A SUSTAINABLE SOLUTION FOR PREFABRICATED RESIDENTIAL BUILDINGS

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Abstract. For the European Union (EU), the energy demand of the building sector is evaluated at 40% of final energy consumption. Within this, the residential sector accounts for 63% of total energy consumption. These values justify the sustained effort for increasing building energy performance and to obtain efficient building materials, designs and solutions. However, the exclusive use of conservative construction products creates further problems as they require a considerable amount of energy for production and end-of-life management, in a context where EU priority issues are an efficient post-use of building materials, preferably in a circular economy context, and moving towards "zero carbon" buildings, a concept that soon will integrate the embedded energy and CO_2 emissions. Therefore, it is essential to find new ways to reduce both the embedded CO_2 in building materials, as well as CO_2 associated with operational energy and to facilitate the post-use integration in economy. This paper presents a sustainable solution that meets these requirements, by integrating natural resources and agriculture by-products, with minimum embedded energy, in a novel design suitable for industrialization. The model is assessed from the point of view of the building energy demand and compared with a conventional unit using same architecture.

Key words: prefabricated building components, energy efficiency, carbon sequestration, circular economy, recycling.

1. Introduction

In the last decades, an intensive effort was made in European Union (EU) to improve the buildings energy efficiency and to increase the use of renewable energy sources (RES). This is justified as the existing building stock of the member states is responsible for about 40% of final energy consumption (Cao *et al.*, 2016; Dodoo *et al.*, 2011; Volkov *et al.*, 2013), and the residential sector accounts for 63% of total energy consumption in the European Union (EU) (Balaras *et al.*, 2007). Buildings are also a major pollution source, and the most important greenhouse gas (GHG) is carbon dioxide (CO_2), which accounts for 82% of total EU emissions in 2002. Moreover, as energy needed for building operation decreases, it gets more important to pay attention both to the energy required for material production and to the aspects of the recycling potential (Thormark, 2002; Constantinescu, 2020).

One of the present downsides of building high energy efficiency buildings is the quantity of thermo-insulating materials used for the building envelope, to achieve the required high thermal resistance (Vasile *et al.*, 2019). The existing technologies are in majority based on conventional materials as polystyrene (EPS), polyisocyanurate (PIR), polyurethane (PUR) foams, or mineral wool (MW). A large amount of energy, therefore global warming potential due to associated CO_2, is embedded in this kind of insulation. This makes embedded energy an important factor in assessing the total energy required for a building, in its lifespan (Hammond and Jones, 2008). For a single-family high-efficient dwelling unit, a study (Beck *et al.*, 2004) concludes that if polystyrene is used to provide thermal insulation properties, the amount of embedded energy is enough to heat this house for ten to fifteen years. Thormak (2002) observed energy use for Swedish high-efficient buildings and found that, for a one-family home, over a life span of 50 years, embodied energy accounted for 45% of the whole-life energy requirements.

The recent years' trend in the European Union has been to move in the direction of „zero carbon" buildings and Sodagar (Sodagar *et al.*, 2011) appreciate this would be a growing market in the near future, even though there are still many barriers (Osmani and O'Reilly, 2009). For the moment, this only addresses the operational energy use and carbon dioxide emissions related to this issue. In the future, however, the assessment would extend on the construction materials and technologies, as a responsible materials management in the design and construction stage is a practical and straightforward approach to decrease the environmental impact of construction (Eaton *et al.*, 2007). Using unconventional materials as reed, straws (Aciu and Cobîrzan, 2013; Asdrubali *et al.*, 2015) and other agricultural waste could fulfil this objective.

Another priority issue in the EU is the efficient management of post-use materials arising from the building sector (Dodoo *et al.*, 2009), and the transition to a circular economy, where the value of materials, products, and resources are maintained and circulated in the economy for as long as possible, using recycling activities. These aspects also create problems when focusing only on virgin materials and products, while generates potential for innovation when developing new ways to integrate industry by-products.

In general, when using straws, the buildings usually employ a classic approach, i.e., first to rise a structure and then later fill the gaps with straw-bale (Ashour *et al.*, 2011; D'alessandro *et al.*, 2017; Garas *et al.*, 2009; Krick, 2016; Mutani *et al.*, 2020). A better approach is to use prefabricated building components, which helps to provide a constant and, overall, a higher quality of the product. Moreover, in nearby future this technology could target new customers, interested in using ecological products, but still skeptical now, as they don't have enough time or energy for a time-consuming construction site.

