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Towards an energy sustainable community: An energy system analysis for a village in Switzerland

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ABSTRACT

This paper aims to integrate decentralized energy systems in a village in Switzerland, which has the goal to phase out fossil fuels and rely on local renewable energy sources. To reach this ambitious target, a revision of the current energy system is required together with retrofitting of the building stock. The method applied is based on the energy hub concept, which can be used to optimize the energy consumption during planning and operation. To apply the energy hub concept at neighbourhood level, a three step approach is required, including modelling the energy demand of the buildings, the evaluation of the local renewable potential, and the management and optimization of demand and supply. Centralized and decentralized local renewable sources are investigated, namely photovoltaics, biomass, or small hydro power. Scenarios are evaluated based on their environmental performance and savings of CO_2 emissions. Results show that an energy sustainability (ratio of energy demand covered by renewables) of 83% and a CO_2 emissions reduction of 86% can be achieved. The results further suggest that up to 50% of the available energy potential from renewables cannot be utilized in this community when insufficient storage is provided in the energy system.

1. Introduction

As a result of the Fukushima's nuclear accident in 2011, Switzerland has decided to phase-out of nuclear power till 2050 [1]. This requires a significant reduction of the current energy consumption, and a restructuring of the country's energy system. Studies report that the future energy system of Switzerland will not rely on a single centralized energy technology but rather on a mix of multiple distributed energy systems (DES) [1]. For the case of Switzerland, a major share of the energy demand will be covered by hydro power and DES such as photovoltaics (PV), geothermal heat, wind energy, and biomass [1]. Since energy supply from renewables is highly fluctuating over time and dependent on climatic and local conditions, a reliable integration is a challenging task. DES are typically integrated at building level and account for a small fraction of required energy. To increase the renewable energy share, a careful planning and operation strategy is required. Current trends promote the integration of hybrid DES, to increase reliability and economic performance [2,3]. Moreover, hybrid DES are frequently more highly integrated at district level, where energy can be shared amongst various consumers [e.g. [4]]. Another advantage of integrating DES at district level is that multiple technologies can be incorporated, which makes the system more efficient than only taking a single building and technology into account. Moreover, building integrated renewable energy technologies such as PV, solar thermal collectors, hybrid collectors, or wind turbines can be combined with local and regional scale distribution technologies such as micro-grids, district heating and cooling networks [5]. To optimize the future energy system and to effectively integrate DES requires concepts to sufficiently improve the energy efficiency of the building stock on the one hand and to manage energy supply from renewables on the other hand [6]. Recently a lot of attention has been paid in promoting net-zero energy measures for new buildings, which resulted in tightened regulations and standards for the construction of buildings [e.g. [7]]. However, the existing building stock remains one of the main energy consumers. Especially buildings from the 1970s or before would require refurbishment, to efficiently integrate DES [6,8]. To find the optimal solution for future energy systems depends on multiple factors,

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Nomenclature

ACH	air change rate (h^{-1})
ASHP	air source heat pumps
A_{surf}	active array area of PV (m^2)
CHP	combined heat and power
DES	distributed energy systems
DH	district heating
GSHP	ground source heat pumps
H	effective pressure head (m)
I_g	global irradiance incident (W/m^2)
P	electric power (W)
PV	photovoltaic
Q	volume flow rate (m^3/s)
η_{cell}	conversion efficiency of PV (–)
η_{invert}	conversion efficiency DC to AC (–)
η	hydraulic efficiency of turbine x generator efficiency
ρ	gravity (m/s^2)

