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PHOTOVOLTAIC PANELS AS A MAIN COMPONENT OF ENERGY SUSTAINABLE COMMUNITIES: COMPARATIVE ENERGY ANALYSIS OF A VILLAGE UNDER SWISS AND SOUTH AFRICAN CLIMATIC LOADS

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ABSTRACT

At the community level, it is difficult to rely on a single centralized energy technology when considering renewable energy and the use of a mix of multiple distributed energy systems (DES) seems advantageous. DES, e.g. photovoltaic panels (PV), are typically integrated at building level and account for a small fraction of required energy. Since energy supply from renewables is highly fluctuating over time and dependent on climatic and local conditions, a reliable integration is a challenging task. In this paper, we use a recently developed concept, that allows to sufficiently improve the energy efficiency of the building stock, to manage energy supply from renewables and to optimize the future energy system using the energy hub approach, while effectively integrating DES. Using the same village characteristics, we found that, due to mismatch of available solar potential and the electricity demand, 18% of available solar potential cannot be utilized in Zernez, while in Johannesburg, this mismatch amounts to 22%.

INTRODUCTION

When considering renewable energy at the community level, a single centralized energy technology cannot be considered to be reliable and the use of a mix of multiple distributed energy systems (DES) offers clear advantages. DES, e.g. photovoltaic panels (PV), are typically integrated at building level and account for a small fraction of required energy. Since energy supply from renewables is highly fluctuating over time and dependent on climatic and local conditions, a reliable integration is a challenging task. To increase the renewable energy share, a careful planning and operation strategy is required. To increase the reliability of DES, current trends are towards integration at district level where energy can be shared amongst various consumers.

In this paper, we use a recently developed concept, that allows to sufficiently improve the energy efficiency of the building stock, to manage energy supply from renewables and to optimize the future energy system using the energy hub approach, while effectively integrating DES. 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 can be applied at different levels of complexity to optimize energy flows, costs and emissions and evaluate the performance of different energy carriers at neighbourhood scale.

In a recent work, a village in Switzerland, Zernez, which has the goal to phase out of fossil fuels and rely on local renewable energy sources, was the object of a study that led to the identification of the optimal mix of renewable energy sources together with energy conversion technologies. In this first study, PV is used for both heating and electricity demand due to appliances and lighting. In this case around 6% of PV is used for heating and the rest is used to cover the electricity demand.

We use the same village geometry and building characteristics, but subject it to the climate of Johannesburg to evaluate the potential of integrating DES in different climatic conditions.

NOMENCLATURE

ACH	[h-1]	air change rate
A_{surf}	[m^2]	active array area of PV
I_g	[W.m^{-2}]	global irradiance incident
η_{cell}	[-]	conversion efficiency of PV
η_{invert}	[-]	conversion efficiency DC to AC

PROBLEM DEFINITION

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.

Figure 1 Image of the village of Zernez

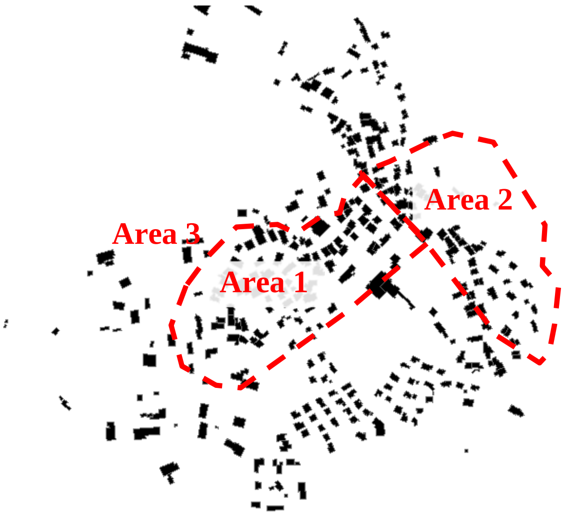

Figure 2. Map of the village showing 3 areas: 1=historical centre of the village, 2=central area, 3=remaining buildings within the village

