Experimental Analysis of Microscale Trigeneration Systems to Achieve Thermal Comfort in Smart Buildings

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ABSTRACT

The transformation of the building energy sector to a highly efficient, clean, decentralised and intelligent system requires innovative technologies like microscale trigeneration and thermally activated building structures (TABS) to pave the way ahead. The combination of such technologies however presents a scientific and engineering challenge. Scientific challenge in terms of developing optimal thermo-electric load management strategies based on overall energy system analysis and an engineering challenge in terms of implementing these strategies through process planning and control. Initial literature research has pointed out the need for a multiperspective analysis in a real life laboratory environment. To this effect an investigation is proposed wherein an analytical model of a microscale trigeneration system integrated with TABS will be developed and compared with a real life test-rig corresponding to building management systems. Data from the experimental analysis will be used to develop control algorithms using model predictive control for achieving the thermal comfort of occupants in the most energy efficient and grid reactive manner.
The scope of this work encompasses adsorption cooling based microscale trigeneration systems and their deployment in residential and light commercial buildings.

KEYWORDS

Adsorption Cooling, Experimental Investigation, Grid Integration, Microscale Trigeneration, Predictive Control, Thermal Comfort in Buildings

1 INTRODUCTION

Trigeneration systems or combined cooling, heating and power (CCHP) systems are a technological extension of combined heat and power (CHP) or cogeneration systems. Here the waste heat of the cogeneration process is used to produce cooling, usually in thermally activated chillers. Due to the fact that an energy cascade is developed and a single fuel source is utilised for multiple energy conversions the exergy efficiency of trigeneration systems is higher than individual conversion units. Ghaebi *et al.* (Ghaebi et al., 2010) demonstrated this is in their in-depth exergy and thermoeconomic analysis of a trigeneration system. Wu *et al*. (Wu et al., 2006) and Jrade *et al*. (Jrade et al., 2014) have also discussed the benefits of trigeneration in their reviews and the progress it has made in the last few decades in terms of different prime movers, chillers, operation strategies and government policies supporting its further development and implementation.

Trigeneration systems are frequently deployed in small (<1MWel) and medium scale (1-10 MWel) applications in industries and commercial complexes. Here, absorption based thermal chillers that utilise high temperature waste heat (>100°C) are most dominant. However in the past decade studies, e.g. Zhai et.al. (Zhai and Wang, 2008), have shown promising results of microscale (<20kWel) adsorption cooled trigeneration systems in terms of grid flexibility and demand side management for smaller buildings having less cooling load. The capability of adsorption chillers to work with low temperature waste heat (60–80°C) increases their integration potential with other renewable sources and thermally activated building structures (TABS). The focus of this research is only on adsorption cooled microscale trigeneration systems and hereon referred to as simply microscale trigeneration systems.

2 MULTIPERSPECTIVE ANALYSIS

Although microscale trigeneration systems have the potential to play a vital role in the building energy sector their deployment is hindered due to interdisciplinary scientific and engineering challenges as summarised in figure 1.

