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Extending building integrated photovoltaics (BiPV) using distributed energy hubs. A case study in Cartigny, Switzerland

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Abstract

The integration of renewable energy technologies in the existing energy infrastructure plays a key role in improving the sustainability of cities. Due to the stochastic nature of some renewable energy sources, primarily wind and solar energy, direct integration into the grid is challenging. One solution is to use distributed multi-energy hubs which make it possible to intelligently integrate renewable energy sources into the grid and optimize resources. This paper presents an energy hub development and its integration in the Swiss village of Cartigny. Energy demand of buildings is estimated with CitySim Pro, hourly results are then exported to the microgrid simulation tool HOMER Pro to perform optimization, and system performance and lifecycle cost are evaluated under different BiPV capacities. The results for Cartigny show that relying entirely on renewable energies is not yet realistic due to their stochastic nature. They also show the importance of integrating daily and seasonal storage systems.

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Keywords: Energy Hub, Urban energy modelling, Building integrated photovoltaics

1. Introduction

Swiss energy strategy 2050 strictly emphasizes the importance of integrating renewable energy technologies in the existing energy infrastructure. Due to the increased share of decentralized renewable energy sources, as well as their stochastic nature, it is essential to promote multi-energy hubs. Multi-energy hubs help to match the local production with the consumption by integrating generation, conversion and storage technologies [1]. However, the role of an

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energy hub and its various configurations, designed in order to integrate solar BiPV (in multiple steps), has not been studied much, especially considering the Swiss context. Energy hub is a conceptual model which represents the interactions between the energy conversion systems and the storage technologies [2]. The first conceptualization of the energy hub was proposed by Geidl [3], defined as a mixed energy carrier power system, able to provide input/ output, conversion and storage of different energy carriers. The energy hub concept was later modified, by including the modelling and optimization of the energy systems, already at the concept stage [4][5]. Several case studies were already performed at the urban scale, showing the nice potential of integrating multi- energy hubs in existing villages, as an example the village of Zernez [6] [7]. The aim of this study is to present a comprehensive techno-economic analysis for a distributed energy hub which can be implemented in Cartigny, a small village in the Canton of Geneva in Switzerland. To achieve the above aim the present study focuses on the following steps: (i) modelling energy demand (thermal and electrical) of the village on an hourly basis using the urban energy modelling tool CitySim Pro [8], (ii) coupling the building simulation model with the energy hub model using Homer [9], a microgrid simulation tool. The proposed model, a multi-energy hub, will be directly interacting with the main grid and consists of BiPV panels, wind turbines, a bio-gas generator, and H2 fuel-cells. Finally, (iii) the system configuration of the energy hub is optimized while maintaining BiPV capacity as a constraint. System performance and its lifecycle cost are then evaluated under different BiPV capacities. In addition, (iv) different scenarios for the energy consumption are also considered in the modelling, that is, through (a) occupancy profiles (including electric lighting and appliances, as required by the Swiss normative), and (b) proposing the refurbishment of the village according to Minergie-ECO standards [10].

2. Case study and methodology

2.1. The village of Cartigny

Cartigny (46.18 North, 6.01 East, 430 m a.s.l.) is located in the canton of Geneva in Switzerland (Fig.1). The village, with a population of 865 inhabitants, is situated on the left bank of the Rhone River. The village is characterized, according to the Koeppen climatic classification [11], by a Cfb climate (C: warm temperate; f: fully humid; b: warm summer). Based on the data retrieved from Swisstopo, the village is composed of 370 buildings, most of which are residential houses. Cartigny acts strongly towards sustainability and it has obtained the energy label "Cité de l'énergie" in 2007 and 2010. The central wood-fired heating system provides the heat energy for 95% of the buildings; on the rooftop of the building, BiPV are installed, producing 19,300 kWh per year. The central wood-fired heating system produces 6 million of kWh hot water, at 75°C, which is sent by the central heating system to the buildings and, after the use, back at 63°C [12]. The solar potential of the site is huge. However, due to the rural and historical value of the village, it is classified, by the Geneva Canton, as "Zone 4B Protected", to preserve the esthetic value of the site. Due to this regulation, installation of PV on the buildings is a challenge, and their unobtrusive integration in the built stock is essential.

