.00	0.12385	1.00
OXYGEN	0.13075	0.00	0.13075	0.00
NITROGEN	0.71502	0.00	0.71502	0.00
CARBON MONOXIDE	0.00	0.00	0.00	0.00

☐ Ignored

Figure 5: Example of component properties in the simulation model, the picture shows the data sheet for a heat exchanger, all temperatures, thermal properties and size is given.

The heat exchangers used in the system are hard to find as standard components and often has to be custom designed for each application.

The high heat flux in many parts of the system can be used to make them small and effective. A particularly challenging heat exchange task is the generation of steam for the reformer operation. Steam generation involves phase change and can cause pressure fluctuations, which can result in flow and reactor instabilities.

This is especially critical for smaller systems. Various solutions that offset these fluctuations can be implemented. These can range from mechanical dampening systems to control adjustments via flow offsets.

In Figure 6, the heat exchanger network for the heat recovery and the water condesation is shown.

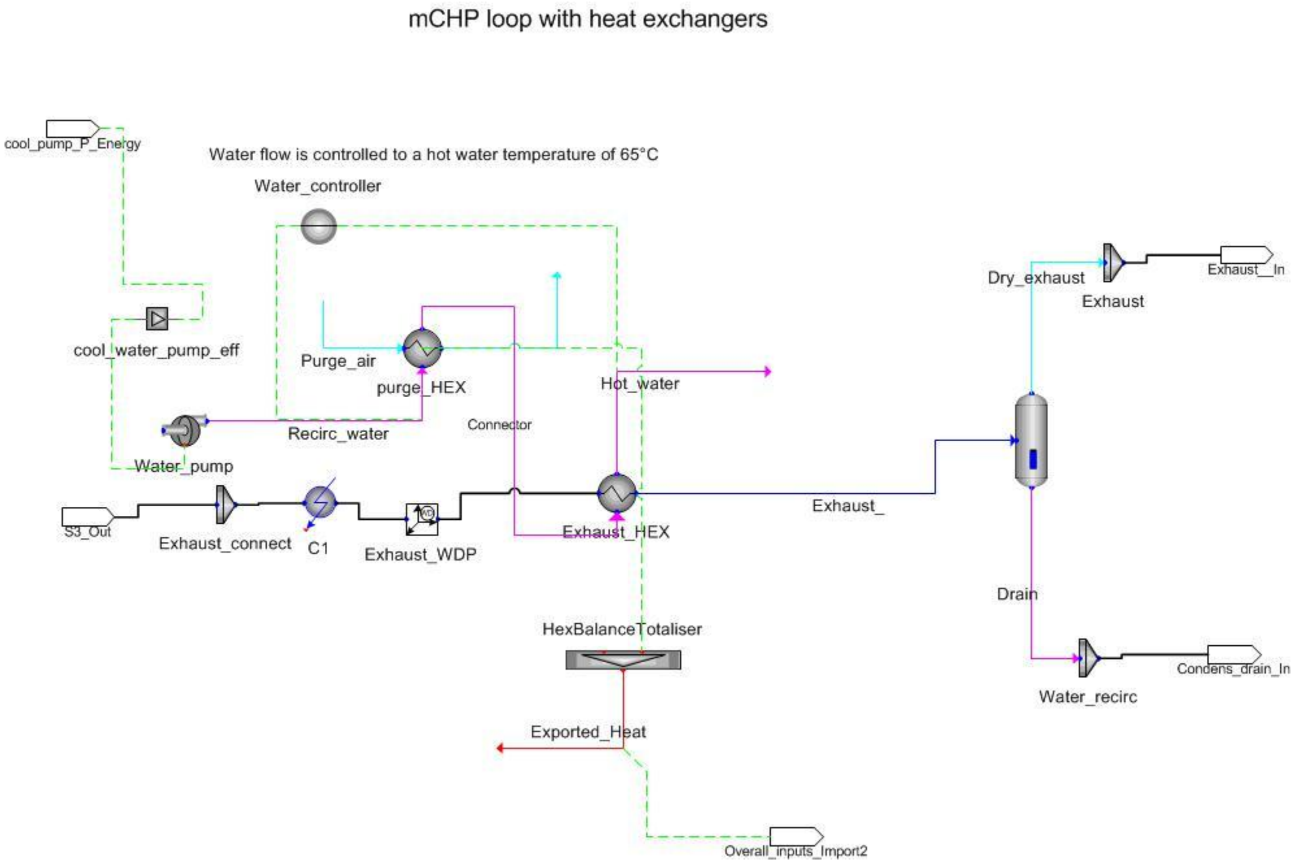


Figure 6: Heat Exchanger network for heat recovery

The fuel cell model was developed using the reactors scheme as shown in Figure 7: Fuel cell stack model. Unlike a combustion process that converts chemicals to reaction products (e.g., H_2O and CO_2) and heat, the fuel cell produces electric power, heat and reaction products. A single cell consists of a membrane-electrode assembly (MEA) and a current-collection system. The operating potential for a cell is approximately in the range 0.6 – 0.8 volts.

The fuel cell functions as an electrical power supply that can drive an external load. The electrons produced at the most electrically negative anode, flow through the load and back to the fuel-cell at the most electrically positive cathode. Thus, the electrochemical oxidation of the fuel delivers electrical power to the external load.

The SOFC model assumes that charge transfer proceeds only through hydrogen oxidation and oxygen reduction (reactions (iii) and (vi) in **Fejl! Henvisningskilde ikke fundet.Fejl! Henvisningskilde ikke fundet.**). The hydrogen is produced as a result of the reforming process (reactions (i) and (ii) in **Fejl! Henvisningskilde ikke fundet.**). Although CO is available, CO charge-transfer is assumed to be slow compared to H_2 charge-transfer. Therefore, it is assumed that CO take parts only in the water-gas shift process which is represented in reaction (ii) in **Fejl! Henvisningskilde ikke fundet.**.

In **Fejl! Henvisningskilde ikke fundet.**, the fundamental reactions considered in the fuel cell mass and energy balances are shown.

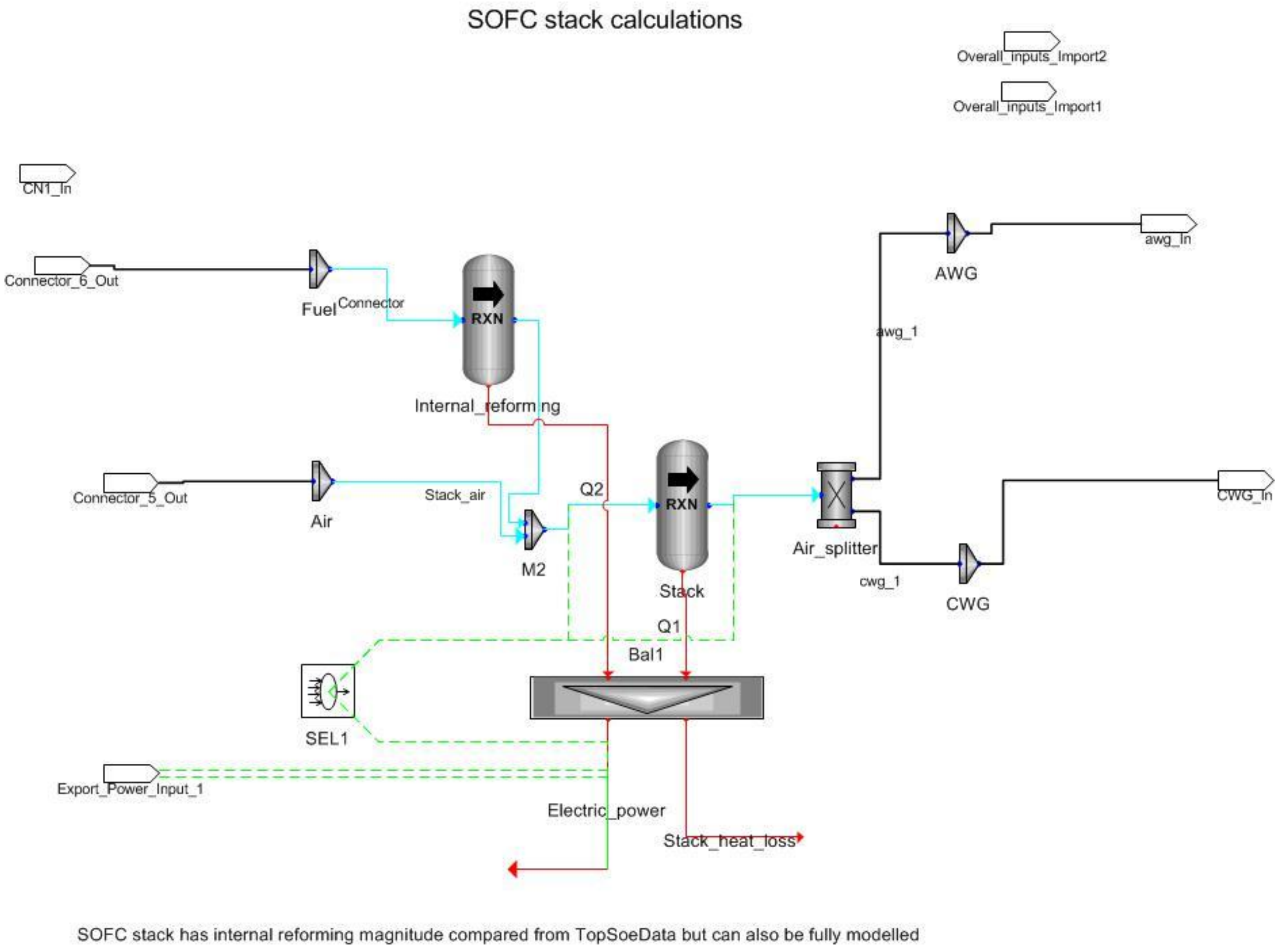


Figure 7: Fuel cell stack model

Name	Reaction	
Steam reforming reaction	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	(i)
Water gas shift reaction	$CO + H_2O \rightleftharpoons CO_2 + H_2$	(ii)
Hydrogen oxidation reaction	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	(iii)
Oxygen reduction reaction	$1/2\ O_2 + 2e^- \rightarrow O^{2-}$	(iv)

Table 1: Reactions occurring in the fuel cell

The fuel cell micro CHP system has been upgraded, to a second generation, which adopts the recirculation of anode gas by means of a pump.

Below, in Figure 8 and Figure 9, a comparison between configurations with the use of anode off-gas recycling by means of a pump and an ejector are given.

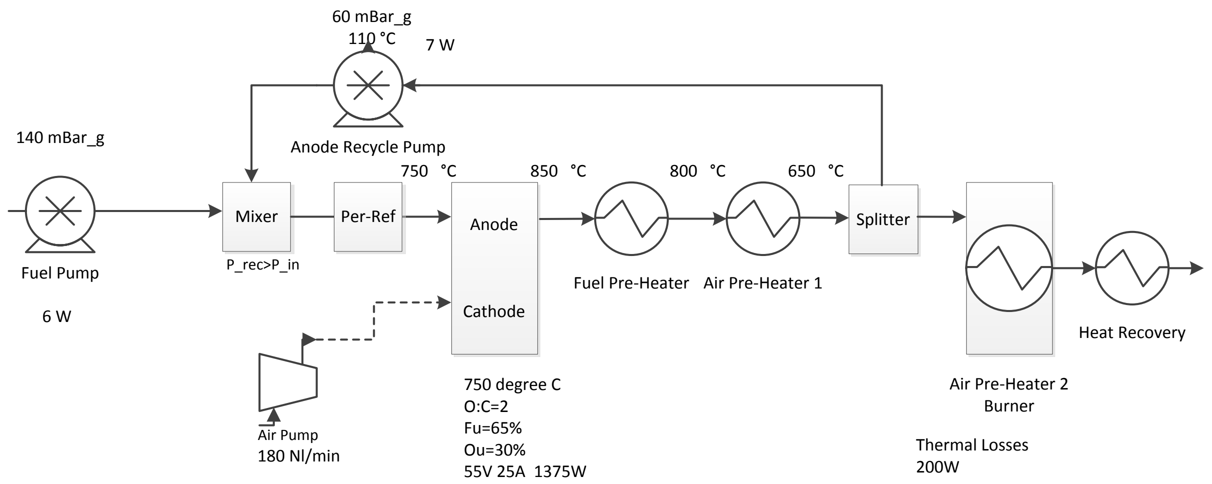


Figure 8: Fuel cell system with recirculation of anode gas by means of a pump

Using anode gas recirculation, the stack fuel utilization can be reduced from 80% to 60%, and still keeping a constant fuel utilization of 80% on system level.

The use of anode gas recycle increases the anode inlet gas flow, thereby lowering the cell fuel utilization at a given current. In this way cell area can potentially be lowered.

Furthermore, the anode gas recirculation implies a lower steam concentration in the mixed gases from the cathode and anode, to the burner (Air pre-Heater 2), because a part of the anode off gas has been reused in the fuel cell.

Due to a lower steam content, the combustion temperature in the burner increases and the sensible thermal energy of the exhaust gas increases. Decreasing the anode recirculation fraction decreases the steam-to-carbon ratio - going below a recirculation fraction of approximately 0.55 results in a high risk for carbon formation which will destroy the reformer and stack rapidly.

