Towards Carbon Neutral Operating Buildings

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Abstract
Starting with various definitions of “carbon neutral“ buildings according to Paris Climate Agreement, AIA, ASHRAE, EU, etc. the paper concentrates on operating energy of buildings. Basic principles of passive and active measures as well as renewable energy supply on site or off site are explained. Two examples for the moderate climate zone of Germany are presented in more detail: residential multi-storey buildings with 160 dwellings and an office building with 20,000 m².
The residential buildings, which are finished in 2020, achieve the EU standard of “nearly zero-energy buildings”. Passive measures are thermal insulation and air tightness of the building envelopes, while active measures are combined heat and power (CHP) distributed by micro grids to the dwellings. The cogeneration is run by bio-methane supplied from the public gas grid, and the annual primary energy consumption for heating, domestic hot water and ventilation can be decreased to 13 - 20 kWh/m²a. This solution proved to be the most cost efficient one.
The office building is based on passive measures of thermal insulation, air tightness, and optimized daylighting and on active measures of heat pumps, heated or chilled floors and ceilings, as well as mechanical ventilation with heat recovery. Nearly the total energy demand is supplied by roof integrated photovoltaics combined with short time storage by batteries and seasonal storage by hydrogen. The building, designed to operate by carbon neutral electricity generated by solar radiation on site, will be realized in 2024.

Keywords: *Carbon neutral buildings, bio-methane driven cogeneration, photovoltaics, power to hydrogen*

1. Introduction

Carbon neutral building is an emerging definition which relates to reducing or offsetting carbon energy used by buildings [1]. The design of energy efficient buildings (passive and active measures) and the application of renewable energies (e.g. wind, solar) will reduce the carbon emissions significantly and, in the best case, bring them down to nearly zero. There will still be a small amount of carbon emissions, even for the generation of renewable energies. This applies particularly to the total life cycle of a building, including “grey” energy for production, maintenance and elimination as well as operating energy for running the building. This study focusses on the operating energy of buildings. If they are fully powered from on-site and/or off-site renewable energy sources, they are defined as “net zero carbon buildings” by the World Green Building Council [2]. The European Commission defines “nearly zero-energy buildings” (NZEB). The low amount of energy that these buildings require comes mostly from renewable sources. The Energy Performance of

Buildings Directive [3], to be applied by the EU countries, requires all new buildings to be nearly zero-energy by the end of 2020.

Buildings with a combined supply of renewable energy from on-site and off-site sources are widespread, e.g. by building integrated photovoltaics and a connection to the public power grid. They allow for delivery of excess power to the grid in sunny periods and for power supply from the grid in periods with low insolation. If the annual balance of power consumption and solar power generation is even, it´s a net zero solution. Buildings with a stand-alone solution powered by an on-site source of renewable energy alone are quite rare. Usually they need an extra storage, in the case of photovoltaics a battery.

Comparing both solutions, there will be extra costs for the storage of the autarkic solution. But the stand-alone solution may be more efficient than the grid connected solution. And how can feed-in peaks of solar power be handled by the grid? Either there will be temporary overloads and feed-in interruptions or the grid capacity has to be enlarged for the feed-in peaks. Considering all these aspects a high degree of self-sufficiency is advantageous, if an efficient storage system for renewable energy is available. Beside batteries hydrogen can be used, especially for long term storage of solar electricity.

An alternative to the decentral generation and supply of renewable energy is the central grid-supply. Both green electricity and bio-methane are delivered by the public grid nowadays, and contracts for exclusively green energy are offered.

2. Development of nearly-zero energy buildings

This study intends to demonstrate the great variety of solutions to realize nearly zero-energy buildings. Two examples are described: a multistorey housing estate with combined heat and power (CHP) run by bio-methane from the public gas grid and an office centre with a roof integrated PV plant and a combined storage for excess electricity by batteries and hydrogen. The residential buildings in Bonn were finished 2020, while the Future Office Campus Borken is in the design process to be finished in 2024.

