WP3 Report

Work Package Energy- and socio-economic analysis of (existing) field studies	
Date/Time 2020-08-14	Output ID 92298
Work package begin 2019-09-01	Work Package end 2020-06-30

List of symbols and abbreviations

Abbreviation	Definition	Unit
AdC	adsorption chiller	
BAT	battery	
CC	compression chiller	
CCHP	combined cooling, heat and power	
CHP	combined heat and power	
COP	coefficient of performance (for heat pumps)	
CWS	cold water storage	
EER	energy efficiency ratio (for chillers)	
el	electrical	
FE	final energy	kWh
HP	heat pump	
HWS	hot water storage	
PE	primary energy	kWh
PEF	primary energy factor	
PV	photovoltaic	
STC	solar thermal collector	
th	thermal	
V	volume	m^3
η	efficiency	

1. Introduction

Research objectives

The overall aim of the project ACA-MODES is the development of advanced algorithms to control energy systems consisting of a variety of thermal and electrical power generation units, so called hybrid systems. The control algorithms are able to optimize both, a single hybrid system as well as various connected systems to supply local areas. Optimization goals are either reduction of operation costs, emissions or primary energy consumption or to relieve the public grid considering the growing share of volatile energy sources.

Six partners are collaborating in the ACA-MODES project, five of them bringing in one of these hybrid systems. In the beginning, these systems are operated with regular or standard control algorithms. The control setpoints, e.g. hysteresis dead-bands for storage temperatures and ambient temperature operational limits, are not unified among the partners.

Work Package 3 is documented in this report. It covers the effectiveness of the included energy systems, based on several criteria, which are:

1. primary energy consumption,

2. CO_2 emissions,

3. costs

Later on, this information will be used to compare the pursued advanced control algorithms with the conventional controls, thus to be able to evaluate the achieved improvements.

Exergy will not be considered here, because it became clear that the fact of non-uniformity of the different systems and applications would lead to huge complex input sets and incoherence, which would lower the clarity and interpretability. Exergy is rather suitable to evaluate the system behavior of a single system described in detail.

Methodology

Existing field studies from five different laboratories with different energy systems are analyzed regarding primary energy consumption, CO_2 emissions as well as regarding fuel and electricity costs for typical load cases. All systems are capable of producing electricity, heat or cold or a combination of them. The results are compared with a defined reference system. All energy systems are conventionally operated by ON/OFF or PID controllers.

A calculation template for all partners is used for the calculation of the primary energy savings, carbon dioxide emissions and the fuel and electricity costs. The input data are 15 minutes mean values. Periods between 5 hours and 3 days are investigated depending on the lab and case. A screenshot of this template is shown in Appendix A.

The calculation is executed according to current French, German and Swiss factors for primary energy, CO_2 emissions and costs. The results are discussed separately for each country, as the current technical and socio-economic conditions in each country are different.

Based on these evaluations, various action recommendations for designing energy systems to improve the regional efficiency and sustainability are established.

Costs for investment and maintenance are not included as the goal is to optimize control.

Locations and laboratories

A short description of the laboratories of the different partners and the specifications of the relevant components for the experimental analysis of a hybrid system are given in Figure 1 to Figure 6.[1]

At the **Hochschule Koblenz** a Stirling engine is used as CHP for a winter case (heating and electricity production). An adsorption chiller combined with simulated solar thermal input covers a typical summer case (cooling demand). There are two water storages, one for heat and another for cold storage each with a nominal water volume of V = 1.0 m³. A dry-cooler is installed outside the lab building.

components	abbr.	specification
combined heat and power (Stirling)	*CHP*	P_{el} = 0.7 kW P_{th} = 5.0 – 7.0 kW η_{th} = 85 % η_{el} = 10 %
hot water storage	*HWS*	V = 1.0 m³

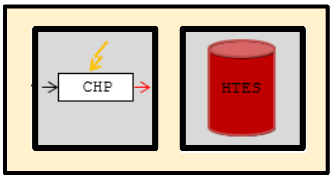

Figure 1: Nominal data and setup for CHP with HWS at Hochschule Koblenz

components	abbr.	specification
solar thermal collectors	*STC*	~29.6 m² flat plate STC, ~17.3 m² vacuum tube STC
hot water storage	*HWS*	V = 1.0 m³
adsorption chiller	*AdC*	P_{th} = 10.0 kW; EER_{th} = 0.65
cold water storage	*CWS*	V = 1.0 m³

Figure 2: Nominal data and setup for solar cooling at Hochschule Koblenz

A micro-scale trigeneration system with a combustion engine cogeneration unit, an adsorption based thermal chiller, a reversible heat pump, a compression chiller, hot and cold-water thermal storages, and two-way connection to the electricity grid is installed at the Institute of Energy Systems Technology (INES) at **Hochschule Offenburg** (Offenburg University of Applied Sciences) [1].

components	abbr.	specification
heat pump	*HP*	P_{th} = 16.7 kW P_{el} = 3.8 kW COP_{el} = 4.45
hot water storage	*HWS*	1.5 m³

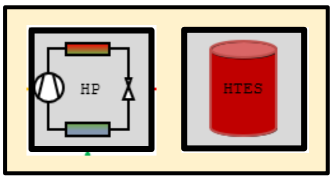

Figure 3: Nominal data and setup for heat pump operation at Hochschule Offenburg

components	abbr.	specification
combined heating and power	*CHP*	P_{th} = 10.5 kW P_{el} = 5.3 kW η_{th} = 66 % η_{el} = 30 %

[1] Laboratory data from INSA was unavailable at time of creation of this report

hot water storage	*HWS*	1.5 m^3
adsorption chiller	*AdC*	P_{th} = 10 kW $EER_{th,AdC}$ = 0.45
cold water storage	*CWS*	1.5 m^3

Figure 4: Nominal data and setup for CCHP operation at Hochschule Offenburg

At **Hochschule Karlsruhe** (Karlsruhe University of Applied Sciences), a solar thermal climate system is installed [2]. The system consists of two types of solar thermal collectors that support a stratified hot water thermal storage. During winter, the gathered heat can be used for heating support of parts of a faculty building. During summer, the heat is used to drive an adsorption chiller that cools down a stratified cold water thermal storage. The produced cooling energy can then be used to cool down a part of a faculty building. During times of low ambient temperatures, also free cooling can be utilized.

