Integrated Renewable Hybrid Energy Systems

Coupling of different energy streams for industrial and private applications

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***Abstract*—Integrated Hybrid Energy Systems (HES) with storage are suited for optimal utilization of fluctuating renewable energies generated by wind turbines and photovoltaic systems (PV). By integrating the energy streams for electricity, thermal processes and mobility the economy of renewable projects can be increased and the ecological impact of the energy provision decreased. Storage systems allow the energy time shift to better match demand and supply and reach a higher electricity coverage with the renewable system.**

Keywords: hybrid energy solutions, CO_2 emission reduction, energy stream integration, sector coupling, electricity, cooling, heating, hydrogen infrastructure, energy management, mobility, photovoltaic, battery storage system, ice storage, heat pump, renewable building solutions, off-grid, island grid

I. Introduction

A hybrid energy system (HES) is here defined to consist of at least two different energy generation units. Technically this can be a combination of wind turbines and/or PV systems with or without a thermal generator (e.g. diesel genset or CHP unit). A storage system can be included to increase the utilization of the intermittent renewable source and decrease the dependency on fossil fuels further. For the mean of storing energy for hours, typically electrochemical storage systems (batteries) are considered. For longer durations, chemical storage e.g. in the form of hydrogen or thermal storage units, are used. HES with PV, wind turbines and batteries have been built to power isolated electric grids on islands (e.g. [1]). While these projects are focusing more on an electrical power provision, current attempts concentrate on the full integration of several energy streams for electricity, thermal processes and mobility concepts. This attempt is sometimes referred to as sector coupling or sector integration (e.g. [2]). Industrial micro-grids or living districts are possible applications. Islands can also make use of the technologies investigated for such HES.

Within the next sections, a finalized implementation within an office building as presented in [3] and a planned HES system for a living district are described in more detail. The latter section illustrates the options of four differently designed energy systems to cover electricity and reduce CO_2 emissions. Besides PV and battery storage systems, innovative technologies as well as the concept of sector coupling are investigated.

II. Realized Integrated HES Project for a Building Complex

A. Starting position

The firstly implemented HES is a business campus in Wiesbaden (Germany), which was built between 1964 to 1990 in several phases. The campus includes five buildings with an area of approx. 9,000 m². With 40 companies and over 350 employees, the overall electricity and heat consumption reaches 350 MWh and 1,055 MWh annually, respectively. At night, the electrical base load is still at 25 to 30 kW_e in total. The existing heating system was installed at two separate locations within the building and was commissioned in 1990 and 1994. Thus, the four boilers are in operation for over 20 years by now.

B. Technical details on the HES

In 2015, ABO Wind installed a new HES with the goal to increase efficiency, consequently reducing the use of fossil energy and therefore also lowering CO_2 emissions. In addition, the building owner wanted to reduce the energy costs for his tenants.

In the first phase, the heat distribution was renewed and the power distribution extended. Initially the two central heating systems were connected with each other to gain a thermal network. This was a requirement for the installation of two combined heat and power (CHP) units. These units produce electricity for the building with natural gas and the resulting heat is directly fed into the local thermal network. To reduce CO_2 emissions, ABO Wind installed a roof-mounted PV system.

Overall, the HES consists of the following components:

- 2 condensing boilers 2 * 395 kW_{th}
- 2 CHP units 40 kW_e / 80 kW_{th}
- PV system 55 kW_{peak}

In the second phase, a redox-flow battery was installed to store electrical power at times of lower demand and to supply power at times of higher demand. The main goal of this phase was optimizing on-site consumption of the electricity produced. For this project, ABO Wind has developed an energy management system (EMS), which balances production and consumption. The configuration of the system as well as the communication and power connections are schematically illustrated in Figure 1.

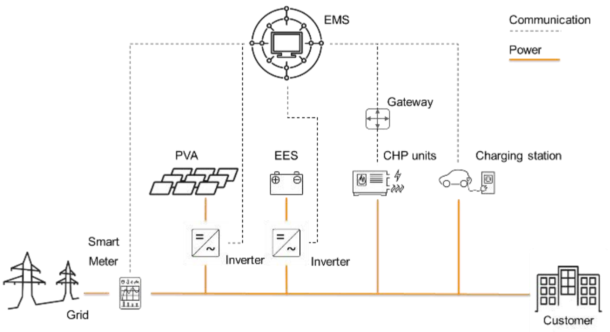

Figure 1. EMS for integrated HES

The optimization function of the EMS is used to decrease electricity costs for the tenants. This is achieved by an increased local consumption of the electricity produced and a subsequent reduction in electricity purchased from the grid. The production cost of the electricity directly consumed is around 12 €ct/kWh, while the electricity prices reached the level of 24 €ct/kWh. The feed-in of the CHP unit during the night can deliver an additional revenue stream.