In the simulation the lowest limit for the steam-to-carbon ratio is 1.8 as recommended by the SOFC hardware supplier.

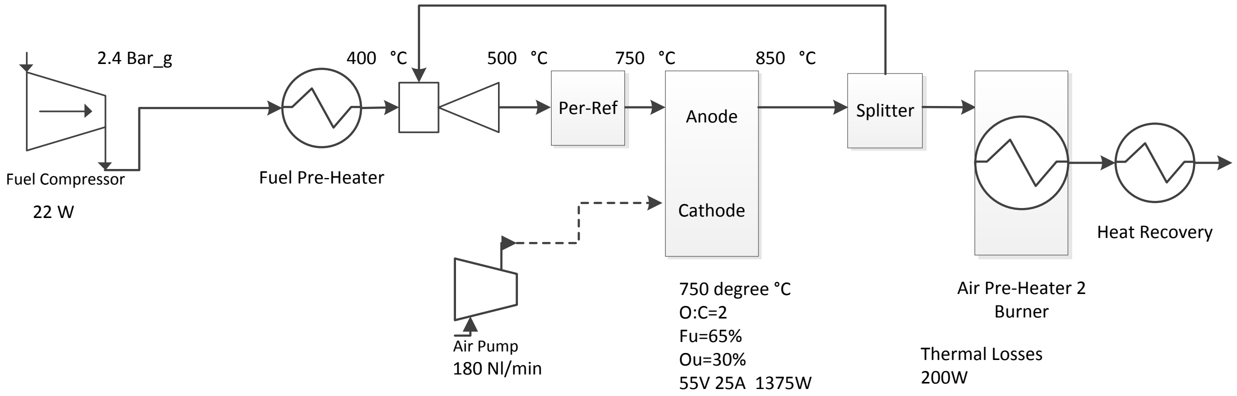


Figure 9: Fuel cell system with recycle of anode gas by means of an ejector

The air pre-heater heat exchange duty, air blower size, useful heat recovery, net system efficiency, and combustor temperature are dependent on the amount of system airflow. Lower airflow rates result in higher combustor temperature.

Thus, reductions in airflow must be balanced against combustor and metallic heat exchanger temperature limits.

Lowering the degree of pre-reforming significantly increases the cooling effect produced by the internal stack-reforming and, hence the electrical efficiency. The amount of internal reforming should however be controlled precisely, due to the risk of carbon depositions on the anode during long-time operation.

It was further determined that reducing the fuel utilization benefits the system performance in the cases without recirculation. In the cases with recirculation it actually had a negative influence. Though lowering the stack voltage, cathode recycling improves both electrical and thermal efficiency by minimizing the need for air blown into the system.

The main advantages of anode off-gas recirculation are (i) the elimination of external steam production, (ii) the potential reduction of cell count in the stack due to lower in-cell fuel utilization, and (iii) a lower steam concentration in the exhaust gas which improves the system thermal efficiency. The electrical efficiency will also increase due to a better heat management. An additional advantage is the reduction of fuel preheating heat transfer by direct contact of fresh fuel and exhaust gas. It is also important to note that the anode off-gas recycle accomplishes the purpose of conserving the de-mineralized and de-ionized water within the system. Many system studies were carried out; all of them confirm the advantages at system level of the anode gas recycle in SOFC systems.

The recycle of anode gas can be controlled indirectly in the way described as follow. Steam is produced at the anode side by the electrochemical reaction:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

Steam can be produced also by Reverse water-gas shift (CO_2+H_2=CO+H_2O) and combustion process. These reactions can be disregarded. The steam content at the anode outlet can be determined indirectly by the following equation

$$\text{Water production}=\frac{P_e}{2V_C F}\text{moles s}^{-1}$$

In fact, electric power and voltage can be measured on the fuel cell. Finally the Oxygen-to-Carbon ratio at the reformer inlet can be determined by the following equation.

$$\text{O/C}=\frac{\text{Recycle Ratio}\cdot\text{Water production}}{\text{Fuel Inlet+(1-}U_f\text{)}\cdot\text{Recycle Ratio}\cdot\text{Fuel Inlet}}$$

The Recycle ratio, the fuel inlet and the fuel utilization (U_f) can be directly measured. In this way the amount of steam at the steam-reformer inlet can be controlled in order to avoid carbon formation.

WP2: Fuel cell application simulation model

The main goal of this work package is to make a model, which models the PFD (Process Flow Diagram) taking the following into account:

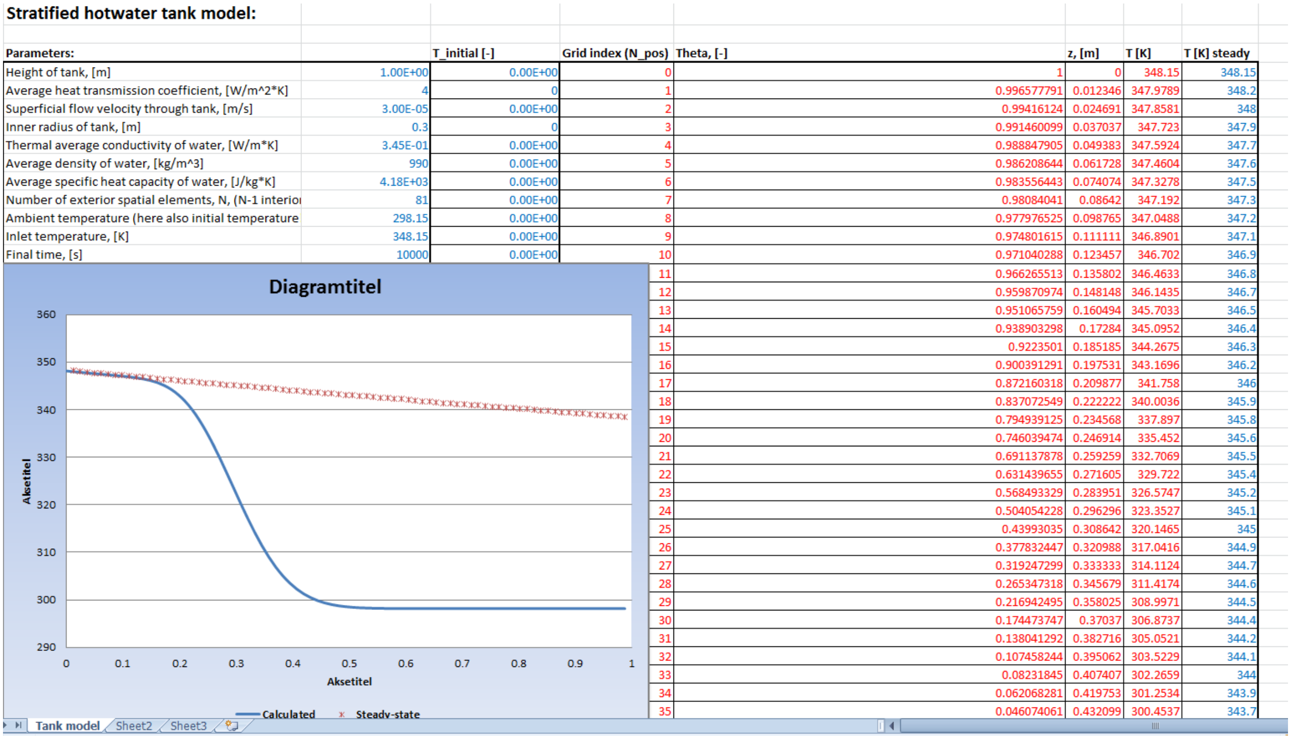
- FC electricity and user demand of electricity;
- FC heat, auxiliary heat (boiler or heat pump) and user heat demand, both hot water and domestic heat;
- "On time" of auxiliary heater and the coverage of both heat and electricity.

From the outcome of this model, it is possible to evaluate:

- The size of the SOFC system corresponding to the user demand of electricity and heat;
- Heat storage and SOFC size is two important parameters that we can change / influence, but we need an accurate tool for evaluating this;
- The most economical feasible control strategy in terms of operational cost, investment cost (heat storage);

The fuel cell application model is closely coupled to the economic model. This work package is divided into separate engineering tool to be able to simulate operation on several levels.

- Stratified hot water tank model by Aalborg University, both diffusion and convection is accounted for. This model is used to benchmark the simpler and faster models implemented by Dantherm Power
- Thermodynamic model for simulating heat storage capacity, model has a timeframe of 24 hours and a time resolution of 6 minutes. The model shows interaction between the boiler, mCHP system and house heat and hot water demand.
- Capacity simulation model, based upon customer heat demand and inputs from the thermodynamic model. Time resolution either in hours or in days. This model is a bit more top level and is to be used for business case evaluation.



Stratified hotwater tank model:

Parameters:		T_initial [-]	Grid index (N_pos)	Theta, [-]	z, [m]	T [K]	T [K] steady
Height of tank, [m]	1.00E+00	0.00E+00	0	1	0	348.15	348.15
Average heat transmission coefficient, [W/m^2*K]	4	0	1	0.996577791	0.012346	347.9789	348.2
Superficial flow velocity through tank, [m/s]	3.00E-05	0.00E+00	2	0.99416124	0.024691	347.8581	348
Inner radius of tank, [m]	0.3	0	3	0.991460099	0.037037	347.723	347.9
Thermal average conductivity of water, [W/m*K]	3.45E-01	0.00E+00	4	0.988847905	0.049383	347.5924	347.7
Average density of water, [kg/m^3]	990	0.00E+00	5	0.986208644	0.061728	347.4604	347.6
Average specific heat capacity of water, [J/kg*K]	4.18E+03	0.00E+00	6	0.983556443	0.074074	347.3278	347.5
Number of exterior spatial elements, N, (N-1 interio	81	0.00E+00	7	0.98084041	0.08642	347.192	347.3
Ambient temperature (here also initial temperature	298.15	0.00E+00	8	0.977976525	0.098765	347.0488	347.2
Inlet temperature, [K]	348.15	0.00E+00	9	0.974801615	0.111111	346.8901	347.1
Final time, [s]	10000	0.00E+00	10	0.971040288	0.123457	346.702	346.9
			11	0.966265513	0.135802	346.4633	346.8
			12	0.959870974	0.148148	346.1435	346.7
			13	0.951065759	0.160494	345.7033	346.5
			14	0.938903298	0.17284	345.0952	346.4
			15	0.9223501	0.185185	344.2675	346.3
			16	0.900391291	0.197531	343.1696	346.2
			17	0.872160318	0.209877	341.758	346
			18	0.837072549	0.222222	340.0036	345.9
			19	0.794939125	0.234568	337.897	345.8
			20	0.746039474	0.246914	335.452	345.6
			21	0.691137878	0.259259	332.7069	345.5
			22	0.631439655	0.271605	329.722	345.4
			23	0.568493329	0.283951	326.5747	345.2
			24	0.504054228	0.296296	323.3527	345.1
			25	0.43993035	0.308642	320.1465	345
			26	0.377832447	0.320988	317.0416	344.9
			27	0.319247299	0.333333	314.1124	344.7
			28	0.265347318	0.345679	311.4174	344.6
			29	0.216942495	0.358025	308.9971	344.5
			30	0.174473747	0.37037	306.8737	344.4
			31	0.138041292	0.382716	305.0521	344.2
			32	0.107458244	0.395062	303.5229	344.1
			33	0.08231845	0.407407	302.2659	344
			34	0.062068281	0.419753	301.2534	343.9
			35	0.046074061	0.432099	300.4537	343.7

Figure 10: Stratified hot water tank model, developed by Aalborg University. It solves diffusion, convection and heat loss from the heat storage. The model itself is programmed in Matlab and then ported to C# and imported into Excel through DDL in windows.

The model calculates also the amount of hot water and space heating on the basis of the numbers of liters of water used. This is calculated on the daily based.

