

# Permafrost thermal stabilization using renewable energy sources

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## ABSTRACT

Increasing air temperatures are leading to thermosyphons being undercooled in winter and unable to prevent thaw in summer. Fossil fuel-powered refrigerators have to be used to maintain soil frozen in critical cases. We suggest dual use of solar panels as a sun shield and a power source alongside horizontal shallow ground probes rather than vertical in-depth ones to prevent heat penetration in soil at all. We performed a number of numerical experiments to evaluate the performance of this approach for different objects (railroad embankment, ice cellar, coastal cliff, winter road, buildings) and conditions; estimated its geographical application according to weather data and optimized heat pumps for intermittent power supply. We have also built 3 experimental setups – railroad embankment with heat diverted to residential facilities (made artificial permafrost in moderate climate); foundation thermal stabilization with heat diverted to a greenhouse (tomatoes and cucumbers yield increase in sub-Arctic); prolonged operation of a winter road with a heat pump directly connection to horizontal thermosyphons (shared refrigerant loop) and vertical bifacial east-west oriented solar panels. These experiments, both numerical and physical, have shown high potential technical, environmental, and economic benefits of the suggested approaches.

## 1 INTRODUCTION

Building on permafrost has always been full of challenges (Muller et al. 2008). Most of those were resolved during the construction boom in the Arctic in 1970s to large extent using underfloor ventilation and thermosyphons for enhanced soil cooling during winter time (Li et al. 2018). Now, with global warming, the cost of sufficient solutions is increasing as is the need for constant monitoring of infrastructure and the underlying ground thermal regime. This problem becomes particularly pronounced for linear infrastructural objects such as motorways (Yinfei et al. 2016), railroads (Luo et al. 2018), pipe (Li et al. 2018) and power (Wang et al. 2018) lines connecting remote settlements. To prevent disasters like the Norilsk 2020 oil spill, chilling units accompanied by power plants, fuel tanks, and staff have to be used in the most critical cases.

Permafrost thaw occurs as winters become milder and shorter while summers become hotter and longer. Particularly for this reason, widely used thermosyphons are currently operated out of designed conditions, so are not capable of keeping soil frozen. Industrial users have reported that thermosyphon performance is half of that used in calculations. Moreover, there are operational data showing about 30% of thermosyphons can be damaged at mounting and up to 50% more breakdown within a decade. Thermosyphon replacement is not always possible following construction. The problem is not easily addressed by increasing the density of thermosyphons as this can lead to soil heaving due to overcooling in winter.

Noteworthy, major research trends in this area are related to precise soil thermal state simulation rather than development of new or optimized methods of thermal

stabilization (Kong 2019; Kong et al. 2019). The need for innovation is characterized by the following situation. Thermosyphons are typically proposed for soil freezing under the foundation piles, which are well below the seasonally thawed layer. This approach is widely used as it works well but does not work well for thermal stabilization of the road embankments where soil of the upper layers is moving laterally. The effect of deep freezing using vertical thermosyphons is rather poor for roads. Some reconsideration has started recently, and a combination of sloped, or flat looped thermosyphons (Holubec 2008) and insulation of the surface is used to prevent upper soil layers thawing (Mu et al. 2016). However, this combination of two methods, the complexity of assembly, and delivery costs for high volumes of insulation nearly double the cost of the solution compared to traditional vertical thermosyphons.

Heat is supplied to soil via convection at natural air motion, solar radiation absorption and can also be introduced with infiltrating rain. There are solutions to minimize this heat flow: solar reflectors and shields (Gagnon et al. 2022; Qin et al. 2020), heat insulation (Luo et al. 2018) and waterproof layers (Yinfei et al. 2016). But obviously neither of these passive methods is capable of completely eliminating ground warming. Active cooling methods are well developed in general, but demand power supply, so are very expensive and non-sustainable when using fossil fuel, unless waste heat is available on-site for absorption heat pumps (Lavrik et al. 2023).

Recently, suggestions to use solar power for active thermal stabilization of permafrost have appeared (Hu et al. 2020; Sun et al. 2024). However, these researchers did not use a significant effect of shielding solar radiation and precipitation by solar panels. Hu et al. (2020) still rely on

vertical, in-depth cooling by isolated devices. Sun et al. (2024) have switched horizontal barrier cooling and using the benefits of centralized power and chill supply: electric and cooling energy redistribution.

