Energy 214 (2021) 118907

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Boosting silicon photovoltaic efficiency from regasification of liquefied natural gas

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ARTICLE INFO

Article history:
Received 1 July 2020
Received in revised form
17 August 2020
Accepted 19 September 2020
Available online 24 September 2020

Keywords:
Silicon solar cells
Temperature dependence
Efficiency enhancement
Liquefied natural gas
Regasification
Cryogenic

ABSTRACT

The regasification of liquefied natural gas from 111 K to ambient temperature represents a standard large-scale process that currently dissipates a worldwide total of ~105 TWh/yr of cold energy to seawater. We consider the potential efficiency enhancement attainable by exploiting this nominally free cold energy to cool conventional silicon photovoltaics. Whether the temperature dependence of photovoltaic performance at ordinary operating conditions can be extrapolated to cryogenic temperatures has remained unexplored territory. In measuring the principal PV performance variables down to cryogenic temperatures, we show that such cooling can boost PV efficiency by close to 80% relative.

1. Introduction

This paper focuses on a way to take advantage of the free cold energy from the regasification of liquefied natural gas (LNG) to prodigiously boost the conversion efficiency of the crystalline silicon (c-Si) phovotoltaic (PV) systems that overwhelmingly dominate the landscape of installed PV power. With the installed prices of high-efficiency c-Si PV modules having descended to ~$0.3 per peak W, and comprising no more than ~30% of total system cost, appreciably improving conversion efficiency η (as opposed to further reducing cost) has become the principal focus for superior cost effectiveness. Modules have achieved conversion efficiencies of ~23% [1] at Standard Test Conditions (STC) meaning an irradiance of 1 kW/m^2 (1 sun), a PV temperature T of 298 K, and an AM1.5G spectrum. Given how close η is to the fundamental limit for c-Si [2], the room for realistic noticeable efficiency enhancements would appear to be modest.

For c-Si, the fundamentally maximum η, corresponding to an idealized cell in the eponymous Shockley-Queisser (SQ) limit [3], is commonly cited as 31%, but this pertains specifically to STC. The SQ limit is in fact itself a function of T, irradiance and spectrum. It has been evaluated for c-Si, as well as a variety of other PV materials, over broad ranges of T and irradiance [4,5], showing that η is a decreasing function of T, with theoretically-maximum efficiency values for c-Si well above 31% at the ultralow temperatures considered here. Prior studies did not explore this temperature domain, but rather focused on temperatures close to and above those of the environment.

Even for realistic (non-ideal) c-Si PVs, lowering temperature increases η, mainly from a linear increase of their open-circuit voltage (V_{oc}) via the exponential decrease of the equilibrium concentration of intrinsic charge carriers in any semiconductor [2]. A slight worsening of efficiency with cooling can result from the reduction in short-circuit current density J_{sc} as a consequence of the increased bandgap, and a slight improvement in efficiency can come from the behavior of the fill factor FF parallelling that of V_{oc} [2]. But both these effects are small compared to the impact of V_{oc}.

The paucity of experimental evidence that these temperature dependences remain linear, and can be extrapolated, as temperature is lowered into the cryogenic regime, calls into question

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https://doi.org/10.1016/j.energy.2020.118907
0360-5442/

whether there are potentially dramatic efficiency enhancements of the type that motivate the application portrayed in this paper. The measurements presented below therefore constitute new results, offered partially in the spirit of filling that gap, and confirming that, at least down to the temperatures pertinent for LNG regasification, major efficiency gains are credible and realizable. The fact that such linear extrapolations cannot remain valid down to arbitrarily low temperature [6] also indicates that it is essential to determine the functional forms and magnitudes of the temperature dependences.

The magnitude of the efficiency's temperature coefficient lessens as cell quality improves, with high-efficiency c-Si modules typically exhibiting a temperature coefficient $d\ln(\eta)/dT$ of $-0.003\ K^{-1}$ [1]. This is based, however, on measurements over a restricted temperature range from typical environmental temperatures up to ~50 K higher. PV temperature coefficients have been published for the c-Si technologies that comprise the vast majority of PV installations, and were determined according to industry standards for large numbers of mass-produced modules. Two prominent examples subsume (a) SunPower's large cells (155 cm^2/cell) with an STC efficiency of 25% and a temperature coefficient of $-0.0029\ K^{-1}$ [1], and (b) Sanyo Electric's 23% efficient heterojunction with intrinsic thin-layer Si cells (100 cm^2/cell) with a corresponding value of $-0.0023\ K^{-1}$ [7]. The latter basically achieve the theoretical lower bound of $-0.002\ K^{-1}$ derived for ideal-quality c-Si cells [6]. In no instances, however, were measurements published for the low temperatures of interest here.