components	abbr.	specification
solar thermal collectors	*STC*	~53.3 m^2 flat plate STC, ~31.2 m^2 vacuum tube STC
adsorption chiller	*AdC*	P_{th} = 13 kW $EER_{th,AdC}$ = 0,48
hot water storage	*HWS*	2.0 m^3
cold water storage	*CWS*	1.0 m^3

Figure 5: Nominal data and setup for solar cooling operation at Hochschule Karlsruhe

At the **FHNW Muttenz** a single-family house (SFH45, IEA SHC Task 44 Annex 38) with underfloor heating is supplied with space heating and domestic hot water. The system consists of photovoltaics, a battery, an air/water heat pump and a domestic hot water storage. The photovoltaics and the house are emulated. The other components are real.

components	abbr.	specification
photovoltaics (emulated)	*PV*	5 kW$_p$
battery	*BAT*	5.9 kWh
air/water heat pump	*HP*	4.75 kW (A7/W35) COP 4.6
hot water storage	*HWS*	0.39 m^3

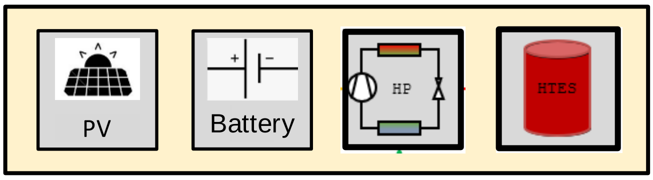

Figure 6: Nominal data and setup for photovoltaics with a heat pump

2. Theoretical foundation and background

Performance indicators

As there are different performance indicators in literature for heating and cooling with heat pumps and thermal driven chillers, we have to define the used performance indicators:

Efficiency (η) is defined as the ratio of output of electrical or heating energy to input of fuel energy in CHP or gas boilers.

The energy efficiency ratio (EER) is the ratio of output of cooling energy to input of energy in chillers including the auxiliary energy (pumps and dry cooler). For compression chillers the input will be electrical energy whereas for adsorption chillers the input energy is the sum of thermal and electrical input.

For heat pumps the coefficient of performance (COP) is defined as the ratio of heat energy output divided by input energy, which is the electrical input energy for compression heat pumps or the thermal/electrical energy input in case of thermal driven heat pumps.

Evaluation criteria and calculation

The criteria used in this work package are the primary energy consumption, carbon dioxide emission and fuel and electricity costs.

Special focus lies on reducing the amount of fossil fuels and increasing the share of renewable energy sources. Therefore, the not renewable share of the primary energy factor PEF_{nr} is used. Consequently, renewables will have a very low factor in this investigation.

The primary energy consumption is calculated as follows:

$$\text{primary energy consumption} = \sum \text{FE} \cdot \text{PEF}_{\text{nr}}$$

PEF_{nr} = primary energy factor (not renewable share)

The carbon dioxide emissions are calculated as follows:

$$\text{carbon dioxide emissions} = \sum \text{FE} \cdot (\text{specific CO}_2 \text{ emissions})$$

specific CO_2 emissions in [kg CO_2/kWh]

Instead of variable costs only fuel and electricity costs are calculated without maintenance / service / wages of operators. The fuel and electricity costs are calculated as follows:

$$\text{fuel and electricity costs} = \sum \text{FE} \cdot c_{\text{FE}}$$

c_{FE} = specific costs of final energy [€/kWh]

All criteria are calculated for each energy system. The regulations and given market price levels in each region will be taken into account.

System boundaries and design convention

We distinguish between primary, final and useful energy.

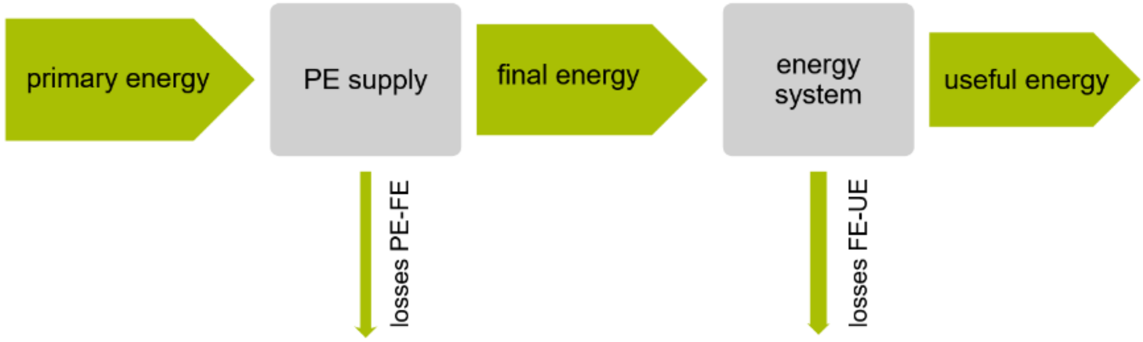

Figure 7: Types of energy and conversion steps

The examined energy systems use final energy (FE) as an input and they produce useful energy (UE) as an output. Final energy used in our laboratories and reference systems are:

- natural gas,
- electricity from the grid,
- solar or ambient heat,
- electricity from photovoltaic and
- biomass.

Useful energies are:

- electricity,
- heat and
- cold.

The energy balance for each load type (heating, cooling and current load) can be calculated as follows:

$$\mathrm{Load} - \sum (|\mathrm{producer}| - |\mathrm{consumer}|) = \Delta \mathrm{E}$$

ΔE results in loading/unloading energy storages or buying/selling electricity from the grid. Within the laboratory facilities in which changes in thermal or electrical storage can be measured, the above-mentioned calculation is not needed whereas the calculation of selling/buying electricity from the grid is always executed.

