IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: Daniel Satola *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 072065

IOP Conf. Series: Materials Science and Engineering **609** (2019) 072065 doi:10.1088/1757-899X/609/7/072065

Assessing the annual power reliability of a residential building in relation to its ventilation system type: The case study of the off-grid container house in Shanghai.

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Abstract. In developing countries, electrification of rural and remote areas is an essential need for improving socio-economic conditions. However, increased access to adequate electricity and upgraded facilities may double or even triple present greenhouse gas emissions related to residential buildings operation. From both socio-economic and environmental perspective, implementation of solar-powered houses is widely considered as a sustainable. Power reliability is a key indicator used in assessing the annual performance of the off-grid housing operation. The primary objective of this article is to ascertain the impact of three main ventilation system types: natural (NV), mechanical with heat recovery (MV) and hybrid (HV) on annual power reliability of the case, off-grid building located in Shanghai. Firstly, three scenarios of hourly electricity loads profiles were calculated from an annual simulation via building performance software (BPS). Secondly, electrical load profiles were integrated into a developed model of alternating current (AC) coupled battery off-grid energy system model. The results indicate that the HV system provided the lowest annual electricity consumption (2847 kWh) and the best annual power reliability (98.6%) when compared to MV (2935kWh, 98.5%) and NV (2901kWh, 98.0%). The article discusses correlation between building ventilation scenarios, electrical loads and resultant annual power reliability. In conclusion economic viability of mechanical/hybrid ventilation implementation in off-grid housing is called into question.

1. Introduction

Globally, nearly 1.1 billion people still lack any access to electricity supply [1]. For this reason, the World Bank, together with the International Energy Agency forecast that the installed global electrical capacity has to double toward 2050 to meet the growing energy needs of emerging societies [1]. However, increased access for billions of people to adequate electricity, housing and better than bare minimum facilities may lead to double or even triple current greenhouse gases emissions related to the residential construction sector [2]. Therefore, the shift from fossil fuels use towards clean and renewable energy sources is an uncontested need to guarantee a sustainable, global development [3].

The term 'solar powered, off-grid house' means a residential building in which all energy needs are covered by renewable solar generation combined with an energy storage system, without connection to the conventional electricity network. This particular type of housing is engaging interest, both in research and in the market community. Internationally, the majority of effort has focused on delivering affordable and reliable solutions to non-electrified rural areas in developing countries [4-6]. However, rising electricity prices and increasingly frequent power outages have resulted in a surge of interest in the off-grid housing concept in already developed economies [7-9].

Annual power reliability is the most significant performance indicator of the off-grid building operation. Reduction of building energy demand is the most reasonable way towards minimising necessary photovoltaic (PV) power and energy storage system capacities - and related investment cost. This cannot succeed without incorporating integrated building operation, including maximising the sealing of building fabric, increasing of thermal insulation and implementing highly efficient energy sources. However, airtight houses with an inefficient ventilation system can be a source of thermal discomfort and poor indoor air quality, leading to an unhealthy indoor environment [10]. Focusing on the correct type choice and design of ventilation system, hence, becomes a requirement for off-grid houses, as their stand-alone operation is highly sensitive to both outdoor and indoor environmental conditions.

Basic classification of ventilation systems types used in residential buildings includes natural ventilation (NV), mechanical ventilation (MV) and hybrid ventilation (HV). NV is widely implemented and regarded as a comfortable method for adjusting indoor temperatures in residential buildings located in the warm and humid climate zones of China [11]. It does not require any electrical energy consumption. Nevertheless, in airtight buildings characterised by low infiltration rates, wind and stack pressures may be not sufficient to maintain acceptable air change rates [12]. NV may also result in frequent windows opening by occupants, which can increase energy consumption related to space heating and cooling [13].

In contrast, the mechanical ventilation system enables controlled air change rates. However, this necessitates operational electricity consumption by fans and control system. Air-to-air heat exchanger is commonly part of mechanical ventilation system and can enable energy savings by way of reduction of thermal energy demand related to space heating and cooling needs. [14]. Still, the implementation of a heat recovery system should be carefully examined according to designed airflow and climate conditions [15].

