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Achieving energy sustainability in future neighborhoods through building refurbishment and energy hub concept: a case study in Hemberg-Switzerland

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Abstract

This study aims to investigate the role of distributed generation through the energy hub concept and refurbishment of existing buildings. More specifically, a computational platform combining (i) the urban energy modelling tool CitySimPro and (ii) the microgrid simulation tool Homer is developed. The energy flow on hourly basis is assessed for buildings in Hemberg, a small village in Switzerland, considering occupancy, lighting and appliances profiles, as defined by the Swiss normative. System design of the energy hub is optimized considering three energy system configurations: (i) present scenario, (ii) energy hub catering electrical demand, (iii) energy hub catering both electrical and thermal demand including heat pumps. Results for the integration of an energy hub on site show that the current use of renewables can be increased from 0.15% to over 60% by integrating heat pumps in the city energy network.

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Keywords: Energy hub; building refurbishment; energy efficiency; renewable energy integration

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1. Introduction

Switzerland has ambitious goals for increasing the use of renewable energy and reducing CO_2 emissions. In particular, the Swiss Energy Strategy 2050 aims at phasing out of nuclear energy by 2035 and a possible 50-80% reduction in CO_2 emission by 2050. Buildings have the largest share in energy demand in Switzerland: heating, ventilation, and air conditioning account for roughly 40% of the overall energy demand; 32% of the national electricity demand is also caused by buildings (HVAC, lighting, space heating). Therefore, transition towards (i) low-carbon energy supply technologies and (ii) increased energy efficiency of buildings (primarily through the building envelop, retrofitting, and user behaviour) are an important part of the "Swiss Energy Strategy 2050". In order to make cities environmentally sustainable, integrating renewable energy technologies in the built environment and improved building energy-efficiencies are scenarios of great potential. Several studies focus only on integrating renewable energy technologies (e.g. solar PV and micro-wind turbine) in the built environment [1,2] using different energy system modelling tools and approaches [3, 4]. Also, many studies propose solutions for the energy efficiency of buildings through improvements at system level such as HVAC, improvements in the building envelope, or improvements at the component level such as window glazing and insulation materials for walls [5, 6, 7, 8]. Very few studies, however, explore the possibility of combining solutions for renewable energy integration in buildings and to improve their energy efficiency and minimize the carbon footprint of buildings [9]. Also, as regards energy system improvements using the energy hub concept, many studies focus on the building scale while very few studies explore the optimization of energy systems at neighbourhood or district scale [9, 10]. Improving energy efficiency of buildings through retrofitting, integrating renewable energy technologies into buildings, and optimizing energy systems at neighbourhood scale are three closely interconnected activities that cannot be simply formulated as a simple optimization problem. Therefore, each activity should be assessed and linked to the others in order to propose a promising path towards a sustainable energy strategy for future neighborhoods. In this preliminary study, we develop a computational platform using several existing software programs to handle this process. Section 2 of the article presents a brief overview of the computational methods and tools used for (i) energy demand and potential estimation, (ii) energy system components and related costs. Section 3 of the article presents a brief overview of the village and the available data in order to explore a comprehensive assessment of the village energy system. Section 4 presents the results of the study. In Section 5, conclusions for the study are presented focusing on a sustainable energy strategy for the village.

2. Methodology and tools

2.1. Energy demand and energy potential estimation

In order to optimize the energy hub, an hourly profile of the village energy demand must be provided. The software CitySim Pro has been used to simulate the energy demand of the buildings in the village. CitySim Pro is an urban energy modelling tool which has been developed at Ecole Polytechnique Fédérale de Lausanne (EPFL). It allows us to simulate building-related resource flows by taking into account the location (climate and horizon data), the physical characteristics of buildings (shape, material, occupancy) and the energy conversion systems. The input data are as follows: 3D-geometry of the buildings coming from QGIS and Rhinoceros 5, climate and horizon data, and several other parameters including occupancy, materials as well as roofs, floors and walls insulation, opening properties, and surface reflectance. The original heating system is considered to be a boiler and there is no cooling system. As regards energy potential, short-wave irradiation is one output of CitySim. Short-wave irradiation is useful to optimize the PV panel layout and estimate the PV electricity production.