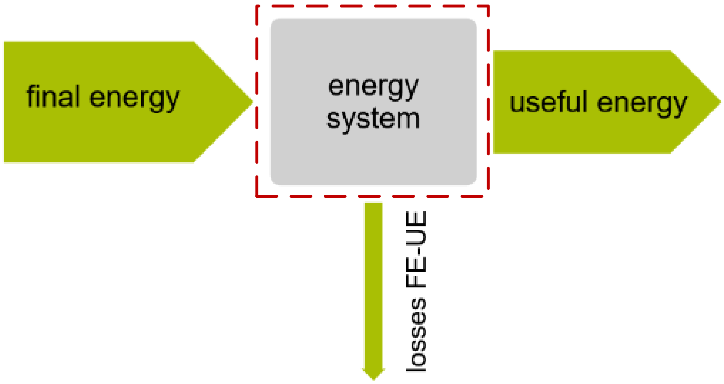

Figure 8: System boundaries for the energy system

Any loads (heat load, cooling load and current load) are defined as positive values in the energy balancing.

Final energy flows into our energy system have a positive sign. Selling or extracting it from the system will get a negative sign. Within our energy system producing energy (e.g. heat and electricity from CHP) and unload a thermal storage is defined as positive, as it presents an energy source within our system. Whereas consuming energy by components (e.g. heat consumption by AdC) or loading storages is counted negative, as it is counted as an energy sink within the energy system.

An example of thermal energy balance for heating in a CCHP system:

- CHP produces heat (positive sign, energy source),
- AdC consumes heat (negative sign, energy sink),
- if heat production is higher than consumption the hot water storage is loaded (negative sign, energy sink),
- if heat consumption is higher than production the hot water storage is unloaded, our system receives energy from the storage (positive sign, energy source).

Reference system

A virtual reference system is introduced to serve as a comparison system for the analysis. It consists of a condensing boiler (η_{th} = 95 %) including auxiliary and distribution energy which uses natural gas for heating, a compression chiller (EER_{el} = 4.0) for cooling and electricity is purchased from the local grid. The power consumption of the compression chiller will be covered by the grid. The reference system does not include any thermal or electrical storages. Nevertheless, the energy differences in heat and cold water storages in the laboratories are taken into account in the reference system by increasing or decreasing energy production. For the summer cases only cold and electricity is produced although a CCHP system may have a significant change in a heat storage.

Energy mix, primary energy factors and CO_2 emissions for each country

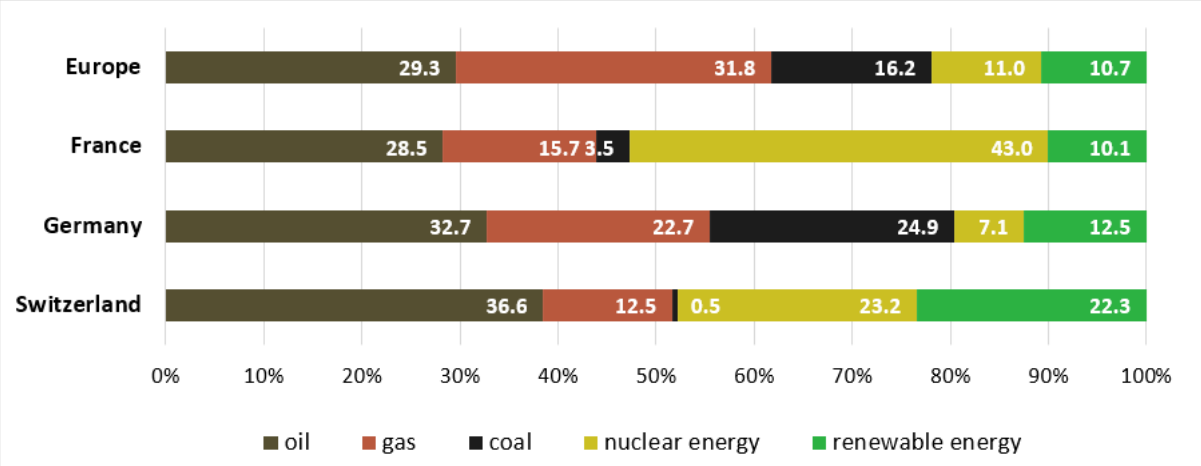

Figure 9: Energy mix for Europe, France, Germany and Switzerland in 2016 [3]

Despite the ongoing reduction of the oil share in **Germany**, oil still accounts for about one third of the total primary energy consumption, including mobility. Gas consumption has risen continuously since years due to the implementation of modern gas-fired power plants and the increased use of natural gas for space heating systems. At the same time, a larger share of renewable energies can be observed, although nuclear energy still has not been replaced. Nuclear power will be phased out completely up to 2022.

The new coal compromise of the German government provides for the gradual decommissioning of existing coal-fired power plants up to 2038. This can only be achieved by distinctive expansion of wind turbines, solar power plants as well as gas-fired power plants for peak loads. Flanking measures like development and expansion of storage technologies (pumped-storage power plants, power-to-x technologies, etc.) will be necessary to stabilize the growing volatile energy supply. Another unsolved problem is the distribution of the electrical energy by a suitable grid appropriate for huge power transfer from offshore parks in the North and Baltic Sea to the southern parts of Germany.

Switzerland has the highest share of oil in its energy mix, which is caused by the high prevalence of oil in space heating. The consumption of natural gas is composed of space heating and electricity purchases from neighboring countries. The small fraction of coal is exclusively due to purchased electricity. The nuclear component predominantly comes from domestic nuclear power plants and the renewable component from domestic hydro power.

In **France** the energy mix is dominated by nuclear power due to a long-standing policy based on security of supply. Renewable energy counts 10 % of the energy mix and the leading source are wood fuels. Wood is used in domestic heating, industry and district heating. Due to high share of nuclear power, coal does not play a big role in the energy mix of France, only 3.5 %. Additionally, gas and oil have smaller share than in other countries.

The primary energy factors (PEF) are split into a fossil, nuclear and renewable part. As one goal is to reduce the fossil and nuclear primary energy, the not-renewable part is listed in Table 1. All calculations for primary energy consumption are executed with those values. Therefore, the renewable sources like photovoltaics and solar thermal energy are always weighted with PEF = 0 and of course will outmatch fossil fuels in direct comparison.

