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Electricity Generation from Heatwaves

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Abstract

We chose a definition of heatwaves (HWs) that has ~4-year recurrence frequency at world hot spots. We first examined the 1940-2022 HWs climatology and trends in lifespan, severity, spatial extent, and recurrence frequency. HWs are becoming more frequent and more severe for extratropical mid- and low-latitudes. To euphemize HWs, we here propose a novel clean energy-tapping concept that utilizes the available nano-technology, micro-meteorology knowledge of temperature distribution within/without buildings, and radiative properties of earth atmosphere. The key points for a practical electricity generation scheme from HWs are defogging, insulation, and minimizing the absorption of infrared downward radiation at the cold legs of the thermoelectric generators. One sample realization is presented which, through relay with existing photovoltaic devices, provides all-day electricity supply sufficient for providing air conditioning requirement for a residence (~2000-watt throughput). The provision of power to air conditioning systems, usually imposes a significant stress on traditional city power grids during heatwaves.

Keywords

Heatwaves, Climate Warming, Clean Energy Generation by Thermoelectric Generator, Ameliorate and Transcend Heatwaves, Climate Warming Mitigation and Adaptation, Thermoelectric Generator (TEG), IR Interaction with Periodically Arranged Nanostructures, Optical Properties of Nano Fabricating, Passive Clean Energy Tapping/Generation

1. Introduction

Heatwaves (HWs) are sporadic natural phenomena for lower- and mid-latitudes. The societal economic effects include damage to human health (physical as well as emotional stress; Ref# [1] and references therein), traffic safety, infrastructure, and reduction of crop yield. As a result of atmospheric blocking, rippling effects from heatwaves include sandstorms, droughts and even insect infestations (e.g., emerging pattern of certain broods of cicada matched closely with surface temperature patterns). The social-economic impacts and lessons learnt from the July 12-16, 1995 Chicago heatwaves are discussed by Klinenberg [2] in great detail. In the changing climate, heatwaves may occur in regions previously not suffering from such phenomena, in addition to prospects for becoming more intense, more frequent in occurrence, and longer-lasting [3] [4] [5] [6] [7]. On the other hand, the rapid expansion of mid-size tropical/extra-tropical cities, such as Austin, TX (and many south-east Asian and Indian Peninsular cities) into large industrial cities guarantees that existing power grids will be stressed to their limit [8]. Air conditioning contributes in excess of 15% of electricity consumed by buildings in the USA. To date, there is copious research on extreme trends in a warming climate. However, the mitigation and adaptation strategies still are a direction not fully investigated. While reduction in CO_2 emission works in the long-term to prevent vegetation and animal species extinction, a more immediate proactive solution is necessary to save human lives in the event of severe heatwaves. The focus of this study is on an innovative application of thermoelectric generators to tap clean energy from HWs. The electricity generated can be used, for example, for air-conditioning systems to improve quality of life.

Typically, existing photovoltaic (for solar energy harvesting) and thermoelectric devices are proposed without sufficient consultation with atmospheric scientists. Especially for thermoelectricity, the satisfactory behavior demonstrated in a controlled laboratory environment cannot warrant a similar performance with respect to power throughput efficiency in the open environment such as on building roofs. As of the time of writing, none of the existing devices includes a defogging mechanism for enabling a persistent performance for effective radiative cooling for the cold legs of the thermoelectric device, in order to not reach thermal equilibrium with the ambient free air. While more exotic proposals are available, such as using nano-coating to create a radiative cavity (for infrared wavelength), and for effective radiative cooling in the atmospheric window frequencies (8 - 11 μm), insulation technologies that effectively isolate the device from free environmental air around the cool-end of the system (e.g., roof-top, well-mixed planetary boundary atmosphere) also are critical. Without transformative solutions to these features, thermo-electric devices cannot achieve the desired energy tapping efficiency. That requires extending their operation from daytime—only to include the nocturnal period, thereby achieving all-day stable output power efficiency.