We suggested an approach that combines minimizing heat flow into the soil by shielding solar radiation and liquid precipitation, and making a near-surface solar-powered heat diversion layer to stop heat penetration in soil depth (Loktionov et al. 2022). This concept has been patented (Sharaborova et al. 2020) and proven experimentally (Loktionov et al. 2023; Loktionov et al. 2024; Sharaborova et al. 2022). An example of such a heat diversion layer in the form of ground probe loops to be covered with 25 cm embankment is presented in Figure 1. However, this is not the only way of implementation, it can also be artificial snow or cooled thermal insulation layer, cold gas injection or inflatable mats, all of those with their own pros and cons. Our approach can provide not only improved soil thermal stabilization at competitive price only (200 \$/m<sup>2</sup> compared to 180 \$/m<sup>2</sup> for thermosyphons), but can also recover these costs (75 \$/m<sup>2</sup> year) by selling energy for monitoring systems and heating. Long-term negative trends in PV panels (-15% CAGR) and heat pumps (-10% CAGR) are going to make this approach more favourable.

A cheaper but less efficient way is to use solar power to move surface heat insulation up for winter (so turning it into ventilated blinds) and back down for summer (Sharaborova and Loktionov 2022).

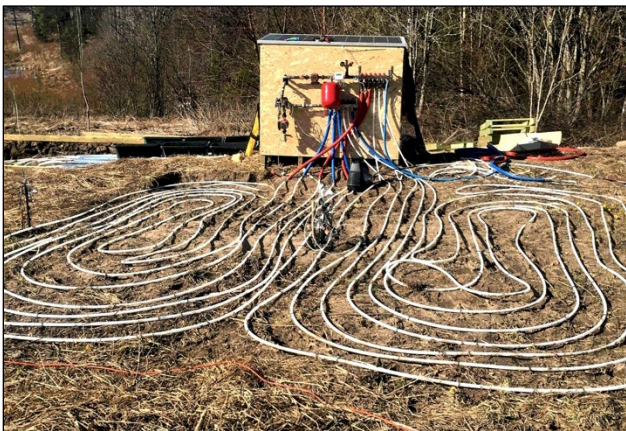


Figure 1. Ground probes of the thermal shielding layer under solar panels at the greenhouse site.

In this paper we are reporting the current progress in application of this concept to different types of objects, both in numerical simulations and experiments.

## 2 METHODOLOGY

Our approach to thermal stabilization has been described in details elsewhere (Loktionov et al. 2022). Solar panels are used as blinds to shield radiation and rain in summer and to keep a ventilated gap for natural cooling in winter. PV also provides power for a heat pump. We are cooling soil within an active layer (Figure 1) reducing its thickness and preventing heat penetration in permafrost, Figure 2

illustrates this effect. The coolant average temperature is -7.5 °C. Note, the brighter the sun is, more chill is available, and soil thermal inertia provides free energy storage to eliminate the main solar energy shortcoming — intermittency, particularly, once variable power output is used (Klokov et al. 2023a).

For thermal calculations, we have used Frost-3D Multi-Core GPU software (<https://frost3d.ru/eng/>) which has been specially developed for permafrost soil calculations, its results validity has been verified by analytical solutions (Dauzhenka and Gishkeluk 2013) and practical applications, compared to the most popular FEM packages (Alekseev et al. 2018), and conformity to relevant national and corporate (Gazprom) construction regulations certified. The details of calculation methods and data are presented in (Loktionov et al. 2022).

To date, three sites have been built to test the suggested solutions: 1) road embankment (Figure 3; Sharaborova et al. 2022); 2) greenhouse and seasonal insulation (Figure 4; Loktionov et al. 2024); 3) winter road (Figure 6; Loktionov et al. 2023). All of those were equipped with temperature (0, 10, 20, 40, 80, 160, 320, 500 cm depth) and heat flux (at heat exchange surfaces) sensors, at reference plots as well.