The latter is possible in non-working hours between 7 p.m. and 7 a.m, when the demand for electricity is low and reaches the base load values stated above. At these times, the CHP units can run at a surplus power of 10 to 15 kW_{el}.

The resulting electric energy of 120 to 180 kWh_{el} can be fed into the electrical distribution grid or could be stored locally. A first economic evaluation comparing capital expenditure and avoided electricity costs with this system was conducted by Stemmer [4]. He calculated the optimal sizing of the chosen redox-flow battery to be 10 kW_e of power and 80 kWh_{el} of energy capacity.

Figure 2 shows the analysis of data measured with Discovergy smart meters over one full year for the described system. During the night periods, the contribution of the CHP units can be seen clearly. Even without an active load management, the peak supply from the grid was reduced from formerly around 120 kW_e to 100 kW_e.

With this project, ABO Wind demonstrates that CO_2 emissions can be reduced by about 50.6 % with the implemented HES compared to the conventional gas-fired system, while energy costs decreased by about 2.5 %.

If the systems balance sheet integrates also a mobility concept, an even larger effect can be seen. The use of two electric cars instead of diesel cars with an annual mileage of each 20,000 km reduce the CO_2 emission by about 3.5 t/a[1] or 62 % and the operational expenditures, which include the fuel cost, decrease by about 37 %.

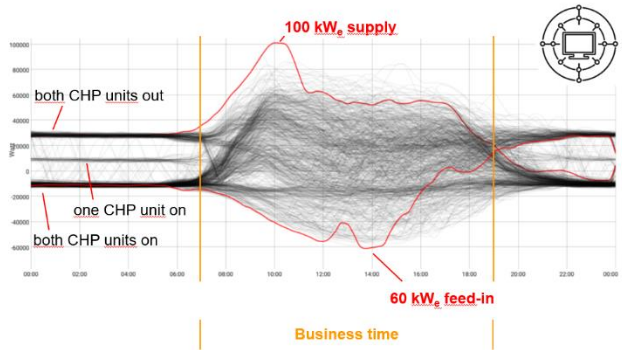

Figure 2. Results of EMS analysis

III. RENEWABLE HES PROJECT FOR LIVING AREAS

A. Starting position

For a living area near Frankfurt/Main airport (Germany), a HES is planned with an unique combination of electricity, heat as well as cooling and mobility. All components rely on renewable energy.

The integrated planning process for the buildings includes urban planners, architects and engineers from the beginning. In several workshops, the different parties focused on innovative technologies for the HES concept. As a result, this project will be built with the best technical components to reach the highest energy efficiency standard.

The urban development plan in Figure 3 shows the full construction, which consists of six buildings (total floor area 23,700 m², 12,000 m² of which are used as a hotel). These are interconnected through air-conditioned halls, which have the function of a high comfort zone for the tenants and visitors and fit for events as well. In addition, they function as thermal buffers and thus have a climate regulating function. Their large-scale glass areas will be used for integrated glass-glass PV modules.

The central component of the urban development concept is an integrated mobility and energy centre with a fully automatic multi-storey car park system illustrated in Figure 3.

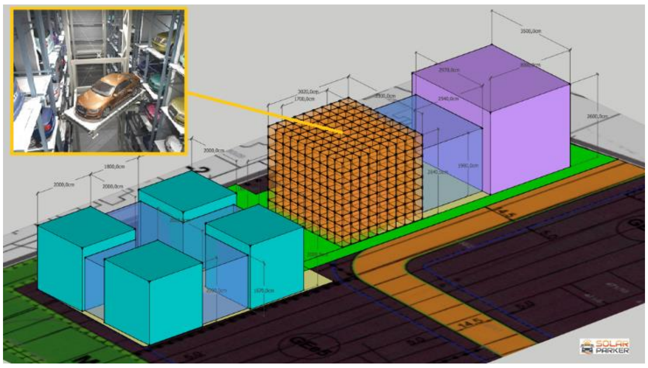

Figure 3. Urban structure layout

First the planning group defined heating demand on the base of passive-house standards as 15 $kWh_{th}/(m^2*a)$. Electricity demand shall also be as low as possible and is aimed to be 20 $kWh_{el}/(m^2*a)$ and 40 $kWh_{el}/(m^2*a)$ for the hotel area.

[1] The assumption is 140 g CO_2 per driven km vs. 20 kWh per 100 km driving distance and 267 g/kWh electricity as mix from the German grid and own PV generation.