The village Zernez [1] (Figures 1 and 2), used as a case study, is located at an altitude of 1474 m above sea level with a mean annual air temperature of 4.8 °C and global horizontal incident solar radiation of 1170 kWh.m^{-2}. It has a population of 1150 inhabitants and consists of approximately 300 buildings, of which about 230 are residential and retail, and some additional buildings pertaining to agriculture, restaurants, industry, hotels, public buildings etc. As a starting point the existing situation concerning the energy demand of the village with respect to different uses (heating, lighting, etc.), the different energy sources (fossil fuel, gas, grid electricity, wood, wood chips), and their distribution and networks (e.g. district heating) are analysed. Additional available information pertains to building characteristics such as age, type, construction method, insulation quality, and type of heating system. The majority of the buildings are equipped with electrical heating systems; additional heating is provided by oil boilers, wood chip boilers, wood stoves, and very few ground and air source heat pumps. The village is connected to the national electricity network. It has a small district heating network which is connected to a wood-fired power-station, for which some of the wood is brought to the village by truck. Additionally, two small combined heat and power (CHP) units connected to a gasification unit fired by organic matter are used. Figure 2 shows the map of the village. Areas 1 and 2 are two centralized zones which consist mainly of historical buildings. The remaining buildings form Area 3.

To identify the energy consumption of the buildings, information on annual electricity, oil, and wood consumption and delivered energy from the district heating network was collected, and further analysed to identify the energy used for heating and for electricity. Table 1 shows consumed energy over the period of one year from the different energy sources together with resulting CO2 emissions.

Table 1. Delivered energy in terms of energy carrier for a full year (October 2010-October 2011) together with resulting CO_2 emissions

Energy carrier	**Delivered energy or energy carrier**	**Calorific value [MWh]**	**CO_2 emissions [t CO_2]**
Electricity from the grid	10 400 MWh	10 400	1 543
Heating oil	670 200 l	6 824	2 307
Wood chips local (district heating)	-	5 028	235
Wood chips imported (district heating)	-	5 448	254
Wood	780 m^3	2 497	58
Electricity from renewables	11 MWh	11	1
		29 796	4 399

METHODS AND TOOLS

The integration of DES at neighborhood scale depends on the energy consumption of the neighborhood, the available potential of energy from different energy sources and the management of these two aspects. 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. Figure 3 shows the main points of the concept. The three steps are further described.

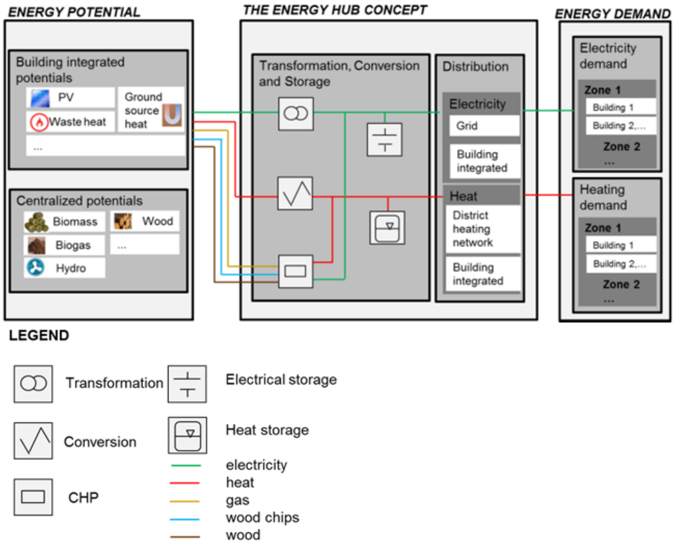

Figure 3 Concept of model components to integrate decentralized energy technologies at neighborhood scale.

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 [2]. 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.

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 [3, 4] is used.

Energy potential

Potential energy sources have to be investigated, in this case from renewable energy sources. Relevant energy sources pertain to building integrated potentials such as PV, ambient and ground heat and centralized potentials such as biomass, and waste wood.

