State-of-Art Report

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1. Introduction

Flexible hybrid energy systems like cogeneration and trigeneration systems contribute to the reduction of usage of conventional energy carriers through high efficiency devices and application of renewable energies (Angrisani et al., 2016; Liu et al., 2014). Together with advanced control algorithms, hybrid energy systems offer possibilities to align local electrical power generation, sector-coupling, and decentralised energy supply. In this context, the scope of the Interreg V Upper Rhine project ACA-MODES is on the development of cross-system, grid-friendly operation strategies for sector-coupled hybrid energy systems, with a focus on the inclusion of renewable energy sources.

In the following, Section 2 provides a brief introduction to hybrid energy systems and summarizes the relevant technologies and economic and regulatory frameworks for the ACA-MODES project. An overview on modelling approaches for different applications is given in Section 3. Afterwards, Section 4 presents different approaches for the design of hybrid energy systems and Section 5 different types of control strategies for such systems. This is followed by an overview on existing field studies for the operation and control of hybrid energy system in Section 6 and a short summary of key findings in Section 7.

2. Hybrid energy systems

Hybrid energy systems are defined as integration of multiple technologies for energy conversion and storage to combine sustainability, sector-coupling, and economic objectives into one set-up.

The common features for these systems are:

- decentralised set-up,
- high renewable energy usage,
- flexible operation, and
- micro-scale or small-scale components.

Due to the multitude of possible combinations, hybrid energy systems can deliver highly efficient solutions for energy generation. The different types of technologies and economic-regulatory frameworks corresponding to the planning and operation of hybrid energy systems in the context of this project are outlined in the following.

Technology types

Various technology types are identified in the literature for the planning and design of hybrid energy systems (Jin et al., 2011; Kneiske et al., 2018). Suitability of their application depends, amongst others, on available fuel sources on the generation side, the availability of a grid connection or a heating network, and the considered application scenario. In this scope, utilization of technologies such as:

- photovoltaic systems,
- solar-thermal collectors,
- mini-wind turbines,
- micro-cogeneration systems,
- reversible heat pumps, or
- thermal chillers

can be considered. Typical storage technologies often deployed in these systems are, amongst others,

- water thermal storages,
- ice storages,
- thermally activated building systems, or
- battery storages,

and facilitate load management or demand side management (Bruni et al., 2015; Pfafferott, 2004). In the future, power-to-X elements like, e. g., electrolysis cells powered by renewables, hydrogen storages, and fuel cells will also be involved in available technology types. Finally, on the distribution side, low-temperature heating and high-temperature cooling systems or flexible power storages like electric cars are used.

The technologies under focus of this project are Combined Heat and Power (CHP), solar thermal, adsorption chiller, heat pumps, photovoltaic, battery storage, and water thermal storage. The distribution side would be emulated with thermal and electrical load generators.

Economic and regulatory framework

The economic and regulatory frameworks are complex representations of energy markets, national government policies, and tariffs of the regional distribution grid operators. In the European context, such frameworks are typically designed to strengthen an integration of renewable energies by developing and implementing policies, rules, standards and incentive schemes. The practical implementation of these complex technologies may, however, vary for different countries and locations.

As the projects aims to investigate the optimal control and management of different energy systems in the upper Rhine region, the relevant framework aspects for operation of these cross-border systems were identified as the local electricity tariff structure, feed-in tariff policies, regional or national laws for the particular technologies, and the cross-border trade schemes. Exchanges between two countries are limited by the maximum power flow decided by the transmission system operators over different branches. Within the scope of this project, it is assumed that the EPEX Spot price structure considers this technical limitation, in addition to reflecting the grid's status in terms of consumption and generation profiles, grid congestion, and utilisation of grid connectivity. Due to these reasons it is planned to calculate a combined grid signal, as recommended in certain literature, based on the EPEX prices to be used as a reference variable for the grid-responsive control of the systems (Kalz et al.,2018).

Overview on technology and framework aspects for ACA-MODES

An overview on hybrid energy system technologies considered in the scope of the ACA-MODES project and relevant regulatory and economic information is summarised in *Table 1.* The project relevant information focuses only on specific quantifiable policies and regulations that can influence cross-border operation of such systems, influence planning and operation of the selected technologies, and are established by national governments or local grid operators.