2.1 Bonn Housing Estate

The private investor organized an architectural competition for the 160 rented flats to be built in Bonn-Bad Godesberg. Together with the winning architects, Planquadrat, Darmstadt, an energy concept was developed in co-operation with e² [4], considering the special requirements of the local building regulations, reducing the maximum energy consumption to 55% in comparison to the national regulations (KfW55-standard). Beyond that the design team aimed to realize the “nearly zero-energy building” standard [3].

Passive solar heating by windows was optimized by adjusting the site plan as to position and height of buildings (Fig. 1). The thermal insulation of the building envelope was improved (mean heat transmission demand H_T = 0,41 W/(m²K) and the ventilation system combines natural ventilation and mechanical exhaust ventilation

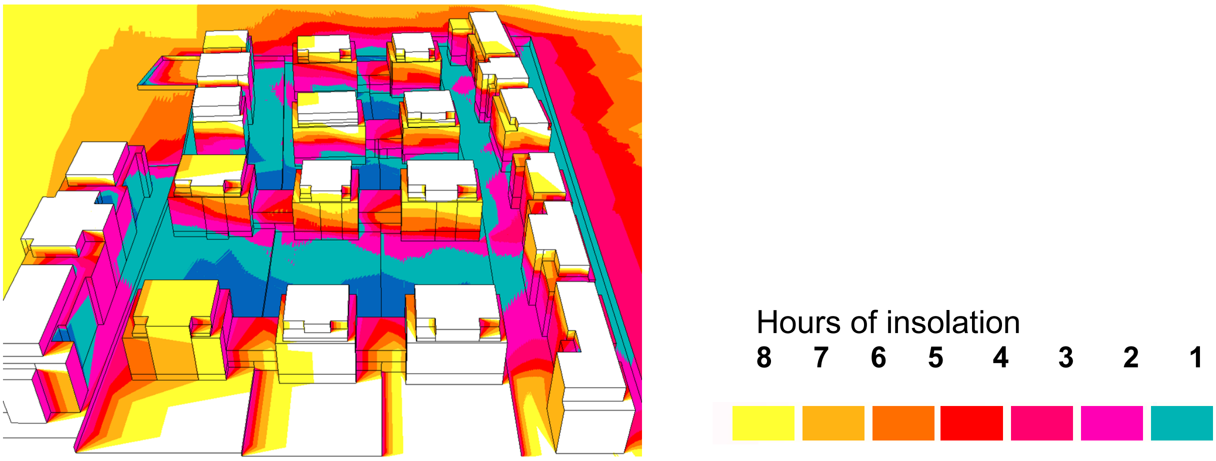

Fig. 1: Hours of insolation on buildings on January 17th [4]

for kitchens and bathrooms. The optimal solution for heating and energy supply proved to be combined heat and power (CHP) run by bio-methane (Fig. 2). The heat is distributed by a micro grid from the central CHP plant to transmission stations and heat storages for domestic hot water in each building. A minimum demand of primary energy (11 kWh/(m²a)) and delivered energy (47 kWh/(m²a)) is achieved. Thus, high energy efficiency is combined with a tenant friendly energy consumption. The achieved primary energy consumption is down to 15% of the boundary value of the German building regulation EnEV (75 kWh/(m²a)). These values, calculated in the initial design phase for one typical building, were exceeded slightly by the proved values of the different buildings realized (13 to 20 kWh/(m²a)). The main reasons are varying building geometry and two boilers for the cogeneration, one for the basic load run by biogas and one for peak loads run by fossil gas.