In this study, we first examine heatwaves in the 20th century using the hourly and daily meteorological reanalysis data (https://cds.climate.copernicus.eu/cdsapp#!/data-set/projections-cmip5-daily-single-levels?tab=form). Characteristics of heatwaves are estimated using indicators calculated in the reanalysis period. We then propose a passive way for tapping the electrical energy contained in heatwaves. The definition of appropriate heatwave indicators and detailed description of the quality assured hourly ERA5 reanalysis are presented in Ref# [9]. The passive clean energy tapping from heatwaves depends on a thorough understanding of heatwaves, especially with respect to the boundary layer air temperature distribution. As this section involves physics that is not familiar to the general readership, a supplementary text (**Appendix**) is provided for interested readers.

2. Generating Electricity Using Strong Radiative Cooling during Heatwaves

Radiative cooling may be used to generate electricity when combined with a thermoelectric generator (TEG) utilizing the Seebeck-effect (**Figure 1**). As a mature technique, TEGs have been widely used in cars and aircraft for tapping moderate amount of DC electricity from exhausts, which has a temperature hundreds of kelvin in excess of the environmental temperature. Limited by space, the basics are briefly described in **Appendix**. A thermoelectric device is still a heat engine that directly converts heat into electricity. The maximum achievable efficiency of a thermoelectric device is dual-controlled by the Carnot efficiency $\eta_T = \frac{T_h - T_c}{T_h}$ (thermal) and figure of merit of alloys $Z(T)$ (electrical) making the working material (Equation (1) in **Appendix**). Material science, especially nano-technology has made significant progress in the device area. For large-scale application in earth environments, the major challenge is to identify the largest possible temperature contrast/gradient achievable. Since the high-end temperature is the ambient air temperature, the practical way is left only to minimize the low-end temperature through radiative cooling, and through an improved insulation approach. Note that even in a confined space, such as in attics of a normal home (**Figure 1**), air temperature can be 20˚C hotter than the temperature of the external free atmosphere outdoors. Once the electric generating device operates, the temperature will quickly be lowered to close to ambient air temperature, considering the limited volume of the attic and the rather low air density and specific heat.

The major challenge for achieving the lowest possible practical cold-end temperature through passive radiative cooling is reducing the longwave (microwave) downward radiation (LDR), which is ~200 $\text{W}\cdot\text{m}^{-2}$ for a clear summer day (See Ref# [10] and references therein). Due to the curvature of earth, direction of facing of the cold end plate (blue color unit in **Figure 1**) does not increase radiative path length significantly. Even with perfect insulation technique applied, it is impossible to lower/reduce the T_c to below 10˚C before reaching a thermal-equilibrium, for mid-latitudes. A misconception in the field is that of using nano-technique to modify cold-end plate to emit in the wave-length range of atmospheric window (8 - 11 μm). Regarding the device cooling requirement, it does not matter what wavelength it emits. Considering that the installed area of the clean-energy device covers an insignificant portion of the earth's surface, whether or not the emission is emitted to space without interfering with the atmosphere's ongoing warming in a tangible way. In other words, the radiative impact of this device on the earth's atmosphere is not significant given its relatively