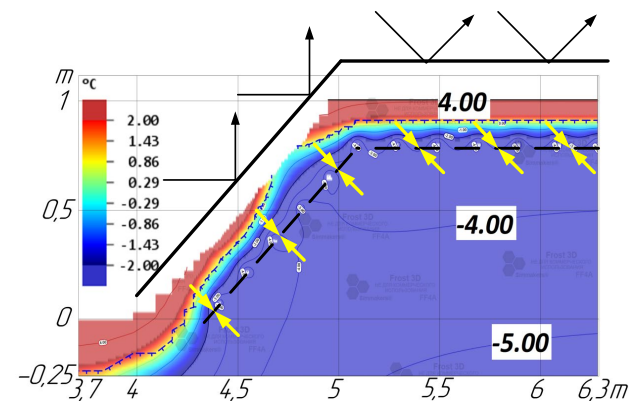


Figure 2. The effect of solar panels shielding (solid line) and heat diversion layer on road embankment in Norilsk by September, 15.

### 2.1 First tests in moderate climate

A detailed description of site 1 is given in (Sharaborova et al. 2022). It is a scaled model of the railroad embankment consisting of sand, and the upper surface was covered with solar panels. However, Loktionov et al. (2022) showed that solar panels could be moved from the upper surface to the embankment foot with some increase in nameplate capacity to compensate for thermal load increase. This experiment was conducted 100 km SW of Moscow, far from the permafrost extent to have better access to the equipment. In such conditions, thermal load is higher and solar panels output is lower than in the Arctic, so energy balance was accounted for. The heat was diverted to the house.



Figure 3. Road embankment site.

## 2.2 The greenhouse and seasonal insulation site

The greenhouse experiment site was near near Arkhangelsk, about 150 km SW of the sporadic permafrost region. The objective was to test the area's thermal stabilization with heat utilisation leading to some multiplicative effect. The heat was diverted to a greenhouse (6 x 3 m) here to test the possible effect on the yield compared to the reference. Vegetables are delivered to remote communities by air that makes those expensive and rarely available (Loktionov et al. 2024). We estimated this approach could return investment in thermal stabilization just in one year for the most remote settlements by selling these vegetables. This approach is an extension of the agrivoltaics that gains popularity recently (Klokov et al. 2023b).



Figure 4. Aerial view of the greenhouse site and seasonal insulation-shield plot (bottom right).

The ground probes in the greenhouse were 30 cm deep that ensured heat wave reaching the surface with about 12 h delay to its extraction due to heat conduction in the ground, so warming the space at night which is cooler than day even if the sun is still above the horizon. Rain water was collected from the solar panels surface (2° inclined) to the barrel equipped with an automatic valve and drop irrigation tubing. The greenhouses were equipped with automatic ventilation frames. We also performed additional phyto-lighting using the energy harvested by solar panels and stored in small batteries (Figure 5). The heat source area (5.5 × 5.5 m) was bigger than the heat sink, resulting in soil warming up to 36 °C and low performance of the heat pump due to high

temperature in the sink loop, so the latter had to be improved.

Site 1 had a straight layout with battery storage for solar power output intermittency compensation and a start-stop heat pump. High battery cost and its fast degradation due to intense cycling had led us to using inverter heat pumps as a variable load that follows actual power output (Klokov et al. 2023a; Tutunin and Loktionov 2023) for sites 2 and 3. To implement that we have used a solar pump inverter (by Veichi) that has an input from PV panels directly and adjusts the output frequency automatically to match the available power.

We also have tested a seasonal thermal resistance change here. Extruded polystyrol of 50 mm thick was placed in wooden frames covered with metal sheets (with a ventilated air gap between those and insulation). These frames were lying on the ground in summer to reduce heating and elevated about 1 m above the ground in winter to ensure reduced snow cover for better cooling (Gagnon et al. 2022).



Figure 5. Illumination of the experimental greenhouse at dull weather when energy is insufficient for heat pump operation.

## 2.3 The winter road site

Winter roads are the only terrestrial way to reach many remote communities in the Arctic. These roads are impacted by climate change not only in terms of operation duration but performance predictability as well. Very often problems along short sections of the road control the availability of the whole road. These problematic areas need to have some backup cooling systems to resolve the issue (Loktionov et al. 2023). At sites 1 and 2 LDPE and PE-X ground probes were filled with ethylene glycol anti-freeze solution (isopropanol could be also used as a less hazardous medium that does not need refill every 5 years). In case of pipes damage, the anti-freeze penetrates into the soil, after that, it is extremely hard to freeze it. To avoid that, the pipes should be metal rather than plastic and filled with gas rather than liquid. This brings us close to the traditional horizontal thermosyphons in the road embankments.