1. Geothermal energy, micro grid, heat pumps for each building (decentral)	1.1. Stratified storage per building	1.1.1. Exhaust air mech. ventilation
		1.1.2. Mech. ventilation with heat recovery
	1.2. Stratified storage + solar thermal plant per building	1.2.1. Mech. ventilation with heat recovery
2. Wood pellet boiler, central, micro grid	2.1. Stratified storage per building	2.1.1. Exhaust air mech. ventilation
		2.1.2. Mech. ventilation with heat recovery
	2.2. Stratified storage + solar thermal plant per building	2.2.1. Mech. ventilation with heat recovery
3. Biomethane fired cogeneration (CHP), central, micro grid	3.1. Stratified storage per building	3.1.1. Exhaust air mech. ventilation
		3.1.2. Mech. ventilation with heat recovery

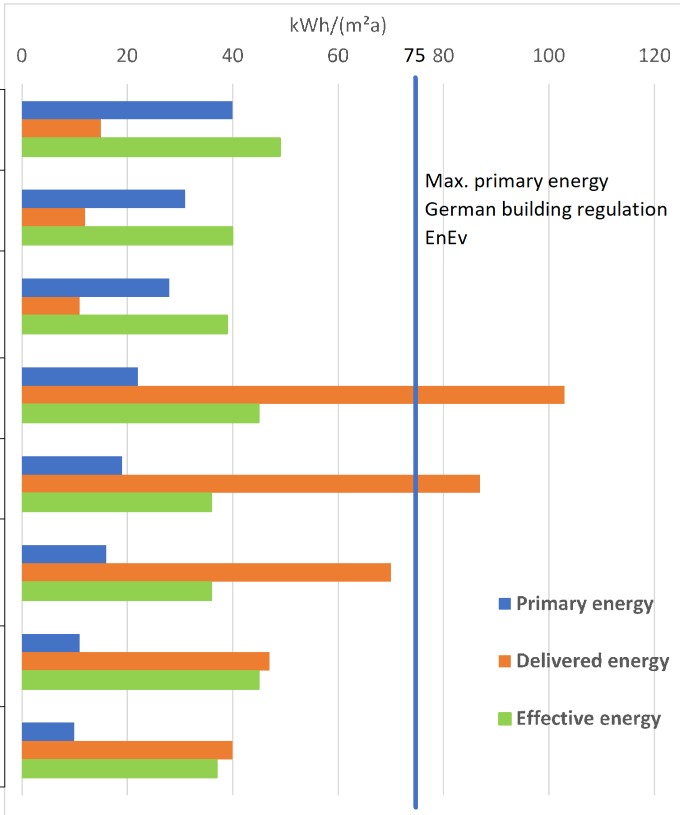

Fig. 2: Variation of building services and energy supply (design phase) [4]

The realized solution is the most economical one as to energy and investment costs (Fig.3). In comparison to a standard reference solution with decentral gas boilers for each house and roof integrated solar thermal collectors for domestic hot water the central cogeneration fired by biogas is significantly cheaper. The running energy costs are reduced to a minimum for the biogas cogeneration, if the fees for electricity according to the legal feed-in tariff are taken into account. This example demonstrates clearly, that nearly zero-energy houses need not be more expensive than standard houses nowadays. The investment can even be lower than that for standard solutions, if energy supply is planned for larger quarters instead of single buildings.