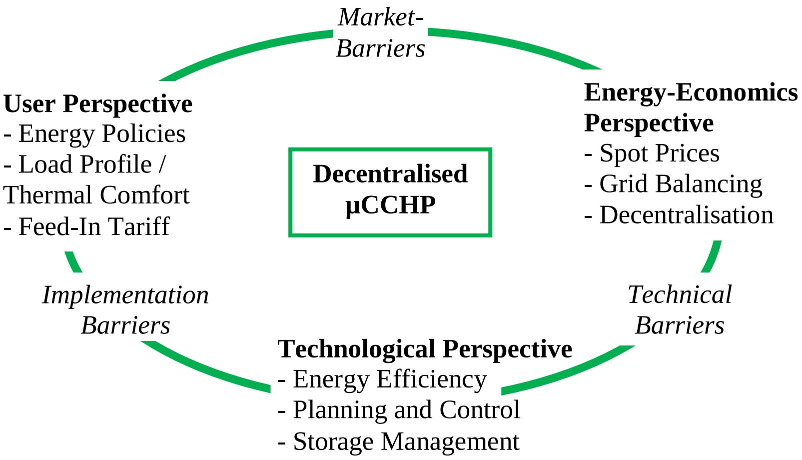

Figure 1: Multiperspective analysis of decentralised µCCHP system

Scientific challenges arise due to supply and demand mismatch for power and the heating/cooling loads especially in a smart building setup with combination of other renewable sources. Here, energy storages and integrated systems demonstrate the potential to enhance the system’s flexibility for optimal scheduling. However, this increases the system’s complexity and accordingly optimised operation strategies considering multiple perspectives (energy-economical, technological and user based) must be developed.

Various optimisation approaches for CCHP systems focusing on system operational costs, primary energy consumption and emission reduction have been published in recent years. For instance, Chandan *et al.* (Chandan et al., 2012) proposed a non-linear programming (NLP) method by making use of forecasted electric and thermal demands for the optimal control of a CCHP plant with a thermal storage. Rong *et al.* (Rong et al., 2005) proposed an enhanced linear programming method specialised to optimise operating costs of producing any three energy commodities simultaneously. Kavvadias *et al.* (Kavvadias et al., 2010) and Piacentino *et al.* (Piacentino et al., 2008) followed a multi-objective approach based on the cost and emissions reduction taking into account the energy load and price variations on an hourly basis. Zhao *et al.* (Zhao et al., 2015) demonstrated the application of model predictive control (MPC) using a NLP method to develop optimal scheduling of active and passive energy systems in buildings based on time sensitive electricity prices. Although no single method has been established to offer the best possible solution, MPC is the forerunner for recent optimisation studies because it facilitates application of powerful programming algorithms such as nonlinear, mixed integer linear and mixed integer nonlinear algorithms.

Implementation of such complex scheduling strategies further leads to engineering challenges such as planning, standardising, operation and control of these systems. Thus, real life test-rig research is necessary to develop, validate and implement algorithms that will enhance the integration of microscale trigeneration systems into smart grids for residential and light commercial building applications.

Majority laboratory research focuses on analysis and improvements of the adsorption chiller or the thermal storages on a component level. For example Huangfu *et al*. (Huangfu et al., 2007) performed an experimental investigation for analysing the performance of the adsorption chiller under varying heating conditions. Wang *et al*. (Wang et al., 2009) pointed out the adsorption deterioration as a non-negligible factor adversely affecting the service life of adsorption chillers. Schmidt *et al.* (Schmidt et al., 2014) introduced the concept of heat recovery between the adsorption and desorption cycle of the chiller using stratified storages. However, some researchers such as Kong *et al*. (Kong et al., 2005) developed a comprehensive database for the operating parameters of an entire microscale trigeneration system in a test facility with a natural gas engine and a two bed adsorption chiller. Becker *et al*. (Becker et al., 2013), Angrisani *et al.* (Angrisani et al., 2012), Henning *et al.* (Henning et al., 2010) and a few others have also performed similar real life experimental investigations of the system as a whole in laboratory environments. Although the potential of these systems was established in these studies a characteristic deduction has been the need for improved control strategies, integration of other building heating/cooling technologies and standardisation of system planning and operation.

Raimondo et al. (Raimondo et al., 2013) demonstrated the ability to utilise water at higher temperatures (such as those achieved by thermal chillers) for space cooling in thermo-active building system (TABS) during field tests supported by dynamic simulations. In an extensive field test and measurement study Kalz et al. (Kalz et al, 2014) recorded and analysed data for thermal comfort and energy efficient cooling of 42 office buildings in Europe. It was stated that TABS system can achieve energy efficient cooling solutions for buildings and in most cases an average room temperature of 22,5-25,5°C was achieved. However for higher thermal comfort requirements and fluctuating user profile additional backup systems are necessary. Another field test project (Fraunhofer, 2015) will focus on providing an integrated energy and building concept considering aspects on renewable energy integration and energy efficiency.