In this context it is interesting to assess the heating energy demand of a residential building structure integrating a substantial quantity of materials from agricultural byproducts. This innovative approach sequesters an important amount of CO_2 through the straws used as thermal insulation, require less operational energy, has little embedded energy as materials are less processed, and provides a sustainable use for agricultural waste, with no problems regarding the post-use management. For the conventional construction materials, it is usually possible to evaluate the total embodied energy or gross energy requirement (as the embodied energy integrated into the construction materials, plus the operational energy – the energy demand for heating and cooling), and there is possible to evaluate the minimum product energy required (Hammond and Jones, 2008; Van Gool, 1980), and associate it with the CO_2 emissions, therefore obtain the carbon footprint of the building element. This is not the case for building elements integrating by-products as straws, as this technology securely capture in the building envelope, for a long time, the CO_2 naturally embedded in them by the photosynthesis process. For conventional insulation products, the CO_2 footprint of the building first grows as we use thicker layers, while savings occurs on the building lifespan, as less energy is then required.

2. Method

We identified a working eco-friendly prefabricated dwelling and evaluated the operational energy required for heating, versus the energy required for heating other models with the same architecture but using conventional materials and heating systems.

2.1. Architecture model

Nidus modular homes (Fig. 1) represents a concept of low-energy prefabricated dwellings, integrating a high percent of natural, low-processed materials. They are designed to be completely personalized and delivered ready to be assembled in-situ. The evident advantages are: (a) low-embedded energy as thermal-insulation consists from chopped straws; (b) improved quality as the process is industrialized; (c) the building process on site is fast, safe and efficient compared with a conventional house; (d) the finishing of the façade elements facilitates a harmonious integration in the natural environment (Fig. 2).

2.2. Building models and simulation hypotheses

To identify some clear benchmarks that are useful to understand the building energy performance of this dwelling in a larger context, and to evaluate the impact of different systems on its efficiency, we use the simulation to obtain the heating energy demand for eight building models based on the same architecture (Fig. 3, Fig. 4), positioned in Romania climate zone 2. State-of-the-art approaches for high-efficient buildings are summarized in three categories: passive energy-saving technologies, energy-efficient building service systems and renewable energy production technologies (Cao *et al.*, 2016). Even if it is not an exhaustive assessment, we evaluate all these aspects:

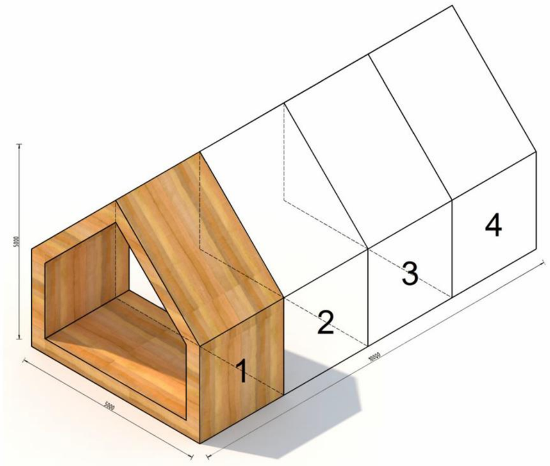

Fig. 1. Nidus concept for modular home.

Fig. 2. A completed Nidus home.

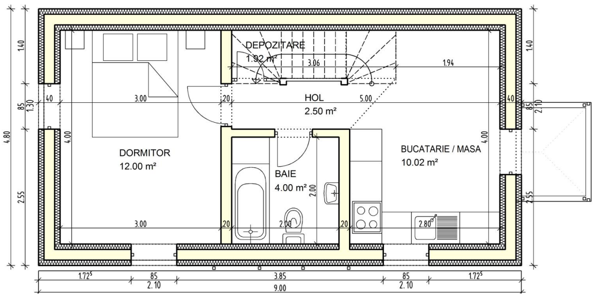

Fig. 3. Nidus plan, ground level.