2.2. Energy hub components

The Energy Hub Concept has been implemented through the software HOMER. The software HOMER is a micropower optimization model developed by the U.S. National Renewable Energy Laboratory. It allows choosing a design for the energy hub and optimizing it. The designs are not only differentiated by their electricity and heating production systems but also by the storage options and the optional grid connection. Several components are calculated using HOMER. These include wind speed, PV panels, Renewable Fraction, levelized cost of energy, and the net present cost. The following assumptions have been considered in order to estimate the mentioned components:

- Resources and loads are constant for each considered hour of the optimisation.
- The grid electricity price is assumed to have a constant rate.
- It is assumed that the investment is paid at t = 0.
- Lifetime = 20 years.
- Discount rate = 2%.
- Inflation rate = 1%.

HOMER calculates the wind speed (m/s) at the height of a wind turbine. The wind power output depends on the type of the turbines. The manufacturers provide the power curve to HOMER so that it can be directly used for the calculation. Several wind turbines are proposed in the software and the Northern Power NPS100C-24 has been chosen for the models. The shape of the power curve and the capacity (95 kW) were the main decision criteria. PV electricity power is calculated in HOMER assuming panels to be tilted at 47 degree and to face south. The renewable fraction corresponds to the fraction of the total electrical production which is produced by renewable sources. It should be mentioned that the grid electricity is considered as E_{nonren}. Thus, the renewable fraction of a system shows the “direct” renewable fraction used for serving the energy demand. The levelized cost of energy (COE) represents the cost of the system per kWh. In HOMER, the LCOE represents the levelized cost of electricity only and does not take the thermal load into account. Also, HOMER does not rank systems based on the COE. The net present cost (or value) of the system is the present value of all the costs it occurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, operating and maintenance costs, fuel costs and the costs of buying electricity from the grid. Revenues include salvage value and grid sales revenue. HOMER ranks all systems configurations by the NPC in the optimisation results.

2.3. Costs of energy hub components

To have a relevant price for the PV panels, the report "Market Observation 2016" [11] from the Federal Office of Energy (OFEN) seemed to be the most reliable source available. The price for wind turbines is given by the Swiss association for the wind turbines [12]. The price of the grid electricity was assumed to be constant over time since no hourly data are provided from Swissgrid. Moreover, it has also been assumed that there is no "peak/off peak" differentiation. The Federal Commission of

Electricity (Elcom) provides the grid price for each commune in Switzerland. Regarding the battery cost, lead-acid batteries are still the cheapest ones on the market and may be the only ones that can be competitive with the grid price. On the other hand, lithium-ion batteries are undergoing major development and can last longer than lead-acid batteries. However, they are still more than twice more expensive and the higher lifetime does not compensate the price. This is the reason why lead-acid batteries have been investigated in this report.

3. Case study and data preparation

Hemberg is a village located in north-east Switzerland in the canton of St. Gallen at an elevation of 945 m (3,100 ft) and west of the Neckar river. In 2006, the area of Hemberg was 20.2 km^2. The village had a population of 927 in 2015. The following data is used for assessing the energy system of the village: the 3D geometry of the village, which has been modelled using QGIS and Rhinoceros 5. QGIS is a free and open-source geographic information system (GIS) and is used to convert a qgis file to a .dxf file. Then Rhinoceros 5 has been used to convert the .dxf file to a readable format used by CitySim Pro for further energy simulation. The contours of the buildings are available in a 2D format from the Swisstopo database but the heights of the buildings are missing. We use a laser device to measure the building heights in Hemberg. The laser device gives the distance between the bottom of the device and the first object met by the laser beam. Positioning the laser upright and close enough to the wall leads to the roof height. So, in order to get the average height of a building, two measurements are needed: the height of the roof top level and the height of the roof bottom. Hemberg counts approximately 150 buildings. 300 measurements have been conducted and other data were collected at the same time, such as the type of each building.