Table 1 Technologies for a hybrid energy system and their relevant economic and regulatory inputs

Technology type	Region	Scale of component	Regulatory framework	Project relevant information	Reference
CHP: Combustion engine	Offenburg, Germany	Microscale <= 5 kW_{el}	KWKG, BAFA, KfW, EEWärmeG, EEG	# CHP-incentives # Promotion without Borders	(BMWi, 2016; Bundesnetzagentur, 2019)
PVT	Strasbourg, France	Microscale	Réglementation thermique 2012	-	
Stirling	Koblenz, Germany	Microscale <= $1kW_{el}$	KWKG, BAFA, KfW, EEWärmeG, EEG	-	
Solar thermal: Collectors	Koblenz, Germany	Microscale Collector area 3-10 m²	BAFA	Funding	(BAFA,2020)
	Karlsruhe, Germany	Medium-scale collector area, ~80 m²	BAFA	Funding	(BAFA,2020)
Heat Pump:	Offenburg, Germany	Heating $16kW_{th}$ Cooling $12kW_{th}$	BAFA	Funding	(BAFA,2020)
Thermal chillers	Offenburg, Germany	Max. $12KW_{th}$	BAFA	Funding	(BAFA,2020)
	Karlsruhe, Germany	Max. $13KW_{th}$	BAFA	Funding	(BAFA,2020)
Grid:	Local grid operators			Tariffs	

3. Modelling of hybrid energy systems

Mathematical models of systems and components can be used for various tasks in the scope of design and operation of hybrid energy systems, such as simulation of behaviour and interaction of components and storage technologies, testing of system design and control strategies, as well as for the development of optimization-based dimensioning and control applications.

It should be noted that the chosen modelling approach can affect the applicability of a model for a certain application to a high extent. While very detailed components models can be a good choice to evaluate the efficiency and consumption of a system within a full-year simulation, simpler models might be required for the optimization-based design or model-predictive control of a system to facilitate suitable computation times.

In order to understand the existing approaches for mathematical modelling of hybrid energy systems and components for use in simulation and (optimization-based) control, a literature analysis was conducted. An overview of models that were identified as potentially relevant for the project and some of their characteristic properties are given in *Table 2.*

Table 2 Illustration of HVAC model classification

	Modelling Class/Methodology	Size/Complexity of Model	Objective of Study/Model	Validation Results	Reference
<u>Adsorption chiller:</u> Silica gel-water	• Nonlinear dynamic white-box models	• > 20 parameters • > 4 states	Study effects of following parameters on the machine's performance: • operating temperatures • switching time • cycle time	Visual, quantitative	(Chua et al., 1999; Li and Wu, 2009; Saha et al., 1995; Sakoda and Suzuki, 1984)
-	• Linear static grey-box model • Energy balance • Constant heat recovery ratio and COP of machine	• 1 state	Application in an NLP algorithm to solve an economic-MPC for optimal scheduling of primary HVAC equipment	-	(Zhao et al., 2015)
<u>CHP:</u> Gas engine	• Linear static grey-box models • Linear interpolation or quadratic regression of predefined parameters for different load factors • Energy balance	• > 2 parameters	Application in an MILP or MINLP algorithm for cost based optimisation to design and operate a CCHP system in a simulation environment	-	(Bracco et al., 2013; Cho et al., 2009a; Ren et al., 2008)
Gas engine micro-CHP	• Nonlinear dynamic input-output black-box model • Transfer function using step-response analysis	• 1 state	Application in active voltage management using a proportional integral controller	Visual	(Hidalgo Rodriguez et al., 2012)
Photovoltaic /thermal (PVT)	• Non-linear dynamic white-box model • Block-oriented modelling • Energy balance • Exergy analysis	• 1 state	Thermodynamic modelling of PVT solar system	-	(R.M. da Silva, et al., 2010; J. Tamayo Vera et al., 2014; G. Evola, et al., 2014)