Hybrid ventilation is controlled by switch algorithm between modes. In conditions where natural ventilation is insufficient, the use of supplemental MV is provided. Studies have shown that the use of a hybrid ventilation system can result in considerable HVAC energy savings in warm and humid climates, in comparison to NV and MV stand-alone systems [16,17].

There had been a limited amount of research assessing the impact of building services operation on the power reliability of off-grid buildings. Research conducted by Pradhan, et al. (2013) [5] and Akinyele, et al. (2016) [9] provided a general analysis of grid-independent energy systems, suitable for houses respectively in India and New Zealand. Goldsworthy and Sethuvenkatram (2018) [7] analysed the effect of high-efficiency air-conditioning and energy load shifting during daytime on the economic cost of off-grid houses in Australia. They concluded that the occupant behaviour pattern change from on-grid to off-grid connection is essential for the affordable and comfortable operation of this special type of housing. A study by Hu and Augenbroe (2012) [8] presented an energy management system concept based on a stochastic model designed for off-grid system operation in Georgia, USA. Herein, the authors held that temperature tuning was able to reduce the risk of power unavailability up to 24% when compared to constant heating or cooling temperature set points.

There seems to be a research gap connected with assessing the impact of different ventilation system types to power independence of the off-grid houses. Thus, the main aim of this article is to fill this gap by conducting research based on case study house located in Shanghai. In doing so, methodology (Section 2) was used to evaluate annual power reliability in relation to different ventilation systems types. Results are then shown and discussed (Section 3) before conclusions are stated (Section 4).

2. Methodology

2.1 Case residential building model

A case study of a residential building was selected for this research. The house was designed as an affordable and transportable solution for developing rural areas in the hot summer and cold winter

(HSCW) climate zone of China. A reusable steel shipping container framing was used as this building's structure. The total, one module house dimension was 9m in length, 3m in width and 2.6 in height. The south-oriented roof was equipped a PV mounting construction - a steel frame tilted at an angle of 30^0. So as to maximise a solar energy generation, as well as reduce unintended solar heat gains, overhang steel construction was implemented on the south side *(Fig. 1).*

The residence was partitioned for bathroom, office, common room and a small kitchen area (*Fig. 2*). The floor had a conditioned area of $21m^2$ and a volume of 54.6 m^3. The total window surface was $9.5m^2$, giving a windows to floor area ratio of 46%. The building was designed for the occupancy of two adult persons who were predicted to stay outside the building between 7:00 -17:00 during weekdays. The heat transfer coefficient of external partitions and standard double pane windows were 0.27 and 2.8 $W/(m^2K)$, respectively. In addition, continuous wind and vapour barriers were used to maintain building airtightness $n_{50} = 1[1/h]$. Moreover, the space heating and cooling systems were based upon an air to air non-ducted split reversible heat pump placed in the common room, with a rated cooling/heating capacity of 3.0kW and a declared seasonal efficiency of SCOP=2.8(heating) and SEER=4.4(cooling). The predicted domestic hot water consumption (40^0C) was 25l/person, delivered and storage in a hot water tank (50l) with 1.2kW installed electric heater. Declared efficiency of the electric heater was 95%. The maximum rated power of energy-efficient lighting (LED) was 100W, whereas appliances were 800W. Both lighting and appliances systems worked with fixed schedules typical to rural Chinese household patterns [18].

Figure 1. Container house structure

Figure 2. Floor plan

2.2 Simulation of building hourly electricity load.

Hourly profiles of case building electricity loads were evaluated by using dynamic and multi-zone building performance simulation software – IDA ICE 4.8 [19]. Information including building geometry, thermal performance of building fabric, energy system efficiency, internal gains, appliances schedule and specific ventilation system type (Section 2.3) were integrated into a multi-zone thermal model. Furthermore, building performance was assessed for a typical weather year (IWEC 2.0) for the Shanghai location. The results of electricity load profiles, together with solar energy generation and energy storage models served as the base for simulating the annual power reliability of the off-grid house (Section 2.4). The operative indoor temperature set point was defined as 20^0 C during heating and 26^0 C during cooling. According to the typical occupant behaviour of controlling the HVAC system in Chinese households, the air-air heat pump was predicted to be on only during building occupancy [20].