T_hot	39	C
T_ref	15	C
CP	4,188	kJ/kg-K
Total 4t	200	L

Hot Water kWh		Q_househeat kWh
0,000	0	2,4174
0,000	0	2,5245
0,000	0	2,7234
0,000	0	2,6622
0,000	0	2,3868
0,140	0,025	2,1267
0,279	0,05	1,8207
0,419	0,075	1,5147
0,558	0,1	1,0251
0,419	0,075	0,6426
0,279	0,05	0,4131
0,279	0,05	0,3519
0,223	0,04	0,2754
0,279	0,05	0,2448
0,168	0,03	0,2142
0,112	0,02	0,2142
0,168	0,03	0,2448
0,279	0,05	0,3213
0,419	0,075	0,4437
0,558	0,1	0,7497
0,447	0,08	1,1322
0,279	0,05	1,4688
0,140	0,025	1,7289
0,140	0,025	1,8819
5,584	kWh	29,53

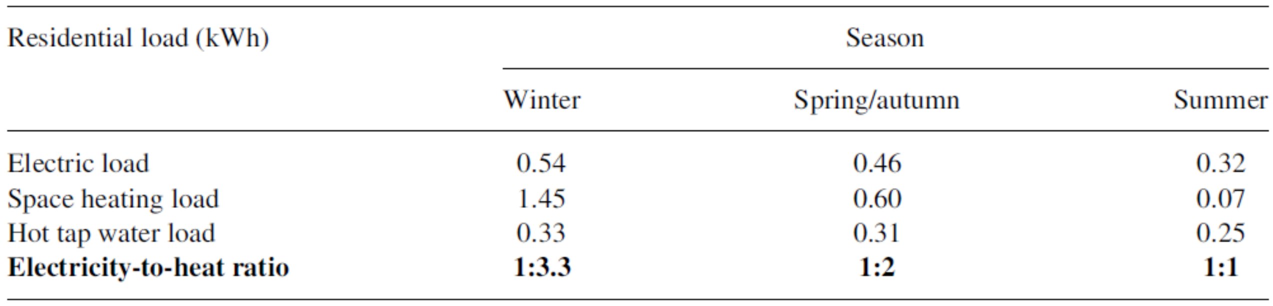
T_hot	39	C
T_ref	15	C
CP	4,188	kJ/kg-K
Total 24t	300	L

Hot Water kWh		Q_househeat kWh
0,000	0	2,4174
0,000	0	2,5245
0,000	0	2,7234
0,000	0	2,6622
0,000	0	2,3868
0,209	0,025	2,1267
0,419	0,05	1,8207
0,628	0,075	1,5147
0,838	0,1	1,0251
0,628	0,075	0,6426
0,419	0,05	0,4131
0,419	0,05	0,3519
0,335	0,04	0,2754
0,419	0,05	0,2448
0,251	0,03	0,2142
0,168	0,02	0,2142
0,251	0,03	0,2448
0,419	0,05	0,3213
0,628	0,075	0,4437
0,838	0,1	0,7497
0,670	0,08	1,1322
0,419	0,05	1,4688
0,209	0,025	1,7289
0,209	0,025	1,8819
8,376	kWh	29,53

Table 2: Household hot water and heat demand as a function of total hot water supply (200l, 300l)

Using data from Danish single-family detached houses, in Table 3, average values of the residential load for each period of the year is shown. In this case the electricity-to-heat ratio is between 1:1 and 1:33.

The annual average consumption of the house is around 5000 kWh of electricity, 12000 kWh of space heating, and 5000 kWh for hot tap water.



Residential load (kWh)	Season		
	Winter	Spring/autumn	Summer
Electric load	0.54	0.46	0.32
Space heating load	1.45	0.60	0.07
Hot tap water load	0.33	0.31	0.25
Electricity-to-heat ratio	**1:3.3**	**1:2**	**1:1**

Table 3: Household hot water and heat demand as a function of total hot water supply (200l, 300l)

24hr simulation model

The 24hr simulation model is the most detailed model which can simulate different operation strategies for both natural gas boiler and mCHP system combined with user heat demand. The model assists developers when they are to determine control temperatures and response.

Stratification in the heat storage is also key information in this simulation tool, it is important for a high efficiency that the top heat storage is hot and that the bottom is cold to ensure cooling for mCHP system and hot water to the consumer.

Turn down capability of the system is something that can be simulated in this tool. Different approaches can be taken; the current is a turn down signal to the mCHP system based on a high temperature in the heat storage.

The only drawback with this very customizable simulation tool is that the calculation time for an entire year would be more than 15 minutes and we choose to divide the model into 2 layers; a 24hr model and a 1 year simulation model.

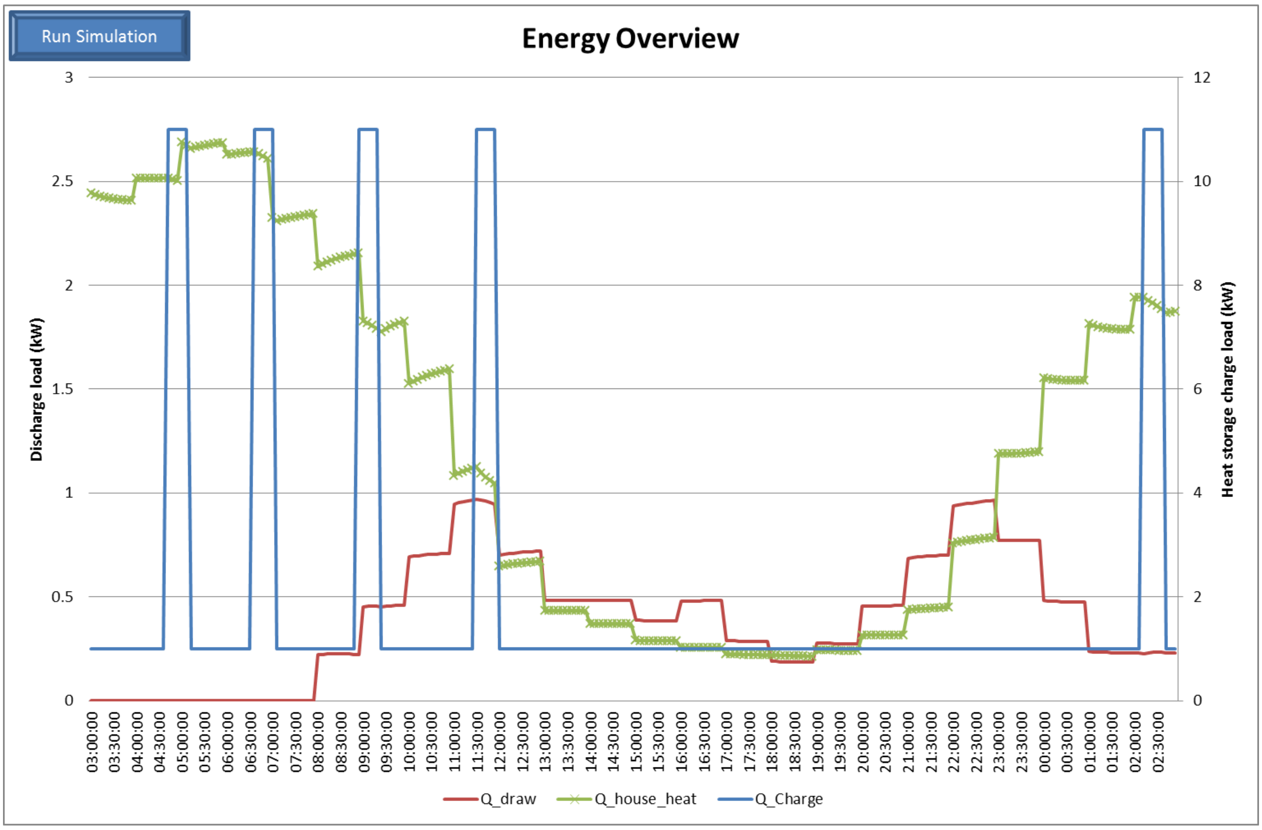
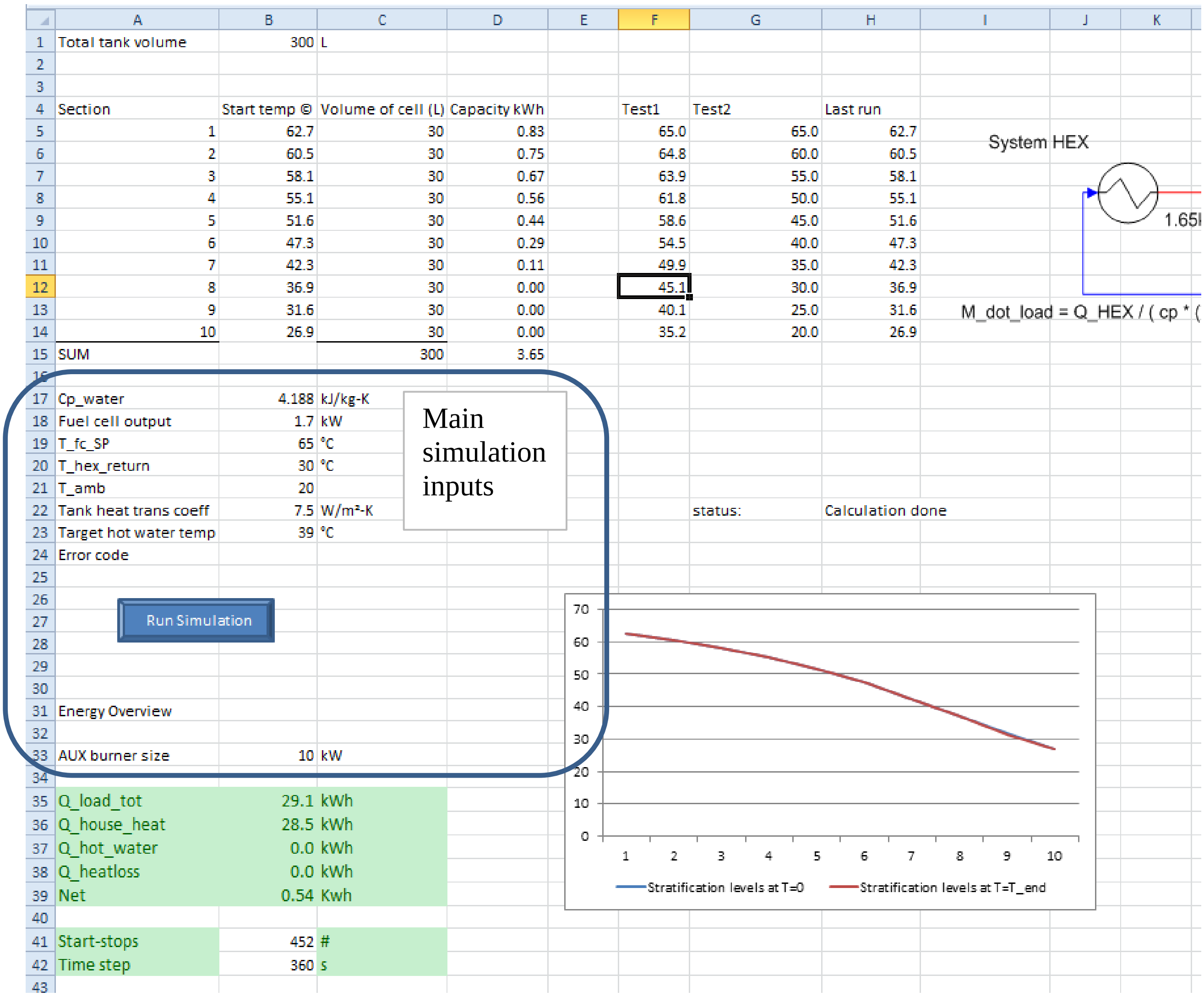


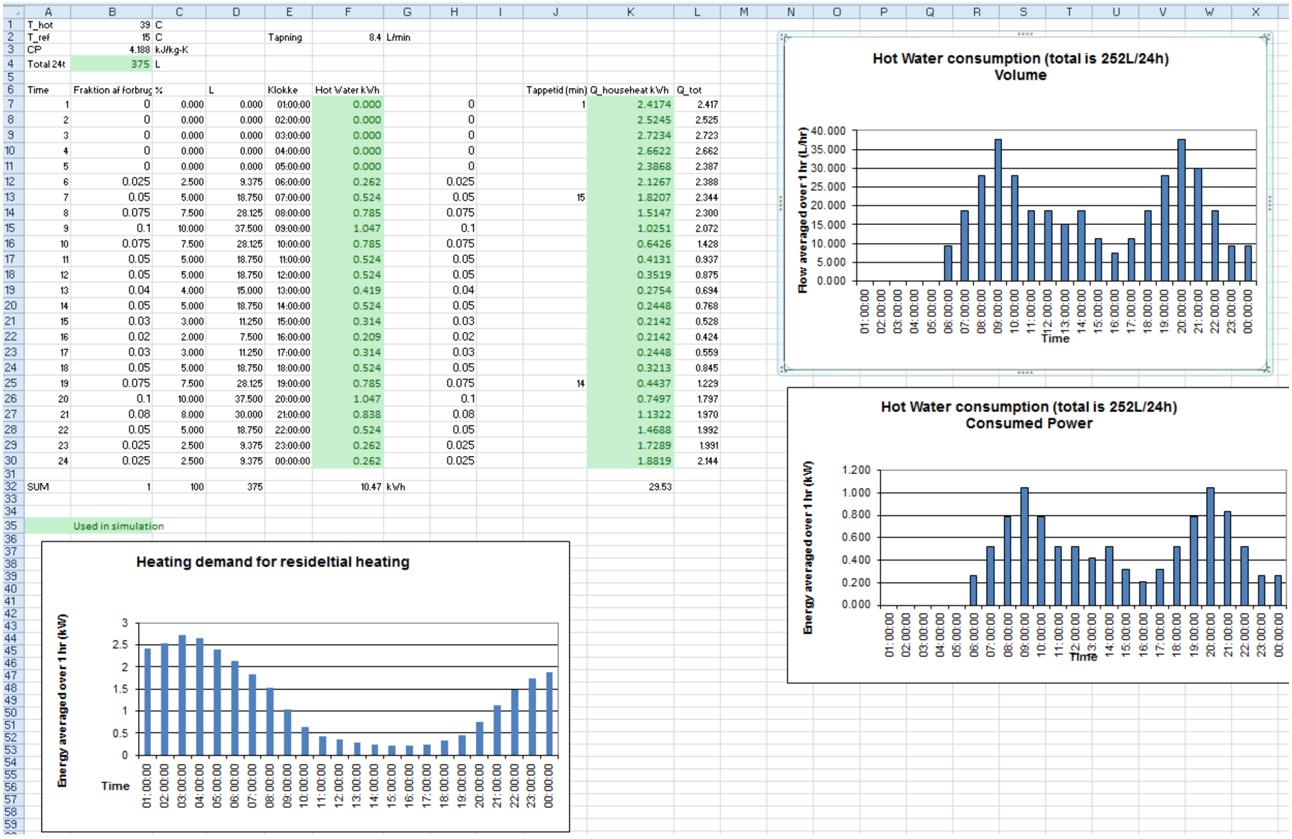
Figure 11: Graph that shows the peaks of the natural gas boiler when heat storage temperature falls below comfort set point. Left axis is hot water consumption and heat demand, while right axis is FC and boiler thermal output.