Lower-quality c-Si PVs may have lower efficiencies, but exhibit a greater magnitude for the efficiency's temperature coefficient [4,7,8], meaning that the *relative* efficiency enhancement for a given degree of cooling is more pronounced. As explained below, although we also procured small low-quality commercial c-Si cells and measured their performance down to cryogenic temperatures - in the process confirming this point - we preferred to focus on high-efficiency solar cells as the truly viable candidates for large-scale systems of the type depicted here.

The performance benefits of lowering temperature notwithstanding, actively cooling PVs is a losing battle because the energy invested in cooling more than compensates for the corresponding energy gain. However, an unorthodox method for cooling PVs by ~200 K by utilizing the putatively free cold energy from the regasification of LNG performed at large receiving terminals around the world (Fig. 1) will be shown here to hold the potential for substantial efficiency boosts. This is contingent upon: (a) measuring PV performance down to cryogenic temperatures, (b) establishing that the magnitude of the temperature coefficient of PV efficiency does not decrease considerably in that temperature range, (c) demonstrating that no damage is incurred under repeated thermal cycling between ambient and cryogenic temperatures, and (d) confirming that the requisite additional collateral components are readily available, affordable, and do not require significant operating power. All of these will be scrutinized here - plus relating to the problem of frost formation on the PV modules - including the presentation of our own extensive PV performance measurements down to cryogenic temperatures on a recent generation of commercial c-Si cells.

2. Liquefied natural gas regasification

There is an expansive and mature LNG trade and technology, comprising liquefaction, transport, storage and regasification. It is a multi-billion-dollar industry, currently growing at ~10% per annum [9]. The principal (but not exclusive) end-use for importers is fueling conventional power plants with the cleanest-burning fossil-fuel alternative, natural gas (NG). With NG's density being ~600 times lower than that of LNG, it is liquefied at atmospheric pressure and stored in sea-faring vessels at 111 K. At the receiving terminal, LNG is typically stored on-shore and then regasified back to ambient temperature (Fig. 1) via heat exchange with seawater.

Numerous schemes for exploiting the ostensibly free cold energy of LNG regasification have recently been proposed (most notably for electricity production from turbines) [10–12]. Due to the ephemeral nature of sunlight, the sizing of the conventional regasification plant (which can function continuously all day) remains unaffected by the PV system. The fraction of the LNG diverted to the PV system for partial regasification will depend on ambient conditions, solar irradiance, PV efficiency and economic factors. The conventional plant supplies the remaining heating of LNG to ambient temperature.

Our proposal is predicated on the fact that NG is being liquefied and shipped around the world independent of any scheme for recuperating the energy that is currently dissipated to the sea upon regasification. Namely, the energy invested in liquefaction and shipment is not part of the equation here. Neither are we advocating that NG be liquefied for the purpose of cooling PVs upon regasification. Rather, the comparison is between our strategy vs. continuing to dissipate available cold energy.

3. On Si PV performance down to cryogenic temperatures

Published data are scarce for the operating conditions that are pertinent here, namely, PV temperatures down to 111 K, at solar irradiance values up to 1 kW/m^2. No such data appear to have been published for the PV technologies that have been, or are being, installed around the globe. The only studies we found on Si PVs at such temperatures were motivated by satellite missions to the planet Jupiter and beyond [13,14], where, in addition to PV measurements at the very low irradiance values so far from Earth, low-temperature tests were also performed up to ~1 sun. However, only a small number of these customized cells were fabricated and tested. Furthermore, the cells differed distinctly from the mass-produced high-efficiency c-Si PV cells that dominate current worldwide solar power installations. Many of the cells were also plagued by Schottky-barrier formation [14]. So we did not view these data as being pertinent for the PVs addressed here.