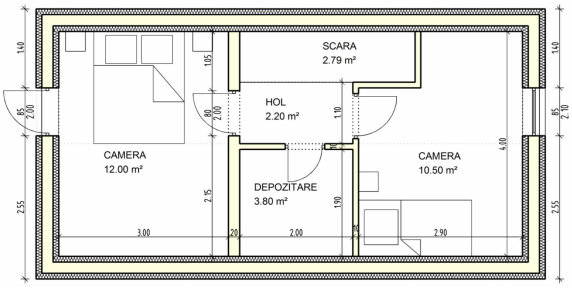

Fig. 4. Nidus plan, first floor.

- **Building model no. 1**, corresponding to a construction from early ’60 up to late ’90, having 37 cm solid brick walls and double-glazing windows with timber frames, using gas burning stove for heating. The stove, typical for that years, is characterized by a very low efficiency, compared with a present gas boiler, therefore it alone leads to an inefficient use of the energy. This building model has a higher permeability to air than the other models, of 0.7 h^{-1} in our simulation, even if real air exchange ratio could be higher as shown by recent researches, but also finds no direct correlation with building age (Vinha *et al*., 2015; Sinnott and Dyer, 2012). Another reason for not using a superior air change rate is that an increase will result in a higher energy demand and a recent research (Sunikka-Blank and Galvin, 2012) found through monitoring that in low-efficient buildings occupants consume, on average, 30% less heating energy than the calculated rating. This phenomenon is identified as the „prebound” effect. Therefore, that average air rate also has the role to include the prebound effect;
- **Building model no. 2**, a state-of-the-art conventional building that follow the latest requirements for building elements, which „for Romania are stated by the Ministry Order no. 2641/2017. It requires for dwelling houses a thermal corrected resistance of minimum 1.80 [m^2K/W] for vertical walls, 0.77 [m^2K/W] for the glazing elements, 5.0 [m^2K/W] for the attic floor, 4.50 [m^2K/W] for the slab on the soil. The heating source is a typical wall-mounted gas boiler. There are no requirements for the mechanical ventilation or air permeability, but in simulation we use a value of 0.5 h^{-1} for the building air changes per hour;
- **Building model no. 3**, integrating natural materials as chopped straws. Implementing building elements that

uses straws as thermal-insulating product, there is an initial carbon sequestration as the straws are embedded in the building elements. This is followed by further reduction in operative energy use, as the U-value of the building envelope is particularly low. It means that in this approach thicker insulation material causes additional carbon savings, with no disadvantages, this is why we choose to simulate the maximum thickness for the vertical walls, with 40 cm thermal insulation. Tests on chopped straws shows at a density of 50 kg/m3 a thermal conductivity value of 0.045 W/mK. Similar results were found in the literature (Vėjelienė *et al.*, 2011), although literature is focusing more on whole straws (Pruteanu, 2010; Petcu *et al.*, 2017; Beck *et al.*, 2004). Although now there is no obvious reason to expect an increase in the thermal conductivity of the materials, as a quite conservative approach, we included in the simulations a depreciation coefficient of 10%. Nevertheless, field thermal resistance of the building element is 8.62 m^2K/W, corresponding to a field thermal transmittance U of 0.116 W/ m^2K. The glazing has a thermal resistance of 1 m^2K/W, which for the moment corresponds to the best quality / price ratio available in the market. The heating source is a wall-mounted condensing gas boiler;

- **Building model no. 4** is the same as no. 3, with the use of a central ventilation system using an 80% efficiency air exchanger unit;
- **Building model no. 5** is the same as no. 3, but for the heating instead of a condensing boiler it uses a heat pump with a seasonal performance factor of 1.5. The results show a reduction in the energy used but also a significant increase in primary energy use. The same is document in literature (Sala-Lizarraga and Picallo-Perez, 2019), as for an electrically driven heat pump to be a system using renewable energy, the SPF should be above 2.5;
- **Building model no. 6** is the same as no. 5, with the use of a central ventilation system using an 80% efficiency air exchanger unit;
- **Building model no. 7** is the same as no. 5, but for the heating it uses a heat pump with a seasonal performance factor of 2.8. As data obtain through monitoring shows an average SPF of 2.8 for air/water heat pumps using the ambient air (Dones *et al.*, 2004), it is feasible to use a heat pump that have no negative effect on the primary energy aspect and the overall CO_2 emissions;
- **Building model no. 8** is the same as no. 7, with the use of a central ventilation system integrating an 80% efficiency air exchanger unit.