- **Wind resource data**. The hourly wind speed for Hemberg has been taken from Meteonorm since HOMER only provides monthly data. The latter had to be scaled since the wind turbines will be placed outside the village. It has been assumed that the wind speed distribution outside the village is the same as inside the village and at the precise location of the wind turbines because of their proximity. Therefore, the annual average value input in HOMER was scaled to 5.8 m/s (average wind speed outside the village). By comparison, the value for the village itself is 4.7 m/s. Thus it can be assumed that the wind turbines will be installed at around 1000 meters from the village. The accuracy of the wind data is very important in order to perform a precise analysis of the wind turbine power output. To be able to scale the wind profile of the village itself (which has been imported) to 5.8 m/s, HOMER uses the four advanced parameters including Weibull K, 1 hr. autocorrelation factor, diurnal pattern strength, hour of peak wind speed. A Weibull distribution curve was fitted to the wind speed data with Matlab in order to determine the Weibull shape factor k which depends on the wind distribution at a given location.
- **Temperature resource.** The temperature hourly data has also been taken from Meteonorm because it provides values out of a more recent time range, namely 2000-2009 compared to 1985-2005 in HOMER. This allows the optimization to be more accurate because HOMER simulates with monthly average data if no hourly profile is imported.
- **Hydroelectricity potential**. Switzerland is known for its large use of hydroelectric power. Nowadays, this technology accounts for around 56% of the total Swiss electricity consumption and is used to store the excess of electricity by using the pumped hydro storage. The potential for micro hydroelectricity has been investigated with the help of the GIS research program for small hydroelectric power plants in Switzerland. We found that their potential in the area of Hemberg is very limited.

3. Results

4.1. Analyzing energy potential estimation

CitySim has been used to simulate the yearly PV electricity production of the village. Monocrystalline PV panels with an efficiency of 20% are selected for the study. Since not all of the PV panels are optimally exposed to the sun due to orientation and shadow of neighbouring buildings, locations with an irradiance lower than 1000 kWh/m2/yr are removed. The reasons for this limit are explained in Robinson et al., 2005 and Mohajeri et al., 2016 [13, 14]. Short-wave irradiation data has been used to know which roofs of Hemberg are under this limit value and thus which panel locations need to be excluded. The annual electricity potential from PV in Hemberg is 5,177 MWh with PV on selected roofs, considering the limit of irradiance.

4.2. Analyzing energy demand

Energy demand of Hemberg simulated by CitySim includes space heating, water heating, and electricity demand. While the internal gains from occupancy and appliances reduce the space heating demand by 11%, a shell refurbished according to the Minergie labelshell allows to reduce it by 70%-85% compared to the base scenario. The ratio between the yearly electricity production and electricity demand is equal to 274% for Hemberg. It does not necessarily imply that all the electricity demand can be provided by PV all year round because the solar energy significantly fluctuates on a daily basis and on a seasonal basis. However, it can be concluded from the value 274% that an excess of electricity production will appear and will potentially be sold to the grid. Another ratio to compare the energy demand and production is the ratio between the yearly PV electricity production and the yearly energy demand including space heating, water heating and electricity. Figure 1 summarizes these ratios for each scenario.