Heat Pump: Water-to-water heat pump	• Nonlinear static grey-box models • Parameter estimation from catalogue data • Mass and energy balance over chiller internal components	• > 10 Parameters	Application in energy calculation and/or building simulation programs	Visual, quantitative	(Jin and Spitler, 2002)
Air cooled compression chiller	• Nonlinear static grey-box models • Parameter estimation from catalogue data and experimental results • Pressure-enthalpy based mass and energy balance over chiller internal components	• > 10 Parameters	Application in calculation of cooling energy generated and power input required for an air-cooled chiller with limited catalogue data	Visual	(Lemort et al., 2009)
Water storage tank Stratified small-scale tank	• 1-D dynamic multilayer model • Fourier's equation for heat flow • Mass and energy balance per layer • If-else logic for charging/discharging • Effective vertical heat conductivity	• 1 state per layer • < 8 parameters	Simulation of the transient temperatures in a stratified tank. A simplified 2-layer model with 2 states per layer applied in nonlinear MPC for scheduling of a chiller plant in simulation environment	Visual	(Dwivedi, 2009; Eicker, 2006; Ma et al., 2009)
Mixed large-scale tank	• Mass and energy balance • Figure of merit concept • Tank charging and discharging rate as control variable	• 1 state	Application in a MILP algorithm for dynamic optimisation of a chilled water plant design or in a MINLP algorithm for optimal design of a DH network	-	(Henze et al., 2008; Tveit et al., 2009)
Stratified small-scale tank	• 1D dynamic multilayer model • Continuously differentiable model, suitable for optimization-based control applications	• 1 state per layer	Development of simplified dynamic component models of a polygeneration system for use within optimization-based control	Visual, quantitative	(Sawant et al., 2020)

4. Design of hybrid energy systems

For designing a hybrid energy system that is suitable for a certain application, it is important on the one hand to choose appropriate technologies for generation of the desired forms of energy, including considerations on possible interactions, synergies, and redundancies in between technologies, and on the other hand to determine appropriate dimensions for the associated components, including considerations regarding different types of storage technologies.

In the following, three major types of approaches for the composition and dimensioning of hybrid energy systems are presented that can be found in the literature and/or in industrial practice. As the approaches vary in effort and complexity, their suitability should be assessed regarding their expected potential for a specific application.

Design based on best-practices and typical load scenarios

System composition and dimensioning can be conducted according to best practices for a considered application scenario, and/or typical loads for heating, cooling, and electrical energy that are estimated or calculated for a specific application, cf. (Quaschning, 2019). Decisions for selection of technologies and component dimensions can then be based on suggestions provided by, e.g., manufacturer data sheets of considered components.

Illustrated for the example of a CHP, the dimensioning of such a machine can be conducted according to expected heat and/or electricity demand situation, depending on the main focus of a considered application (heat supply, electricity peak shaving etc.). If the heat produced by the CHP is not required during certain periods, it might be considerable to utilize the excess heat for driving an absorption/adsorption cooling machine in case the application yields cooling demands during these periods instead, cf. (Pistohl et al., 2016). In the presence of sporadic peak loads, installation of suitable storage technologies or auxiliary devices can be considered to facilitate installation of smaller dimensioned components.

While utilization of such approaches can be advantageous as their application is rather straightforward and the associated effort is comparatively low, these typically do not provide the possibility to investigate the behaviour and development of a system during operation, such as changing storage temperatures and associated changes in operation efficiency of machinery. However, a more detailed investigation on the interaction of system components during operation and under different load scenarios can reveal potential for optimization of both dimensioning and component utilization, especially in the presence of storage technologies.

Dynamic system simulation

Dynamic system simulations, i. e., simulations that are able to depict the development of the state of a system in the form of temperatures, stored electrical energy etc. over time, facilitate an assessment of the suitability of storage dimensions (Wang et al., 2018) and can depict changes in operation conditions of machinery, revealing potentials for efficiency improvements (Buonomano et al., 2017) and peak load shaving (Marini, 2019). At the same time, these allow for development, testing, and tuning of control strategies for a considered system, cf. (DeConinck et al., 2014).

Compared to "static" planning approaches as presented in the previous section, the effort in preparation and conduction of such dynamic simulations is typically higher. However, without dynamic considerations, assessment of storage capacities and their impact on functionality and operation efficiency of a system might become difficult, as exemplified by (Sourbron et al., 2009). Also, the power and efficiency of technologies such as adsorption cooling can depend strongly on current operation temperatures, cf. (Chang et al., 2007).

While dynamic simulations provide the possibility to tests and tune system configurations and control strategies, such typically require that suitable system configurations are provided by the planner. Especially for large and complex systems, the composition and dimensioning as well as the development of control strategies under different operation conditions can be elaborate, e. g., due to alternative possibilities for realization and interdependencies of synthesis and control strategies, with possibly counter-intuitive optimal solutions, cf. (Buerger et al., 2020).

