PAPER • OPEN ACCESS

An energy-economic analysis of real-world hybrid building energy systems

View the article online for updates and enhancements.

You may also like

An energy-economic analysis of real-world hybrid building energy systems

Parantapa Sawant[1], Christian Braasch[2], Manuel Koch[3], Adrian Bürger[4], Sonja Kallio[5]

[1]Offenburg University of Applied Sciences, Badstrasse, Offenburg, Germany
[2]Koblenz University of Applied Sciences, Konrad-Zuse-Straße, Koblenz, Germany
[3]University of Applied Sciences and Arts Nortwestern Switzerland, Muttenz, CHE
[4]Karlsruhe University of Applied Sciences, Moltkestraße, Karlsruhe, Germany
[5]ICUBE, INSA University of Strasbourg, Boulevard de la Victoire, Strasbourg, France

parantapa.sawant(a)hs-offenburg.de

Abstract. A coordinated operation of decentralised micro-scale hybrid energy systems within a locally managed network such as a district or neighbourhood will play a significant role in the sector-coupled energy grid of the future. A quantitative analysis of the effects of the primary energy factors, energy conversion efficiencies, load profiles, and control strategies on their energy-economic balance can aid in identifying important trends concerning their deployment within such a network. In this contribution, an analysis of the operational data from five energy laboratories in the trinational Upper-Rhine region is evaluated and a comparison to a conventional reference system is presented. Ten exemplary data-sets representing typical operation conditions for the laboratories in different seasons and the latest information on their national energy strategies are used to evaluate the primary energy consumption, CO_2 emissions, and demand-related costs. Various conclusions on the ecologic and economic feasibility of hybrid building energy systems are drawn to provide a toe-hold to the engineering community in their planning and development.

1. Introduction

Hybrid building energy systems such as PV-heat pump and trigeneration units that facilitate higher energy-efficiency and usage of renewable energy in buildings have been studied for many years. However, with the dawn of modern energy networks with more decentralization, digitalization, prosumer coordination, and sector-coupling, advanced control for such systems has come into focus [1], [2]. Such advance control methods not only facilitate the utilization of the technical flexibility of individual systems (storage, combination of different energy sources, and operation modes), but also the coordination between them to support the energy grid of the future having a high share of volatile renewable energy. Although micro-scale (< 15 kW$_{el}$) and small-scale (< 50 kW$_{el}$) systems may not have a significant impact on the energy grid individually, and may not always have large economic benefits, recent studies have shown the advantages of a coordinated operation of many such systems in a neighborhood or campus in terms of supporting the energy transition on a regional level [3], [4]. One of the goals of the trinational (Switzerland, Germany, and France) research project "Advanced Control Algorithms for Management of Decentralised Energy Systems" (ACA-MODES) is to demonstrate a

real-time coordinated operation of multiple energy laboratories (plants) spread over the Upper Rhine region. In order to evaluate different variants of such a coordinator in terms of its possible benefits in socio-economic or energy-environmental aspects an evaluation tool is needed for a quick and reliable comparison of experimental data from the laboratories.

Previous studies have reported on such tools using both simulation results and experimental data and have often presented results of a sensitivity analysis, evaluating the effects of parameter variations like fuel costs, component sizes, and efficiencies on a plant level [5], [6]. Similar work was also done in the ACA-MODES project for evaluating experimental data of the individual labs in a parameter analysis revealing benefits and detriments of hybrid systems with respect to the energy policies of their country of installation [7]. The current study adds to existing knowledge by comparing operational data of typical hybrid systems under almost identical conditions.

In Section 2, the methodology for this analysis is explained, including an introduction to the different laboratories and the evaluation tool. Important results and a brief discussion of the findings are presented in Section 3. Finally, concluding remarks are provided to aid in planning and development of hybrid renewable energy systems for buildings.