Thus due to the economic and environmental benefits it is becoming more meaningful to deploy microscale trigeneration systems in combination with TABS for decentralised grids and buildings. However, for analysing the interdependency of the integrated components in such systems and developing optimal scheduling it is necessary to perform laboratory tests.

This study will therefore address the issue of developing control algorithms and testing them on a real life test-rig to realise the potential of adsorption cooled microscale trigeneration systems integrated with TABS in an energy efficient and grid reactive manner.

3 PROPOSED INVESTIGATION

A flow chart of the proposed plan to investigate the optimal scheduling of a trigeneration system is shown in figure 2. Analytical models for the system components will be developed using basic physical energy balance equations. The focus will be on making robust models to facilitate the use of MPC. Simultaneously an experimental lab is being set-up. The lab is described in more detail in the following section of the paper. A mathematical optimisation problem will be developed using load profile of building, spot prices, weather forecasts and feed-in tariff data as inputs. The constraints on optimisation will be the thermal comfort of occupants, security of power supply and the physical constraints of the components. An MPC solver will be implemented to provide optimal scheduling strategies which will be then implemented in the real life test-rig. Feedback from the lab will be used for validating and further developing the models.

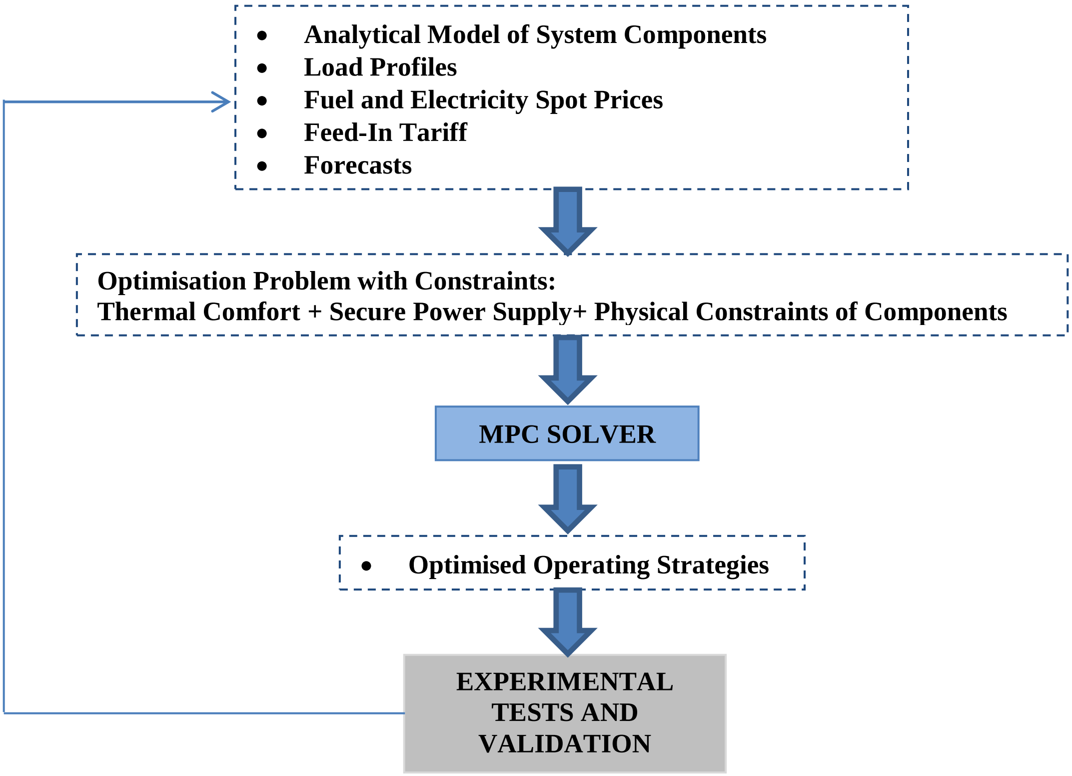

Figure 2: Flowchart of proposed research

4 THE EXPERIMENTAL SET-UP

A microscale trigeneration lab is being set-up to facilitate thermo-electric load management for the smart microgrid concept of the institute. The specifications for main components are shown in Table 1 below.