Optimization based design

Especially for complex systems and in the presence of multiple alternative technologies for energy production and storage, it can be useful to rely on optimization-based approaches for determining a suitable system design. Such approaches allow a planner to let a suitable optimization algorithm determine optimized system designs and dimensions with regard to a chosen objective, such as minimization of cost or emission, cf. (Stadler et al., 2014). Often, these can also directly yield optimized operation strategies for a system, which might not be derived trivially for complex systems where, e. g., multiple technologies can be employed for compensation of a certain demand, cf. (Oluleye et al., 2016).

In the literature, multiple approaches can be found that rely on Mixed-Integer Linear Programming (MILP) techniques, as this problem class yields several advantages, such as the possibility to be solved to global optimality and the availability of powerful numerical solvers, cf. (Urbanucci, 2018), while a variety of linearization techniques have been developed that can replace different nonlinear model formulations, such as piece-wise linearization, cf. (Bohlayer and Zöttl, 2018). Exemplary applications of MILP-based approaches can be found in (Alberizzi et al., 2020), (Lamedica et al., 2018), and (Theo et al., 2016). Apart from MILP-based approaches, also applications of meta-heuristics such as genetic algorithms can be found, cf. (Ismail et al., 2014), (Suresh et al.,2020).

5. Operation of hybrid energy systems

For any application scenario and configuration of a hybrid energy system, the operation strategy is a critical factor governing the system's overall performance. For operation of such systems, either application of conventional control strategies can be considered, or a system can be operated using optimization-based and predictive approaches, as outlined in the following.

Conventional control strategies

For hybrid energy systems based on cogeneration, the two main types of configurations are *Full Load Matching (FLM)*, wherein cogeneration covers the entire electrical or thermal load of system, and *Base Load Matching (BLM)*, wherein the cogeneration unit covers only the base load. Based on the type of configuration, the two main control strategies are *Following Electric Load (FEM)*, where the cogeneration unit follows the electrical load of the system, and *Following Thermal Load (FTM)*, where the cogeneration unit covers the thermal load including requirement of thermal chiller. A comprehensive explanation of the conventional design process and control strategies is given by (Badea, 2014). While their implementation can be comparatively straight-forward, such conventional strategies may not be able to achieve the best possible operation of the system and can therefore lead to considerable waste of energy (M. Liu et al., 2013; P. Liu et al., 2013).

Additionally, information on the weather forecasts and/or predictive usage of storage capacities should be included in a system-wide control strategy (Cho et al., 2014). In the upcoming section, the benefits of optimization based and predictive control strategies are outlined in more detail.

Optimization based, predictive control strategies

Using optimisation algorithms for the operation of hybrid energy systems yields several advantages. On the one hand, operation of the system does not need to rely on a fixed rule set for (de)activation of components, but an optimization method can determine favourable system configurations based on models of system components with respect to a defined operation objective, such as, e. g., minimization of cost or emissions. On the other, such methods facilitate to incorporate not only current measurements from the plant, but also future system behaviour and operation conditions, such as weather conditions, in current control decision, which allows for a predictive operation of a system and utilization of available storage capacities.

Applying optimisation algorithms for the operation of a decentralised trigeneration system has shown promising results for their energy-efficient, sector-coupled (power-to-heat or gas-to-electricity) and grid-reactive scheduling (Al Moussawi et al., 2016; Andiappan, 2017; Cho et al., 2014; Gu et al., 2014; Jradi and Riffat, 2014). Researchers have quantified potential economic benefits of 29 % (Cho et al., 2009b), 8.5 % (Chandan et al., 2012), 9.5 % to 26 % (Kim and Edgar, 2014), 49 % to 84 % (P. Liu et al., 2013) and 8 % to 100 % (Facci et al., 2014) by applying optimal control instead of conventional control to a wide range of stand-alone trigeneration systems or to micro-grids utilising trigeneration systems. Also, a reduction of 50 % in thermal energy wastage of a residential PV-trigeneration system (Liu et al., 2014) and up to 24 % in primary energy consumption and CO_2 emissions of a large-scale trigeneration plant (Ortiga et al., 2013) is reported.

The choice of the optimization algorithm to be used for system operation depends strongly on the time frame of the optimization, the employed system model, the formulated operational constraints, and the desired guarantees on feasibility and optimality of the employed methods. While application of linear modelling and optimization techniques allows for efficient and global optimal solution of the formulated optimization problems, this is not generally possible in the presence of nonlinear model formulations, cf. (Nocedal and Wright, 2006). On the other hand, however, nonlinear modelling might facilitate more flexible options for description of relevant characteristics of system components and constraints.