	A	B	C	D	E	F	G	H
1	Total tank volume	300	L					
2								
3								
4	Section	Start temp ©	Volume of cell (L)	Capacity kWh		Test1	Test2	Last run
5	1	62.7	30	0.83		65.0	65.0	62.7
6	2	60.5	30	0.75		64.8	60.0	60.5
7	3	58.1	30	0.67		63.9	55.0	58.1
8	4	55.1	30	0.56		61.8	50.0	55.1
9	5	51.6	30	0.44		58.6	45.0	51.6
10	6	47.3	30	0.29		54.5	40.0	47.3
11	7	42.3	30	0.11		49.9	35.0	42.3
12	8	36.9	30	0.00		45.1	30.0	36.9
13	9	31.6	30	0.00		40.1	25.0	31.6
14	10	26.9	30	0.00		35.2	20.0	26.9
15	SUM		300	3.65				
16								
17	Cp_water	4.188	kJ/kg-K					
18	Fuel cell output	1.7	kW					
19	T_fc_SP	65	°C					
20	T_hex_return	30	°C					
21	T_amb	20						
22	Tank heat trans coeff	7.5	W/m²-K				status:	Calculation done
23	Target hot water temp	39	°C					
24	Error code							
25								
26								
27								
28								
29								
30								
31	Energy Overview							
32								
33	AUX burner size	10	kW					
34								
35	Q_load_tot	29.1	kWh					
36	Q_house_heat	28.5	kWh					
37	Q_hot_water	0.0	kWh					
38	Q_heatloss	0.0	kWh					
39	Net	0.54	Kwh					
40								
41	Start-stops	452	#					
42	Time step	360	s					
43								

Main simulation inputs

Figure 12: Screenshot from the 24hr simulation model for heat integration simulation. This windows provide the user with information about whether the simulation has finished with succes and also sums the thermal powers.



	A	B	C	D	E	F	G	H	I	J	K	L
1	T_hot	39	C									
2	T_ref	15	C		Tapning	8.4	L/min					
3	CP	4.188	kJ/kg-K									
4	Total 24t	375	L									
5												
6	Time	Fraktion af forbrug	%	L	Klokke	Hot Water kWh				Tappetid (min)	Q_househeat kWh	Q_tot
7	1	0	0.000	0.000	01:00:00	0.000		0		1	2.4174	2.417
8	2	0	0.000	0.000	02:00:00	0.000		0			2.5245	2.525
9	3	0	0.000	0.000	03:00:00	0.000		0			2.7234	2.723
10	4	0	0.000	0.000	04:00:00	0.000		0			2.6622	2.662
11	5	0	0.000	0.000	05:00:00	0.000		0			2.3868	2.387
12	6	0.025	2.500	9.375	06:00:00	0.262		0.025			2.1267	2.388
13	7	0.05	5.000	18.750	07:00:00	0.524		0.05		15	1.8207	2.344
14	8	0.075	7.500	28.125	08:00:00	0.785		0.075			1.5147	2.300
15	9	0.1	10.000	37.500	09:00:00	1.047		0.1			1.0251	2.072
16	10	0.075	7.500	28.125	10:00:00	0.785		0.075			0.6426	1.428
17	11	0.05	5.000	18.750	11:00:00	0.524		0.05			0.4131	0.937
18	12	0.05	5.000	18.750	12:00:00	0.524		0.05			0.3519	0.875
19	13	0.04	4.000	15.000	13:00:00	0.419		0.04			0.2754	0.694
20	14	0.05	5.000	18.750	14:00:00	0.524		0.05			0.2448	0.768
21	15	0.03	3.000	11.250	15:00:00	0.314		0.03			0.2142	0.528
22	16	0.02	2.000	7.500	16:00:00	0.209		0.02			0.2142	0.424
23	17	0.03	3.000	11.250	17:00:00	0.314		0.03			0.2448	0.559
24	18	0.05	5.000	18.750	18:00:00	0.524		0.05			0.3213	0.845
25	19	0.075	7.500	28.125	19:00:00	0.785		0.075		14	0.4437	1.229
26	20	0.1	10.000	37.500	20:00:00	1.047		0.1			0.7497	1.797
27	21	0.08	8.000	30.000	21:00:00	0.838		0.08			1.1322	1.970
28	22	0.05	5.000	18.750	22:00:00	0.524		0.05			1.4688	1.992
29	23	0.025	2.500	9.375	23:00:00	0.262		0.025			1.7289	1.991
30	24	0.025	2.500	9.375	00:00:00	0.262		0.025			1.8819	2.144
31												
32	SUM	1	100	375		10.47	kWh				29.53	
33												
34												
35		Used in simulation										

Figure 13: Screenshot of user demand inputs for the 24hr simulation model. Inputs can be 1hr mean data or with a resolution down to 6 minutes. The demand shown in picture is equivalent to 2 adults and 2 children.

1 year simulation model

The 1 year simulation tool is built into the economic model presented in the WP5 section; however the non-economical part will be discussed here.

In this model the heat storage is simplified to a thermal capacity of a number kWh's, neglecting comfort temperatures and control parameters. The main goal of this feature is to determine the overall thermal efficiency of the system. The operational pattern for this routine is that if the heat storage is fully loaded and heat demand is below turndown capability, the system will shut down.

The operational strategy for the year is key information from this model, as it will try to select an operational pattern with the least amount of start-stops for the fuel cell system, to optimize for system-lifetime and economy. The algorithm for operation optimization is still at its early stage and will assume 1 major heating season (Winter). However, this is a reasonable simplification for the level of information needed at Dantherm Power.

The heat requirement used in the house is presented in the following 2 figures (Figure 14 and Figure 15).

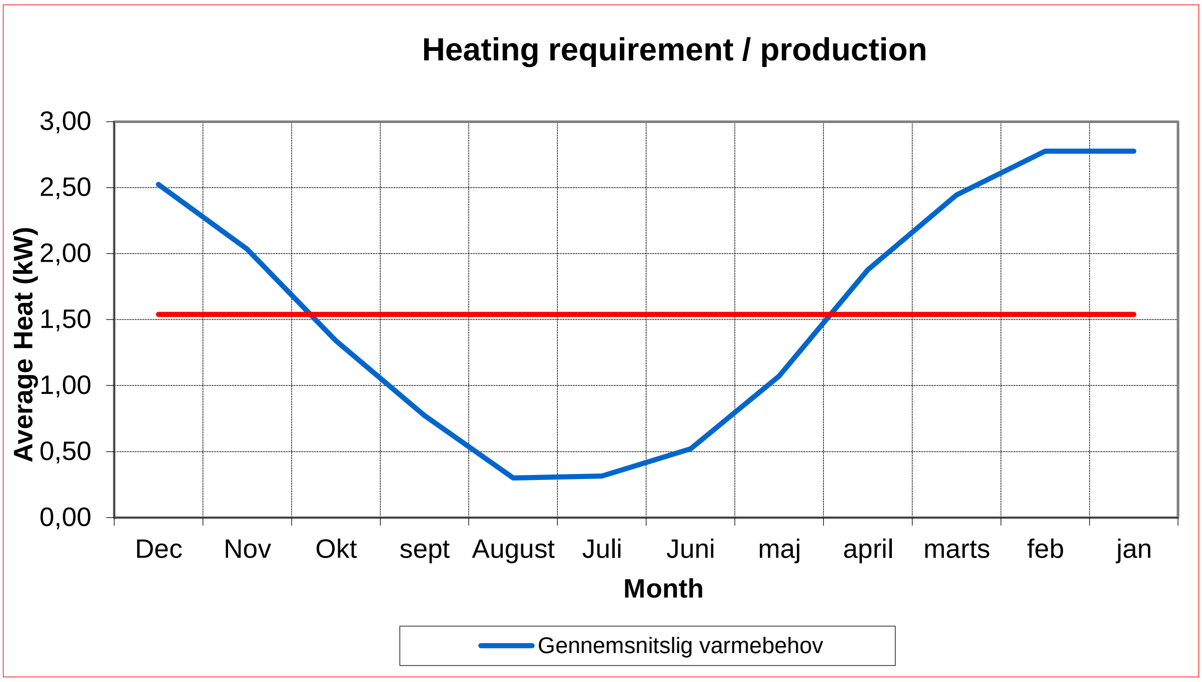


Figure 14: Yearly base Heat request. The demand shown in picture is equivalent to 2 adults and 2 children.

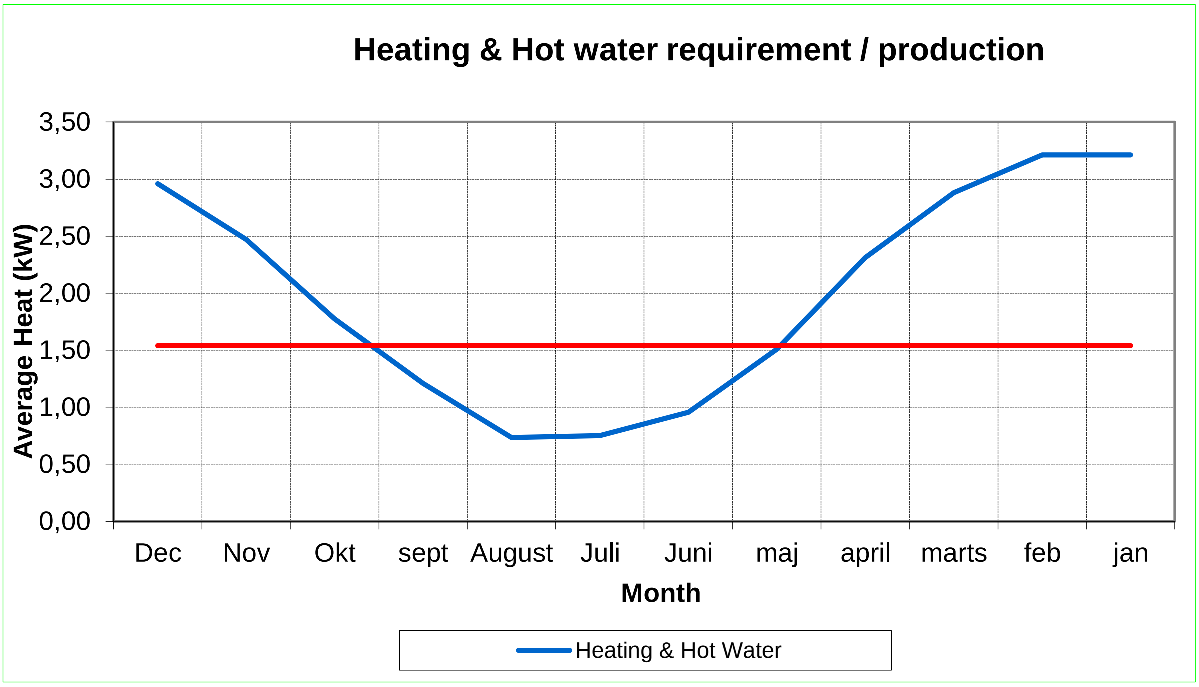


Figure 15: Yearly base heating and hot water demand. The demand shown in picture is equivalent to 2 adults and 2 children.

WP3: Gathering of user data for input to simulation model

In this work package the main goal was to collect information about future customer needs, to have a better chance of developing products that fulfills the broadest market demand.

Getting hour-by-hour data from potential customers current heat demand was difficult, if not to say impossible. However, during this project it became clear to us that we needed to find an elegant solution for estimating the heat demand of different house types.

The solution was to use a modified version of degree days for calculating the heat demand. The approach is as follows:

1. Collect hour to hour data for ambient temperature, wind and sun conditions at the location of interest
    a. This data is readily available, since it does not by itself violate any personal data protection regulations or have a direct link to being commercial confidential.
    b. The degree day principle is that heat demand / heat loss of a house is proportional with the temperature difference between ambient and comfort temperature of the house (in Denmark this is set to 17.6°C, but will in future decrease because electronics equipment eject heat)
    c. Customer data at yearly basis is easier available, since many customers need to balance heat consumption on a yearly basis (projected versus actual usage).
    d. An algorithm that solves for the specific heat loss of the house is then applied
        i. Sometimes the specific heat loss is known e.g. from the Danish construction code
    e. The current algorithm does not take into account wind chill and solar radiation through windows; however this could be added later for better accuracy.

$$E_{total} = \sum_{1st\ january}^{31st\ December} Specificloss * (T_{comfort} - T_{ambient})$$

The end result is, that we by this method can generate general data comparable to several/different house types and locations without getting into commercial conflict with existing heat providers and hereby prevent the need for having user data logged on hourly basis, as this is expensive and not custom in a normal house installation today.