In the case study the utilization of the solar potential is restricted to PV, since electricity demand due to appliances is relatively high. To evaluate the energy potential from building integrated PV installations the simulation tool EnergyPlus is applied which allows to calculate the hourly incident of global irradiance incident on building surfaces. Subsequently, the potential for energy output from PV is calculated based on equation 1 [4, 5]:

$$P = A_{surf} \cdot I_g \cdot \eta_{cell} \cdot \eta_{invert} \qquad (1)$$

where A_{surf} is the active array area (m^2), I_g is the global irradiance incident on the array ($W.m^{-2}$), η_{cell} is the conversion efficiency of the PV array (-), η_{invert} is the DC to AC conversion efficiency (-).

THE VILLAGE

Buildings energy demand

Information pertaining to energy usage was retrieved by energy bills, and information provided by the inhabitants. Additional available information pertains to building characteristics such as age, type, construction method, insulation quality, and type of heating system. Some data could be retrieved from a statistical building data-base in Switzerland [6]. Additionally, information was retrieved by a survey conducted amongst the inhabitants. Weather information for the relevant period was measured with a local weather station [7]. To effectively integrate renewable energy technologies, and improve the energy sustainability of the village throughout the whole year, the measured annual energy demand had to be further processed, to retrieve energy demand in hourly resolution. Hence, the hourly electricity demand due to use of appliances and lighting is calculated for the categories of housing, hotels, and office spaces based on the Swiss standard SIA 2024 [8] and further extrapolated using the total floor area of the buildings.

To identify the hourly space heating demand of all the buildings in the village, buildings are clustered into different categories. Selected categories differ in terms of use type and age of the buildings. From each category a representative building is selected and modelled using the simulation tool EnergyPlus [3]. The simulation model is calibrated using collected information from energy bills. The net heating floor areas of all buildings are selected to extrapolate the simulated heating demand for representative buildings to the whole neighborhood. Selected buildings and additional information pertaining to construction period, building type, and total floor area is summarized in Table 2. Once the simulation model is set up, it is used to evaluate different retrofitting options.

Table 2. Building categories, construction period, building type, floor area per category

Category	Construction period	Type of building	Floor area in category [m^2]
A	Before 1900	Housing	53 281
B	1900-1980	Housing	20 990
C	1980-2000	Housing	15 045
D	2000-	Housing	11 343
E	1945-2000	Trade/ Industry	20 921
F	Before 1900	Hotel	14 508

Solar energy potential

For the case study the local renewable potential is investigated. This includes the available solar potential on roof surfaces for the use of PV and the local biomass potential. As for the local solar potential, roof surfaces of the buildings in the village with orientations from East, South, and West and inclinations from 0° to 45° are investigated in case of the northern hemisphere. The available global solar radiation incident is modelled using the simulation tool EnergyPlus together with climatic data, which are retrieved from a local weather station [7]. An efficiency of 15% of the PV panel is assumed, it is further assumed that 80% of the roof surface can be used to install PV.

The biomass potential in the case study is restricted to waste wood, since other sources are either already utilized or not feasible. Note that biogas is additionally produced by using organic wastes from kitchens, co-substrates from farming, and sludge from the water treatment plant. The biogas is used for two small CHP-units, from which the waste heat is directly used for heating a connected building, and for processes in the water treatment plant. The resulting electricity, amounts in approximately 370 MWh and is exported to the grid. Since the resulting electricity is relatively small, compared to other potentials, it is not further considered in the present study. To estimate the waste wood potential (used as wood logs and chips), information from the local forester and the ministry for forestry was taken into account.

The resulting renewable potential for PV and local wood and wood chips over the period of one year amounts in 3133 MWh and 2056 MWh respectively. Figure 4 shows the calculated available annual solar radiation potential on roof surfaces of the buildings.