6. Field studies

Microscale decentralised hybrid energy systems have been a relevant field of engineering research since a few decades. Accordingly, various field studies using different technologies and of different scales have been performed. In *Table 3*, a selection of field studies from the scope of planning and operation of such hybrid systems is presented.

The most significant output of this qualitative analysis was the identification of the need for optimal control of individual decentralised systems and more importantly demonstration of their operation in a centralised grid or microgrid. This finding was is in accordance to the emphasis of this project on development and demonstration of advanced control algorithms for managing decentralised energy systems.

Table 3 Summary of field studies using hybrid energy systems

Technologies	Scale of study	Objective of field study	Location	Project relevant information	Reference
CHP and thermal chillers	Micro and Medium scale systems	Review various CHP and TDC technologies	Freiburg, Germany	# 12 different demonstration projects	(Sicre et al., 2009)
CHP, electrical and thermal chillers	Medium scale systems	Experimentally explore and assess the feasibility of micro- trigeneration systems in the residential sector	Napoli, Italy	# Identified need for optimal control of	(Angrisani et al., 2012)
CHP, solar collector, and adsorption chiller	Microscale	Energy analysis of a trigeneration system	Kempten, Germany	# Reduction in primary energy consumption expected with trigeneration systems	(Becker et al., 2013)
CHP, heat pump and thermal chillers	Microscale	Performance analysis and energy benchmarking	Toronto, Canada	# Identified need for optimal control	(Afram and Janabi-Sharifi, 2015)
CHP, absorption chiller, boiler	Medium-scale	Energy evaluation	Sao Paulo, Brazil	# Benchmarking of technology	(Preter et al., 2010)
Solar thermal, adsorption chiller, gas heater	Medium-scale	Experimental application of MPC for a solar cooling plant	Milan, Italy	Feasibility study for energy system MPC	(Rathod et al., 2019)
Solar thermal, PV, electric heater, battery, water storage	Microscale	Experimental application of MPC for a small-sized building	Astana, Kazakhstan	Feasibility study for energy system MPC	(Khakimova et al., 2017)
PV, batteries (partly used for simulating a CHP), fuel cell, electrolyzer, desalination unit	Microscale	Experimental application of MPC for a microgrid	Pikermi, Athens, Greece	Feasibility study for energy system MPC	(Parisio et al., 2014)

A sophisticated analysis of literature published in the last fifteen years focusing on the field of model predictive control for building energy plants, optimisation of trigeneration systems, optimal scheduling, or economic dispatch of energy systems, was conducted to establish a state-of-art in this field. The results of this analysis are presented in the radar-chart in *Figure 1*[1]

It was concluded that a majority of the work in operation optimisation or optimal control of hybrid systems is performed in a simulation environment, with a focus on calculating the theoretical potential of optimal control for stand-alone or grid-connected CCHP systems. The need to simplify the optimisation problem for these complex systems is reflected in the number of studies using no storage tanks or mixed storage tanks. Due to the popularity of medium-scale and large-scale trigeneration, more studies are conducted for larger systems that deploy absorption-based chillers and/or electric chillers.

On the other hand, a less tackled field of research is the experimental demonstration of optimal control or MPC based strategies for building energy source side (scheduling) in comparison to control of distribution equipment (Bruni et al., 2015). This gap is also identified in works that establish the need for a real-time supervisory controller using optimisation in conjunction with MPC (Jradi and Riffat, 2014; Rong and Su, 2017). The deployment of smaller trigeneration systems in micro-grids and zero energy buildings is a relatively new concept and needs further research. Ensuing from this is also the absence of adsorption chillers in the explored studies, since they are more attractive for micro-scale and small-scale trigeneration systems (Huangfu et al., 2007).

[1] Literature analysed for this section is provided separately in Annex 1 to this report.