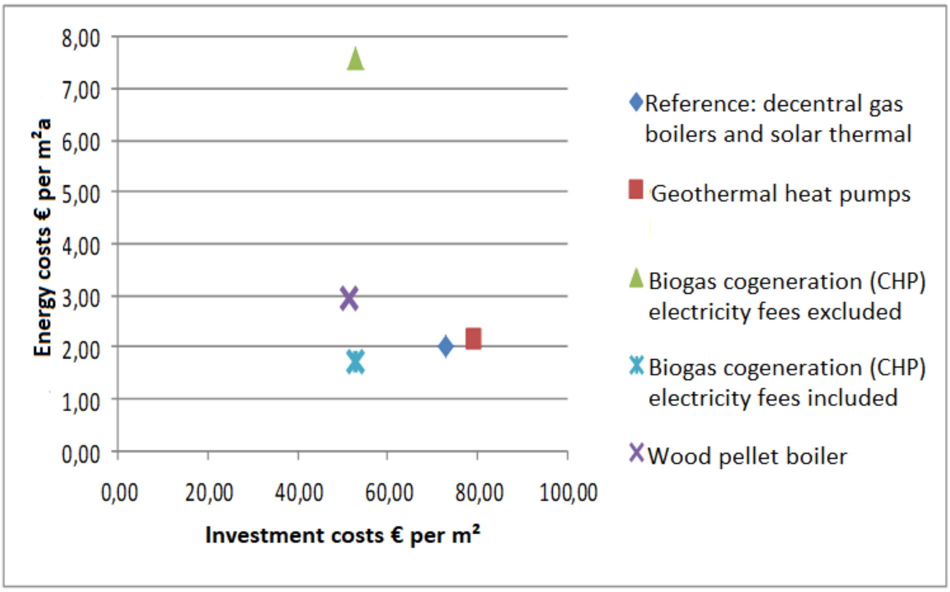

Fig. 3: Energy and investment costs for building services and energy supply [4]

Fig. 4: Realized Buildings, Bonn-Bad Godesberg

2.2 Future Office Campus Borken

The office campus, designed by the architects Manuel Thesing, Borken, and Peter Böhm, Cologne, is located in a new building area out of town without any infrastructure for energy supply. The building is lifted from the ground to minimize the interference with the green landscape, and the total office area of 20,000 m² is placed in the 1st and 2nd floor (Fig. 5 - 6). The energy concept strives for nearly zero-energy and a high degree of autarky because of the location.

Fig. 5: Site plan with continuous landscape and building lifted above ground

Fig. 6: Elevation of building on columns with free ground floor

The relatively large roof area of the two-story building is well suited for the integration of photovoltaics (PV), as Fig. 7 - 8 show. Approximately 70% of the roof area are necessary to cover the total energy demand of the building. Fig. 8 shows this PV area located in a 6 m wide fringe of the roof.

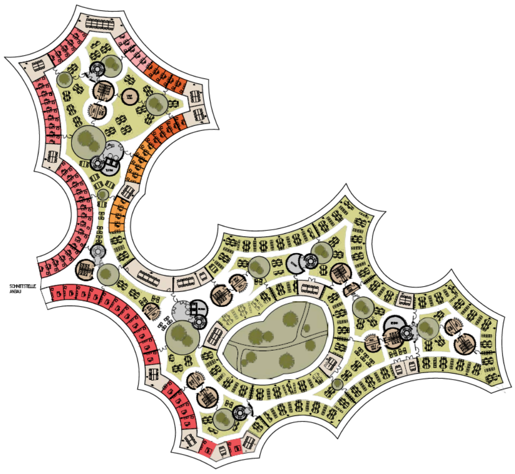

Fig. 7: Plan of 1st and 2nd floor

Fig. 8: Roof plan with solar panels (blue)

The energy demand of the building was optimized by a well-insulated building envelope (u = 0.20 W/(m²K)), triple heat- and solar protective glazing, chilled and heated ceilings, heat-pumps, mechanical ventilation with heat recovery for extreme heating and cooling situations, and daylight-controlled LED lighting. Table 1 gives a survey of the annual energy demand for the consumers, showing the electrical appliances with nearly 70% of the total amount of 85.8 kWh/(m² a).