Table 1: Non-renewable primary energy factors for France, Germany and Switzerland (selection)

energy source		France [4]	Germany [5]	Switzerland [6]
fossil fuels	fuel oil	1.0	1.1	1.2
	natural gas	1.0	1.1	1.1
	brown coal	1.0	1.2	
biogenic fuels	biogas		0.5	0.3
	wooden pellets	0.0	0.2	0.2
district heating	out of CHP, fossil fuel		0.7	0.6
	out of CHP, renewable fuel		0.0	0.2
	out of heating plants, fossil fuel		1.3	1.6
	out of heating plants, renewable fuel		0.1	0.1
electricity	electricity mix	2.58	1.8	1.8/2.5[2]
environmental energy	heat (geothermal, ambient, solar thermal)		0.0	0.1 – 0.9
	electricity (photovoltaics, wind)		0.0	0.1 – 0.5
waste heat	from processes		0.0	
nuclear power				4.2

It may be surprising that the primary energy factor for the electricity mix in Switzerland (PEF = 2.5) is far beyond the value in Germany (PEF = 1.8). While the production energy mix in Switzerland is 1.8, the consumer mix is 2.5, due to the amount of imported electricity from France and Germany, which have a high share of fossil and nuclear sources.

In Germany, the PEF for all renewables is evaluated with 0, whereas in Switzerland the PEF is defined in a more detailed way and can vary between 0.1 and 0.9, based on the specific technology.

To create consistency between the partners in the different countries, PEF = 0 for all renewables is chosen. The PEF for natural gas in France is raised from 1 to 1.1.

Table 2: specific carbon dioxide emissions for France, Germany and Switzerland in [kg CO2/kWh]

Energy source	France[7]	Germany [8], [9]	Switzerland [6]
electricity mix	0.057	0.485	0.090
district heating		0.280	0.097
fuel oil	0.325	0.294	0.288
natural gas	0.227	0.202	0.205
brown coal	0.377	0.381	
diesel	0.322	0.266	0.293
wooden pellets		0.023	0.022
biogas		0.148	0.040/0.130

Switzerland has noticeably low carbon emissions for electricity and district heating. This is because most of the electricity comes from nuclear and hydro power. District heating is often powered by waste heat from nuclear power plants and waste incineration plants. The latter is considered to be a partially renewable energy source for two reasons: Some of the energy comes from biological waste. Furthermore, the waste exists and is incinerated, whether the power is used or not.

[2] 2.5 is used in the calculation template for sake of uniformity

In **Germany** the specific emissions for electricity are noticeably higher due to high share of fossil fuels like coal and natural gas in power plants.

The high share of nuclear power in **France** leads to lowest CO2 emissions for electricity among the three countries.

Table 3: specific fuel and electricity prices in [EUR/kWh]

Energy source	France[10]–[13]	Germany[14], [15]	Switzerland[16]–[18]
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

In 2018 the price for electricity in **Germany** consists of production, sales and margin (25 %), EEG allocation (21 %), network charges (23 %), taxes and duties (31 %). Although the production and sale prices slowly decrease, the overall price continuously rises distinctively since 2010, mainly driven by the taxes and allocations. The feed-in rate for photovoltaics is on a low level (8,9 ct/kWh in June 2020) and will decrease even more. The incentive for new installations is mainly cost reduction by high self-consumption of the electricity.

The feed-in tariff for electricity produced in a CHP plant is governed by the "Kraft-Wärme-Kopplungsgesetz" in Germany. It varies depending on factors such as the nominal capacity of the plant and type of fuel. In the scope of this work, the selling rate was taken as a constant value of 0.151 €/kWh considering a base load price of 0.063 €/kWh, 0.008 €/kWh avoided grid costs, and a micro-CHP bonus of 0.08 €/kWh [15], [19].

In **France** the PV production feed-in tariff for installations ≤ 9 kWp is 0.10 €/kWp and for installations above 9 kWp the tariff is 0.06 €/kWp. Additionally, the self-consumption of the PV production is encouraged and supported with a self-consumption premium which depends on the installed capacity. The premium for installations ≤ 3 kWp is 390 €/kWp, ≤ 9 kWp is 290 €/kWp, ≤ 36 kWp is 180 €/kWp, ≤ 100 kWp is 90 €/kWp and for installations above 100 kWp the premium is zero. The premium is divided by five and paid during next five years [10].

3. Results

All results of the measured series of the different setups in the hybrid systems introduced in Chapter 1 are analyzed in comparison to the defined reference system Chapter 2 with country-specific PEF, emissions, and costs. The reference system comprises mostly of the status-quo with separate production of electricity, heating, and cooling.

CHP, winter cases

In **Koblenz** the Stirling engine runs about 5 h with one startup and one shutdown in the measured series. The average electrical efficiency is 9 %, the average thermal efficiency is 75 %, so that the overall efficiency amounts to 84 %.

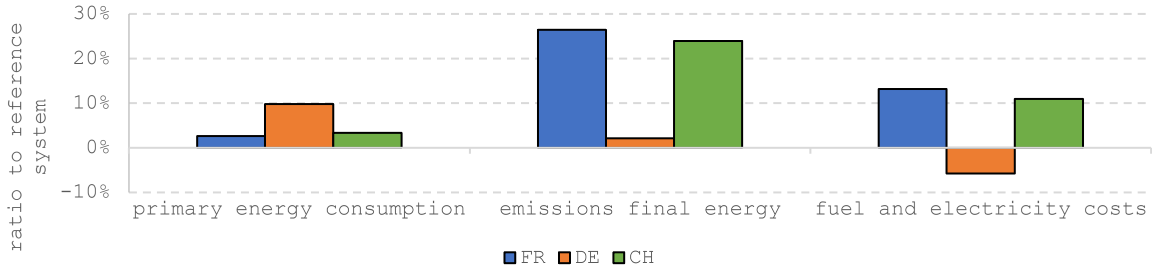

Figure 10 Energy, emissions, and economic analysis results for a CHP system with 5 hours of measured data

As shown in Figure 10 the primary energy consumption is 3 – 10 % higher with the Stirling engine in all countries. Since the specific emissions of electricity are very low in France and Switzerland compared to Germany, the carbon dioxide emissions show huge differences. Germany is the only country with cost savings, because of the high electricity price.