2.3 Simulated ventilation scenarios, assumptions and limitations.

Three different ventilation strategies were simulated: a natural ventilation system (NV), a mechanical ventilation system with heat recovery (MV) and a hybrid ventilation system (HV). Design, operation and control of each ventilation scenario enabled proper indoor air quality during the occupancy of the simulated case building. Assessment of indoor air quality performance was limited to identification of indoor CO_2 concentration [ppm] in the living room and office zone. Here, the upper limit was set as 1000ppm - meeting China Indoor Air Quality standards [21]. In addition, the outdoor CO_2 level was fixed as 400ppm, and each person was assumed to generate 18l/h of CO_2 gas [22]. Of note, the influence of CO_2 emission from cooking processes was omitted due to the cooking area being equipped with an outdoor ventilating kitchen hood that is in operation while this activity was undertaken. Beyond the aforementioned, indoor concentration of CO_2 in the living room was calculated as an hourly average value in the entire zone, with no simulation of its stratification. In all scenarios, windows were opened during possible free-cooling conditions (Outside temperature in the range of 21^0C-25^0C) and occupant's presence.

2.3.1 Natural ventilation system (NV). In the NV scenario, windows in the common room and office were opened to one-quarter of their maximum openable range when the indoor concentration of CO_2 in the occupied zone exceeded a value of 1000ppm. The windows were shut when the indoor in-zone temperature fell below 16^0C during space heating periods or when temperatures exceeded 28^0C during space cooling periods. Hysteresis value of opening and closing windows was set on 300ppm of indoor CO_2 concentration. If windows were closed, infiltration airflow was based on leak sizes, wind pressure and thermal buoyancy effects. The annual average infiltration rate was approximately 0.4 air changes per hour (ACH) when all windows were shut. Wind pressure coefficients were based on data [23] recommended for low-rise buildings with exposed, rural location and length to width dimension ratio of 3:1. Pressure coefficient of the window openings and internal doors between zones was set as 0.75 and 0.65, accordingly [24].

2.3.2 Mechanical ventilation with heat recovery (MV). In the MV ventilation scenario, no windows were opened despite free-cooling conditions. The system was characterized as constant and balanced with total airflow of $60m^3/h$ and supply air rate of $40m^3/h$ in the common room and $20m^3/h$ in office. The exhaust air outlets were placed in the bathroom ($40m^3/h$) and office ($20m^3/h$). The utilized MV contained a heat recovery system with a rate thermal recovery efficiency of 75%. Fan energy power consumption was estimated as $0.5W/m^3/h$ according to standard Chinese ventilation system data. Note, MV was only operational during building occupancy.

2.3.3 Hybrid ventilation . The HV system was based on infiltration flow when indoor CO_2 concentration was below the zonal threshold of 1000ppm. Otherwise, the system switched to MV mode.

2.4. Building the off-grid energy system model.

The alternating current coupled battery off-grid system was modelled in Matlab software. This consisted of combined modules of PV energy generation, building electricity loads, control regulator (switch), multi-mode inverter/charger and energy storage system.

2.4.1 Solar energy generation from the PV system. A total of 20 multicrystalinne modules composed the PV plant. The PV module had a nominal power of 275W and efficiency of 16.80% - (values measured at STC). The modules were grouped into two strings, leading to the total DC installed power of 5.5kW. Each string (10 modules) was connected to a power inverter with a nominal power output of 3kW, with weighted efficiency of 96%. System predicted hourly energy production was calculated by using the PVsyst software V6.78 [25].

2.4.2 Energy storage and energy management system. Energy storage system consisted of lithium-ion batteries with a voltage of 24V and total system capacity of 24kWh. To maintain long system durability, deep of discharge (DOS) was set on 60%.

An idealised energy battery storage model was implemented with constant supply voltage during the discharge cycle. The energy management system consisted of a switchboard (regulator) that transferred generated on-site energy directly to building services or to a multi-mode inverter/charger according to current conditions. A multi-mode inverter/charge managed the process of charge/discharge of batteries and changing the electricity current in two directions AC/DC (charging) and DC/AC (discharging). The efficiency of charging/discharging process was set at 92%. Solar energy generation profile from PVsyst software, together with hourly electricity building demand profiles from IDA-ICE software were integrated into an off-grid energy model as input data.