2. Methodology

For analyzing the performance of different types of hybrid systems, operational data from five energy laboratories in the trinational Upper-Rhine region was used. Each laboratory consists of a renewable energy system in the built environment and various primary HVAC components, such as heat pumps (HP), cogeneration units (CHP), adsorption chillers (AdC), compression chillers (CC), photovoltaics (PV), and solar-thermal collectors (ST) are installed in the different locations. A hysteresis dead-band logic over the storage temperature was used as conventional control in the tests. Experiments with a duration varying between 5 hours to 3 days representing both short- and long-term system dynamics were performed and the data-sets were filtered using 15-minutes mean values. In addition to evaluating typical performance factors such as thermal and electrical efficiencies for cogeneration units and coefficient of performance (energy efficiency ratio) for heat pumps (compression chillers), following operational key performance indicators (KPI) were also evaluated for each system: (a) primary energy consumption (PEC), (b) CO_2 emissions, and (c) Demand-related costs. These indicators were selected based on the three-task method for stakeholder identification and bi-method for KPI selection [8] and would also be later used in the project for forming the mathematical framework to coordinate the operation of the various energy labs. Additionally, the analysis with these operational KPIs makes it possible to compare the regulations and demand-related costs of the plants according to their locations (to a certain extent countries) and allow both internal (plant planners and operators) and external (regulators) stakeholders to draw key information for multi-level energy performance analysis. The PEC of a plant Q_{pe} is calculated using the final energy produced in the plant Q_{fe} and the non-renewable part of the primary energy factor (PEF) f_{pe} for its location as shown in (1). Similarly, the total CO_2 emissions EM_{total} and demand-related costs for the final energies $Cost_{fe}$ were calculated in (2) and (3) respectively. Here, f_{EM} is the emission factor for the respective final energy and $Price_{fe}$ is its purchasing price.

$$Q_{pe} = Q_{fe} f_{pe} \qquad (1)$$

$$EM_{total} = Q_{fe} f_{EM} \qquad (2)$$

$$Cost_{fe} = Q_{fe} Price_{fe} \qquad (3)$$

2.1. Energy laboratories

To show the variety of components and their sizes, pictures of the individual laboratories are shown in *Figure 1*. The main components are listed in *Table 1*. Detailed information on the set-up of the

laboratories and examples of the building automation and control framework can be found in previous works of the authors [9], [10].

Figure 1 (a) Polygeneration lab in Offenburg University of Applied Sciences (HSO), (b) Solar cooling lab in Karlsruhe University of Applied Sciences (HKA), (c) Trigeneration lab in Koblenz University of Applied Sciences (HSKo), (d) Micro-cogeneration lab in National Institute of Applied Sciences Strasbourg (INSA), (e) Building technologies lab at University of Applied Sciences and Arts Nortwestern Switzerland (FHNW)

Table 1 A selection of components in the five energy laboratories

	HSO	HKA	HSKo	FHNW	INSA
Adsorption chiller (AdC)	x	x	x		
Battery storage				x	x
Compression chiller (CC)	x				
Micro-cogeneration (CHP)	x		x		x
Cooling tower (dry)	x	x	x		
Heat pump (HP)	x			x	
Photovoltaics (PV)				x	x
Photovoltaic-Thermal (PVT)					x
Solar-thermal (ST)		x	x	x	
Water storage	x	x	x	x	x
Thermal load emulator	x	x	x	x	
Electrical load emulator				x	

2.2. KPI parameters and data collection

The parameters for the three countries are summarized in *Table 2*, *Table 3*, and *Table 4*, with original data available in a previous work of the authors and other reports [7], [11], [12]. The PEF for fossil fuels is similar in all countries. However, the PEF for electricity is considerably higher in France and Switzerland considering high import of electricity. However, France and Switzerland have a lower emission factor for the general electricity mix, owing to the higher share of nuclear energy in their energy mix. The electricity buying price in Germany is higher than the other two countries. Additionally, due to the *CHP-Act* in Germany, the selling price for CHP electricity is higher than the other two countries. The selling price for PV is highest in the Swiss system. The selling price in France are the lowest amongst the three countries.

It is noticeable that the PEF and CO_2 emission factors are also a reflection of the energy mix of the respective countries, with more renewables in Germany, compared to more nuclear energy in France and Switzerland [13].

Table 2 A selection of primary energy factors (PEF) used in the study.

		France	Germany	Switzerland
Fossil fuels	Fuel oil	1.0	1.1	1.2
	Natural gas	1.1	1.1	1.1
Electricity	Electricity mix	2.58	1.8	2.5

Table 3 A selection of CO_2 emission factors used in the study [kg CO_2/kWh].

	France	Germany	Switzerland
Electricity mix	0.057	0.485	0.090
Fuel oil	0.325	0.294	0.288
Natural gas	0.227	0.202	0.205
Diesel	0.322	0.266	0.293

Table 4 A selection of fuel and electricity rates used in the study [€/kWh].