This method is also supported by the load profiles we have acquired from Germany which are based on similar correlations for thermal load and power demand. The data are acquired through *German Association of Energy and Water Industries (*BDEW*).*

As Dantherm Power starts to deploy systems in the field, customer heat demand data will automatically be acquired and a benchmark study can start to underpin the validity of the model.

Private consumer electricity data was just as difficult to get a hold off as the heat demand data (when being a commercial business). However normalized data was available, and could be scaled to the yearly consumption, as this is easier to obtain from future customers, than real-time date.

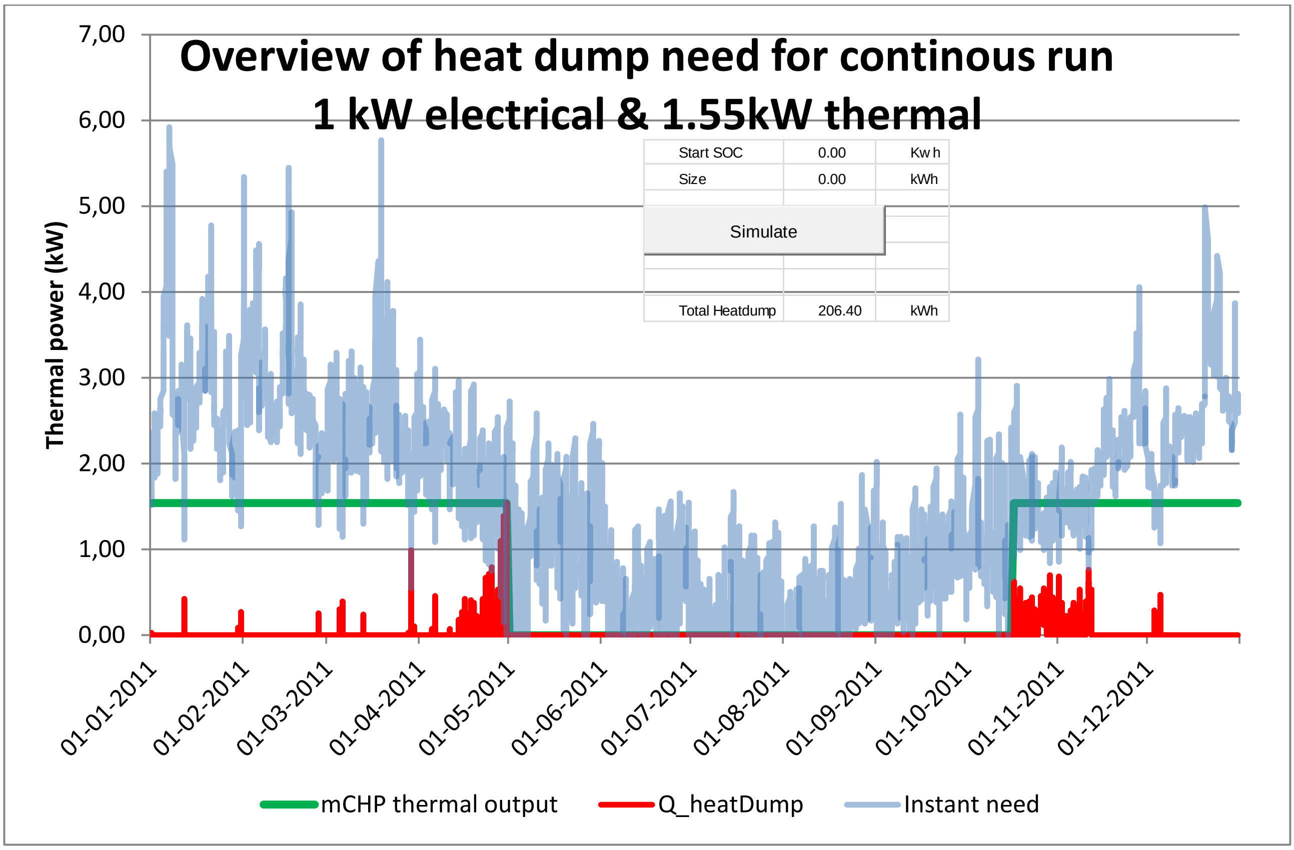


Figure 16: Example of simulated heat demand and supply by mCHP. Heat dump means that there will be a need to store heat either in a hot water tank or raise the house comfort temperature slightly.

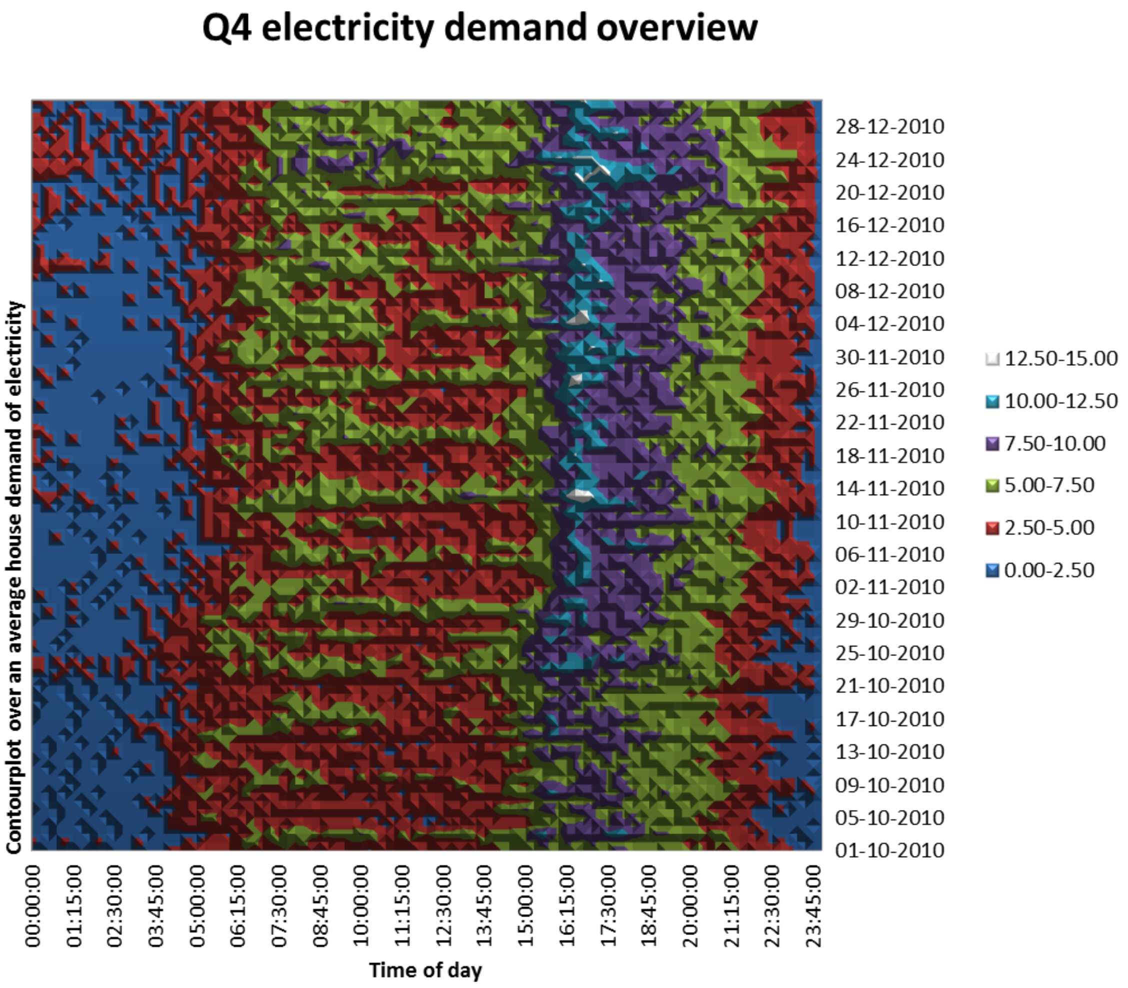


Figure 17: Electricity consumption for a standard house hold based upon a yearly total of 4500kWh and normalized data of distribution. The contour plot shows that the peak power usage is approximately 16:30, where the peak power demand is 12kW. Contour is showing averaged data of 1 hour in kW.

WP4: New concept/ Intelligent Control

The main goal in work package 4 is to improve the inputs necessary in the simulation. Dantherm Power sees WP4 as an add-on for WP2 for optimizing control strategy.

The operation pattern of a SOFC mCHP system (**m**icro **C**ombined **H**eat and **P**ower) will have a significant impact on the payback economics; therefore this work package should take its starting point in optimizing the value of the system to the customer. In Europe there are different Feed-In-Tariff's for electricity production, and therefore a must have in this project is the ability to navigate/adapt to these differences.

Control strategy can be:

- Heat following, and not caring about the electrical
    - This will not alone be a good solution, but if in some cases the produced electricity will give a good Feed-In-Tariff it's not important to follow the electrical.

- Electric following
    - This will be the best choice if the heat is not of high value
- Economic following
    - This will give the best system performance, since it will operate in the most cost effective way and give the highest value.

Many object function can be adopted:

- Value of produced heat
- Value of produced electricity
- Value is market value compared to production cost
- Optimizing the control to maximize the value of operating

The main focus of the work package should be to find out how to automate the operation of a system to the highest value for both supplier and the customer.

Simulating the consequences of different approaches will speed up the time to market where the value proposition of SOFC system is the highest.

Operation strategies

The micro CHP operation can follow the demand for power or heat. If the unit is controlled by the heat demand of the house, a connection to the electric grid enabling import and export of electricity to the house will be needed in most cases.

Many houses in northern Europe, electrical heated houses excluded, will have an electricity-to-heat rate on an annual basis of some 1:2 to 1:4, which in principle should match various micro CHP technologies well. However, the daily and also hourly demand profiles can largely vary and the electricity and heat demand can reach high peaks.

The demand for electricity varies a lot during the day, depending on the equipment connected and load profiles. Each family or household has their own consumption pattern. If a micro CHP unit is controlled by the demand of electricity (power load following) it will need a fast dynamic response and cover a wide power range. The average power generation will be low, which may lead to poor efficiency in the generation of electricity. Even base load varies significantly from household to household. Operation based on the individual demand of electricity (base load) often leads to smaller units, less/lower annual electricity and heat production compared to a heat controlled unit.

Operating range of the mCHP Heat-to-Power ratio is not sufficient enough to cover the thermal energy demand over the whole year. For this reason an auxiliary boiler and a hot water storage tank must be coupled with the mCHP unit.

In particular, the mCHP system Heat-to-Power Ratio range of 0.5‑1.5 shows good agreement with the hot water and electricity demand in European countries, and is compatible with the warm season heat and electricity demand. Therefore, the mCHP system should be sized according to these warm season energy requirements.

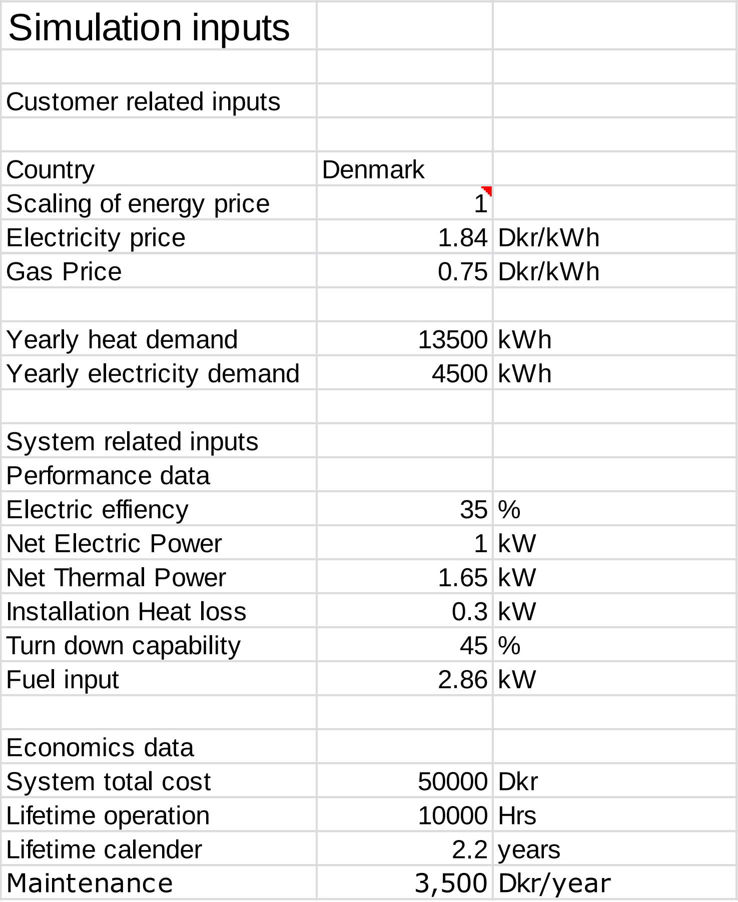
To secure the full potential of this strategy, import/export of power to the grid should be established and heat storage should be included.