3. Results and discussion

3.1. Building electricity load profiles and final annual electricity consumption in relation to ventilation scenario.

Hourly electricity power load profiles according to space heating, space cooling and fans operation in relation to simulated ventilation scenario are shown in *Figs. 4-6,* while a summary of simulation results is presented in *Tab 1.* Operation of the natural ventilation system (NV) resulted in the largest space heating (1066W) and cooling electrical peak loads (628W) among all simulated ventilation scenarios *(Fig.4).* In 63% of the total occupied time, the indoor–hour-average CO_2 concentration in the common room or office was expected to be higher than 1000 ppm when all windows were assumed to be closed. This was mainly caused by building's low airtightness value (n_{50}=1[1/h]) which resulted in low infiltration rate – 0.4 [1/h] (annual average) and, finally, in not sufficient ambient airflow. Inappropriate level of indoor air quality in terms of high indoor CO_2 concentration imposed frequent window opening, leading to increasing heat losses, both in space heating and cooling periods. Total annual electricity consumption related to space heating, cooling and fan operation in NV scenario was calculated as 839kWh (40 kWh/m^{2}a).

The mechanical ventilation system with heat recovery exchanger (MV) reduced both space heating and space cooling electrical demands throughout the year when compared to NV (*Fig.5*). The peak space heating electricity demand and peak cooling electricity demand was reduced, accordingly, by 21% and 7% when compared to NV *(Table 1).* The system ran with constant airflow of 60m^3/h through the whole building occupancy time – 6418h (*Fig. 5*). Annual electricity consumption related to the operation of fans was calculated as 193kWh, whereas the total thermal heat and cold recovery were calculated as 358kWh and 18kWh, respectively. Final electricity energy savings connected with the operation of the thermal recovery system was estimated as 132 kWh. Total annual electricity consumption related to space heating, cooling and fan operation in the MV scenario was calculated as 873 kWh, which is 4% more than in VN scenario *(Table 1).*

The operation of the hybrid ventilation system (HV) resulted in practically identical values (differences of 1%) of peak electrical loads related to space heating and cooling as in the VM scenario *(Fig. 6).* In both cases, peak demands occurred in approximate ambient conditions, while the HV system was working in the MV mode. Annually, during occupied time, HV operated for 63% (4043h) of the time in MV mode, whereas for 37% (2375h) of total time, ventilation was provided by infiltration and window-free cooling operation. Reduction of fans operation time resulted in 37% lower electricity consumption (122kWh) when compared with MV (193kWh). Finally, total electricity consumption related to space heating, cooling and fan operation in HV scenario was calculated as 785 kWh, which is 10% less than in the VM scenario and 6% less than in the NV scenario *(Table 1).*