Additionally, although not designed as solar cells, Si diodes are commonly used in thermometry down to cryogenic temperatures because of the confluence of their voltage being relatively large (typically 0.4–1.1 V at low currents, e.g., 10^{-5} A) and their measured voltage being linear over $T = 30–500$ K [15]. But because the composition and architecture of these diodes differ substantially from those of solar cells, it was not assumed that the temperature dependence of PV performance at cryogenic temperatures could be deduced from them.

Accordingly, we proceeded with experiments to measure the behavior of current commercial c-Si PVs for the relevant operating range.

4. Experimental details and results

Because the cryostat in our laboratory cannot accommodate cell linear dimensions greater than 1 cm, we could not perform measurements on PV modules, or even the large cells that comprise them, typically around 13 cm in linear dimension. So we first ordered sub-cm cells that were cut from common 10-13-cm c-Si cells from several commercial manufacturers. But our measurements revealed that their STC efficiency was only about half the certified value of the large cells from which they were pared.

As a compromise, we procured c-Si cells that are manufactured at a sub-cm scale [16]. We measured their STC efficiency (averaged over a group of 20 cells) to be 17%. This is below the efficiency of

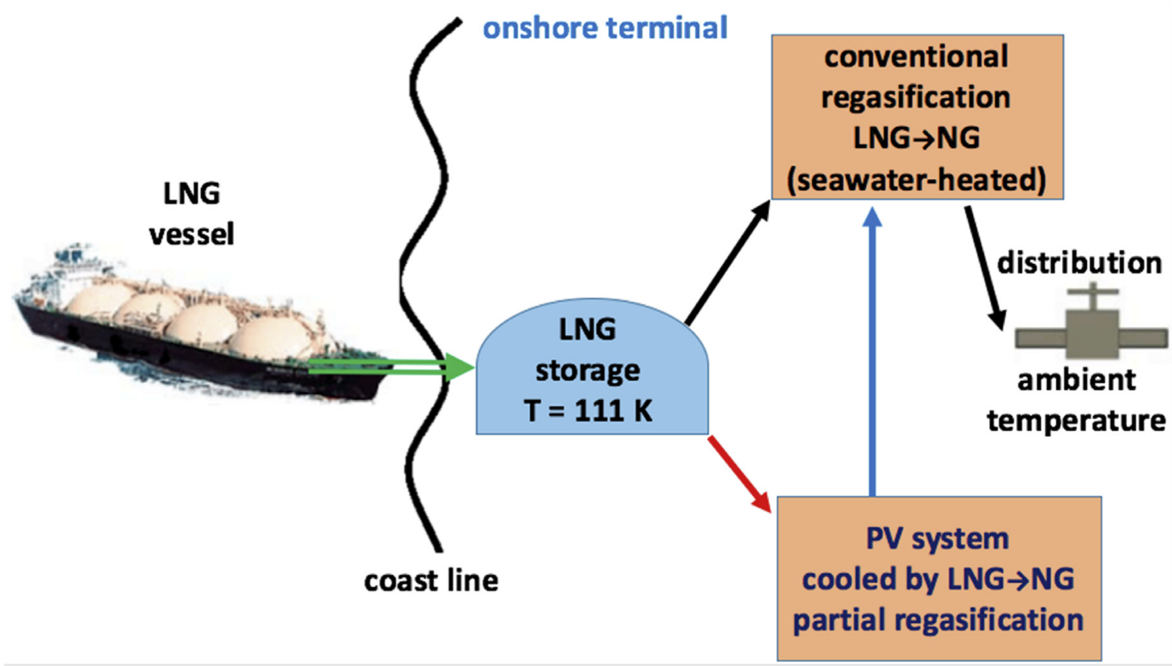

Fig. 1. Schematic indicating that part of the LNG received and stored at an onshore terminal can cool an on-site PV system. Natural gas exiting the PV field continues to a conventional seawater-heated regasification plant to complete heating to ambient temperature and distribution. The fraction of LNG diverted through the PV system will depend on ambient conditions, solar irradiance, PV efficiency and economic factors.

leading c-Si PV modules, albeit greater than what we measured for the sub-cm cells cut from the latter. However, our measurements below show that their temperature coefficients are the same as for commercial high-efficiency c-Si modules over the higher-temperature range for which there are published values based on measurements from numerous cells.