WP5: Economic and Environmental consequences

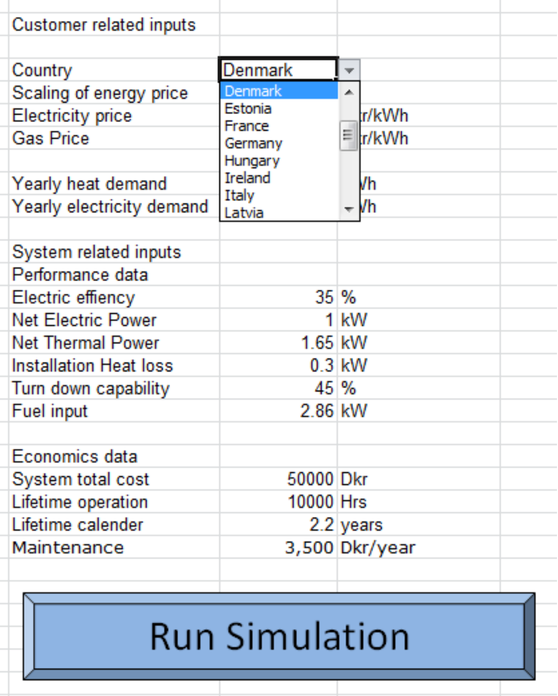
In this work package a generic tool for evaluating economics of a micro CHP system has been developed. The base is a CAPEX & OPEX calculation, which takes its inputs from simulation results.

A test case with a Danish family is run:

The energy prices are stored in a separate database, to ease the use of the software. The user interface is shown in below:



Simulation inputs		
Customer related inputs		
Country	Denmark	
Scaling of energy price	1	
Electricity price	1.84	Dkr/kWh
Gas Price	0.75	Dkr/kWh
Yearly heat demand	13500	kWh
Yearly electricity demand	4500	kWh
System related inputs		
Performance data		
Electric effiency	35	%
Net Electric Power	1	kW
Net Thermal Power	1.65	kW
Installation Heat loss	0.3	kW
Turn down capability	45	%
Fuel input	2.86	kW
Economics data		
System total cost	50000	Dkr
Lifetime operation	10000	Hrs
Lifetime calender	2.2	years
Maintenance	3,500	Dkr/year



Customer related inputs		
Country	Denmark	
Scaling of energy price		
Electricity price		r/kWh
Gas Price		r/kWh
Yearly heat demand		Vh
Yearly electricity demand		Vh
System related inputs		
Performance data		
Electric effiency	35	%
Net Electric Power	1	kW
Net Thermal Power	1.65	kW
Installation Heat loss	0.3	kW
Turn down capability	45	%
Fuel input	2.86	kW
Economics data		
System total cost	50000	Dkr
Lifetime operation	10000	Hrs
Lifetime calender	2.2	years
Maintenance	3,500	Dkr/year

After running the case several results are available, however only top level information is shown here for better overview of the capabilities of the software. The simulation is divided into two segments; one where the heat storage delivers hot water for showering and the other where heat storage only supplies heat to the house and where the hot water is produced on-demand. The reason for separating the solutions is to see what consequence limited space at the customer does to control strategy.

The selected case of Denmark shows the optimal solution of producing exactly the yearly electricity consumption (because of feed-in-Tariff regulation), see Figure 18 and **Fejl! Henvisningskilde ikke fundet.**. The period of operation is winter time to minimize the amount of start-stops because of low heat demand. In case it is possible to install a large volume heat storage for combined operation, it is possible to reduce the system start-stops to once a year, which is a critical factor for the lifetime of a SOFC system. The simulation result of the operation is showed in Table 4**Fejl! Henvisningskilde ikke fundet.** - an important point is; if the space for installation in the house is limited to a small heat storage (100L) the number of start-stops increase to 8 (significant difference on system lifetime).

Another important factor when designing the system is to look at the start-stop economics in Table 5 and Table 6. In most cases the residential customers have an electric grid connection, which makes it possible to optimize system operation to fastest payback instead of the full electricity coverage operation strategy. As shown in Table 5 a minimum run time of 9 hours is required to make a start-stop sequence economically feasible, this is important when optimizing for heat storage capability.

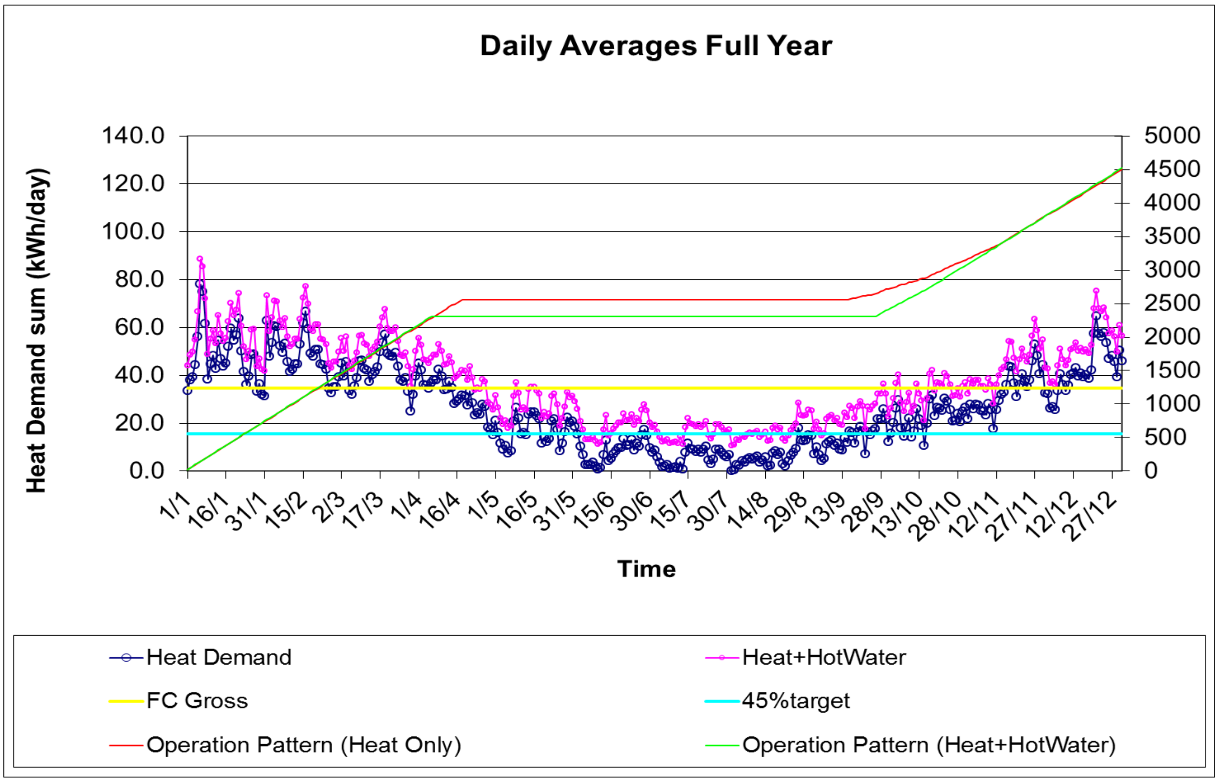


Figure 18: Yearly overview of user demand of heat and electricity, the graphs shows that the system at end of year has produced 4500kWh (target)

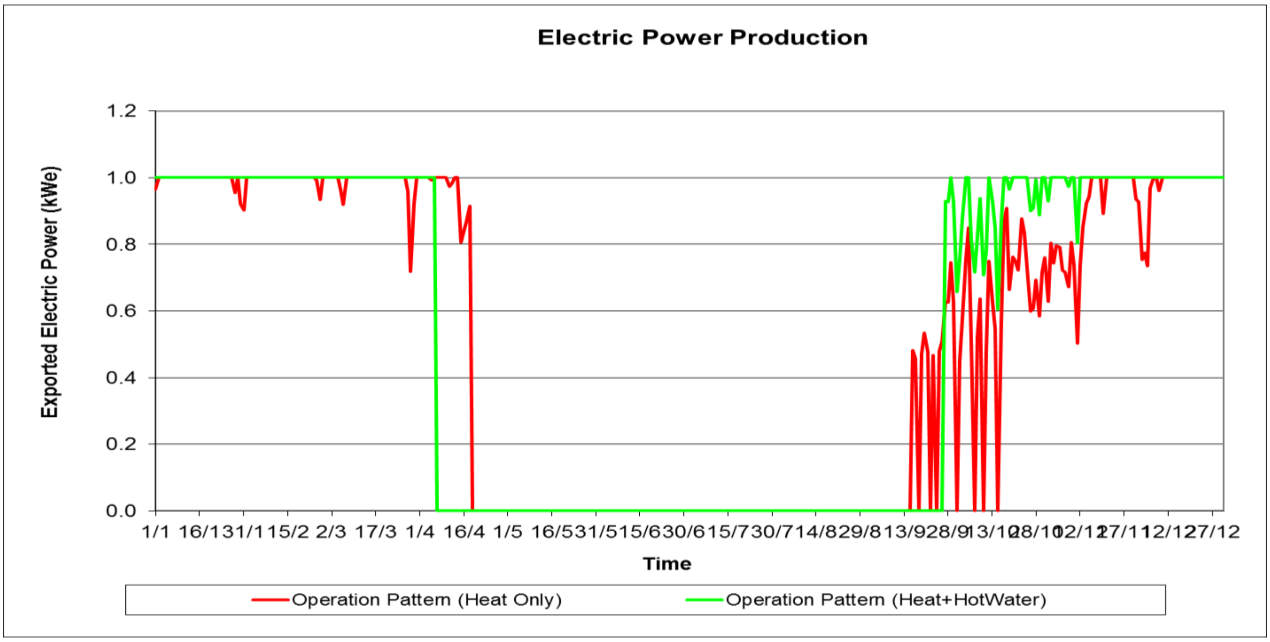
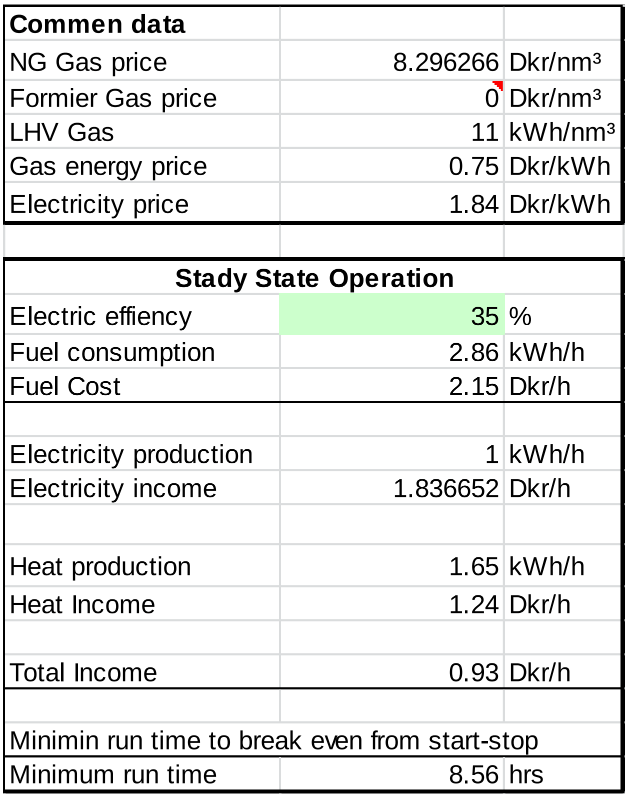


Figure 19: Net electricity output of system over the year, operation is optimized for best economics

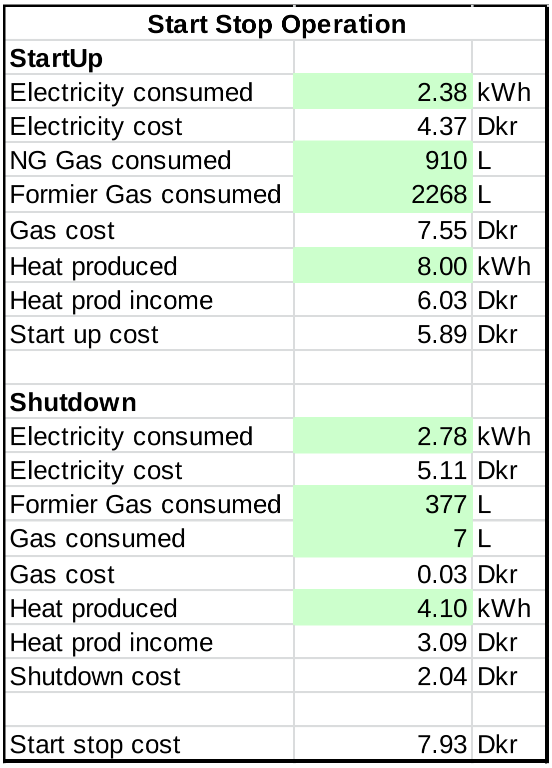
		Heating&HotWater	Heating Only
Days of Operation			
Total On	Days	192	208
Continously On	Days	NA	NA
Continously off	Days	173	157
Produced Energy			
Heat	kWh	6559	6532
Electricity	kWh	4523	4505
Customer Need			
Heat	kWh	9668	9668
HotWater	kWh	3833	3833
Electricity	kWh	4523	4505
Electricity coverage	%	100	100
Heat Coverage	%	49	48
Heat Storage Size	L	300	100
Start/Stops	#	1	8

Table 4: Overview of energy production and operation. Data regarding start-stops and heat storage size also included.