and is a challenging task for planners and policy makers, which requires tools and decision support systems [9] to assist in evaluating improvement measures. Decision support tools for building retrofit, which have been addressed in literature are often based on mathematical programming techniques, such as multi-objective optimization models [10,11]. Similarly, multiple research studies deal with (also multi-objective) optimization of district energy systems [e.g. [12,13]]. So far however, the successful interplay of supply and demand in networks with multiple energy carriers, and the related conversion and storage technologies at building and district level are addressed to a much lesser extent. This can be achieved by applying the concept of an energy hub, and closely link it to methods to optimize the buildings energy consumption. With the concept of an energy hub, different combinations of energy systems can be assessed by controlling conversion, storage, and distribution of energy. The energy hub concept [14,15] can be applied at different levels of complexity to optimize energy flows, costs and emissions and evaluate the performance of different energy carriers. Energy-hub model implementations at different scales [16,17] as well as multi-energy grids [18] are at present an active area of research. Existing energy hub models consider mainly either large-scale electricity generation plants [19] and national supply concepts [20], or – to a lesser extent – individual buildings [21], but also the integration of renewable energy sources [22].

2. Problem definition

Based on this background this paper is aiming to integrate DES in a village in Switzerland which has the goal to phase out of fossil fuels and rely on local renewable energy sources. To reach this ambitious target, a revision of the current energy system is required together with retrofitting of the building stock. The paper describes a three step approach, which involves the evaluation of the retrofitting potential, the potential for renewable energy integration, and the management of the energy flows at neighbourhood level, using the energy hub concept. For the village the optimal mix of renewable energy sources together with energy conversion technologies is identified. The primary goals are to replace existing fossil-fuel based heating systems with more sustainable solutions, integrate local renewable energy sources, and reduce resulting carbon emissions. The following sections present the description of the concept, and the application to the case study by defining and evaluating different future energy scenarios for the village.

3. Methods and tools

The integration of DES at neighbourhood scale depends on the energy consumption of the neighbourhood, the available potential of energy from different energy sources and the management of the two. The concept consequently requires a three step approach, which incorporates the energy hub model to manage the energy flows, the evaluation of the buildings energy demand, and the evaluation of potential energy sources. The energy hub model can include various energy technologies for conversion, transformation, distribution and storage both at building and district scale. The building performance model provides information on the time-resolved energy demand of buildings pertaining to electricity, heating, and cooling. Additionally, information and models which evaluate the time-resolved available energy from decentralized and centralized technologies is included. The following figure shows the main points of the concept (Fig. 1). In the next sections the three steps are further described.

3.1. The energy hub concept

The energy hub concept is used to evaluate and optimize the management of energy flows. The energy hub gives the possibility to store energy, convert energy between multiple energy carriers (e.g. electricity to heat, natural gas to heat, thermal solar to hot water heating, hot water storage, etc.) in order to supply sufficient electricity, heat, cold, gases or fuels to end users. The advantage of the energy hub approach is that energy consumption, costs, emissions etc. can be optimized in relation to conversion, storage and distribution of energy. The energy hub model is a simple tool, which is typically combined with optimization techniques, such as linear or non-linear programming, to evaluate optimal design layouts, operation or control of energy systems. The key concept is the use of multiple input energy sources which will be converted by the hub to multiple outputs. Details about the modelling concept are discussed elsewhere [23]. Within the following case study the energy hub model is used to optimize the energy system of the village and reduce CO_2 emissions due to providing space heating, domestic hot water and electricity use for appliances.

3.2. Energy demand

For the sufficient integration and management of renewable energy technologies, time-resolved information on the energy demand of buildings is essential, which requires a method of reconstructing hourly information from yearly energy consumption values.

To examine the heating demand of a neighbourhood, building performance simulation models are used. These models (e.g. Energy Plus, TRNSYS, etc.) allow calculation of heating and cooling demands for hourly time-steps. For the present study the simulation tool EnergyPlus [24] is used. EnergyPlus has an integrated heat balance based solution technique that allows for simultaneous calculation of radiant and convective effects at surfaces (interior and exterior) for each time step. It is equipped with a combined heat and mass transfer model that accounts for moisture adsorption/desorption effects into the conduction transfer functions. Shortwave radiation is calculated based on a combination of direct, diffuse and reflected solar radiation, whereby EnergyPlus deploys an anisotropic sky model for calculation of diffuse solar on tilted surfaces [25].

3.3. Energy potential

Potential energy sources have to be investigated, in this case mainly from renewable energy sources. Relevant energy sources