All cells [16] had an active area of 0.45 cm^2. They were tested individually in our cryostat (Oxford Instruments MicrostatN with a MercuryiTC controller) which maintained a constant prescribed temperature over the range 80–380 K. Because the cells resided in the evacuated chamber of the cryostat, no frost formation occurred. Each cell was then uniformly irradiated in our solar simulator (Newport Oriel LCS-100 with a 91150V calibration cell) with an AM1.5G spectrum at irradiance levels of 0.3, 0.5 and 1 kW/m^2. Current-voltage curves were traced - each trace requiring 2 s - with a Tektronix Keithley Series 2401 Source Measurement Unit, at temperature intervals of ~20 K, from 380 K to 80 K, and then from 80 K to 380 K, all repeated over multiple cycles. About 3–5 min elapsed between successive runs. There were no perceptible changes in cell behavior at any irradiance or temperature as a consequence of the extreme temperature cycling.

Representative results are plotted in Fig. 2. V_{oc}, J_{sc}, FF and η were all well approximated as linear functions of T for the range of interest (i.e., upward from the LNG boiling point of 111 K), with the dominant contribution to efficiency deriving from that of V_{oc}. Fig. 3a highlights $\eta(T)$ relative to η at a typical 1-sun (uncooled) PV operating temperature of 330 K at an irradiance of 1 sun, showing that cooling from 330 K to 111 K yields an efficiency improvement of 77% relative (i.e., η increased from 0.155 to 0.275). Fig. 3b shows PV output power density at maximum power point as a function of T over a broad range of irradiance values.

At 1 sun, and over T = 111–380 K, we measured $d\ln(\eta)/dT = -0.00281$ K^{-1} (which, to within the error bars of ± 0.0002 K^{-1}, is consistent with the corresponding value of -0.003 K^{-1} for today's commercial high-efficiency c-Si PVs [1]). At 0.3 sun, we measured $d\ln(\eta)/dT = -0.00326$ K^{-1}.

5. Estimating system size and output

Our aim in this section is to coarsely estimate the magnitudes of the size and performance of the PV systems. First, we need to address what is, and is not, our objective. We are not aiming for a detailed design and precise evaluation of a given installation. Rather, we are trying to offer rough assessments of key magnitudes. As such, elements that contribute no more than a few percent to the overall energy balance are not included, e.g., incremental parasitic pumping energy and heat exchanger losses. Similarly, site-specific details such as construction components are also not addressed.

A typical LNG terminal processes 5 Mtpa (Megatons per annum), raising its temperature from the on-board storage value of 111 K (at a pressure of 1 atm) to ambient temperature. The stored cold energy thermal value of LNG is ~830 kJ/kg [17] of which ~58% is latent heat and ~42% sensible heat. This corresponds to ~120 $MW_{thermal}$ (for 24 h/day, 365 day/yr operation). The current cumulative worldwide figure is 500 Mtpa, corresponding to ~12 $GW_{thermal}$.

The PV system could serve as a stand-alone regasification heat exchanger between LNG (at 111 K) and ambient air [18], even when solar is unavailable, but it would be inadvisable (both economically and thermodynamically) due to the heat transfer being markedly inferior compared to the heat exchange with seawater in conventional regasification plants. Hence only part of the stored LNG would be pumped across heat exchangers bonded to the back of the PV modules, during the primary periods of solar availability. Moreover, the PVs would be supplying only part of the energy needed for that limited amount of LNG to emerge as NG at ambient temperature (Fig. 1).

The part of the PV system providing the latent heat would nominally operate at the lowest available temperature of 111 K, and hence at the highest efficiency. We will analyze this first with an illustrative estimate, and then proceed to consideration of the sensible heat in regasification. At an ambient temperature of ~300 K, the LNG liquefaction temperature is ~220 K below the typical PV operating temperature under peak irradiance (~330 K).