	France	Germany	Switzerland
Electricity purchase price	0.155	0.298	0.193
Electricity selling price (CHP)	0.093	0.151	-
Electricity selling price (PV)	0.060	0.089	0.122
Natural gas	0.084	0.061	0.090

2.3. Reference system

A virtual reference system representing separate production of electricity, heating, and cooling was applied for comparison. It was designed with a condensing boiler (η_{th} = 95 %) for heating, including auxiliary and distribution energy operating on natural gas, and a compression chiller (energy efficiency ratio = 4.0) for cooling using local grid-electricity. All electricity requirements were satisfied over the local grid. Since no storages were considered for the reference system, the energy differences in heat and cold-water storages in the laboratories are considered in the reference system by increasing or decreasing energy production.

3. Results and discussion

For sake of brevity, the results of operational data for only 10 exemplary data-sets from four types of hybrid systems representing typical operation conditions for the laboratories in different seasons and scenarios is presented. Other hybrid systems and more data-sets will be evaluated extensively in a future work by the authors. The load profiles were synthetically generated for different types of buildings and one test typically lasted for 10 hours to 15 hours.

In **Figure** *2* results of (a) Stirling engine-based CHP and (b) combustion engine-based CHP are shown. Here, under similar load profile scenarios for a building with low thermal load, it is seen that the combustion engine-based CHP provides significant PEC and cost savings compared to the Stirling engine-based CHP due to its higher electrical efficiency, especially for systems with low thermal loads. However, the CO_2 emissions are higher especially in France and Switzerland due to their electricity mix's lower emission factor. Both cogeneration systems show higher economic benefits for Germany due to the incentives provided by the German energy policy for micro-scale cogeneration systems.
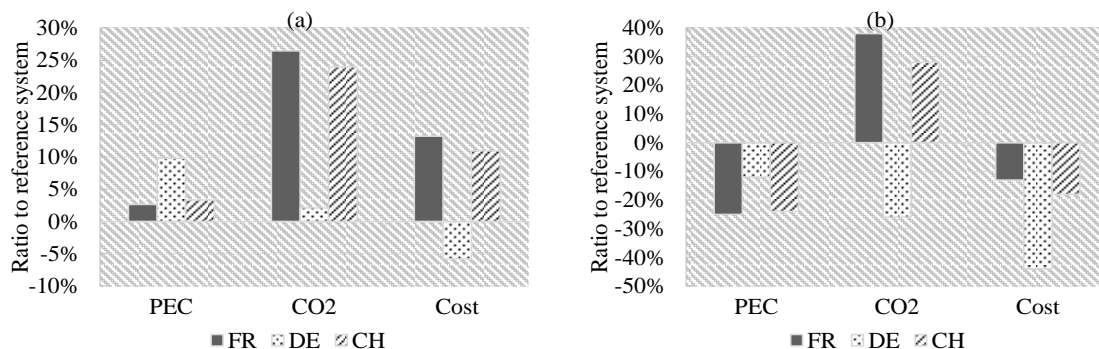

Figure 2 Results for CHP compared to the reference system (a) Stirling engine-based CHP (b) Combustion engine-based CHP. Negative values indicate saving.

In *Figure 3,* results for (a) a grid-only HP system and (b) a PV supported HP system are shown. The HP based system has lower PEC and CO_2 emission, compared to the reference system in all cases. The magnitude in savings cannot be compared directly between both systems, as the load profiles varied significantly. However, it is clearly observed that the PV supported system leads to lower purchase of electricity from the grid, i.e. higher savings. The grid-only HP system has higher operating costs in Germany due to the higher purchase price of electricity.
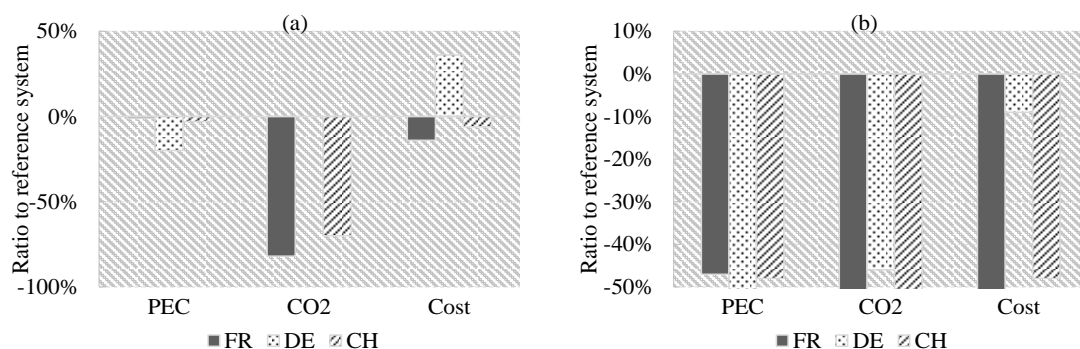

Figure 3 Results for HP compared to the reference system (a) Grid-HP system (b) PV-HP system. Negative values indicate saving.