As an example, the results of a typical CHP test done in **Hochschule Offenburg** in winter with heating load profile of a hospital and test duration of 24 hours are shown in Figure 11. A primary energy saving of more than 10 % is observed in all countries. However, more emissions are produced in the CHP system compared to the reference system for France and Switzerland as the CO2 emission factor for the electricity-mix in these countries is very low compared to Germany due to high percentage of nuclear power (0.05 kg CO_2/kWh in France compared to 0.49 kg CO_2/kWh for Germany). The fuel and electricity costs are reduced in all countries. The highest effect is seen in Germany due to the higher purchase rate and the high feed-in tariff available to microscale CHP systems. During the test an average η_{el} of 31 % and η_{th} of 62 % was observed for the CHP system.

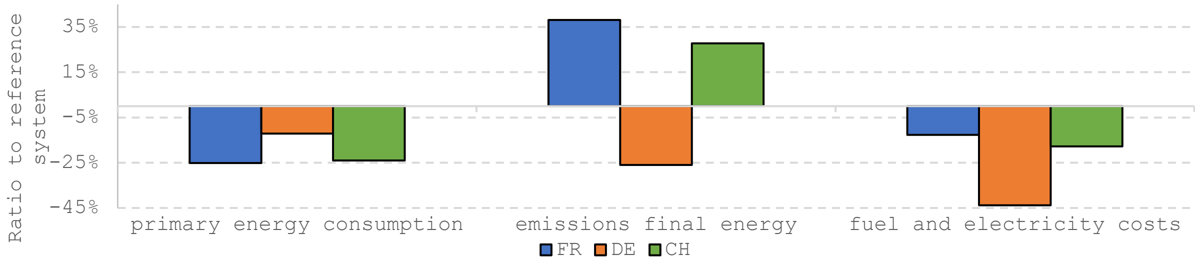

Figure 11 Energy, emissions, and economic analysis results for a CHP system with 24 hours of measured data

For both energy systems, a higher electrical efficiency of the CHP and longer operational hours will lead to higher savings.

CCHP, summer case

As an example, the results of a typical CCHP test done in **Hochschule Offenburg** in summer with a cooling load profile for a hotel and test duration of 16 hours are shown in Figure 12. The hybrid system consumes more primary energy compared to the reference system in case of all three countries. This is particularly noticeable in case of Germany with a PEF of 1.8 compared to 2.6 for France. However, in the case of Germany (with higher electricity rates), a saving in the consumption-related costs is observed as electricity from CHP is used for self-consumption. The preliminary evaluation in this case is based on a load profile with only cooling loads and electrical loads. Heating loads are absent and in cases where all three types of loads are satisfied simultaneously, a better primary energy efficiency should be observed for the CCHP system. Additionally, the electrical efficiency of the CHP unit itself will play an important role in the overall primary energy consumption of the system. To quantify the effect of the load profile and CHP's efficiency a sensitivity analysis is necessary and will be done in the future work. Emissions factors were not adequately available for France and Switzerland and a higher emission in the hybrid system in Germany is seen compared to reference due to gas consumption in the CHP.

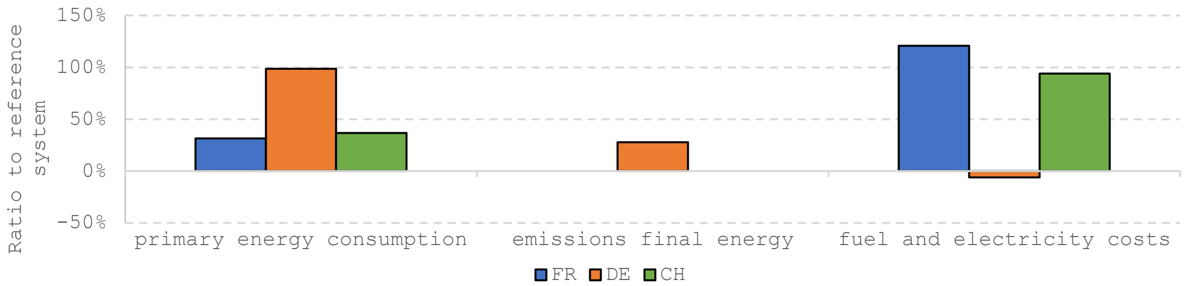

Figure 12 Energy, emissions, and economic analysis results for a CCHP system with 16 hours of measured data

Solar cooling, summer cases

In **Karlsruhe**, operation of the system during a typical summer day is analyzed. During that time, the system is operated to (partially) compensate heat loads of the building. The measured series lasts 24 hours with the AdC starting approx. at 09:45 in the morning and continuously operating until approx. 22:30 in the evening. The AdC operates with an average thermal efficiency $EER_{th,AdC}$ = 0.5 kWh/kWh and the electrical efficiency $EER_{el,AdC}$ = 2.16 kWh/kWh. Compared to the reference system, the solar cooling system consumes 56 % more electricity.

An investigation of the reasons for this higher consumption revealed that the dry-cooler operated for recooling of the system is a main driver for the high electricity consumption of the system. Amongst others, it was found that a continuous operation of the comparatively large dry-cooler of the system at very high radiators speeds might not be necessary to achieve the required recooling temperatures for the AdC. While the radiators' speeds are not adjusted with regard to the current outlet temperature of the dry-cooler in the current control setup of the system, an implementation of such a controller could yield substantial decrease of the system's overall energy consumption, since already small reduction of radiator operation especially at high speeds could yield large energy savings.

In addition to that, the pump on the outdoor-circuit-side of the cooling circuit of the system was identified as a comparatively high consumer of electrical energy, and a careful adjustment of the pump speed based on monitoring data for the circuit temperatures might yield further energy saving potential for this continuously operating pump.

In **Koblenz** the heat curve from the solar thermal collectors in Karlsruhe is simulated with an electrical heater to drive the AdC. The measured series last 9 hours with the AdC starting two times with an average thermal efficiency $EER_{th,AdC}$ = 0.53 kWh/kWh and the electrical efficiency $EER_{el,AdC}$ = 5.39 kWh/kWh. Compared to the reference system, the solar cooling system consumes 26 % less electricity.