Site 3 was also built in Arkhangelsk, close to site 2. We have connected 10 thermosyphons with collectors just under condensation parts and at the tips of the evaporation side, so that refrigerant (R32) outlet and inlet are as far as possible (5.5 m). Via those collectors a joint refrigerant loop with the heat pump was formed. In that case, the heat was



Figure 6. Construction of the winter road site.

diverted to a stream via a submerged corrugated stainless steel hose, that ensured high COP of the heat pump. In winter, these thermosyphons work in their usual way with natural cold.

To power the system, we used vertical east-west bifacial solar panels, 6.6 kW in total specified for one side, elevated higher than normal snow depth. Before that, we made a calculation to estimate power output and shadowing of thermally stabilized area. That gave us a positive effect compared to horizontal panels not in terms of overall energy balance only, but also in power supply uniformity over days and year. In this way, the heat pump is getting enough power from sunrise till sunset.

### 3 RESULTS

The results for site 1 are presented in details in (Sharaborova et al. 2022). The most remarkable one is presented in Figure 7. The soil remained frozen even at continuous +30 °C daytime air temperature, so artificial permafrost was made. It matched our numerical estimations (-2.5 °C in mid-August) well.

We have used the experimental data on heat fluxes, coolant temperatures and solar output for calculations for different cases. One is the coastal cliff (Irrgang et al. 2022; Ogorodov et al. 2020). We considered a hard case of south facing at the edge of the permafrost extent in Mezen (Figure 8). We realise there is a sliding surface so freezing a core should not be the only stabilization measure, but it could prevent catastrophic wash outs during storms. The catastrophic wave erosion takes place in autumn and in dull weather, so we considered a hybrid solar-wind power system for that case. Moreover, snow accumulation at the cliff edge would improve the slope protection unlike in natural conditions, but it was not modelled here.

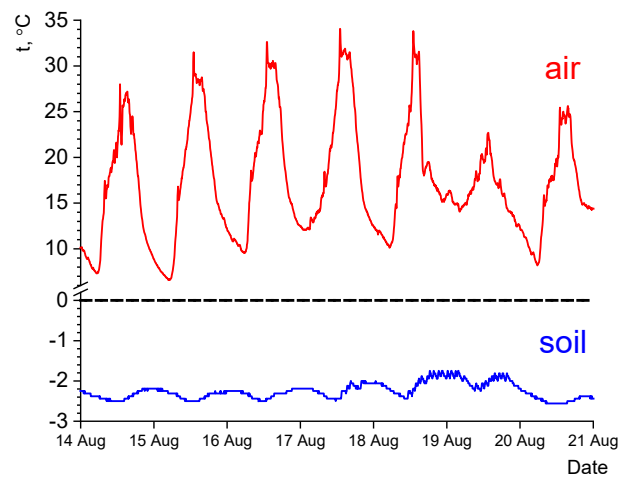


Figure 7. Near-surface air and soil (-26 cm) temperatures at road embankment site (Sharaborova et al. 2022).

Now back to our experimental results. The EER of the greenhouse site heat pump is 3.3 on average due to working most time at compressor's upper pressure limit of 22 bar and supply temperature of 60 °C. The specific yield in experimental greenhouse was twice higher for tomatoes and cucumbers than reference (for quite warm summer), and the harvest season was one month (1.5 times) longer. That resulted in 3-fold yield increase for Arkhangelsk. For the next summer that was about long term-average, the yield was 4-fold. We expect, farther north and in colder than average seasons the difference would be greater, and the weather hazards risks are reduced. This greenhouse could be coupled with the ice cellar to improve remote communities' food security (Loktionov et al. 2024).

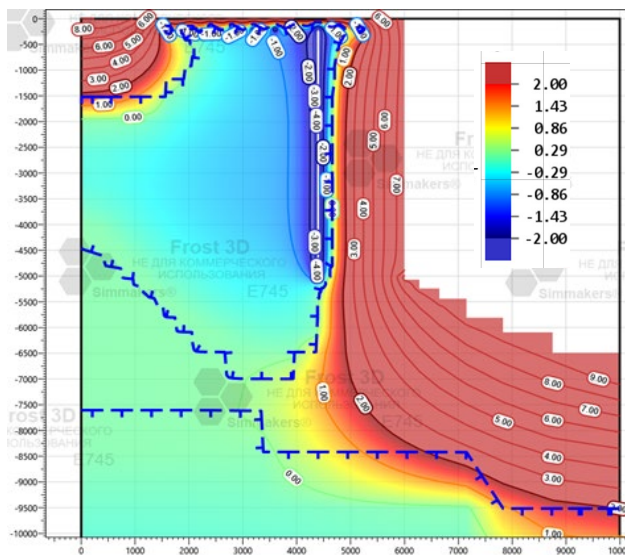


Figure 8. South-faced coastal cliff thermal stabilization in Mezen, September, 15. Permafrost border is shown by blue dashed line.