Commen data		
NG Gas price	8.296266	Dkr/nm^3
Formier Gas price	0	Dkr/nm^3
LHV Gas	11	kWh/nm^3
Gas energy price	0.75	Dkr/kWh
Electricity price	1.84	Dkr/kWh
Stady State Operation		
Electric effiency	35	%
Fuel consumption	2.86	kWh/h
Fuel Cost	2.15	Dkr/h
Electricity production	1	kWh/h
Electricity income	1.836652	Dkr/h
Heat production	1.65	kWh/h
Heat Income	1.24	Dkr/h
Total Income	0.93	Dkr/h
Minimin run time to break even from start-stop		
Minimum run time	8.56	hrs

Table 5: Steady state operation economics, used to evaluate start-stop costs.



Start Stop Operation		
StartUp		
Electricity consumed	2.38	kWh
Electricity cost	4.37	Dkr
NG Gas consumed	910	L
Formier Gas consumed	2268	L
Gas cost	7.55	Dkr
Heat produced	8.00	kWh
Heat prod income	6.03	Dkr
Start up cost	5.89	Dkr
Shutdown		
Electricity consumed	2.78	kWh
Electricity cost	5.11	Dkr
Formier Gas consumed	377	L
Gas consumed	7	L
Gas cost	0.03	Dkr
Heat produced	4.10	kWh
Heat prod income	3.09	Dkr
Shutdown cost	2.04	Dkr
Start stop cost	7.93	Dkr

Table 6: Experimental results, illustrating power and gas consumption during start-up and shutdown. The start-up and shutdown cost will determine the continuously run between start-stops for the system to run economically for the customer.

The economic model has a simple business case strategy target. Figure 20 shows the corresponding cost for the customer for a natural gas boiler and a grid connection, which gives Dantherm a target customer cost profile. The price showed in Figure 20 is the product price including revenue (production cost must then be much lower). The reason for this setup is to highlight the current need for a funding incitement for investing in a Fuel Cell micro Combined Heat and power system. The result for a micro CHP system with 2 years of lifetime (10 000 Operation hours) at this time, will need to have a market price (selling price) from the customer perspective of Dkr. 25 000.

The graph in Figure 20 also shows that a 50% increase in energy prices will allow the system to double in price and the probability of the energy price (gas and electricity) increasing is very high. The business case for a SOFC based micro CHP system is likely to have a reasonable economic feasibility in the near future because of expected increasing energy prices.

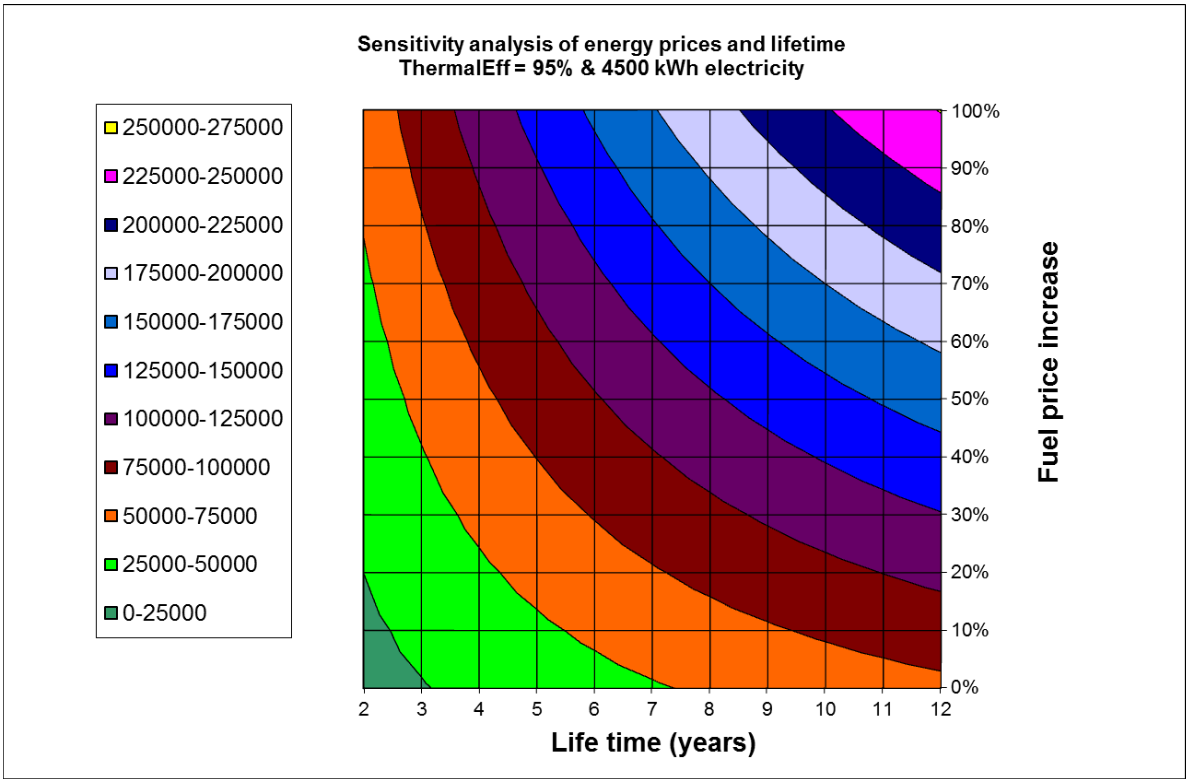


Figure 20: Sensitivity study from the economic model developed in WP5. Graph shows the target customer price for a mCHP system to be able to compete with an existing installation with gas boiler and grid connection. Focus of the study is to show market change for a longer lifetime of mCHP system and also fuel price increase. Fuel price is increased equally for both electricity and gas (expecting a global rise in prises). For a lifetime of 5 years and a selling price of 75 000 Dkr the fuel price target is an increase of 40%

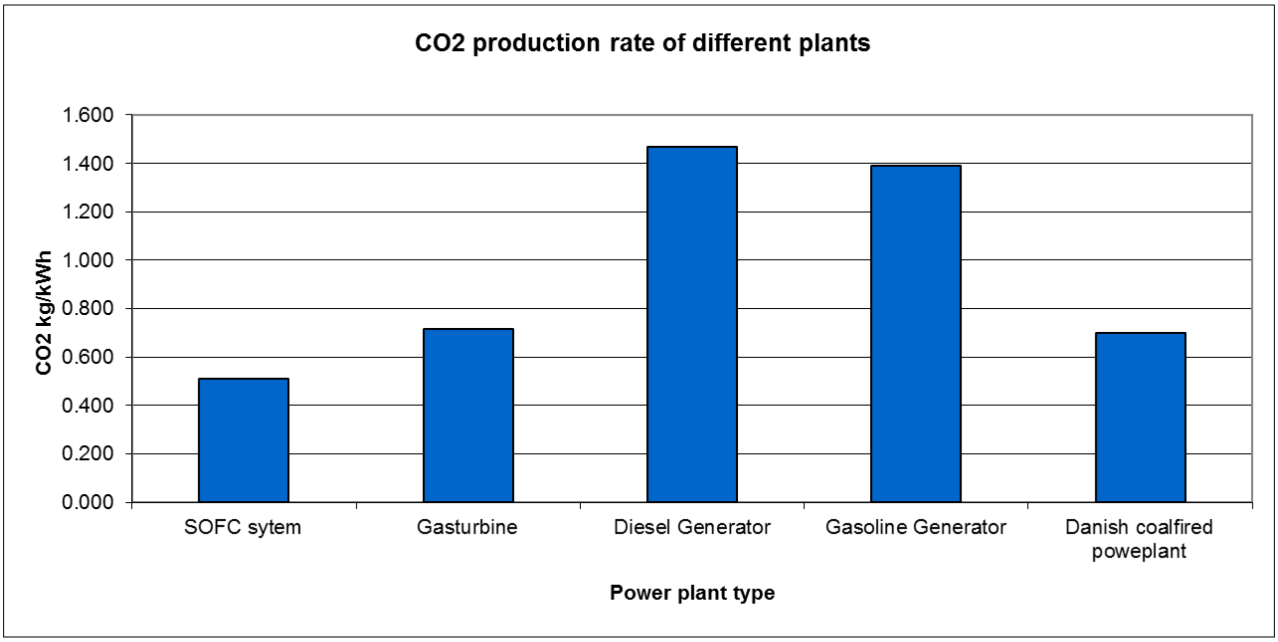


Figure 21: Overview of CO_2 production for power generation for different technologies. Both fuel and electrical efficiency has been taken into account in the shown graph. Even for a coal fired power plant of same LHV->electric efficiency the fuel makes quite a difference (Coal versus Natural gas). Natural gas as a fuel has lower carbon number than Coal.

CO2 savings for SOFC mCHP system		
SOFC system compared to:	CO2 saving (kg/year)	CO2 saving (ton/year)
Gasturbine	931	0.93
Diesel Generator	4308	4.31
Gasoline Generator	3965	3.96
Danish coalfired poweplant	856	0.86

Table 7: Results from the simulation. The values are related to the selected operational strategy (electricity target of 4500kWh/year). Transmission losses from centralized power plants have been neglected to keep the comparison strictly based upon technology rather decentralized versus centralized.

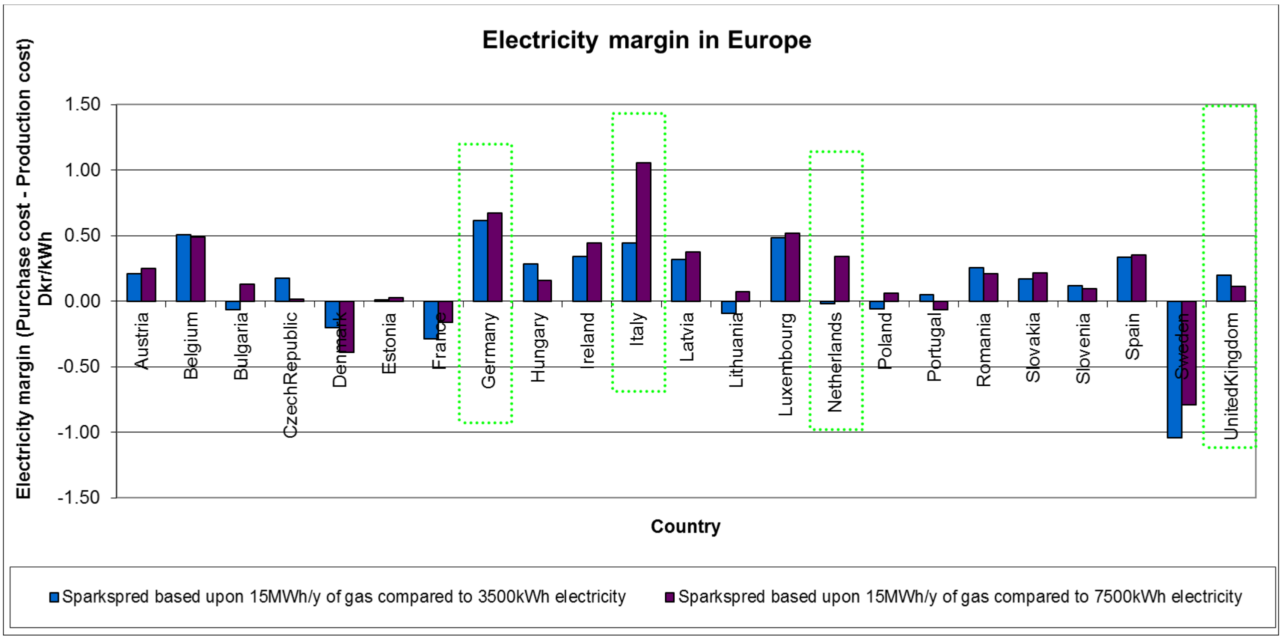


Figure 22: Overview of countries where the gas to electricity price is favorable to mCHP systems. The electricity margin is the difference between the cost of purchasing 1 kWh and producing it from a SOFC system running on natural gas. This graph only looks at electricity; the heat from the SOFC system is not valued here.

WP6: Implementation of software at Dantherm Power R&D

The software simulation models have been successfully implemented at Dantherm Power, R&D. The software package from VirtualMaterials has become the permanent choice of simulation software at Dantherm, as the visual programming tool it is much faster than what was used previously and can rapidly be reconfigured to different or completely new system architecture models. The project outcome is a strong development tool, coupling the marked demands, operation strategy, economics, component specification and complete system development together. The simulation models capabilities are frequently used in R&D to support the Business Development department, when benchmarking different mCHP configurations and concepts to underpin business models and future strategic decisions. Currently it is being investigated, if there is a possible added value in Smart grid and selling electric reserve capacity from mCHP systems, hence the implementation of more wind power in Denmark is expected to make the electricity market more volatile with a higher need for regulating power.