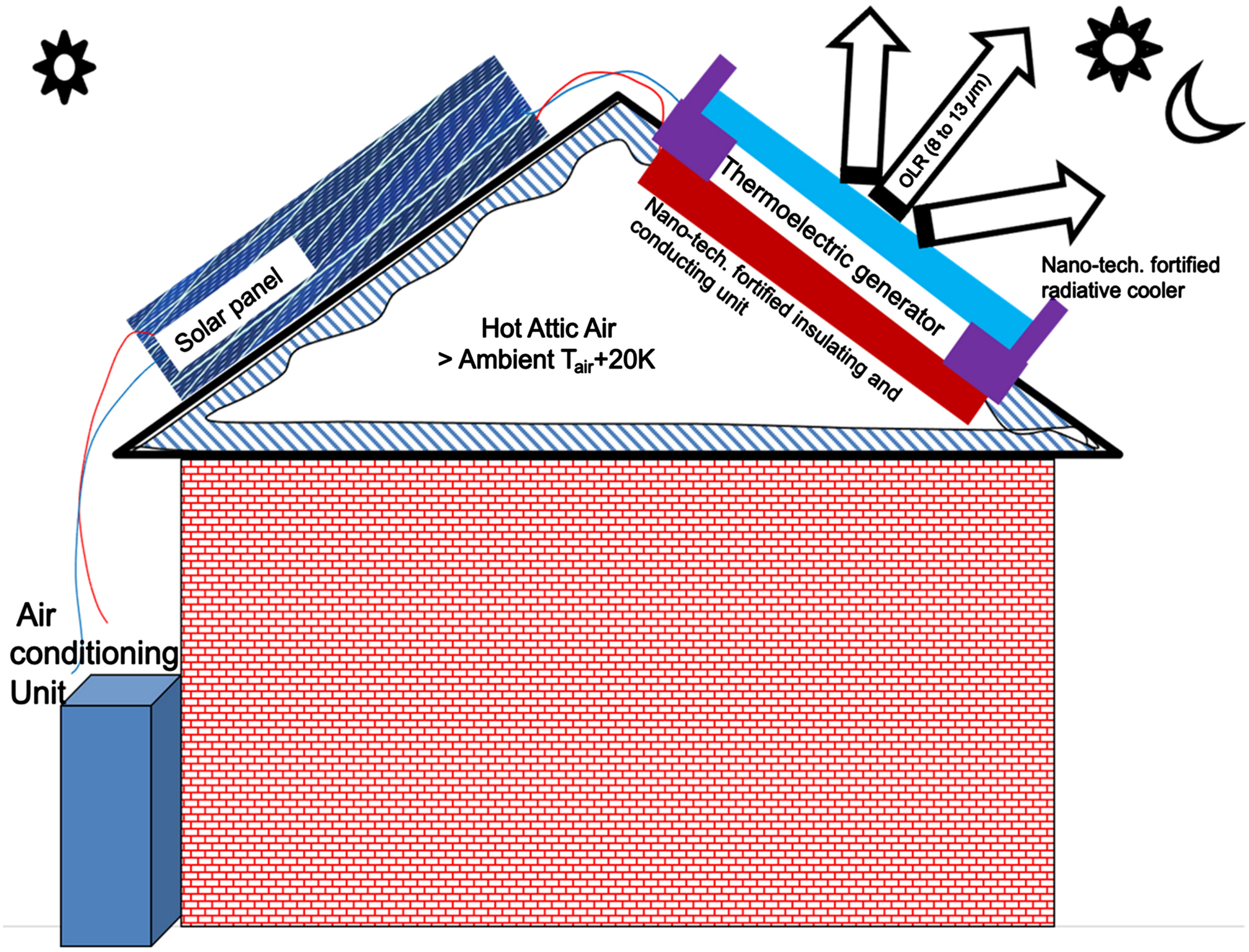

Figure 1. Sketch of a conceptual, all-day (daytime as well as at night) clean electricity-generating system that works very efficiently during weather extremes (e.g., heatwaves). During heatwaves, radiative cooling can be used to generate electricity when combined with a thermoelectric generator. For the thermoelectric generator, supported with nano-technology, cold-leg working temperature in the Fabry-Perot cavity shadow is well below ambient air temperature (e.g., −50˚C instead of ~16˚C without a nano-coating). One example of this realization is that the cold side (shown in blue color shades) is a TiO_2 fabricated (for defog purpose) silver mirror that creates a Fabry-Perot cavity that annihilates the incoming longwave radiation from the sky (LDR). The most challenging part is the advection of the ambient relatively hot air. Several thinner films are integrated to minimize the conductive heating by the ambient air. We here used more affordable alternatives to the best commercially available aerogel as insulation material so even better performance may be expected from the commercialized version. Once placed on the side of a building that is not facing the sun, the reflection of sunlight is of secondary importance. The conversion efficiency of thermal flux into electricity for the Bi_2Te_3 (alloy with some impurity) P-type material-based device can achieve ~15%. Shown are blue and red lines connected to the hot-end P-N nodes after serial concatenation to raise the output voltage. That said, we utilized the strategy of hot-end splitting of the thermocouple units. This is different from many commercial products. Commercially available units are usually very compact in size, though. A hand-made lab-stage device is used in this experimental phase, particularly because we have many experiments on damping LDR on the cold-end plate (*i.e.*, multiple-layer nano-coating). Comparatively, the hot-end plate is just an aluminum solid block, forming an ideal anchor for the wiring. The generated electricity should satisfy the air-conditioning requirement during HWs. A caution is that the provided electricity needs a DC-powered air-conditioning unit, not yet commonly available, but technically straightforward.