Table 1: Specifications of main components in the microscale trigeneration lab

Components	Abbreviation	Specification
Combined Heat and Power Unit	CHP	5kWel; 10kWth; 66%eta_ th; 30%eta_el; Fuel Oil
Hot Storage	HOT/STRG	1500 L; with 6kWel Heat Coil
Adsorption Chiller	AdCM	12kW cooling max.; 0,65 COP max.
Cold Storage	COLD/STRG	1450 L
Mechanical Chiller/ Heat Pump	MC/HP	12,9kW (cooling nom.); 16,7kW (heating nom.); 3,75kWel
Cooling Tower	CT	29kW(cooling max.); 24.000 m^3/h fan airflow; 0,54kWel

The trigeneration lab and the climate chamber are shown in figure 3. The trigeneration lab will integrate with the TABS for heating and cooling application in the climate chamber.

Figure 3: Trigeneration unit and climate chamber (CC) at the Institute of Energy System Technologies (INES)

A multiple regression analysis based control algorithm is developed by Schmelas *et al.*, (Schmelas et al., 2015) for the TABS in the climate chamber. It controls the system to maintain a temperature profile in the test chamber and correspondingly a thermal comfort profile corresponding to building standards, e.g. (figure 4).

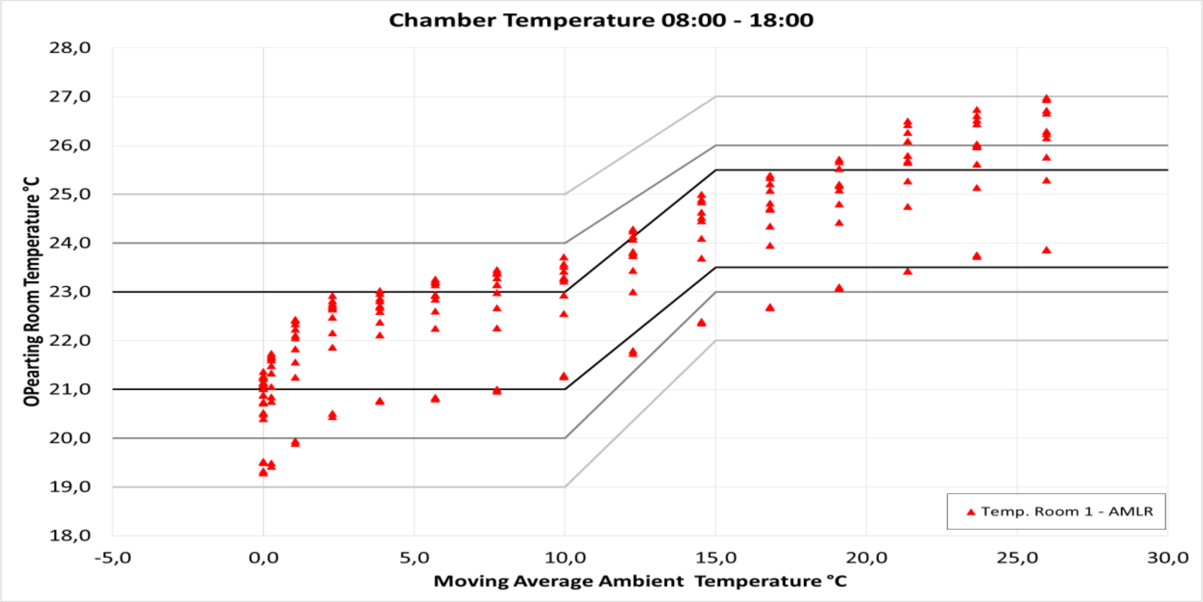

Figure 4: Thermal comfort categories

4.1 Modes of Operation

Different operation modes of the trigeneration system are possible. The basic winter or summer season based operation modes are described in Figures 5 to 8 below.