These experimental findings illustrate that the following aspects should be considered:

- Appropriate design and dimensioning of the cooling system (pump and dry cooler) are very important for the overall performance of the system;
- The radiators of the dry-cooler should be controlled based on required/desired outlet temperatures rather than continuously operating at high fan speeds.
- An adequate adjustment of the volume flow in the water cooling circuit can yield further energy saving potentials.
- Also, if there are currently no cooling demands which have to be fulfilled, the AdC should start operation only when the HWS reaches higher temperatures (e.g. > 65 °C) and the CWS is higher than e.g. 15 °C, as this will lead to high cooling power on the AdC and it will increase the $EER_{el,AdC}$ substantially.

Solar heating, winter case

If cooling facilities are not required during winter times, heat gathered by the solar thermal collectors of a solar cooling system can be used for heating support. For the solar thermal system at **Hochschule Karlsruhe**, Figure 13 shows that during a sunny winter day, energy for space heating support can actually be produced at highly reduced primary energy consumption, emissions, and cost compared to the virtual reference system. At the same time, it should of course be noted that the availability of solar irradiation during winter is rather uncertain, and that during cloudy days almost no solar heat can be gathered by the system.

Nevertheless, using the heat gathered by collectors which would otherwise stay unused during major times of the year as a supportive technology for space heating could under consideration of the depicted, favorable heating production conditions be an interesting opportunity for a system operator. Depending on the system setup, such facilities might also be enabled with comparatively low additional effort regarding installation and automation.

Finally, it should be pointed out that the control strategy chosen during winter for the pumps that operate the solar circuits can have an impact on the overall efficiency and success of the application, and should therefore be chosen with care and consider suitable measurements or estimations for the collector temperatures and possibly other assessments of the current availability of solar energy. Not only can excessive pump operation at low temperatures of the solar liquid lower the overall efficiency of the system, but can also transport larger amounts of cold medium into the building, and in the worst case might even cause damage if solar liquid whose temperature is below the freezing point of water is passed through heat exchangers.

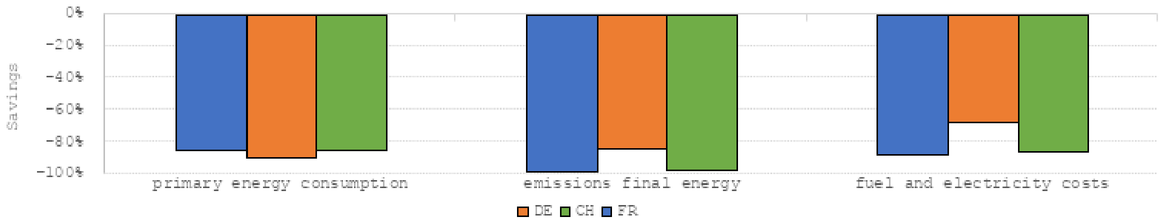

Figure 13: Energy, emissions, and economic analysis results for a solar heating with 24 hours of measured data

Heat pump, winter case

As an example, the results of a typical HP test done in **Hochschule Offenburg** in winter with a heating load profile for a hospital and test duration of 18.75 hours are shown in Figure 14. The hybrid system consumes less primary energy compared to the reference system in case of all three countries. This is particularly noticeable in case of Germany with a PEF of 1.8 compared to 2.6 for France. However, the electric consumption for a heat pump based hybrid system is higher and as in the case of Germany, a higher consumption-related cost is observed due to the higher electricity purchase rate. Considering the lower CO_2 emission factor for the electricity mix in France and Switzerland a high saving in emissions is observed for this hybrid system based primarily on an electrical heat pump.

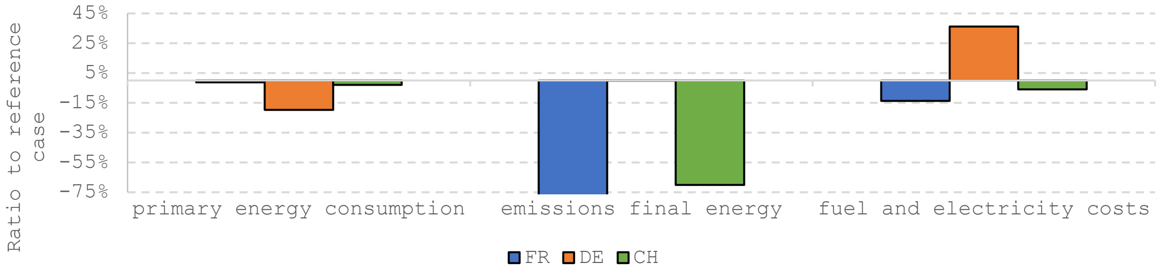

Figure 14 Energy, emissions, and economic analysis results for a HP system with 18.75 hours of measured data

Heat pump and photovoltaic

In **FHNW** two seasonal cases are tested. The winter and summer case.

Winter case

In the winter case, the system supplies domestic hot water and space heating while generating limited amount of electricity i.e. the electric load is mostly satisfied using electricity bought from the grid.

For all three countries, the primary energy consumption is roughly halved. This is because the primary energy factors are relatively similar and the ratio between electricity and natural gas is similar to the COP of the heat pump. Thus, the last two points compensate each other.

In the final energy emissions, France and Switzerland show a greater reduction than Germany. This is because the German electricity mix has a high share of fossil fuels, while France and Switzerland are dominated by nuclear and hydropower.

The largest difference is in the fuel and electricity costs between France/Switzerland and Germany. This is because of the combination of high electricity costs and low natural gas costs in Germany.