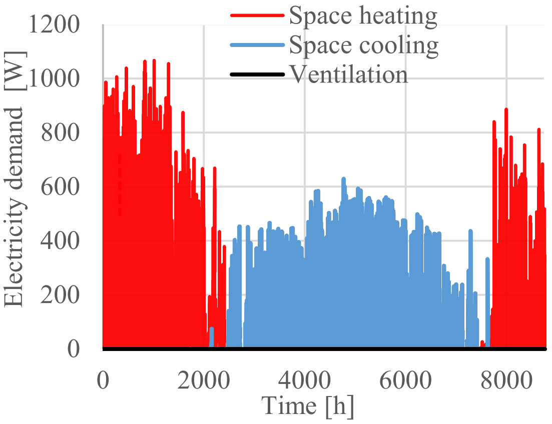

Figure 4. Electricity load profile - VN scenario

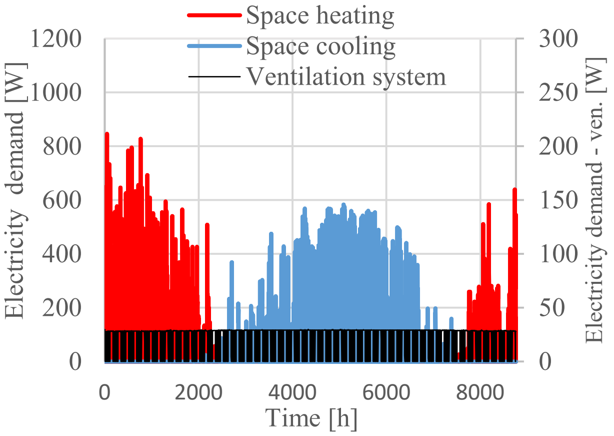

Figure 5. Electricity load profile - VM scenario

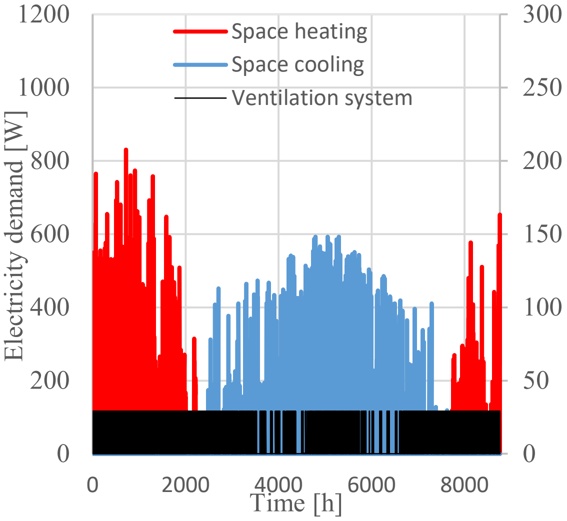

Figure 6. Electricity load profile - HV scenario

Table 1. Summary of building performance simulations results

	Ventilation scenario		
	NV	MV	HV
Max. space heating electricity power [W]	1066	846	855
Max. space cooling electricity power [W]	628	583	592
Final electricity consumption – space heating (H) [kWh]	427	326	318
Final electricity consumption – space cooling (C) [kWh]	412	354	345
Final electricity consumption – ventilation system operation (V) [kWh]	0	193	122
Total final electricity consumption (H+C+V) [kWh]	**839**	**873**	**785**

3.2 Electricity power profiles of the off-grid energy system operation and annual power reliability of the case building.

Hourly electricity power profiles of: energy storage (*BATT*), building demand (*E LOAD*) and PV system (*PV*) in relation to particular ventilation system scenario are presented in *Figs.7-9*. The resultant profile of energy flow (*GRID*) is presented in each figure to illustrate conditions where the operation of a stand-alone energy system is not sufficient to cover all building energy demands.

Summary of simulations results is presented in *Tab 2*. Operating of hybrid ventilation system (HV) resulted in the largest number of hours in which the building power reliability was achieved – 8637h - which was 98.6% of the time of annual system operation (*Fig.9*) This figure is a 0.1%(5h) and a 0.6% (52h) better annual result than, respectively, the MV and NV scenarios (*Fig.8, Fig.7*). Minor differences could be explained by insignificant impact of ventilation system type to average overall electricity load of building through year. The annual energy generation from PV system was estimated as 6184kWh, whereas total annual electricity consumption varied from 2847kWh in HV, 2901kWh in NV, to 2935kWh in MV.