Our activities led to a significant temperature decrease in both experiments (active cooling and seasonal heat insulation) at site 2 (Figure 9). Since the soil was better cooled in summer by the heat pump, it had lower temperatures than under seasonal insulation. Since there is no underlying permafrost at the site, there is a significant heating from deeper ground layers.

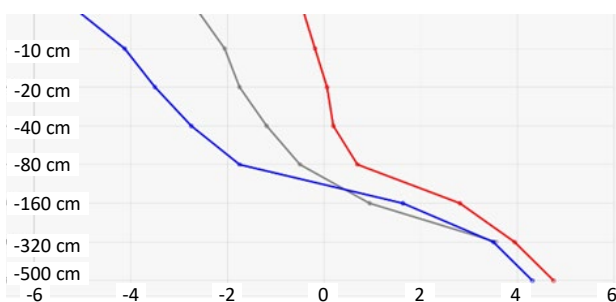


Figure 9. Temperatures (°C) at site 2 by March, 25: blue – heat pump, grey – seasonal insulation, red – reference.

The ice road site (#3) has been operational for just few months by the moment. We can also say that refrigerant temperature reaches  $-18.8\text{ }^{\circ}\text{C}$  and heat flux on thermosiphons evaporators reaches  $900\text{ W/m}^2$  (Loktionov et al. 2024). The facility works with EER of 5.3 thanks to the cold and fast water in the stream. As observed, bifacial panels were supplying  $1.5\text{ kW}$  sufficient for the heat pump operation even at sunrise and sunset, and in midday when direct solar radiation is parallel to their surface.

We have also considered application of our approach of heat diverting layers for the prevention of heat areas merging around oil and gas wells that imposes a serious threat on their stability (Figure 10; Loktionov 2022).

The warm halos did not merge even without using expensive heat insulated lift pipes. This approach also allows to decrease the cost of gas and oil production sites construction by multifold reducing the distance between wells, and so the site size and ground works to build it.

#### 4 DISCUSSION

We should note an extreme importance to measure heat fluxes in permafrost research (Sharaborova et al. 2022). So the permafrost is thawed by the amount of heat (thermal energy) absorbed, not the temperature difference exactly. In calculations, heat flow and heat flux are estimated for border conditions in rather complicated and indirect ways leading to significant inaccuracy. This refers particularly to solar irradiance. Measuring the heat flux at soil surface one can get a warning signal much earlier than observing temperatures in depth, so, seeing the reason not the reaction. These measurements are comparatively more complicated and expensive than temperature ones, but still are quite affordable. The heat flux can be also estimated from near-surface soil temperature measurements with logarithmic increment (like in Figure 9). The heat flux is not a substitution to temperature measurements, but could be a very valuable addition.

It has been shown that at permafrost thawing highest emission rates for  $\text{CO}_2$  occur from 0–40 cm depths, for  $\text{CH}_4$ , from 40–80 cm (Jiang et al. 2020). High abundances of carbon-cycling bacteria, fungi, and archaea corresponded to 0–40 cm depths. Release of hazardous chemicals, e.g., mercury (Ci et al. 2020), has been reported too. So significant reduction of the active layer and its temperature leads not only to better structure stability, but also prevents chemical and biological hazards in the area of human activities (Miner et al. 2021). Our approach can reduce the active layer to the ground probes depth or make it even thinner. Potentially, our approach could prevent methane bubbling (Walter et al. 2006), development of thermokarst and gas emission craters (Dvornikov et al. 2019).

#### 5 CONCLUSIONS

Once solar energy is reversed from heating the permafrost to cooling, it overpowers the rest of heat sources. Our experiments, both numerical and physical, have shown high potential technical, environmental, and economic benefits of this approach. Its implementation is based on the existing technologies. And it is the only permafrost thermal stabilization technology that can pay itself back. We have shown the suggested approach applicability to different cases when permafrost thermal stabilization is needed: area and linear infrastructure, coastal cliffs, ice cellars, oil and gas wells.