4. Conclusion

The analysis showed that country-specific factors have a significant impact on ecologic and economic aspects of the different hybrid energy systems. An energy system which reduces two or more criteria in one country, can show negative impacts in another country. A preliminary investigation revealed that

good knowledge of system design and operation of the hybrid systems is needed to ensure its efficient operation compared to conventional systems, and justify its higher complexity and investment costs. While CHP systems only receive subsidies in Germany, it is shown that they would also be beneficial in France and Switzerland. However, the design and control of these systems must incorporate a high electrical and overall efficiency of the prime mover and high full load operating hours. The heat pump showed good results in all three countries, especially when combined with PV. For comparative studies in the European context, an in-depth discussion of cross-national evaluation criteria is necessary for providing meaningful recommendations on regionally interconnected energy systems in the future energy grid.

References
[1]   J. Drgoňa *et al.*, "All you need to know about model predictive control for buildings," *Annu. Rev. Control*, Sep. 2020, doi: 10.1016/j.arcontrol.2020.09.001.
[2]   G. Serale, M. Fiorentini, A. Capozzoli, D. Bernardini, and A. Bemporad, "Model Predictive Control (MPC) for Enhancing Building and HVAC System Energy Efficiency: Problem Formulation, Applications and Opportunities," *Energies*, vol. 11, no. 3, p. 631, Mar. 2018, doi: 10.3390/en11030631.
[3]   J. Seifert *et al.*, "Regionales Virtuelles Kraftwerk auf Basis der Mini- und Mikro-KWK Technologie," Dresden, 2015.
[4]   D. Kalz *et al.*, "Grid-supportive buildings and districts: Buildings relieve power grids," *BINE Information Service: Themeninfo I /2018 A compact guide to energy research*, p. 24, 2018.
[5]   G. Angrisani, A. Akisawa, E. Marrasso, C. Roselli, and M. Sasso, "Performance assessment of cogeneration and trigeneration systems for small scale applications," *Energy Convers. Manag.*, vol. 125, pp. 194–208, 2016, doi: 10.1016/j.enconman.2016.03.092.
[6]   M. D. Schicktanz, J. Wapler, and H. M. Henning, "Primary energy and economic analysis of combined heating, cooling and power systems," *Energy*, vol. 36, no. 1, pp. 575–585, 2011, doi: 10.1016/j.energy.2010.10.002.
[7]   ACA-MODES, "Energy-and socio-economic analysis of (existing) field studies," Offenburg, 2020. [Online]. Available: https://aca-modes.insa-strasbourg.fr/wp-content/uploads/2020/08/WP3_Report.pdf.
[8]   Y. Li, J. O'Donnell, R. García-Castro, and S. Vega-Sánchez, "Identifying stakeholders and key performance indicators for district and building energy performance analysis," *Energy Build.*, vol. 155, pp. 1–15, Nov. 2017, doi: 10.1016/j.enbuild.2017.09.003.
[9]   P. Sawant and J. Pfafferott, "Experimental Analysis of Microscale Trigeneration Systems to Achieve Thermal Comfort in Smart Buildings," in *36th AIVC Conference, 5th TightVent Conference, 3rd venticool Conference*, 2015, pp. 309–319.
[10]   A. Bürger *et al.*, "Experimental operation of a solar-driven climate system with thermal energy storages using mixed-integer nonlinear MPC," *Optimization Online*, 2019. http://www.optimization-online.org/DB_HTML/2019/10/7422.html (accessed Jan. 29, 2021).
[11]   BMWi, *Kraft-Wärme-Kopplungsgesetz Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung*. Germany, 2016.
[12]   P. Pannier, M;Pehnt, N;Langreder, A;Hermelink, "Untersuchung zu Primärenergiefaktoren, Leistung gemäß Rahmenvertrag zur Beratung der Abteilung II des BMWi," Heidelberg, 2018. [Online]. Available: https://www.gih.de/wp-content/uploads/2019/05/Untersuchung-zu-Primärenergiefaktoren.pdf.
[13]   IEA, "IEA World Energy Balances database," 2018. www.iea.org/statistics.