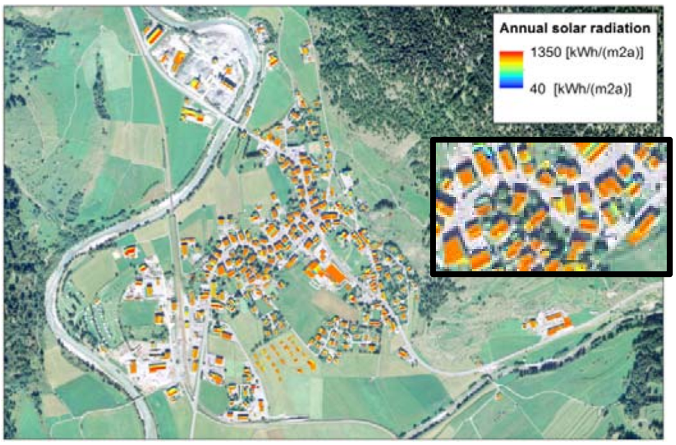

Figure 4 Map of the village showing annual solar radiation potential on roof surfaces, with inserted close-up for visualization.

Scenarios

Based on the available potential, scenarios are proposed (Table 3) which are evaluated using the urban energy hub concept. The scenarios include energy supply by PV, wood, and a connection to the electricity grid and different retrofitting states of the building stock including the existing situation (–b), replacement of windows (–w), and additionally insulated walls and ceilings (-i). Scenario S1-i-storage includes additionally lithium-ion batteries.

Table 3. Summary of scenarios without (S1-) and with storage (S1s-) where (–b) represents the existing situation, (–w) replacement of windows, and (-i) additionally insulated walls and ceilings.

	Scenario	**S1**			**S1s**
		b	**w**	**i**	**i**
Building performance	existing	x			
	new windows		x	x	x
	walls+ceilings insulated			x	x
Storage system	batteries				x

RESULTS AND DISCUSSION

Building energy demand

Figure 5 shows the simulated hourly energy demand for heating and electricity of the village. The total energy demand of the village is 16 440 MWh for heating and 6 185 MWh for electricity used for appliances and lighting. Figure 5 shows aggregated space heating demand for building categories of the village for the base case (b), the retrofitted case which takes the replacement of windows (w), and a fully retrofitted case taking window replacements, insulation of walls and ceilings (i) into account. Total energy consumption due to heating can be decreased by 15% if existing windows are improved and 62% if additionally walls and ceilings are insulated. Building type A, which consists of the oldest buildings in the village, has the highest potential of improvement. Most of these buildings are equipped with oil or electricity space heating systems, which require a revision of their systems to meet the targets in stepping out of fossil fuels. Building type C, D, and F show in total the lowest contribution to the overall energy consumption for both the existing and the retrofitted cases.

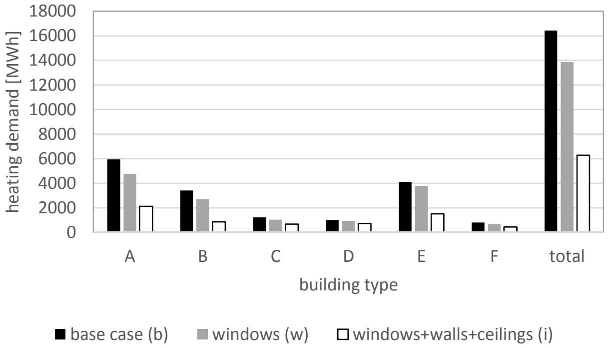

Figure 5 Annual space heating demand per building type for the base case (b), retrofitted windows (w) and windows, walls and ceilings retrofitted (i).

Integration of renewable energy sources

To evaluate the integration of renewable energy technologies the energy hub model is deployed, which optimizes the management of energy supply and demand for hourly time-steps over the year by minimizing CO_2 emissions. Figure 6 shows optimized distribution of energy carriers for the scenario S1-b. The share of unutilized renewable energy results in 13%. Results demonstrate that the potential of energy from PV is typically available in summer periods when the energy demand is not very high, whereas during winter months when both heating and electricity consumption are high, the energy potential is low, which requires additional electricity from the grid (Figure 7). In the case the buildings would be retrofitted as shown in Figure 8, a slight increase in the contribution of PV over the period of a year could be achieved. The integration of batteries achieves a reduction of electricity grid contribution of around 4 % (Figure 9).