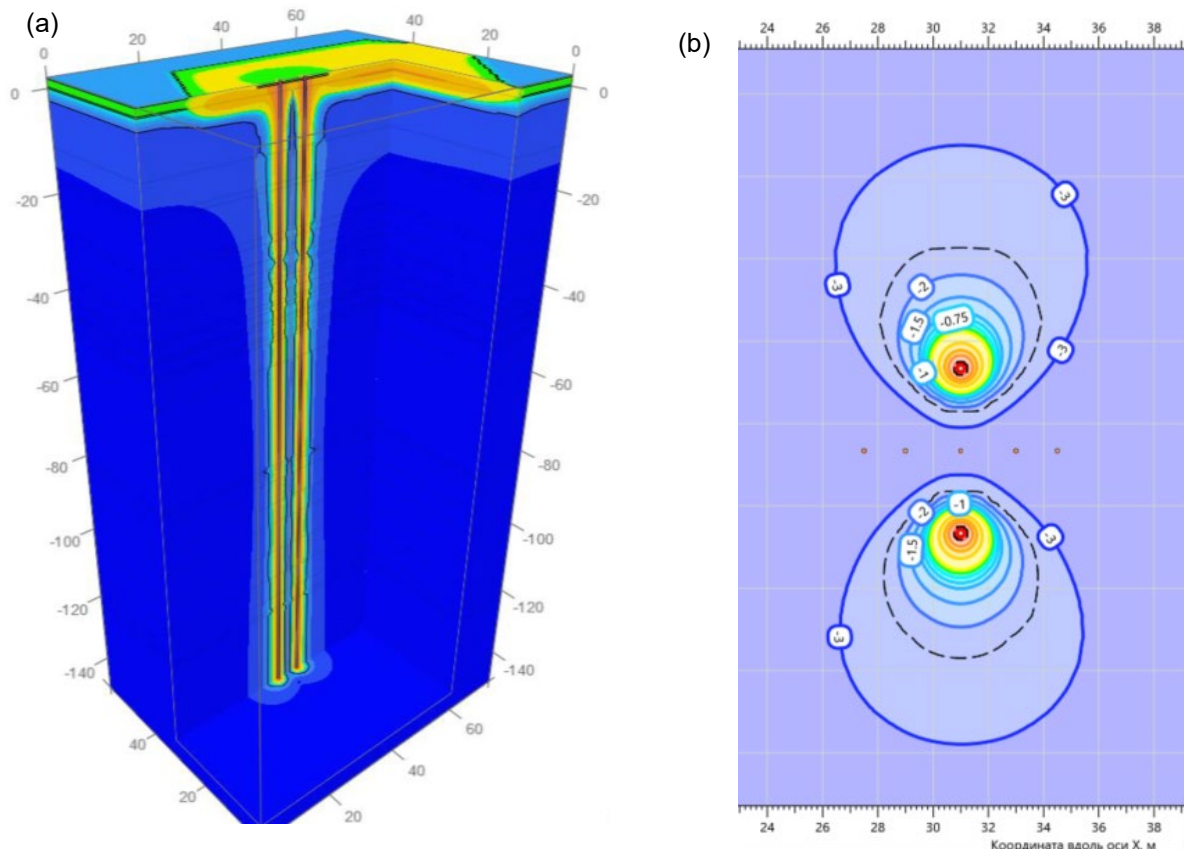


Figure 10. Temperature field in front (a) and critical cross-section (b) of two nearby gas wells with solar-powered heat sink ground probes in between.

We suggest east-west oriented bifacial solar panels are used to power inverter-mode heat pump that is able to adjust its power consumption to actual output (adaptive load). In easier cases, we suggest using solar power to lift surface thermal insulation units up in autumn to make those sun (and actually snow) screens in winter.

Considering opportunities for synergy, it could be a seasonal load for remote communities' renewable energy systems which are under loaded in summer. And it could provide electricity and heat to other activities, including agriculture to make fresh vegetables more affordable by increasing the yield and reducing weather hazards significantly compared to usual greenhouses.

## 6 ACKNOWLEDGEMENTS

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