All the models have the same orientation, similar solar and internal heat gains. Regarding permeability and fresh air, all the models take into consideration a value of 0.5 h^{-1} air changes per hour (ACPH), except for model no. 1 which has 0.7 h^{-1}.

Consistent with other recent articles (Dan *et al.*, 2016; Prada *et al.*, 2020; Toderaşc *et al.*, 2019; Zeghici *et al.*, 2014), the building energy efficiency is evaluated using the algorithm presented in „The calculation method for the energy performance of buildings. Part I - The building envelope” (MC 001/1, 2006) and „The calculation method for the energy performance of buildings. Part III - The audit and building performance certificate” (MC 001/3, 2006). Moreover, some of this methodology (the monthly step algorithm) was experimentally tested showing good correlation with experimental data (Constantinescu *et al.*, 2010).

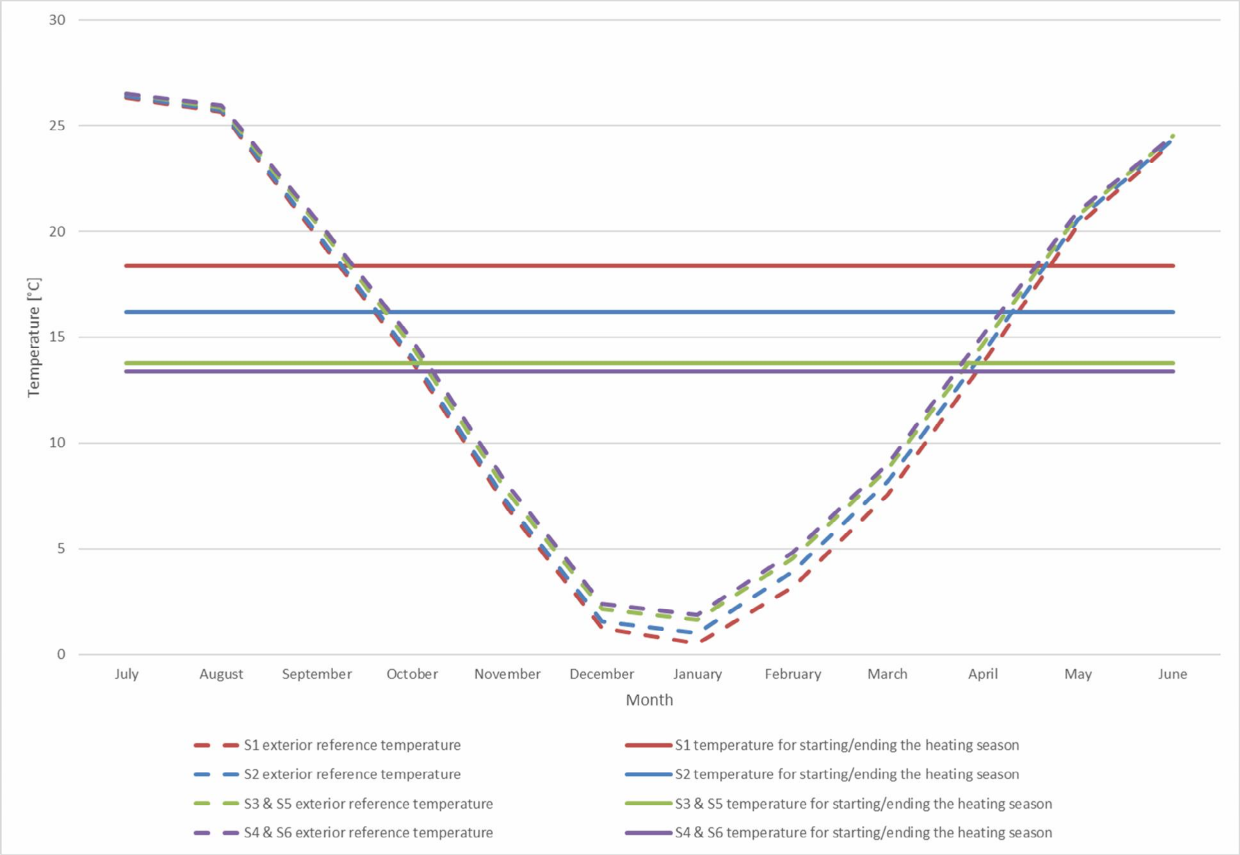

Fig. 5. Heating diagram, showing heating season for different building models.