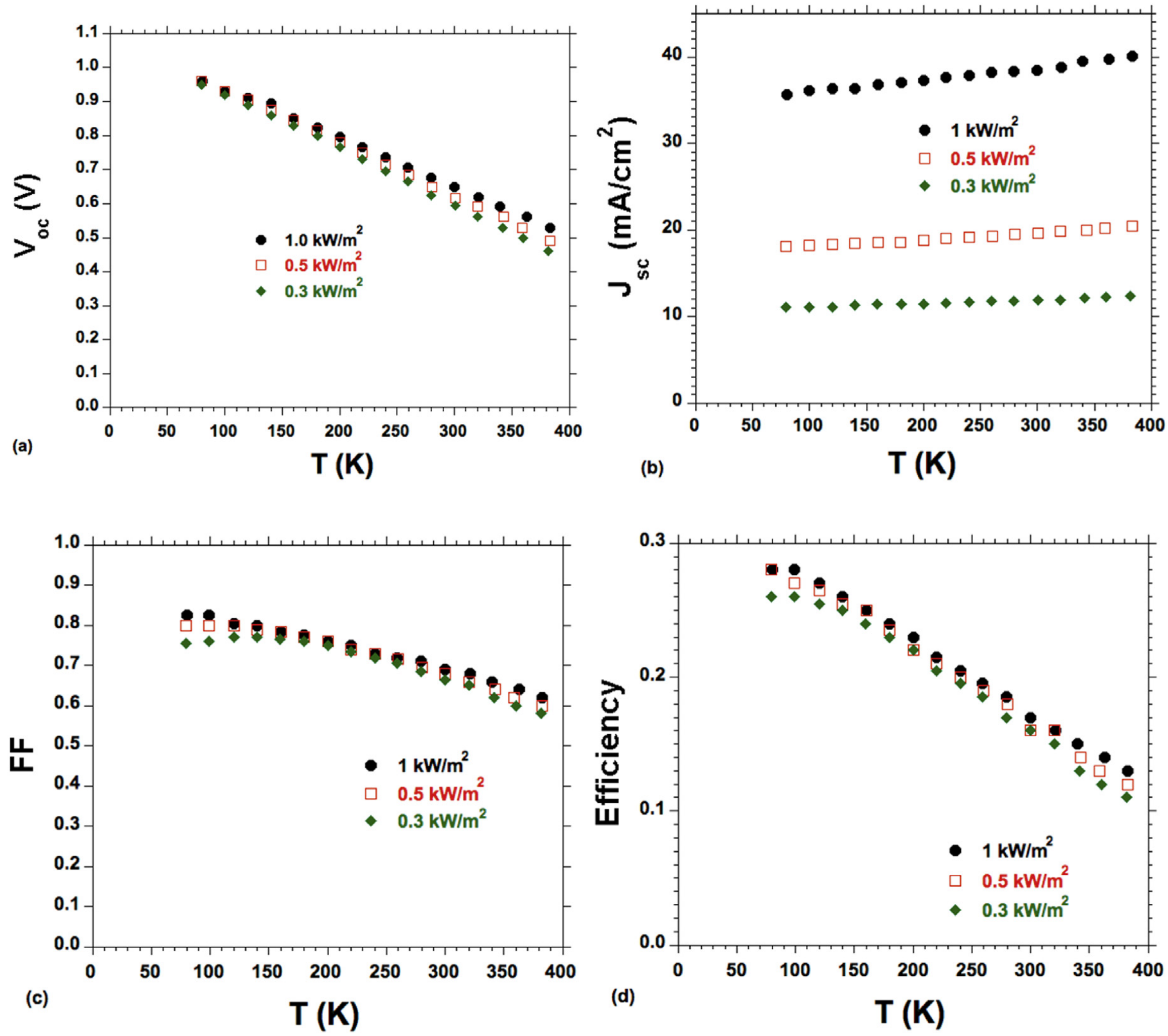

Fig. 2. Representative measured PV performance variables plotted as a function of T from 80 to 380 K, at irradiance values of 0.3, 0.5 and 1.0 kW/m^2. (a) V_{oc}. (b) J_{sc}. (c) FF. (d) η. The experimental uncertainties (error bars) for V_{oc}, J_{sc}, FF and T are smaller than the symbols indicating the data points, and are ±5% relative for η based on the accuracy for measuring irradiance.