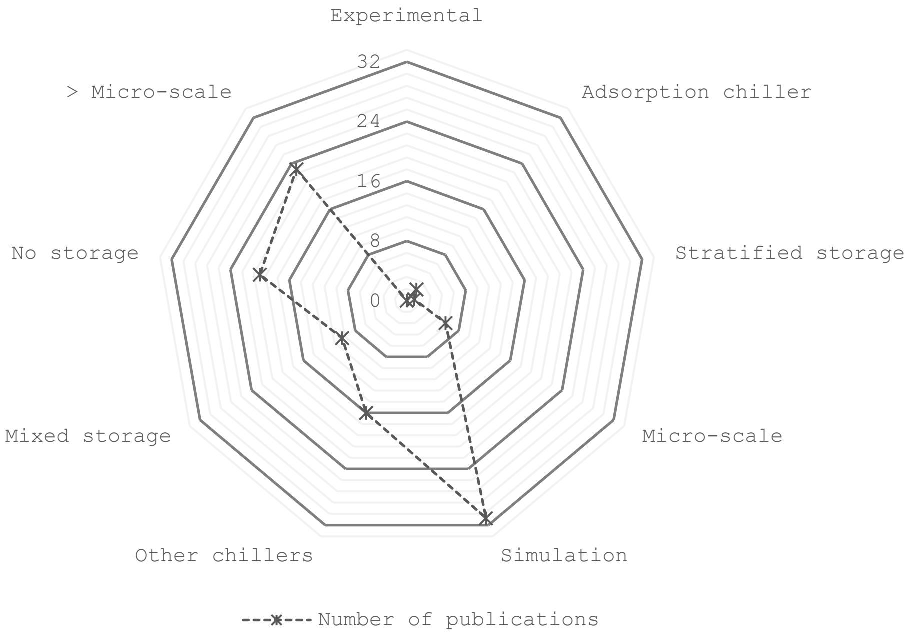

Figure 1 Analysis of literature available on optimization for operation of hybrid energy systems (33 references out of a total 133 references matched the analysis criteria for this investigation).

7. Key findings

The following points summarize the major findings of this report:

- An analysis of existing literature showed that there is great interest in research on various aspects of design and control of hybrid energy systems.

- Optimization-based approaches can yield benefits for both the planning and the operation of energy systems, but can be more elaborate to employ compared to conventional approaches.

- In the terms of detail and complexity, the modelling approach for describing a hybrid energy system should be chosen based on the desired application, as it determines the applicability of optimization-based design and control approaches to a greater extend.

- While the literature provides various simulation studies that reveal the potential for optimization-based control of hybrid energy systems, less experimental studies exist that investigate the applicability of the methods in a real-life context.

8. Glossary

BLM	Base Load Matching
CCHP	Combined Cooling, Heating, and Power
CHP	Combined Heat and Power
DH	District Heating
FEL	Following Electric Load
FLM	Full Load Matching
FTL	Following Thermal Load
HVAC	Heating, Ventilation and Air Conditioning
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Non-Linear Programming
MPC	Model Predictive Control
NLP	Non-Linear Programming
PV	Photo-Voltaic
PVT	Photo-Voltaic Thermal
TDC	Thermally Driven Chillers

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Appendix 1 : Literature research on optimisation for operation of hybrid energy systems

Reference (Years Ascending)	Experimental / Simulation	System Configuration	Chiller Type	Thermal Storage Type	Objective of Optimisation
(Rong and Lahdelma, 2005)	Simulation	• Large-scale power plant • Gas turbine, back-up boiler	None	None	LP to minimize simultaneously the production and purchase costs of three energy components, as well as CO_2 emissions costs
(Ren et al., 2008)	Simulation in the LINGO commercial software package	• Micro-scale system for a two-floor residential building having a total floor area of 250 m² • Gas CHP, back-up boiler	Electric air conditioner	Mixed water storage tank	MINLP determining system's sizes and operational strategies throughout the year
(Wang and Singh, 2008)	Simulation	• 4 PGUs and 2 CHPs • Scale: NA	None	None	Particle swarm optimisation for economic dispatch
(Collazos et al., 2009)	Simulation in a AMPL-CPLEX framework	• Micro-scale for a single family house • Stirling engine CHP and Back-up boiler	None	Mixed water storage tank	MILP for operation cost reduction
(Chicco and Mancarella, 2009)	Simulation	• Medium-scale CCHP for hospital site • 3 micro-turbine CHPs and 6 back-up boilers	2 electric and 2 absorption	None	LP for optimal operation strategy to reduce costs
(Lozano et al., 2009)	Simulation in the LINGO commercial software package	• Medium-scale CCHP • Gas engine CHP, back-up boiler	Electric and absorption	None	LP for optimal operation strategy to reduce costs
(Cho et al., 2009)	Simulation in TRNSYS	• Micro-scale CCHP • Gas CHP, back-up boiler	Absorption	None	LP for optimal design and operation to reduce costs, energy consumption and CO_2 emissions
(Kavvadias and Maroulis, 2010)	Simulation	• Medium-scale CCHP for 300 bed hospital • Gas engine CHP, back-up boiler	Electric and absorption	None	GA for multi-objective design optimisation
(Chandan et al., 2012)	Simulation in MATLAB	• Largescale CCHP • Gas turbine CHP, steam turbine, back-up boilers	7 electric	Stratified water storage tank	NLP look-ahead optimization problem to minimise the operating cost of the plant
(Cole et al., 2012), 5 papers were of interest in this review work but only 1 met the scope of this tabular analysis	Simulation: Sancho-Bastos, Dotzauer, Caldon	• Large-scale gas and steam turbine CCHP: Sancho-Bastos, Dotzauer • Virtual power plant: Caldon	• Absorption: Sancho-Bastos • None: Dotzauer, Caldon	• General storage: Dotzauer, Caldon • None: Sancho-Bastos	LP for optimal control: Sancho-Bastos DP for economic dispatch: Dotzauer NLP for optimal operation: Caldon