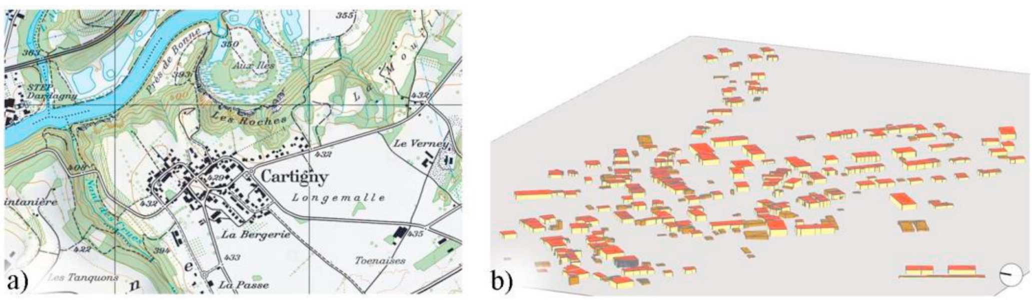

Fig. 1. (a) 2D Map of the village of Cartigny, Source: Swisstopo (b) 3D view of the site, Source: CitySim Pro

Three main energy sources are available on the site: solar irradiance, wind speed and biomass. The global horizontal solar irradiance corresponds to 1,248 kWh·m^{-2} [13] and the average wind speed is between 5 ms^{-1} to 6 ms^{-1} [14]. The daily average weight of biomass delivered to Cartigny (retrieved by the company Serbeco) corresponds to 5.48 $t \cdot d^{-1}$ and the wood imported has a lower heating value of 18 $MJ \cdot kg^{-1}$. The average monthly biomass is higher during winter time (up to 11 $t \cdot d^{-1}$) compared to summer (up to 3.5 $t \cdot d^{-1}$).

2.2. Set-up of the model

In this study, we develop a methodology in order to optimize the energy systems at the urban scale considering the physical constraints of the built environment. The proposed methodology is subdivided into two main parts:

- quantification of the energy demand of the buildings in hourly values using the urban energy modelling tool namely, CitySim Pro
- improvement of the energy systems, by the software HOMER Pro.

CitySim Pro [8] is an urban energy modelling tool, developed at the Solar Energy and Building Physics Laboratory - Ecole Polytechnique Fédérale de Lausanne. CitySim is able to quantify the hourly energy demand, from the building to the city scale, as well as the renewable potential and production. HOMER Pro, a Hybrid Optimization Model for Multiple Energy Resources, is a microgrid software, developed at the National Renewable Energy Laboratory (www.nrel.gov). HOMER Pro optimizes the energy systems according to the selected variables [9].

2.3. Modelling energy demand and solar potential of the site using CitySim Pro

The energy demand of buildings and the solar potential of the site are quantified by the software CitySim Pro. The 3D version of the buildings is built based on 2D building data extracted from Swisstopo. To accomplish this, the data were exported from the geographic information system software QGIS into the 3D computer graphics software Rhinoceros 3D. This allows us to have the layouts of the buildings in 3D while considering their height. The 3D model of buildings was then transferred from Rhinoceros 3D to CitySim Pro, where specific parameters of the model were defined. All the physical properties of the buildings were defined according to the type of building as well as their period of construction. For example, the U-value of the envelope is based on the work performed by Perez [15], which defines the physical properties of the envelope according to the period of construction. Finally, each building is analyzed by adding the occupancy profile, as defined by SIA 2024 [16], as well as the lighting and appliances. The selection of the input parameters has an important impact on correctness of the results [17], consequently, in order to understand the sensitivity of the grid to the physical characteristics of buildings, the following scenarios were studied:

- <u>Scenario I:</u> current village without occupants, lighting and appliances
- <u>Scenario II:</u> current village with occupants, lighting and appliances
- <u>Scenario III:</u> refurbished scenario according to the Swiss standard Minergie-ECO, with BiPV integrated on the roofs. The U-value of walls is reduced to 0.15 $Wm^{-2}K^{-1}$ and 1.0 $Wm^{-2}K^{-1}$ for windows. In order to assess the solar potential of the site, the Sun Forte PM096B00 photovoltaic panels were selected (efficiency equal to 20%) and installed upon 75% of the roofs.