Another tangible result from this project is illustrated below in Figure 23, this is the heat installation concept developed for the Danish mCHP Project, where 20 LTPEM systems, at this point of time, are installed and running in the field. The systems were installed in November 2010 and have accumulated operation for more than 75.000 hours in total. The 20 systems will finish the demonstration in May 2013. The challenge in this specific task was to optimize the system installation and operation regarding to the following points:

- Minimize the heat storage form factor
- Minimize the start and stops as this has a negative impact on operating efficiency and system lifetime
- Combine the fuel cell mCHP system with the existing gas boiler and heat installation in the house

The simulation output from WP 3, figure 16 resulted in a new system configuration without the need for heat storage, only the existing 60 liters buffer tank for hot water was used in combination with the gas boiler and fuel cell mCHP system. The system operation strategy was clear, for a normal family requiring 4500 kWh of electricity a year, along with the possibility of only running the system during the heating season (winter), the heat storage demand is only 210kWh of heat with an approximate value of Dkr 160,- in extra gas consumption. In this case, it would be much more cost effective to dump the heat, in the house, and save the expense of adding heat storage to the system and at the same time having an annual heat loss higher than 1 MWh with 300 liters heat storage. This operation strategy is only valid in Denmark for the time being, since the feed-In-Tariff allows for a yearly-zero-net billing of electricity.

The heat integration in Figure 23 below, can be compared with the former heat integration including an expensive 300 Liters heat storage in Figure 24.

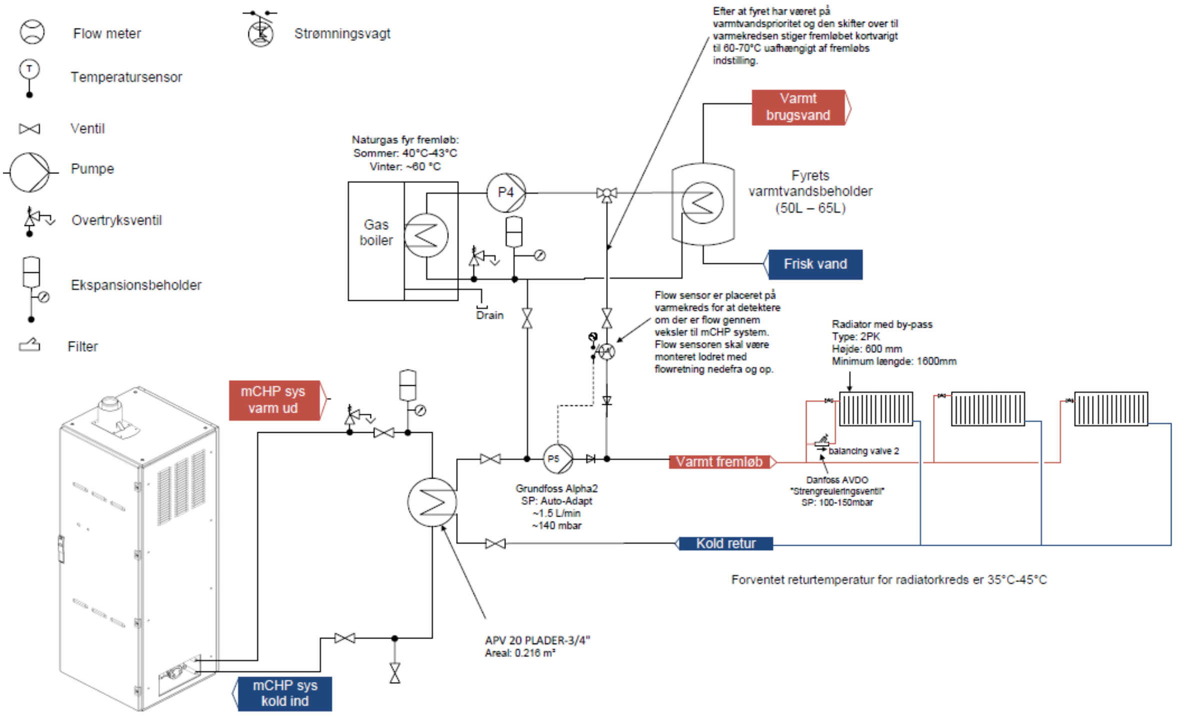


Figure 23: Simplified heat integration based on simulation output from WP3 and economic considerations from WP5

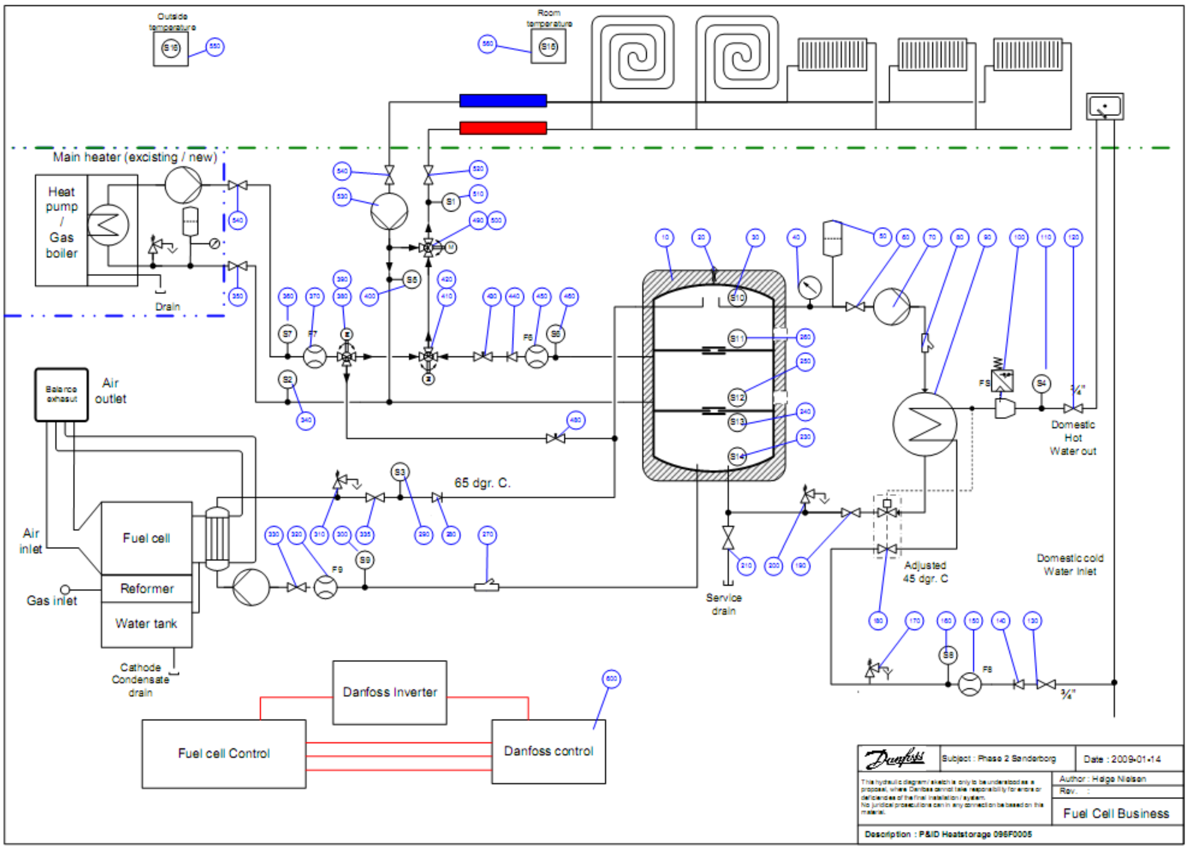


Figure 24: P&id of the SOFC fuel cell system integration with the house heat installation and heat storage.

Figure 25 below is a system overview of the 20 systems in the field operating with the simplified heat integration. The heat integration setup is working fine, after some adjustments in the beginning due to the different gas boilers and existing differences in the heat installations.

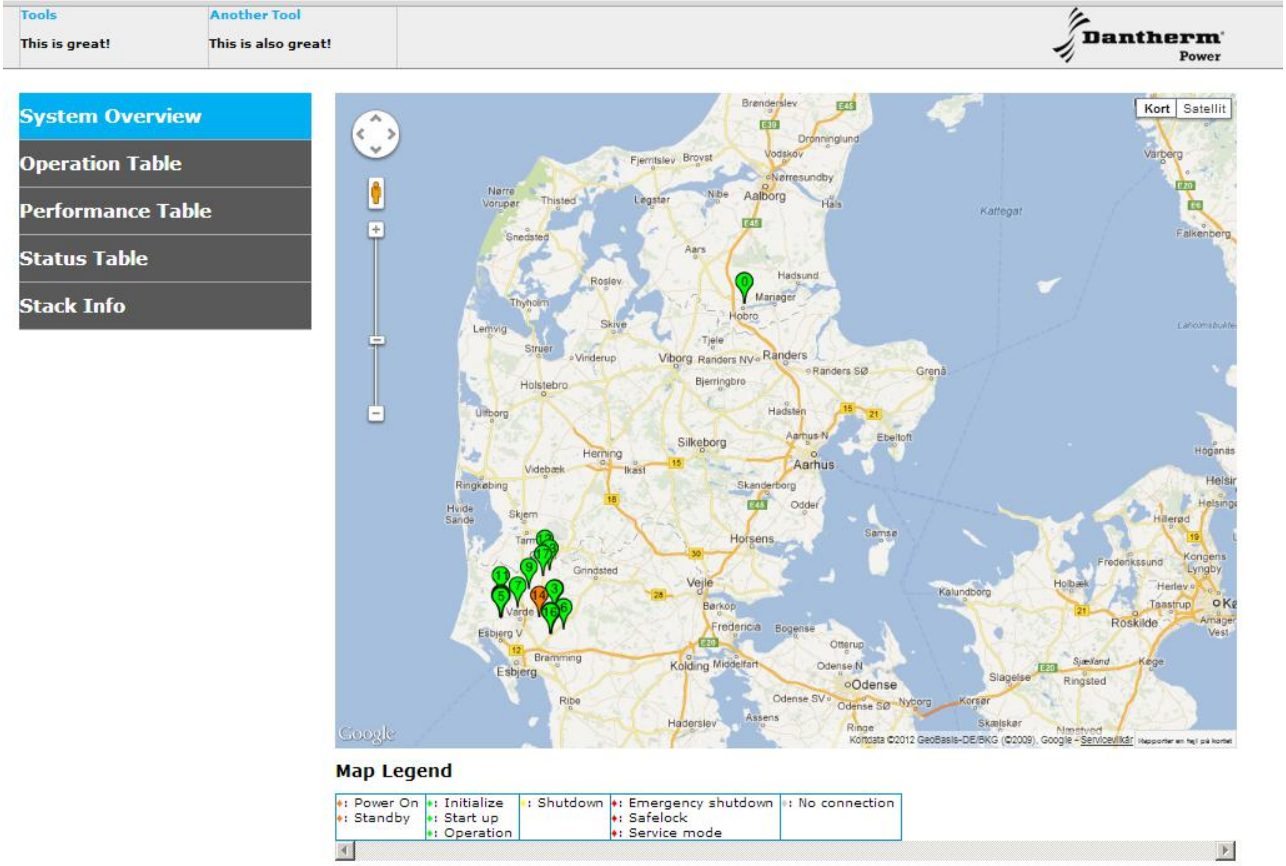


Figure 25: 20 mCHP systems installed in the south-western part of Denmark

Figure 26 below is a picture of one of the Installations of a mCHP system in a single-family house. The system size is 60 x 60 x 180 cm. and is coupled intelligently with the existing gas boiler and 60 liters hot water buffer tank to full fill the instant heat demand.

Figure 26: One of 20 fuel cell mCHP systems installed in the field

Summary and conclusion

The main objective in this project has been to develop a generic and dynamic tool for SOFC systems simulation and development. Developing integrated fuel cell systems is very expensive and therefore having the right tools to reduce the development cost and time to market for products becomes an important feature. The tools developed in this project cover a wide range of needs in Dantherm Power, R&D, and can be divided into 3 categories:

1. Component selection modeling; to define component specification requirements and selection of suppliers
2. Application simulation model built from scratch, which can simulate the interface between customer demand and system output and show operation behavior for different control settings
3. System operation strategy optimization with respect to operation cost and customer benefits
    a. Allows to see how system size, in terms of electricity and heat output, and operation strategy influences a specific business case
    b. Gives a clear overview of how a different property, in the system, affects the economics (e.g. lifetime, electrical and thermal efficiency, fuel cost sensitivity, country of deployment etc.)

The main idea behind the structure of the tool being separated into 3 layers is to be able to service different requirements, from changing stakeholders.

One of the major findings in this project has been related to thermal integration between the existing installation in a private household and the fuel cell system. For a normal family requiring 4500 kWh of electricity a year, along with the possibility of only running the system during the heating season (winter), the heat storage demand is only 210kWh of heat with an approximate value of Dkr 160,- in extra gas consumption. In this case, it would be much more cost effective to dump the heat, in the house, and save the expense of adding heat storage to the system. This operation strategy is only valid in Denmark for the time being, since the feed-In-Tariff allows for a yearly-zero-net billing of electricity, meaning that the consumer could produce heat during winter when heat is always needed and turn off the system during summer to improve operation efficiency.

The development tools have already been tested and used for fuel cell system integration at Dantherm Power, R&D and have proved its worth in savings on components in the order of several thousand Danish kroner.

An area where a future project could contribute to the tools capabilities is to build an intelligent optimization algorithm into the tool and get the software to find the optimal solution automatically.