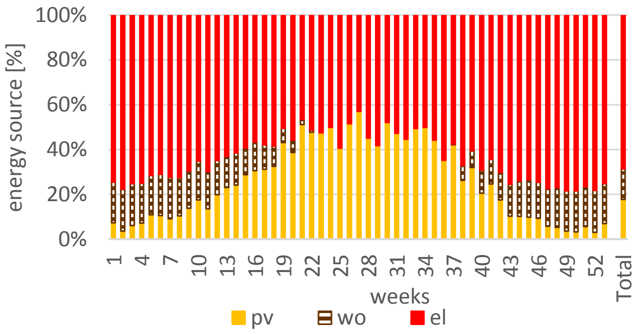

Figure 6. Weekly distribution of energy sources based on the optimization for emissions over one year for scenario S1b pertaining to integration of photovoltaic (pv), wood (wo), and electricity grid (el).

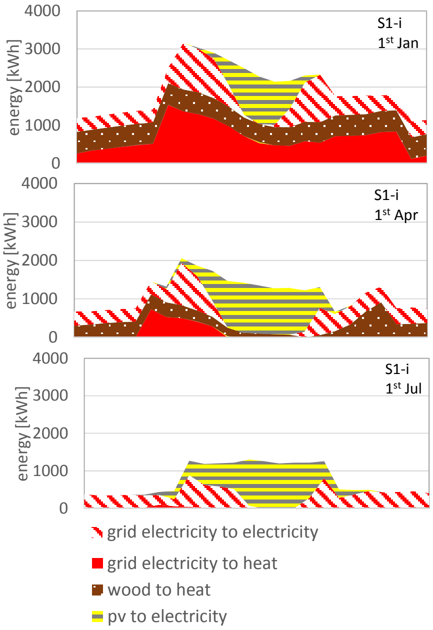

Figure 7. Distribution of hourly energy consumption by different energy carriers for heating and electricity for three days (Jan 1st, April 1st, July 1st) for scenarios S1-i.

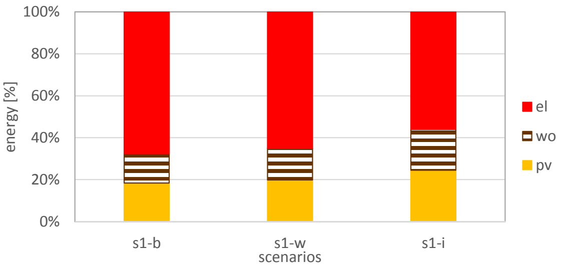

Figure 8. Annual distribution of energy sources based on the optimization for emissions over one year for different building conditions: base case (b), retrofitted windows (w), retrofitted windows, walls, and ceilings (i).

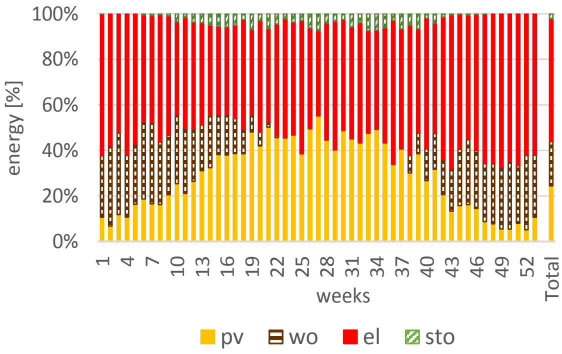

Figure 9. Weekly distribution of energy sources over one year for scenario S1-i-sto that includes batteries (photovoltaic (pv), wood (wo), electricity grid (el), and batteries (sto)).

Renewable energy potential

We use the same village geometry and building characteristics, but subject the village to the climate of Johannesburg to evaluate the potential of integrating DES in South African climatic conditions. Figure 10 shows outdoor air temperatures over the period of one year in Zernez and in Johannesburg. The solar radiation potential was calculated for Zernez and for Johannesburg, annual global horizontal radiation in Zernez amounts in 1175 kWh.m^{-2}.year^{-1} and 2082 kWh.m^{-2}.year^{-1} for Johannesburg, which results in 4800 MWh.year^{-1} electricity potential.