The creation of the energy model of the village requires a large amount of data, to be included into the CitySim model. In order to simplify the process of including the data, an Octave code was developed so as to simplify the creation of the model within CitySim. GNU Octave [18] is a software using a high-level programming language and was initially designed for numerical computations. It also offers a wide variety of functions for manipulating text files. The proposed code simplifies the insertion of the input data and reads directly the XML file, which contains all the information about the CitySim model.

2.4. Optimization of the energy systems using HOMER Pro

Based on the proposed methodology, the multi-energy hub (consisting of BiPV panels, wind turbines, bio-gas generator and H_2 fuel-cells) is used in order to increase renewable energy integration in the most rational and feasible way. The optimization is performed by the micro grid design tool HOMER Pro, which aims at minimizing the total net present cost (NPC) of the system, considering both the optimal system configuration and operation of the system. In order to perform the optimization of the energy systems, the following scenarios are defined:

- Scenario IV: cogeneration using biomass as a resource and boiler along with BiPV, wind turbines, converter and battery bank
- Scenario V: fuel cells, along with electrolyzer and hydrogen tank, with BiPV, wind turbines and converter
- Scenario VI: heat pump (with a COP=3) and biogas generator, along with BiPV, wind turbines, converter and battery bank.

For the above mentioned scenarios (IV, V and VI), we varied the integration of the energy sources, in order to see their effect on the Renewable Energy Fraction (REF). Consequently, trying to identify the suitable amount of renewable energy sources, in order to address the primary loads.

3. Results

3.1. Energy demand and solar potential of the site

The average heating demand of the current village is reduced from 141.8 kWh·m^{-2} (7.8 GWh annually) without occupants (Scenario I) to 125.9 kWh·m^{-2} (7.3 GWh annually) including occupants, lighting and appliances (Scenario II). Effectively, as occupants as well as lighting and appliances generate heat, they reduce the heating demand. The above values correspond to the current Swiss stock, around 200 kWh·m^{-2} for buildings built before 1920. Considering refurbishment of the site (Scenario III), according to the Minergie-ECO standards, the demand would drastically decrease to 28.4 kWh·m^{-2} (1.3 GWh annually). This represents an 80% reduction of heating demand compared to the current situation. Even though this case is unrealistic (due to the economic cost, as well as private interests), our objective is to show that the insulation of the buildings has an important impact on the energy demand. The effect of a refurbishment is even stronger in the Cartigny village because most of the buildings were built before 1919, consequently with a low energy efficient envelope. Even if Cartigny is already supplying most of its heating through renewable energy (wood-fired boiler), a significant reduction in the heating demand would reduce the need for wood dedicated to heating, which could then possibly be used for electricity generation. In this case, the BiPV were added to the energy model (Fig. 2, annual solar irradiance on the site), producing 5.4 GWh electricity; this result is really high, but it considers an ideal case where BiPV are integrated upon all rooftops. Additionally, the results are mitigated by the fact that electrical production is not following the consumption trend. For instance, at night there is no solar power production, while there is an electricity demand.

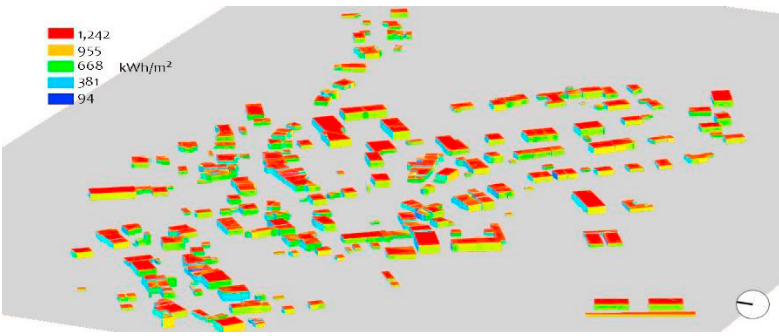

Fig. 2. Annual shortwave irradiance received by the buildings in the Cartigny village.