insignificant surface area. Intentionally making the cold plate emit at 8 - 11 μm limits the temperature to above 20˚C which is impractical for tapping electricity when using existing Ti-Be alloys P nodes (these are most suitable for medium temperature ranges). Instead, the focus of nano-technology should be focused on better (and more affordable) insulation materials and superior ways of annihilating LDR. The interaction of LDR with infrared (IR) wavelength-sized nanostructures is the direction to follow. In the following we describe a working device (not yet commercialized yet that uses the Bi_2Te_3 alloy just as in existing commercial units, with the working temperature range shifted to the lower temperature end and thus to a higher efficiency) that has recently been satisfactorily tested. With serial concatenation of the P-N thermocouples, 120 volt output is achievable for operating an air-conditioning unit equipped with a DC-motor. Note that we used the hot-end splitting strategy, unlike most commercial products, as indicated in **Figure 1**. This follows from the consideration that we have undertaken many experiments on damping LDR on the cold-end plate (*i.e.*, many nano-coating to apply). Comparatively, the "hot-end" plate (exposed to the hot attic air in the illustration of **Figure 1**) is just a thick aluminum plate, forming an ideal anchor for the intended wiring.

We know that water vapor is a strong absorber for microwave and infrared radiation. Accordingly, any water vapor condensation on the cold-end plate will significantly reduce radiative cooling efficiency. This is unavoidable. An approach could enclose the cold-end plate in a vacuum container but that enclosure would face the same problem of surface vapor condensation. Our approach uses a TiO_2 coating because it has ideal merit of self-cleaning–just as Rain-X for car windows. Other technical details including using high efficiency nano-tech products for creating the Fabry-Perot Cavity (formulations will be released once IP issues are resolved). Our hot-end plate (red unit in **Figure 1**) is simply made of aluminum. The cold-end plate is mainly a silver carefully coded with TiO_2 and two other nano-technology products for creating a infrared cavity. With all the efforts, on August 21, 2022, placing on top of a David-Weakley home at Austin, TX, close to −20˚C "low-end" temperature was achieved passively (all-day), without extra effort of a Peltier cooling circuit. If placed on the roof and oriented on the sun-facing roof slope, an extra coating for enhancing the reflectance of shortwave sunlight is further required but it is practical and applied without technical difficulty (e.g., normal Ag-oxides coating with fabrics suffices). This is because the much shorter wavelengths (of the sun light) do not interfere with the nanostructure periodically arranged for dealing with LDR. All current experiments were conducted on a north-facing roof slope. At a ~50˚C temperature contrast, using this apparatus, a 110 m^2 cold-end plate is necessary for obtaining a steady > 2000 watts throughput. If the solar panels are also installed, a significantly reduced area of the device is required to support building air-conditioning consumption. Upon optimization (especially using more effective commercial insulation gels), a commercial stage apparatus would see a superior performance.

3. Summary and Conclusion

This research focuses on an innovative approach in adaptation and mitigation of heatwave impacts in a warming climate. Examining the reanalysis atmospheric parameters reveals the geographic patterns and future trends of weather extremes. A thermoelectric approach for electrical energy tapping is proposed to utilize the positive benefit of this natural hazard. Technical difficulties are fully discussed and the performance of a prototype implementation is discussed. Using high-resolution reanalysis data, we examined heatwave events over North America, Eurasia and Australia during 1940-2022. Comparing the leading and ending 20-year periods, the heatwaves in the second period occurred more frequently, reached higher temperatures in general, and also had longer duration. The mismatch primarily is because heatwaves occurred in marginal places that had not experienced such weather extremes in the first period. For a heatwave definition that assumes a 4-year recurrence frequency at global hotspots and under current climate, a 27%, 18% and 47% increase are identified over Eurasia, Australia and North America, respectively. HWs would be a significant pathway for climate change to threaten ecosystem health, food security, and quality of life.