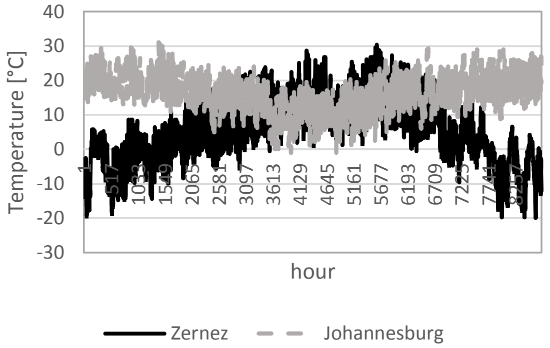

Figure 10 Outdoor air temperatures in Zernez and Johannesburg over one year.

Buildings energy demand

The same buildings, as found in the Swiss village, were modelled with Johannesburg climatic conditions. Figure 11 shows annual heating and cooling demand for the 6 different building types in the base case scenario (Table 2). Results show that the resulting heating demand is relatively low compared to Swiss climate. The more dominating factor in this case is the resulting cooling demand which is negligible in the climatic conditions of Zernez.

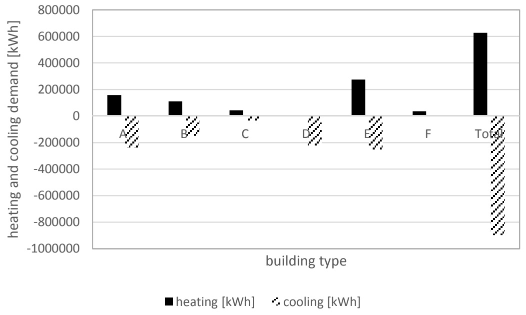

Figure 11 Buildings energy performance results for climatic conditions of Johannesburg for the base case scenario.

Integration of renewable energy sources

As a next step, the integration potential of photovoltaic panels is evaluated with the energy hub concept. Figure 12 shows the distribution of energy sources to cover the electricity demand due to appliances and lighting for the period of a year. If only PV is used to cover the electricity demand, in Zernez around 40% could be covered, whereas in Johannesburg the same area of PV would cover around 58% of the demand, due to the higher solar potential. Due to mismatch of available solar potential and the electricity demand, 18% of available solar potential cannot be utilized in Zernez, and in Johannesburg 22%. If batteries are installed, the grid contribution can be decreased by 4 and 6%, respectively for Zernez and Johannesburg.

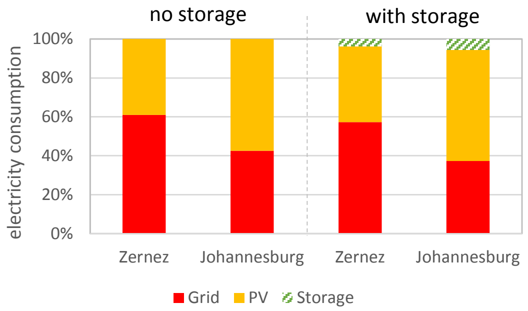

Figure 12. Distribution of hourly energy consumption by different energy carriers for heating and electricity for three days (Jan, 1st, April 1st, July 1st) for Scenarios S1-i.

CONCLUSION

This paper describes a method of integrating DES in a village in Switzerland which has the goal to phase out of fossil fuels and rely on local renewable energy sources. The scale of integration of renewable energy technologies at neighbourhood scale depends on the energy demand of the neighbourhood, the available potential from different energy sources and the management of the two. Future energy scenarios to integrate photovoltaic panels are presented, which are evaluated with the energy hub model of the village, used to minimise CO_2 emissions. We used the same village characteristics, but subject it to the climate of Johannesburg to evaluate the potential of integrating DES in different climatic conditions, it was found that, due to mismatch of available solar potential and the electricity demand, 18% of available solar potential cannot be utilized in Zernez, and in Johannesburg 22%. If PV is additionally used to cover the occurring cooling loads, the utilization of available solar potential in the case of the South African climate could be significantly increased and would warrant a further analysis.

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