3.2. Optimization of the energy systems

One aim of this study is to explore how much Cartigny can further integrate renewable energy into their energy system, in addition to their already implemented central wood burners. In order to achieve this aim, the scenarios related to the three energy system configurations were modelled using HOMER and subsequently analyzed. It should be noted that although increasing solar panel capacity is encouraged from renewable energy integration perspective, its sales to the grid should be carefully managed to maintain the stability of the grid. In order to evaluate the sensitivity of solar energy integration, several simulations were conducted by varying the sale capacity of the grid and optimizing the system configuration. In these optimizations, purchase capacity was set to 1700 kW and its sale capacity was varied from 200 to 1000 kW. The value of 1700 kW was selected to study the variation of the energy costs as function of the PV capacity; furthermore, it was varied with values lower than the peak demand, to decrease the dependency on the grid. The grid is installed to supply, consequently what it can accept to purchase back is limited. Results from the optimization reveal that the Cost of Energy (COE) decreases as PV capacity increases, up till a certain capacity (around 3000 kW) where it starts afterwards: consequently, the integration of PV became economically feasible until a certain capacity installed. Effectively, the grid compensates costs associated to PV production by purchasing back part of it. However, once the sales capacity is reached, there is no longer compensation for the additional generation, only costs. Thus installing too many PV panels, with a capacity > ~3000 kW, leads to an overproduction, which is too large to be sold back to the grid, resulting in both loss of energy and of money. Further, the COE decreases as the grid sales capacity increases. More importantly, the optimum solar panel capacity is greater than the present practice for building integrated solar panels in Switzerland. When comparing the three scenarios it was found that Scenario IV has the best ability to integrate renewable energy technologies in the existing energy infrastructure (47% of cost reductions, Table 1). When considering the lifecycle cost, Scenario V is the best option (0.14 $\$\cdot kWh^{-1}$): the use of fuel cells as single fuel source in order to generate both electricity and heat which improves efficiency and reduces costs. However, fuel cells only cover less than 5% of the electric demand in this case. Finally, the results show that the optimization could well decrease the CO_2 emissions per capita. More specifically, the annual CO_2 emissions per capita in Switzerland in 2014,was 4.77 t [19]. Considering the optimization, the CO_2 emission can decrease to 2.4 t, 2.8 t and 2.9 t, in scenarios IV, V and VI, respectively. All the results are summarized in Table 1.

Table 1 Comparison between the costs of the selected scenarios IV, V and VI.

	Scenario IV	Scenario V	Scenario VI
Cost of Energy ($\$\cdot kWh^{-1}$)	0.183	0.1437	0.197
Initial Cost ($)	3 M	4.2 M	2.9 M
REF (%)	47	34	32

4. Conclusion

The present paper proposes a new methodology to improve the sustainability of a city, by applying the energy hub concept. According to the proposed method, the hourly energy demand of buildings (the current and renovated according to Minergie-ECO scenario) is quantified using the urban energy software CitySim Pro. The results are then imported into HOMER Pro in order to improve the efficiency of the energy systems; in this case, by combining BiPV panels, wind turbines, bio-gas generator and H_2 fuel-cells, in the multi-objective energy hub. In the studied case, results show the importance of a refurbishment of the site, reducing the energy demand by 80%, as well as the importance of BiPV, integrated in the grid. More specifically, in the idealized case where BiPV are installed on every roof, the electricity production could be entirely covered by renewable energies as long as efficient storage is provided. Adding a seasonal storage system (hydrogen storage or hydro-pneumatic storage) would allow the system to work all year round and compensate the renewables stochastic nature, as well as the differences in production between the seasons. In conclusion, we have to assume that, in the specific case study of Cartigny, relying entirely on the renewable energies is not yet realistic, due to their stochastic nature, underlining the importance of integrating daily and seasonal storage system.

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