This results in a total annual demand of the district of 680,000 kWh_{th} for heating, 170,000 kWh_{th} for cooling and 653,000 kWh_{el} for electricity. Additionally, the car sharing fleet with approx. 20.000 km per anno and 20 kWh/100 km [5] will have an estimated demand of 80,000 kWh_{el} annually.

The base scenario compared to the HES is a system with a natural gas condensing boiler and an electric cooling system. The electricity would be supplied by the electricity grid and for the following calculations, the German electricity mix with 565 g/kWh [6] was considered.

The CAPEX is the upfront investment for the system. The stated OPEX include the cost for operation and maintenance expenditures, variable costs e.g. for fossil fuels or additional electricity.

B. Innovative integrated energy scenarios

Four options to design the HES for the consumer profile described above are currently under discussion. The considered technologies are listed in Table 1.

In option 1, the necessary electricity will be partly generated through a local PV system installed on the roof and façade. It will be combined with a battery storage system.

Additionally, a groundwater heat pump and an innovative ice storage system will be integrated for the coupling between electricity and thermal requirements (e.g. heating in winter or cooling in summer). Finally, the infrastructure for e-mobility with charging points will be included to couple the segment electricity and mobility. The planned car sharing fleet shall have 20 electrical vehicles, which will be driven predominantly with the locally produced electricity. For the following calculations, the effect of this inclusion is not yet factored in. It would lead to a larger CO_2 emission reduction and for the full system lower OPEX compared to the following stated values.

In total, the produced electricity can be used directly or stored in the different components for electrochemical or thermal storage. The basic constellation of PV, battery storage and ice storage system is identical in all four options. The first systems are not designed to be completely off-grid and thus includes a connection point to the local distribution grid. However, with a higher investment or a combination with other genset options, a completely independent system would also be possible e.g. as off-grid or island solution.

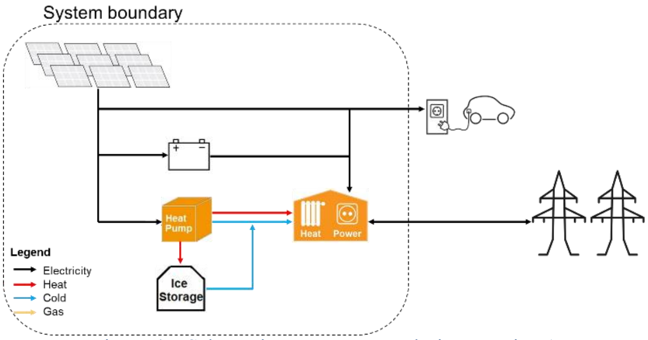

Figure 4: Schematic energy system design – option 1

The solution is able to provide an electricity coverage based on renewable energies of 60 % of the total energy needed ("balanced" coverage). The load profile coverage will be lower and will be simulated if the use case is further detailed but is expected to be around 30 %. In this option, the CAPEX amounts to 2,174,000 €. The OPEX would decrease by 11.7 % and the emissions of CO_2 by approx. 40 %.

The electric mobility concept with 20 cars in the fleet in comparison to conventional cars can reduce CO_2 emissions from 56 to 21.4 t/a or about 61.8 %, while specific fuel costs can be decreased by about 37 %.

Option 2 complements option 1 with a natural gas-fired CHP unit. In this way, the demand of thermal power of the heat pump can be reduced to 300 kW_{th}. For the CHP unit an additional connection to the local gas network is obligatory. Operating the HES of option 2 results in an increase in electricity coverage by renewables to 70 % balanced and 95 % considering the CHP supply. In this option, the CAPEX amounts to 2,259,000 €. The OPEX would decrease by approx. 2.1 % and the emissions of CO_2 could be decreased by approx. 64 % compared to the base scenario with fossil fuel coverage.

Instead of the gas-fired CHP unit, the combination with a natural gas fuel cell is investigated in option 3. The schematic of this system configuration is depicted in Figure 5.

With option 3, an electricity coverage of 120 % balanced can be reached, which means a net export of energy. In this option, CAPEX amounts to 3,061,000 €. The OPEX would be 8 % higher compared to the base scenario, but emissions of CO_2 decreased by over 100 % so that a net positive effect for the connected system could be reached.