Winter Electricity Production: Electricity from CHP will be fed to the grid. Heat will be stored and distributed from the hot storage tank as shown in figure 5.

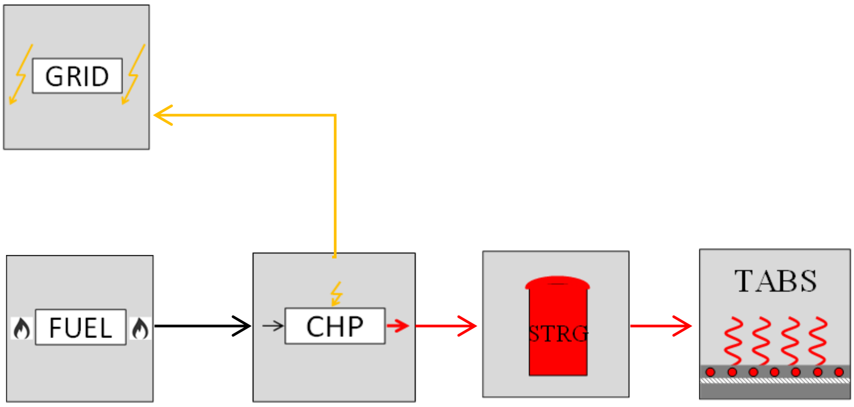

Figure 5: Winter electricity production mode

Winter Electricity Consumption: Electricity will be taken from the grid to operate the reversible heat pump and heat will be stored and distributed from the hot storage tank as shown in figure 6

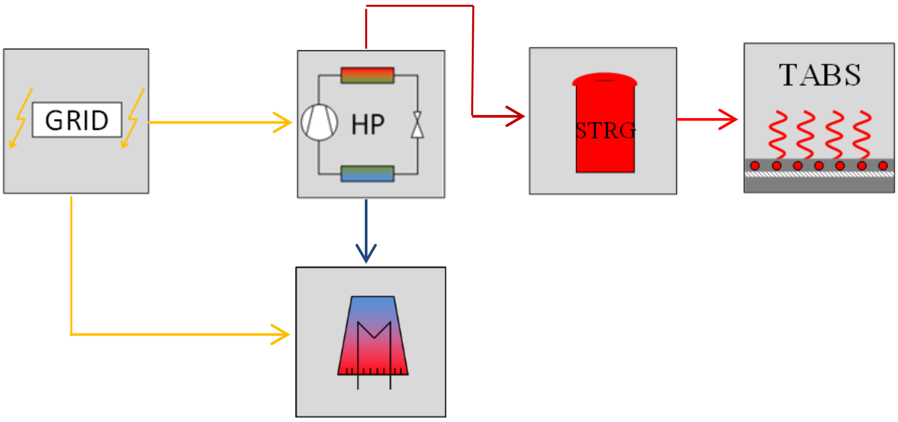

Figure 6: Winter electricity consumption mode

Summer Electricity Production: Electricity from CHP will be fed to grid and heat provided to the adsorption chiller. The chilled water from adsorption chiller will be stored and distributed from the cold storage tank as shown in figure 7