(P. Liu et al., 2013), 8 papers were of interest in this review work but only 1 met the scope of this tabular analysis	• Simulation: Tetsuya, Shaneb, Bosman, Naraharisetti, Kwok, Ren, Morais, Mehleri	• Micro-scale residential micro-grid: Tetsuya, Shaneb, Bosman, Naraharisetti, Kwok, Mehleri, Morais • Medium-scale CCHP: Ren	• Electrical: Ren • None: Tetsuya, Shaneb, Bosman, Naraharisetti, Kwok, Mehleri, Morais	• General storage unit: Shaneb, Bosman, Ren, Mehleri • None: Tetsuya, Naraharisetti, Kwok, Morais	Optimal scheduling with: • LP: Shaneb • MILP: Tetsuya, Bosman, Naraharisetti, Kwok, Mehleri, Morais, Ren
(Ortiga et al., 2013)	Simulation in GAMS	• Large-scale CCHP for urban district • Gas engine CHP, back-up boiler	Absorption	None	LP for optimal operation strategy to reduce costs
(Bracco et al., 2013)	Simulation	Medium-scale to Largescale with multiple gas turbine and engine CHPs	None	None	MILP for system selection, sizing and configuration
(Zhang et al., 2013)	Simulation in a GAMS-CPLEX framework	• Small-scale CHP for smart building with multiple homes and smart appliances • Back-up boilers	None	General storage unit	MILP for adjusting smart building production and consumption patterns
(M. Liu et al., 2013)	Simulation in MATLAB with fmincon.m	• Small-scale for Hotel • Gas engine CHP, back-up boilers	Electric and absorption	None	SQP for cost reduced operation
(Li et al., 2014)	Simulation	• CCHP for residential building • Gas CHP and back-up boilers	Electric air conditioner and absorption	Mixed water storage tank	NLP for capacity and configuration optimisation
(Flores et al., 2014)	Simulation	• Medium-scale for buildings • CHP, back-up boilers	None	None	Economic dispatch
(Facci et al., 2014)	Simulation	Largescale system for hospital Gas engine CHP, back-up boiler	Mechanical and absorption	None	Backward dynamic programming for operation optimisation to reduce costs
(Kim and Edgar, 2014)	Simulation	• Largescale CCHP for university campus • Gas turbine CHP, steam turbine, back-up boilers	Electric	None	MINLP for economic dispatch
(Cho et al., 2014), ca. 20 papers were of interest in this review work but only 2 met the scope of this tabular analysis	Simulation: Sakawa, Guo	• No scale: Sakawa • Boilers: Sakawa • Gas engine and micro-turbine CCHP: Guo • Medium-scale CCHP micro-grid: Guo	Absorption: Sakawa Absoprtion and electric: Guo	• None: Sakawa • Mixed thermal storage: Guo	MILP for operational planning: Sakawa, Guo
(Jradi and Riffat, 2014), 5 papers were of interest in this review work but only 1 met the scope of this tabular analysis	Simulation: Wu	• Gas engine and back-up boiler CCHP: Wu	Adsorption and electric: Wu	None: Wu	MINLP for operational optimisation: Wu
(Gu et al., 2014), 5 papers were of interest in this	No new papers	-	-	-	-