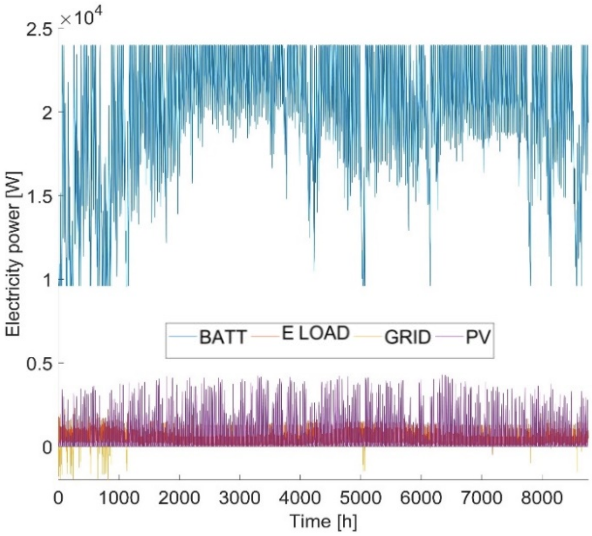

Figure 7. Off grid system operation simulation – NV

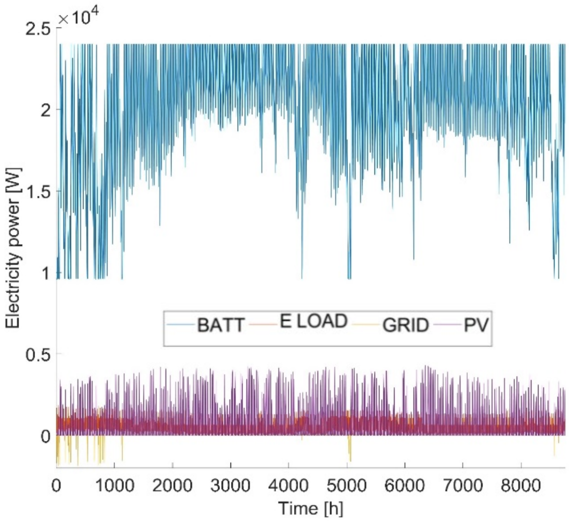

Figure 8. Off grid system operation simulation – MV

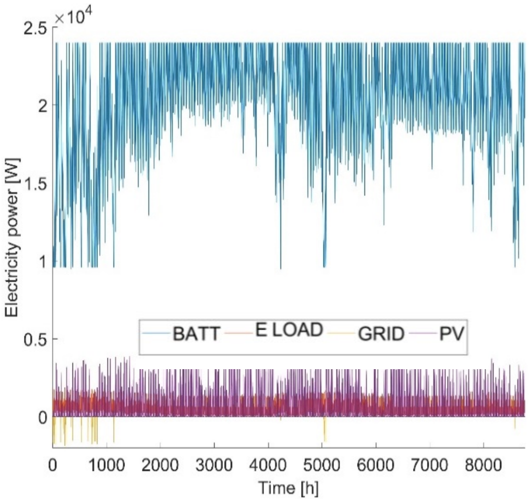

Figure 9. Off grid system operation simulation -HV

Table 2. Summary –off grid energy system simulation results

	Ventilation scenario		
Simulation results summary:	VN	VM	VH
Annual electricity energy consumption [kWh]			
Domestic hot water	808		
Lighting and equipment	1212		
Space heating and cooling	839	680	663
Ventilation system	0	193	122
Total electricity consumption	2901	2935	2847
Annual PV generation [kWh]	6184		
Power reliability [h/year]	**8585**	**8632**	**8637**
Power reliability [%/year]	**98**	**98.5**	**98.6**

4. Conclusions, limitations and future research directions.

In this study, annual power reliability was simulated in relation to the three main residential ventilation system scenarios with regard to an off-grid house located in the humid and subtropical climate of Shanghai. The correlation between ventilation system type, hourly electrical load profiles and annual electricity consumption related to space heating, space cooling and ventilation systems also was derived. The results indicate that the operation of a hybrid ventilation system resulted in the best annual building power reliability. However, the minor annual differences among all scenarios (0.1%-0.6%) call into question the economic viability of implementing mechanical or hybrid systems with heat recovery. It was seen that a mechanical ventilation system and a hybrid ventilation system (due to a contained heat recovery process) reduced electricity demands related to space heating and cooling. However, the combination of high thermal performance of building structure, an efficient heating and cooling source (air-to-air heat pump) and, finally, warm and humid climate conditions resulted in improved power reliability mostly during peak space heating.

It was noted that the changing of the recovery system type from heat to energy (by the use of an enthalpy exchanger) had negligible effect on annual power reliability performance. Yet, the operation of the hybrid ventilation system significantly reduced the time of fan operation mostly during free cooling conditions. However, the resultant reduction of electrical loads is only a low share in total building electrical load and is effectively balanced by high solar energy generation from the PV system, combined with energy storage. What is more, natural ventilation by opening of windows can provide the proper indoor CO_2 concentration in occupied rooms during the entire year, despite few hours (20h) with no wind conditions. The research was based on a simulation of a particular, one module off-grid design wherein the assessment of indoor air quality was limited to indoor concentration of CO_2. In further research, firstly, building design variants constructed from different number of modules should be investigated. Secondly, the impact of outdoor particular matter (PM2.5) drawn into each of ventilation system should be included, together with possible filtration system operation.

Further research should confirm the simulation models by way of real building measurements. Once this is done, the validated model can be further used to optimise building design in the terms of reducing environmental impact brought by building structure, materials and technical equipment. Finally, implementation of results should be extended to South Asia and Sub-Saharan Africa rural areas – both of which hold the highest rural electrification needs.

Acknowledgments

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN).

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