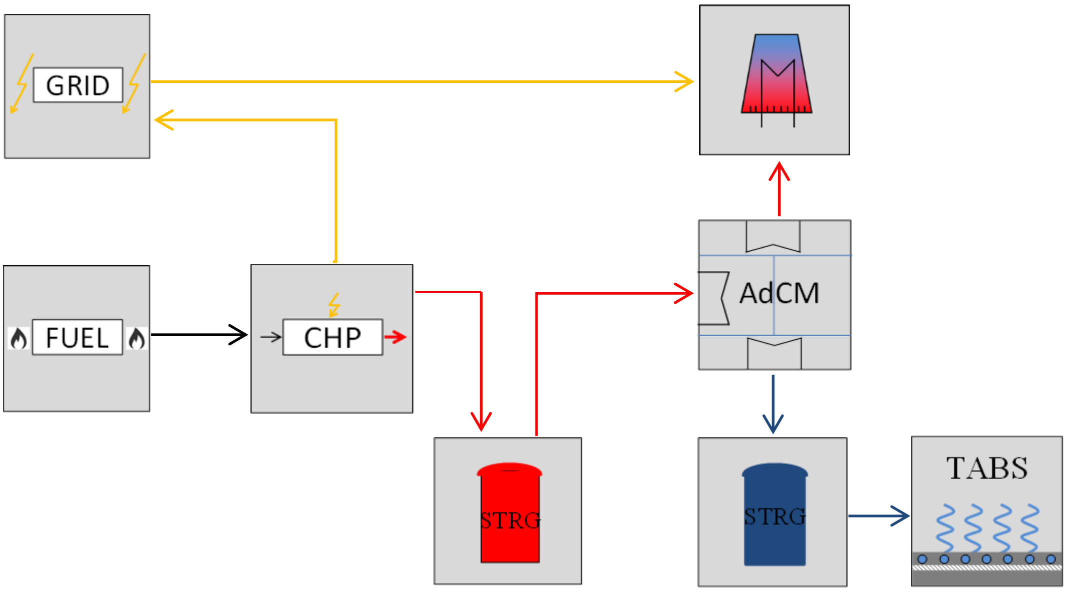

Figure 7: Summer electricity production mode

Summer Electricity Consumption: Electricity from grid will be used to run electrical chiller and chilled water will be stored and distributed from the cold storage tank as shown in figure 8

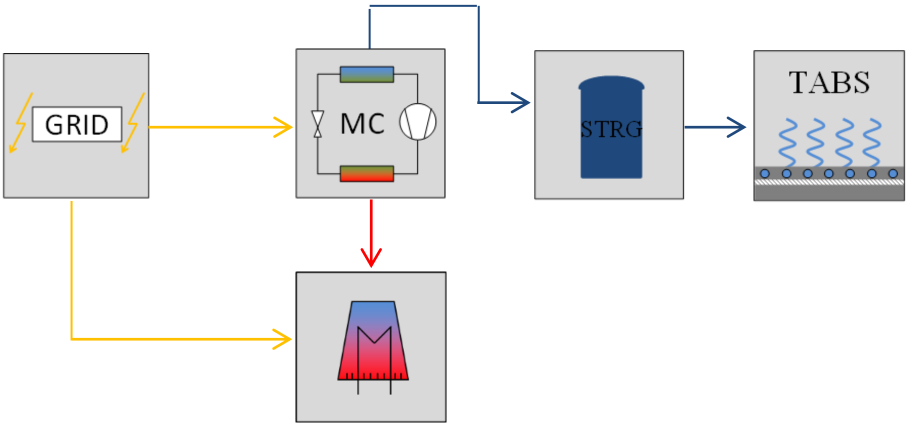

Figure 8: Summer electricity consumption mode

Further advanced operation modes will be analysed to increase overall system efficiency. For instance a step cooling cascade will be developed between the two chillers; where in the thermal chiller will serve as heat sink for the electrical chiller. Here, the higher quality cooling power from the electrical chiller will be supported by waste heat from the CHP and also in turn increase the operating time of the thermal chiller. The possibility to deploy the thermal chiller as a heat pump and the adsorption-desorption exergy balance through stratified storage will also be analysed. The MPC solver will decide on the optimal operation mode in pre-defined time steps for the process shown in figure 9 below:

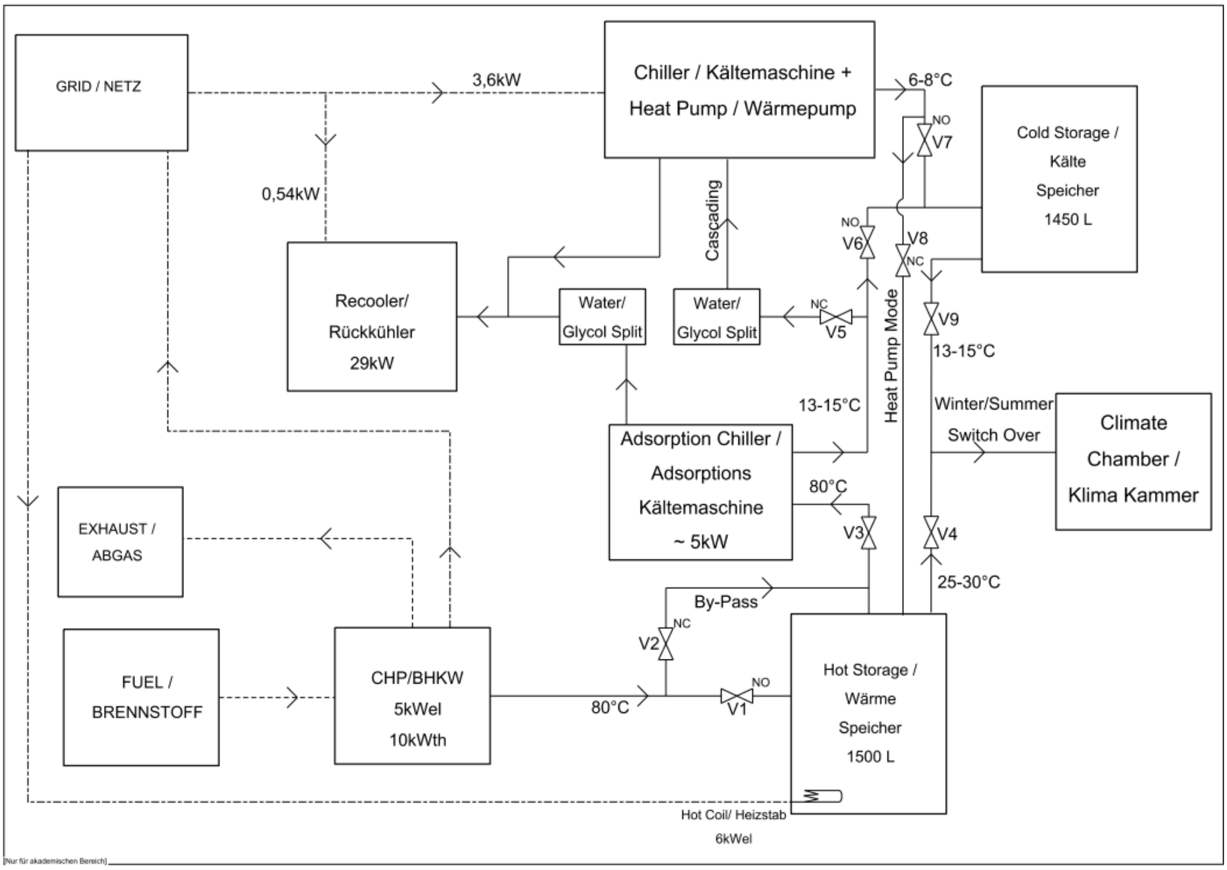

Figure 9: Basic process flow diagram of the trigeneration process

The modi operandi is summarised in terms of the actuating valves in Table 2 below:

Table 2: Valve status for different operation modes

Operation Modes	**Status of Valves**	
	ON	**OFF**
Summer		
Electricity Production	V1, V3, V6, V9	V2, V4, V5, V8, V7
Electricity Consumption	V7, V9	V1, V2, V3, V4, V5, V6, V8
Advanced System Design	V1, V3, V5, V7, V9	V2, V4, V6, V8
Winter		
Electricity Production	V1, V4	V2, V3, V5, V6, V7, V8, V9
Electricity Consumption	V4, V8	V1, V2, V3, V5, V6, V7, V9

The process and instrumentation diagram for the test-rig is shown in figure 10 below. The three primary circuits hot water, cold water and recooling are highlighted with red, blue and green respectively.