review work but none met the scope of this tabular analysis					
(Liu et al., 2014), ca. 10 papers were of interest in this review work but only 2 met the scope of this tabular analysis	Simulation: Zafra, Nosrat, Hashemi	• CHP: Zafra • Micro-scale PV-CCHP: Nosrat • Medium-scale CCHP: Hashemi	None: Zafra Absorption: Nusrat, Hashemi	• None: Zafra • General storage: Nusrat, Hashemi	MPC: Zafra Rule-based dispatch: Nusrat Offline NLP: Hashemi
(Di Somma et al., 2015)	Simulation in MATLAB-CPLEX	• Medium-scale building • Gas turbine CHP and reversible heat pump	Electric reversible heat pump and absorption	Mixed water storage tank	MILP for operation optimisation
(Parisio et al., 2015)	Simulation in Virtual MicroGrid Lab and CPLEX	• Small-scale residential micro-grid • CHPs and reversible heat pumps	Electric	None	MILP for minimising overall cost
(Zhao et al., 2015)	Simulation in MATLAB	• Medium-scale for building • CHP, back-up boiler, Photovoltaic	Electric and adsorption	Mixed water storage tank	NLP for cost reduced optimisation
(Ünal et al., 2016)	Simulation in Visual-Basic using Simplex in Microsoft Excel Data Solver	• Large-scale CCHP for food industry • 4 Gas CHPs, back-up boiler	Mechanical and absorption	None	LP for optimal operation strategy to reduce costs
(Menon et al., 2016)	Simulation	• Micro-scale CHP in a micro-grid • CHP and heat pumps	Electric	Mixed thermal storage	MILP for electricity price based optimised operation
(Fuentes-Cortés et al., 2016)	Simulation in BARON-GAMS framework	• Medium-scale for building with 420 households • Engines, fuel cells, microturbines, Stirling engines, solar water heaters as technology options.	Absorption	None	MINLP multi-objective for design optimisation and control optimisation
(Murugan and Horák, 2016), ca. 5 papers were of interest in this review work but none met the scope of this tabular analysis	No new papers	-	-	-	-
(Al Moussawi et al., 2016), ca. 5 papers were of interest in this review work but none met the scope of this tabular analysis	No new papers	-	-	-	-
(Rong and Su, 2017), ca. 40 papers were of	• Simulation in EES: Ghaebi, • Simulation in AIMMS-CPLEX Framework: Ameri	• Gas tubine CCHP: Ghaebi, Ameri • Large-scale CCHP micro-grid: Ameri, Savola	• Absorption: Ghaebi, Ameri	None: Ghaebi, Ameri	Optimal scheduling with: • Genetic algorithm: Ghaebi • MILP: Ameri

interest in this review work but only 2 met the scope of this tabular analysis	• Simulation in GAMS-BnB Framework:Savola		• Electrical: Ameri • None: Savola		• MINLP: Savola
(Andiappan, 2017), ca. 10 papers were of interest in this review work but only 2 met the scope of this tabular analysis	• Simulation in CPLEX Framework: Bischi, Yokoyama	• Large-scale CCHP micro-grid: Bischi • Small-scale CCHP: Yokoyama	Electric and absorption: Bischi, Yokoyama	• General storage: Bischi • None: Yokoyama	MILP for system planning and operation: Bischi, Yokoyama
(Gu et al., 2017)	Simulation in MATLAB-GUROBI framework	• Medium-scale CCHP for a building • Gas turbine CHP, wind turbine, photovoltaic, back-up boiler	Electric and absorption	Mixed thermal storage	MILP for online optimal operation
(Zhang et al., 2017)	Simulation	• Medium-scale CCHP • Gas turbine CHP	Absorption	None	Linear MPC for optimal scheduling
(Kneiske et al., 2018)	Simulation in a Python-CPLEX framework	• Micro-scale CHP • Gas engine CHP, photovoltaic and back-up boiler	None	Mixed thermal storage	MPC based combined control for PV-CHP hybrid system
(Urbanucci, 2018), ca. 4 papers were of interest in this review work but only 1 met the scope of this tabular analysis	Simulation in MATLAB-GAMS framework: Carlos	• Large-scale CCHP micro-grid for tourist resort: Carlos	Electric and absorption: Carlos	None: Carlos	NLP: Carlos

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