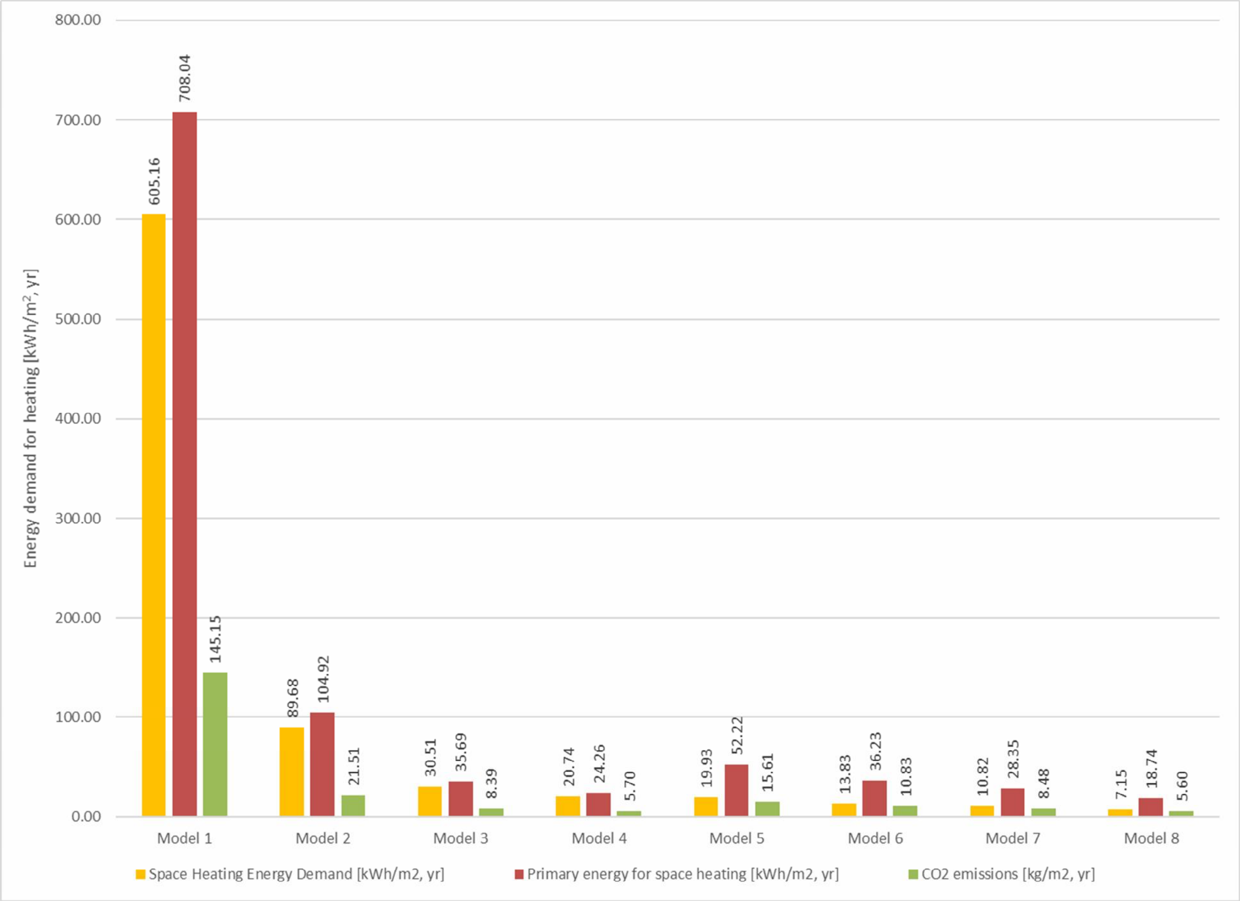

Fig. 6. Impact of different approaches on heat demand, primary energy and CO_2 emissions.

3. Results

3.1. Structure and layout

Applying the calculation methodology, relevant temperatures for the definition of the heating season (the exterior reference temperature, the reduced indoor temperature) are generated, then the energy performance, primary energy and the corresponding CO_2 emissions are obtained for all the building models.