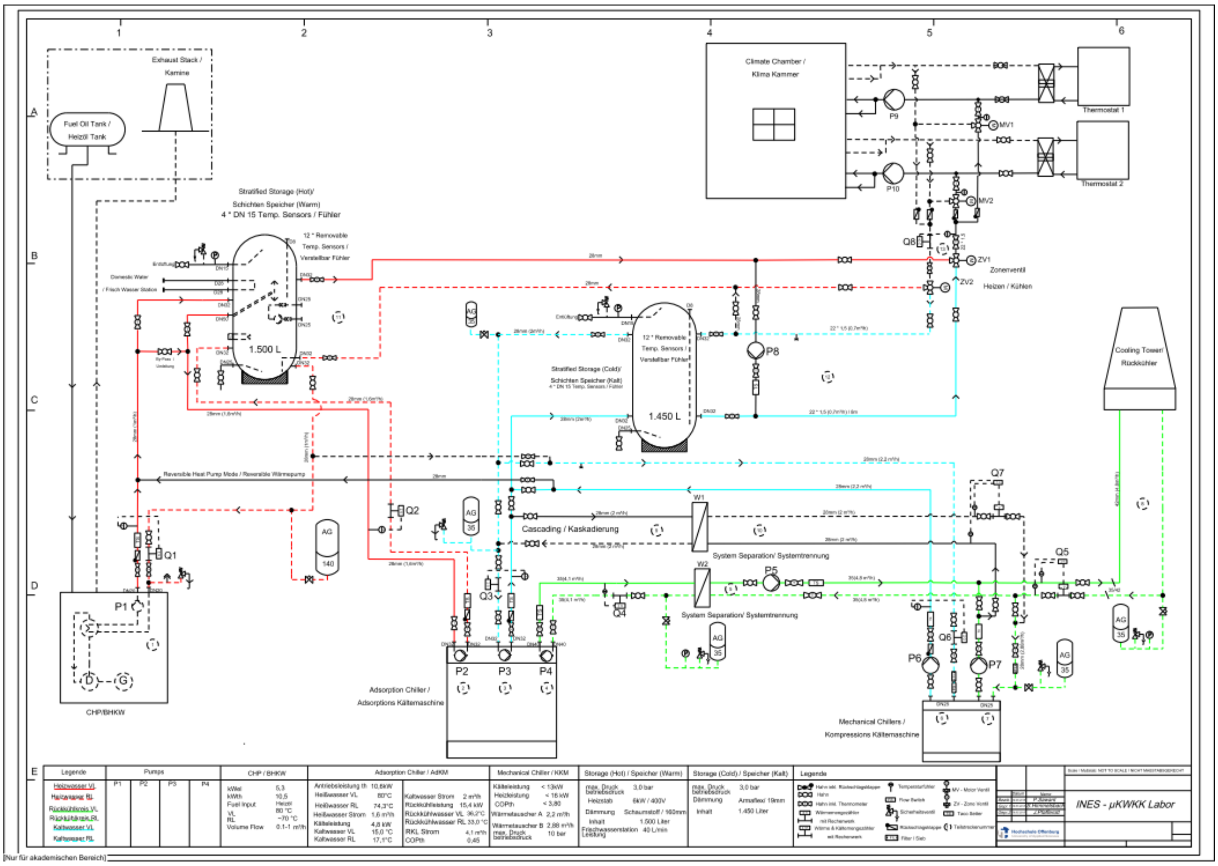

Figure 10: Process and instrumentation diagram of the trigeneration lab

5 CONCLUSIONS

The need for real life experimental analysis of an integrated microscale trigeneration system supported by analytical modelling and simulation is established. An overview of the laboratory set-up and proposed investigation is given. The test facility will help understand the flexibility potential of trigeneration systems for better thermo-electric demand side management in terms of the crowd energy concept and decentralised microgrids.

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