ACA-MODES

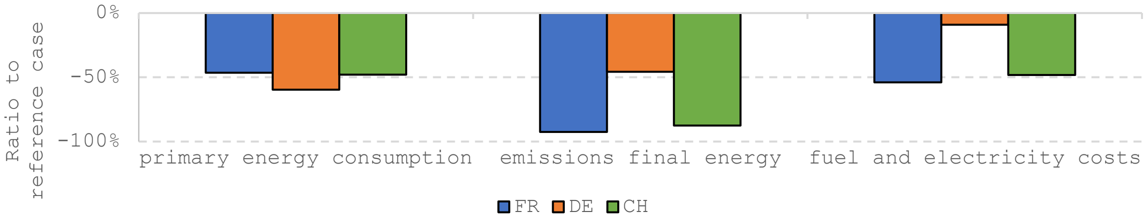

Figure 15: Energy, emissions, and economic analysis results for a PV and HP system with 3 days of measured data

Summer case

In the summer case, no space heating is needed while the domestic hot water consumption is unchanged. At the same time, the PV generates much more electricity. As a result, the energy flows are now dominated by the sale of PV electricity to the grid, which leads to high negative ratios of down to -400 %.

Again, the primary energy consumption is similar for all three countries.

In the final energy emissions, Germany shows the largest reduction. This is because the specific CO_2 emission for electricity from the grid is very high compared to France and Switzerland.

The fuel and electricity costs are reduced to almost zero. However, no profit is generated due to the selling price of PV electricity being much lower than the buying price of grid electricity.

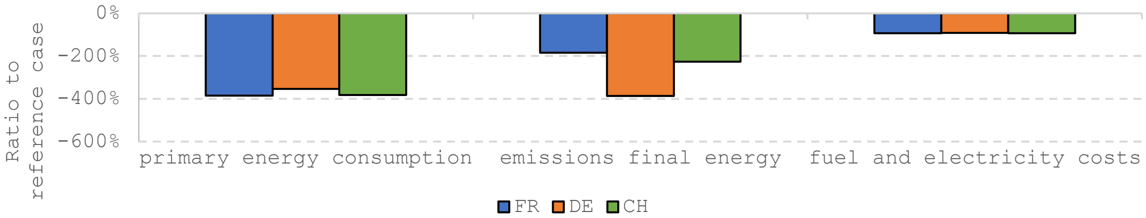

Figure 16 Energy, emissions, and economic analysis results for a PV and HP system with 3 days of measured data

4. Conclusion and outlook

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

In certain scenarios, conventional systems like condensing boilers and compression chillers were (unexpectedly) more efficient than extensive hybrid systems. A preliminary investigation revealed that good knowledge of appropriate system design and operation is needed for the hybrid system to ensure its efficient operation compared to conventional systems and justify its higher complexity and investment costs.

By using CHP systems, a general saving in primary energy and costs was observed, whereas the CO_2 emission was reduced only in Germany. Two key points for successful design and control are high electrical and overall efficiency and high full load operating hours with low number of start-up / shut-down cycles.

The investigated CCHP system could not directly compete with a conventional compression chiller (CC) in terms of primary energy and emissions. The main reasons are low electrical efficiency of the CHP unit and low $EER_{el,AdC}$. As for primary energy and emissions a CCHP system still uses natural gas, whereas the CC uses either nuclear power in France and Switzerland or increasing renewable based grid in Germany. In the near future, as the share of renewable energies in electricity production rises further, the CC will consume lesser fossil primary energy thereby producing even lesser emissions.

The solar cooling system showed that with heating support, savings can be easily achieved, whereas the combination of a STC with an AdC in summer needs detailed planning to run the system efficiently. The most important value is the $EER_{el,AdC}$, which should be maximized through different methods e.g. minimization of electrical consumption or optimal operation, described in Chapter 3.

The heat pump showed good results in all three countries. In the German scenario, the heat pump reduced PE consumption and emissions, but was still economically expensive due to high ratio between electricity and gas price. When combined with a PV all three evaluation criteria: (a) primary energy consumption, (b) carbon dioxide emissions, and (c) fuel and electricity costs showed improvement. When combined with a thermal storage the HP can be used to convert electricity generated by renewables into heat for a power-to-heat coupling.

In summary, an optimal design should be done first, followed by required operation limits given by customers or power unit data. An interesting research question remains to notice how MPC will control the different hybrid systems and their interaction, and compare its performance with a conventional controller. The extent to which optimized hybrid systems can be improved by the MPC should be quantified. Thereby it will be interesting to observe if the MPC will determine the above-described optimizations or if the MPC will find unexpected control decisions.

In the future work packages of the Project ACA-MODES, different hybrid systems will be modelled and simulated and these models will be implemented in an MPC problem for optimal control of the multiple systems. Knowing that the economic analysis only includes electricity and fuel costs, future work packages will include the investment costs more in detail.

5. References

[1] 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.

[2] A. Bürger, P. Sawant, M. Bohlayer, A. Altmann-Dieses, M. Braun, and M. Diehl, “Efficient operation scheduling for adsorption chillers using predictive optimization-based control methods,” in *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 257.

[3] IEA, “IEA World Energy Balances database,” 2018. [Online]. Available: www.iea.org/statistics. [Accessed: 22-Jul-2020].

[4] eRT2012, “Différence entre énergie primaire et énergie finale,” 2014. [Online]. Available: https://www.e-rt2012.fr/conversion-energie-primaire-energie-finale/. [Accessed: 21-Jul-2020].

[5] M. Pehnt, N. Langreder, A. Hermelink, and P. Pannier, “Untersuchung zu Primärenergiefaktoren, Leistung gemäß Rahmenvertrag zur Beratung der Abteilung II des BMWi,” Heidelberg, 2018.

[6] P. Stolz and R. Frischknecht, “Umweltkennwerte und Primärenergiefaktoren von Energiesystemen KBOB,” Uster, 2016.

[7] Observatoire de l’Industrie Electrique, “CO2 fiche pedago contenus carbone des energies,” 2019.

[8] BAFA, “Merkblatt zu den CO2 Faktoren,” 2019.

[9] P. Icha, Geschäftsstelle der Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat) am Umweltbundesamt, and G. Kuhs, “Entwicklung der spezifischen Kohlendioxid- Emissionen des deutschen Strommix in den Jahren 1990 - 2018,” 2019.

[10] Commission de Régulation de l’Énergie, “Le tarif de rachat photovoltaïque en 2020,” 2020. [Online]. Available: https://news.dualsun.com/aide-fiscalite/tarif-rachat-photovoltaique/. [Accessed: 13-Aug-2020].