The use of better building elements, characterized by a high thermal resistance and reduced air permeability, impact the heating diagram of simulated buildings, reducing the interval when heating is required and the number of degrees days (Fig. 5).

The building model based on solid brick walls, coupled with mobile building elements (windows and doors) without gaskets and the use of inefficient gas stoves for heating, lead the building model no. 1 to be very energy intensive, with an energy demand for space heating of 605.15 [kWh/m^2, yr]. The value is consistent with data obtained through monitoring of real buildings made from bricks, in relatively similar climate (Kuusk *et al.*, 2014; Kass *et al.*, 2015), having in mind this is a detached individual dwelling unit. In many cases, due to the high costs related to heating, these kinds of buildings are insufficiently heated and ventilated, which results in poor indoor climate and high indoor humidity loads.

The requirements for new building, (Ministry Order no. 2641/2017), impose the use of energy efficient building envelope elements, especially the ones for slab on soil and the attic floor, where these values could be difficult to fulfil (Babota and Iernuțan, 2019) as larger thicknesses are required (25-30 cm of highly efficient thermal insulation). For the vertical walls the value is quite relaxed at a corrected thermal resistance of minimum 1.80 [m^{2}K/W]. There are no requirements for the heat source efficiency, mechanical ventilation, air heat exchangers or the use of renewables. Despite the building services is ignored by this law, using the imposed values for building elements results in a quite conservative thermal shielded building and consequently, a significant reduction of the energy demand for heating the building model no. 2, at 89.68 [kWh/m^2, yr] (Fig. 6).

Building the same dwelling with highly efficient panels integrating local, natural materials (building model no. 3) results in a highly efficient building, with an energy demand for heating at 30.51 [kWh/m^2, yr], which is 5.04 % of the energy required by the model corresponding to ’60 – ’90 (building model no. 1). Implicit, the reduction in primary energy use (from 708 [kWh/m^2, yr] to 104.92 [kWh/m^2, yr]) and CO_2 emissions (from 145.15 [kg/m^2] to 21.51 [kg/m^2]).

Although it is known from rehabilitation that highest returns are in the first stages of implementing efficiency measures, and there are diminishing returns when trying to achieve a very high energy efficient building, building models 4 to 8 shows there is space for better solutions, as implementing mechanical ventilation with air heat exchanger and using heat pump as heat source. It is important to note that to have an electrical heat pump which is efficient with the primary energy use, it should have a SPF over 2.5 (Sala-Lizarraga and Picallo-Perez, 2019). Using a less efficient heat pump will result in more primary energy consumption as shown in Fig. 1 by model

5, simulated with a heat pump with 1.5 SPF. Nowadays this is not an objective problem, an existing study showed that SPF of 2.8 are feasible even for the air/ water heat pumps, in Switzerland climate conditions (Dones *et al*., 2004). Therefore, building model no. 8 is simulated, which integrates a 2.8 SPF heat pump and mechanical air ventilation with air heat exchanger (80% efficiency). The energy demand of this model is 7.15 [kWh/m^2, yr], that is 1.19% of the energy demand of initial building which corresponds to individual dwellings from early ’60 up to late ’90. The environment impact is at 3.86% from that building, as primary energy consumption drops from 708 to 18.74 [kWh/m^2, yr] and the corresponding CO_2 emissions from 145.15 to 5.60 [kg/m^2].

4. Conclusions

For prefabricated dwellings, Nidus houses represents a paradigm shift as the focus is on the use of natural, low-process materials, especially by-products from agriculture.

The energy required for heating the analyzed dwelling (building model no. 3 in Fig. 6) is just a fraction of what is needed for a regular home. If compared with the model which corresponds to present Romanian regulation, it requires only approximative 30% energy for heating. While a large amount is owing to a very good insulating building envelope, integrating the architectural concept with an adequate heating pump system for heating while using central ventilation system with heat recovery, the energy for heating drops below 10%, compared to the same building, following the present Romanian regulation. This low energy demand and in-situ reduced building effort make them suitable for placement in areas lacking conventional utilities.

From the point of view of configuration there might be a few improvements of the concept, in terms of volumetry and surface exposure. If they will prove feasible, they will be implemented in the near future. Even so, the analyzed dwelling requires only 5.6 [kWh/m^2, yr] energy for heating, a demand that could be provided by on-site solar panels or other kind of renewables.

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