Table 1: Overview on the possible HES designs for the district living project

	Unit	Conventional	1	2	3	4
condensing boiler	kW_{th}	100				
PV system (roofs)	kW_{peak}	-	340	340	340	340
PV system (façades)	kW_{peak}	-	410	410	410	410
battery	kW_e / kWh_{el}	-	280 / 240	280 / 240	280 / 240	280 / 240
heat pump	kW_e / kWh_{th}	-	100 / 500	60 / 300	60 / 300	60 / 300
ice storage system	kWh_{th}	-	100	100	100	100
CHP unit	kW_e / kWh_{th}	-	-	50 / 80	-	-
fuel cell		-	-	-	100 / 80	100 / 80
electrolyser		-	-	-	-	200

Table 2: Results for the designed systems

		Conventional	1	2	3	4
Electricity coverage with EE (balanced)	%	-	60	70	120	120
CAPEX	Mio. €	0.392	2.174	2.259	3.061	3.053
OPEX	k€ / a	279	247	274	302	277
CO2 emission reduction	%	-	-40	-64	-105	-115

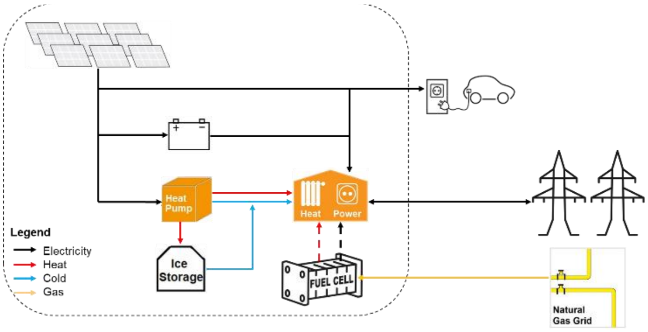

Figure 5: Schematic energy system design – option 3

The final and probably most futuristic solution of option 4 includes an electrolyser and a hydrogen driven CHP fuel cell. The system constellation is depicted in Figure 6. This approach would make it possible to store PV electricity in the summer by electrolysis as hydrogen when there is less demand for electricity within the building. In the winter, electricity according to the load curve, will be produced by the CHP fuel cell unit. The addition of a hydrogen network would also allow the installation of a fuel station for electric vehicles with fuel cells. Such a HES can be a net exporter of CO_2-free energy. The overall energy management system has to integrate all energy streams and further forecasts for production and consumption. With this approach, an optimal distribution among the different generation units and storage systems can be achieved.

The CAPEX amounts to 3,053,000 €. The OPEX will be only 1 % below those of the conventional energy solution and the emissions of CO_2 decrease by approx. 115 %.

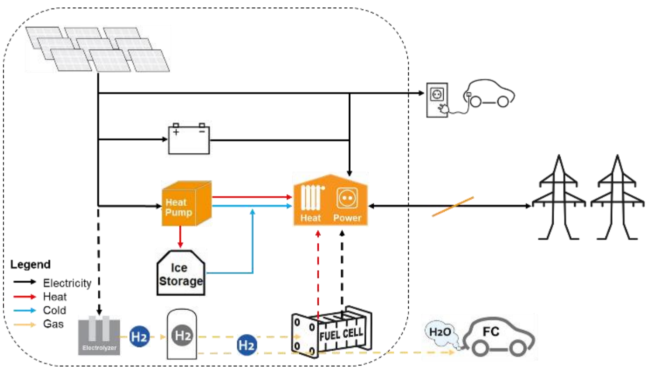

Figure 6: Schematic energy system design – option 4

C. *Implication for island grids*

The above-mentioned concepts for sector integration with power, heat, cooling and mobility can be transferred to applications such as hotels, industrial sites, isolated communities as well as islands. Option 4 is an illustrative example for the possibility given with available technologies to design a system that is completely independent from fossil fuels. For islands, the option to integrate refueling stations for ships and vessels with electricity or hydrogen will be an attractive opportunity in near future.

D. *Conclusion*

This paper describes the implementation of a HES system within an office building in Germany. Additionally, the concepts for four different HES, which will be implemented for a living district, are elaborated. It can be shown that available technologies can decrease overall CO_2 emissions of such a HES by 100 %. The system itself can reach high electricity and thermal coverage. But even with less autarkical HES, CO_2 emissions can be cut in half at lower costs compared to conventional systems. The inclusion of mobility would further increase the value of the system as mean for CO_2 emission reduction. It is noteworthy, that the innovative solutions have higher upfront investments, however the lower maintenance and fuel costs with the right financing model can reach competitive costs to conventional energy supply systems.

This paper points out the benefits in coupling several energy streams for a better utilization of renewable energy supply. It elaborates how the financial and ecologic benefits can increase by integrating a mobility concept into the HES. For this battery electric vehicles or vehicles with fuel cells could be used. The later would use the hydrogen produced during surplus production phases of the renewable sources.

ABO Wind utilizes the potential of these concepts in different applications from remote industry to off-grid or island systems. The expertise in project development gained over decades helps to implement the renewable energy technologies in the best manner for local solutions. This local and low-threshold approach helps to introduce an energy supply with minimal CO_2 emission into the market.

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