Heatwave events, however, provide the ideal opportunity for clean-energy (solar energy and thermoelectricity) harvesting. The generated energy can be used for air conditioning and to save lives. As the fields of nano-photonics and insulation mature, record-setting photovoltaic efficiency is now achieved in the utilization of solar energy. In this study, we propose commercial-grade electricity generation using the strong temperature contrast (which naturally/passively increases the high-end working temperature), combined with a thermoelectric generator. We presented experiments conducted at a normal residential home in Austin, TX. However, similar apparatus may be installed on tall buildings, with further improved thermoelectric conversion efficiency. Many industrial uses of TEGs have a low-end temperature set at a standard air temperature of 25˚C, close to our high-end temperature. From only the thermal efficiency point of view, shifting of the working temperature to the colder direction increases efficiency. It also is true from the considerations of the contacting electric resistance, and even the conductance of the heat flow. The key for a successful tapping of electricity from weather extremes is defog of the cooling plate and minimization of the absorption of the downward longwave radiation. We provided a nano-coating formula for defog of the cold-end plate that does not interfere with LDR dampening. We must admit that, in addition to creative ways of using clean energy at the most critical time of heatwave events, the societal assistance also is critical for us to face the challenge: a well-connected and mutually supportive system to live within the post-pandemic era certainly helps in healing the significant additional stress from upcoming heatwaves [2] [11].

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Data Availability

All data analysed during this study are included in this published article and are publicly available. Reanalysis datasets ERA5 are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip5-daily-single-levels?tab=form). This is open access public repository.

Authors' Contributions

D. Ren finished the experiments and wrote the paper with M. Lynch. This is a meteorologist's contribution to the field of clean energy. The method proposed here works in a tropical setting and should work with minimal modification for other global regions and for typical urban domestic settings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Radiative cooling can be used to generate electricity when combined with a thermoelectric generator. A thermoelectric device is a heat engine that directly converts heat energy into electricity. Many materials with a high-figure-of-merit ($Z(T)$, a unitless metric reflecting the thermoelectric transport properties) [12] have been identified with a high thermoelectric efficiency. The maximum achievable efficiency of a thermoelectric device is dual-controlled by its Carnot efficiency $\eta_T = \frac{T_h - T_c}{T_h}$ (thermal) and $Z(T)$ (electrical) and can be expressed as,

$$\eta_{\max} = \eta_T \frac{\sqrt{1 + Z(T_m)} - 1}{\sqrt{1 + Z(T_m)} + T_c/T_h}, \tag{1}$$

where T is absolute temperature (K), with subscript "c" applied for the cold end and "h" for the hot end of the device. $T_m = \frac{T_h + T_c}{2}$ is the mean temperature of high and low end temperatures. The temperature dependence of thermoelectric merit of working material (e.g., alloys) ideally is expressed as,

$$Z(T_m) = T_m \frac{\sigma \alpha^2}{\kappa} \tag{2}$$

where σ is the electrical conductivity, reciprocal of electrical resistivity ρ (in ohm-meters), κ is the thermal conductivity (again thermal property of the working material, in watt/m/K), and α is the Seebeck coefficient (*i.e.*, thermocouple coefficient in V/K, or $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}\cdot\text{A}^{-1}\cdot\text{K}^{-1}$). For ideal theoretical estimation of the maximum achievable efficiency of a thermoelectric device, the three thermoelectric transport properties are assumed temperature-independent. From Equations (1) and (2), it is apparent that the higher the $Z(T)$, the higher the $\eta_{\max}$. That is exactly why engineers are trying actively to experiment with new materials to improve $Z(T)$ [13] [14]. Here we propose increasing the efficiency by increasing η_T.