[11] Eurostat Statistics Explained, “Natural gas price statistics,” 2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics. [Accessed: 13-Aug-2020].

[12] Statista GmbH, “Electricity prices for households in France from 2010 to 2018, semi-annually.” [Online]. Available: https://www.statista.com/statistics/418087/electricity-prices-for-households-in-france/. [Accessed: 13-Aug-2020].

[13] J.-B. Bouvenot, “Etudes expérimentales et numériques de systèmes de micro cogénération couplés aux bâtiments d’habitation et au réseau électrique,” pp. 1–299, 2015.

[14] BAFA, “Förderübersicht: Heizen mit erneuerbaren Energien 2020,” 2020. [Online]. Available: https://www.bafa.de/SharedDocs/Downloads/DE/Energie/ee_foerderuebersicht_2020.pdf?__blob=publicationFile&v=4.

[15] BMWi, *Kraft-Wärme-Kopplungsgesetz Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung*. Germany, 2016.

[16] Statista GmbH, “Durchschnittlicher Preis für Gas in der Schweiz nach Verbrauchertyp von Juni 2017 bis Juni 2020,” 2020. [Online]. Available: https://de.statista.com/statistik/daten/studie/1023989/umfrage/preis-fuer-gasl-in-der-schweiz-nach-verbrauchertyp/#:~:text=Im Juni 2020 belief sich,0%2C95 Rappen pro Kilowattstunde. [Accessed: 22-Jul-2020].

[17] Statista GmbH, “Durchschnittlicher Strompreis für Haushalte in der Schweiz in den Jahren 2012 bis 2020,” 2020. [Online]. Available: https://de.statista.com/statistik/daten/studie/329740/umfrage/haushaltstrompreis-in-der-schweiz/#:~:text=Im Jahr 2020 bezahlen Haushaltsstromkunden,dadurch insgesamt 932 Schweizer Franken. [Accessed: 22-Jul-2020].

[18] energieheld Schweiz, “Einspeisevergütung in der Schweiz - mit der PV-Anlage Geld verdienen,” 2020. [Online]. Available: https://www.energieheld.ch/solaranlagen/photovoltaik/einspeiseverguetung#einspeisetarife. [Accessed: 22-Jul-2020].

[19] 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.

Appendix A: Screenshot of template for evaluation

1.1	LOAD		measured data	ref.
	Wel,Load~	kWh	134.8	134.8
	Qth,LH~	kWh	180.1	180.1
	Qth,LC~	kWh	0.0	0.0

1.2	Results			
	Qth,CHP,Fuel	kWh	395.0	
	Qth,HP,MT	kWh	0.0	
	Qth,ST	kWh	0.0	
	Wel,PV	kWh	0.0	
	Qth,ref	kWh		241.8
	etath,ref	kWh/kWh		0.95
	Qth,Fuel,ref	kWh		254.6
	Qth,CC,LT,ref	kWh	0.0	0.0
	Wel,CC,ref	kWh	0.0	0.0
	EERel,CC,ref	kWh/kWh		4.0
	Qth,HWS	kWh	-61.7	
	Qth,CWS	kWh	0.0	
	Wel,Bat	kWh	0.0	
	Wel,Grid	kWh	13.8	134.8

2	primary energy consumption		FR	Ref.	DE	Ref.	CH	Ref.
	useful energy	kWh	314.9					
	final energy	kWh	347.1	389.4	347.1	389.4	347.1	389.4
	PEF fuel	kWh/kWh	1.1		1.1		1.1	
	PE fuel	kWh	434.5	280.0	434.5	280.0	434.5	280.0
	PEF HP/ST	kWh/kWh	0.0		0.0		0.0	
	PE HP/ST	kWh	0.0	0.0	0.0	0.0	0.0	0.0
	PEF PV	kWh/kWh	0.0		0.0		0.0	
	PE PV	kWh	0.0	0.0	0.0	0.0	0.0	0.0
	PEF electricty mix	kWh/kWh	2.6		1.8		2.5	
	PE grid	kWh	35.6	347.8	24.9	242.6	34.5	337.0
	primary energy	kWh	**470.1**	**627.8**	**459.4**	**522.6**	469.0	617.0
			-25%		**-12%**		**-24%**	

3	emissions final energy		FR	Ref.	DE	Ref.	CH	Ref.
	CO2-factor electricity	kg CO2/kWh	0.057		0.485		0.090	
	emissions electricity	kg CO2	0.8	7.7	6.7	65.4	1.2	12.1
	CO2-factor natural gas	kg CO2/kWh	0.227		0.202		0.205	
	emissions natural gas	kg CO2	89.7	57.8	79.8	51.4	81.0	52.2
	emissions	kg CO2	**90.5**	**65.5**	**86.5**	**116.8**	**82.2**	**64.3**
			38%		**-26%**		**28%**	

4	fuel and electricity costs		FR	Ref.	DE	Ref.	CH	Ref.
	electricity purchase price (grid)	EUR/kWh	0.155		0.298		0.193	
	electricity purchase (grid)	kWh	24.2	134.8	24.2	134.8	24.2	134.8
	costs electricity (grid)	EUR	3.8	20.9	7.2	40.2	4.7	26.0
	electricity sales price (CHP)	EUR/kWh	0.093		0.151			
	electricity sale (CHP)	kWh	-10.4		-10.4		-10.4	
	costs electricity (CHP)	EUR	-1.0		-1.6		0.0	
	electricity sales price (PV)	EUR/kWh	0.060		0.089		0.122	
	electricity sale (PV)	kWh	0.0		0.0		0.0	
	costs electricity (PV)	EUR	0.0		0.0		0.0	
	specific costs natural gas	EUR/kWh	0.084		0.061		0.090	
	costs natural gas	EUR	33.2	21.4	24.1	15.5	35.6	22.9
	overall costs	EUR	**36.9**	**42.3**	**31.3**	**55.7**	**40.2**	**48.9**
			-13%		**-44%**		**-18%**	

Savings	**FR**	**DE**	**CH**
primary energy consumption	-25%	-12%	-24%
emissions final energy	38%	-26%	28%
fuel and electricity costs	-13%	-44%	-18%