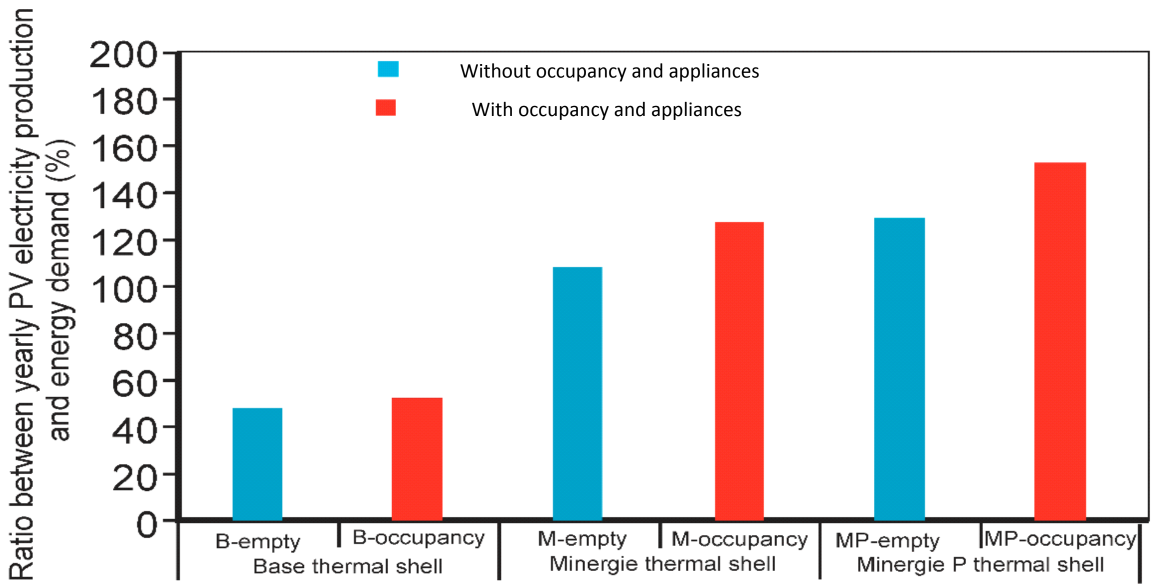

Fig. 1: Ratio between the yearly PV electricity production and the total energy demand for each scenario

As mentioned before, ratios over 100% mean that an excess of electricity production will appear and will potentially be sold to the grid. As shown by Fig. 1, the yearly energy produced by PV is equal to 50% of the energy demand for the base scenario and to 110%-150% for the Minergie scenarios. Again, because of the solar energy seasonality, these ratios do not necessarily imply that the total energy demand can be provided by PV all year round. However, if large installations of storage were considered, it seems that most of the electricity demand could be supplied by solar energy in Hemberg (for these scenarios).

4.3. Energy hub configurations (scenarios 0, 1, 2)

In this section, we propose different energy hub scenarios for Hemberg. Scenario 0 represents the current energy system. This scenario has been modelled in order to be able to compare the possible future energy systems with the current one. In Scenario 1, the objective is to increase the capacity of photovoltaic panels to a large scale and add wind turbines since the region is suitable for this technology due to the high wind speed. On top of that, a battery bank will also be investigated in order to make the system less dependent on the grid. Scenario 1 is still using a non-renewable and old-fashioned heating system (a boiler with fuel oil). Therefore, in Scenario 2 the goal is to investigate the benefits of adding heat pumps in the system (Table 1).

Table 1: Summary of the scenarios for hub configuration.

	Scenario 0	Scenario 1	Scenario 2
PV panels	17kWp	Optimized	Optimized
Wind turbines	-	Optimized	Optimized
Battery bank	-	Optimized	Optimized
Heat pumps	-	-	✔
Grid	✔	✔	✔
Converter	Optimized	Optimized	Optimized
Boiler	Optimized	Optimized	-

4. Conclusion

By integrating an energy hub in Hemberg, Switzerland, the following results are achieved: PV production meets more than twice the electricity demand of the village on a yearly basis. This does not necessarily imply that all the electricity can be provided by PV since the solar energy significantly fluctuates all year round. However, this means that a part of the electricity produced in summer can be either sold to the grid or used for other applications if a storage solution is introduced in the hub. Concerning the space heating demand, six scenarios have been conducted depending on the insulation, the occupancy and appliances. The simulations showed that refurbishment meeting Minergie labels has a significant impact on the energy demand of a building as the space heating consumption is reduced by 70-85%. The HOMER analysis is the result of a non-exhaustive study in terms of the choice of components. Even if the software has some limitations, it has been possible to come up with interesting conclusions. First, the complementarity between solar and wind for Hemberg has been demonstrated through the pattern of the power output from the two renewable resources. Second, the maximum economical potential (COE at its minimum point) is not fully exploited by the proposed energy hubs. There is still a lack of storage to take advantage of this additional electricity that could be produced. Finally, the renewable fraction can be increased to over 60% while meeting the thermal load with heat pumps. The limit is mainly due to the electrical load profile whose monthly average power value varies from 250kW in summer to 750kW in winter. This result brings to the storage issue that every energy system is currently facing because of the high price of this technology. Excess electricity due to grid restriction is the main consequence of non-use of a battery bank.

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