Table 1: Energy demand (electricity)

Consumers	kWh/(a m²)	kWh/a
Heating	9.0	180,000
Cooling	1.0	20,000
Ventilation	0.8	15,560
Lighting	15.9	318,000
Elt. appliances	58.9	1,178,000
Total	85.6	1,711,560

The annual electricity demand 1,711,560 kWh can be supplied by a PV plant of 9,500 m² solar cells with a peak wattage of 1.957 MWp and an output of 1.755 MWh/a. But a direct coverage of the total energy demand by PV is not possible, as there is a mismatch of time: During the winter months with low insolation the demand cannot be reached, as shown by Fig. 9. And in summer the solar PV harvest exceeds the demand by far. There are two options to overcome this mismatch: either the solar excess energy is fed to grid or it is stored. The feed-in tariff may be interesting from

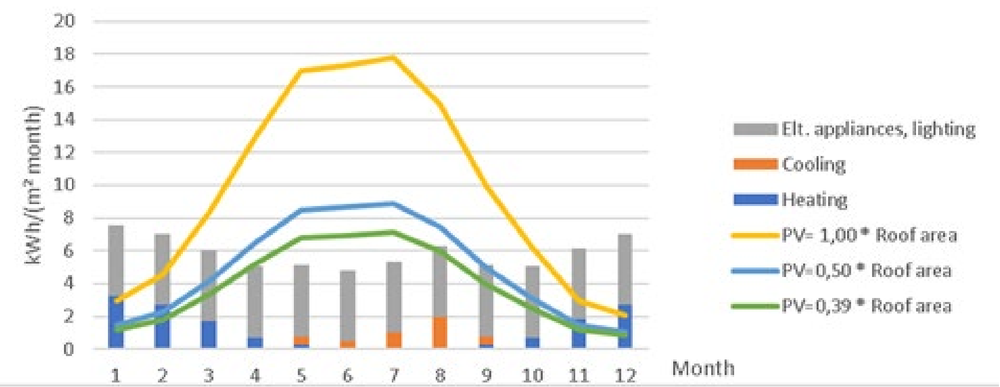

Fig. 9: Energy demand and solar PV power per month and m²

the economical point of view, but overloads of the grid during peak insolation may lead to cut-offs or oversizing of grid. Therefore, storage of excess solar energy for times of shortage is an interesting solution, increasing self-supply and autarky.

The schematic diagram (Fig. 10) shows how the storage and re-use of excess solar power can work. Batteries are used as a short time storage, e.g. for the day-night mismatch. Long-time storage, e.g. from summer to winter, is realized by hydrogen, generated by electrolysis with solar power and kept in steel tanks. In seasons with low insolation fuel cells, run by hydrogen, generate power and heat according to the building demand. A smart energy control system optimizes the interaction of the system components. In Great Britain a first office building with a 10 kW fuel cell was realized as a research demonstration in 2011, using the wind power from a 759 kW generator for an 30 kW electrolyser [5]. In Japan modular H_2-sytems are offered with electrolyser, fuel cell, battery and hydrogen storage for emergency energy supply [6]. In Germany HPS offers a modular system as well for one family houses [7].

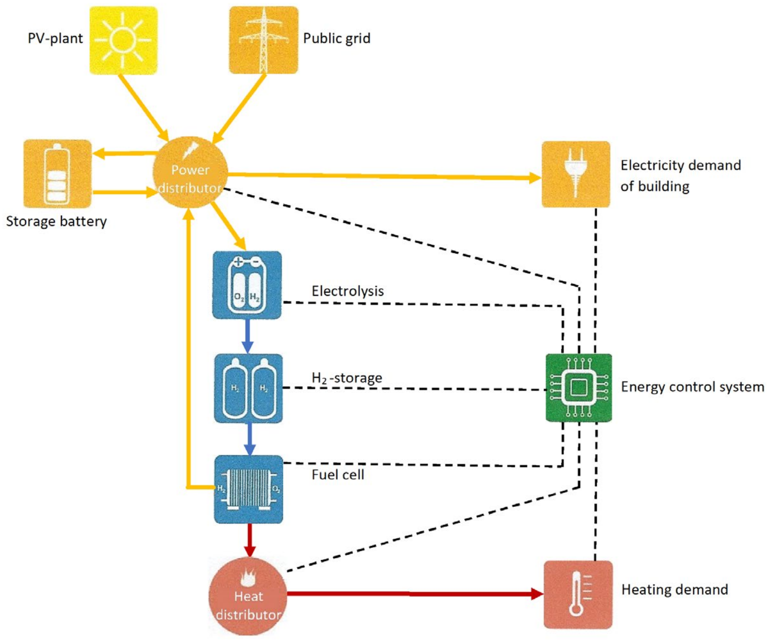

Fig. 10: Schematic diagram of power and heat for a nearly zero-energy building [8]

For the Future Office Campus Borken this principle is applied to utilize the solar power of a nearly 2 MWp PV plant in a highly efficient way. First calculations show, that the heating energy demand can be covered by hydrogen, if heat pumps are applied [Fig. 11]. And about 50% of the total power demand of campus of appr. 1.5 to 1.7 GWh/a (including heating and appliances) can be supplied by PV and hydrogen.

3. Conclusions

CO2 emissions of the building operation can be reduced significantly to nearly zero by different approaches, as could be demonstrated by two examples. The basic principle is to optimize the combination of well-known passive and active means of energy efficient design and renewable energy supply. There can be a central supply of green electricity or gas by the grid, as shown in the first example, or decentral

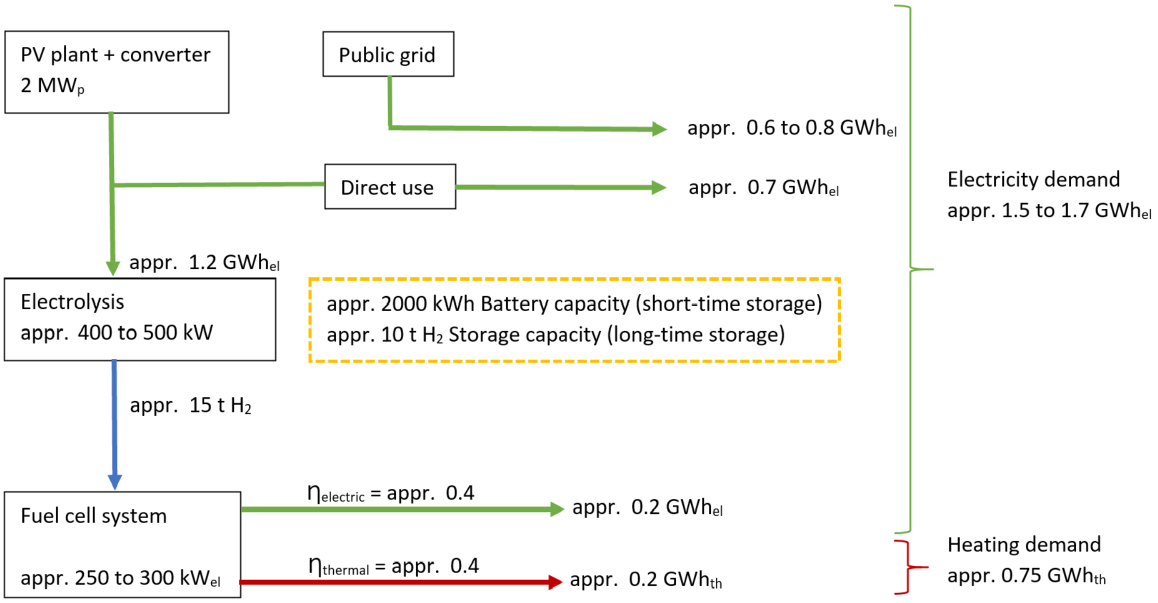

Fig. 11: Rough estimate of generation and direct utilization of PV power as well as storage of excess solar power by batteries (short-time) and hydrogen (long-time). The main function of the batteries is to stabilize the electrolysis [8].

generation and storage of solar power, as shown in project two. The solutions are economical today, if established technologies are applied for larger building areas. Advanced approaches of decentral generation and storage of green hydrogen are technically feasible and efficient. A consequent development and application of the described technologies will enable carbon neutral operating buildings soon.

4. References

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