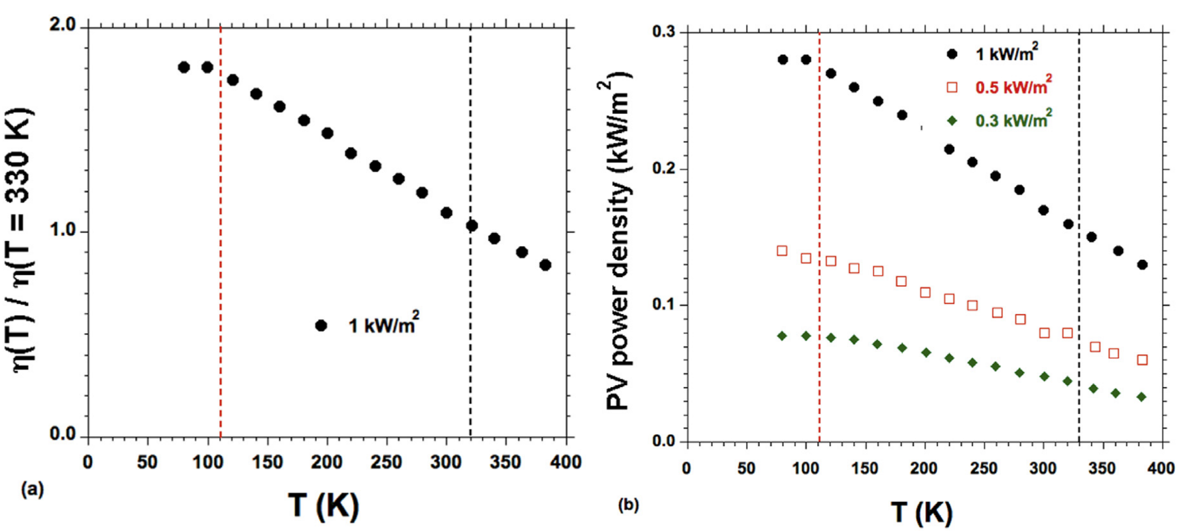

Fig. 3. (a) η(T) relative to η at a typical 1-sun (uncooled) PV operating temperature of 330 K, at an irradiance of 1 sun. (b) PV output power density at maximum power point as a function of T at irradiance values of 0.3, 0.5 and 1.0 kW/m^2. The LNG liquefaction temperature of 111 K and a typical 1-sun uncooled PV operating temperature of 330 K are indicated by the vertical red and black lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The efficiency boost would then be a factor of 1.77 (Fig. 3a), which, for the scenario considered here, would increase η in commercial c-Si PV modules from ~20% (conventional uncooled operation) to ~35% (LNG-cooled). Namely, the incremental gain in peak electricity production would be ~150 W per m^2 of PV module.

Despite the sizable efficiency boost, the fraction of available cold energy that can be converted to electricity is severely and intrinsically constrained by the high rate of heat transfer from the environment to the PV modules, mainly via natural convection, but also with non-negligible contributions from thermal radiation and from module heating due to unconverted solar absorption. To estimate the PV area for providing all the latent heat, we need to estimate the steady-state heating of modules at a PV temperature of 111 K and an ambient temperature of 300 K. Depending on common wind speeds, the convective heat transfer coefficient should be in the range of 10–20 W/(m^2-K), so convective heating (to the irradiated side of the modules) q_{conv} would be ~1900–3800 W/m^2. The corresponding radiative exchange q_{rad} would be ~400 W/m^2. To this we add the solar heating q_{solar} of ~550 W/m^2 of heat rejected from the 35%-efficient PV modules at 1 sun (where account has been taken of a reflective loss of ~10%). So the total heat gain for vaporizing LNG would be ~2850–4750 W/m^2. The total latent heat delivery rate for the plant is 70 MW, which would then require a PV module area A_{PV} of ~14,740–24,560 m^2 ($A_{PV} = 70$ MW/($q_{conv} + q_{rad} + q_{solar}$)), nominally generating a peak electrical power of ~5.2–8.6 MW ($A_{PV} \bullet \eta \bullet 1$ kW/m^2).

The corresponding *net incremental* gain in electricity production (relative to uncooled PV operation) would be ~2.2–3.7 MW ($A_{PV} \bullet (\eta(T = 330K) - \eta(T = 111K)) \bullet 1$ kW/m^2) - only a small percentage of the 70 $MW_{thermal}$ input. An efficiency η_{conv} for the conversion of the thermal cold energy to the net incremental electricity generation can be expressed as

$$\eta_{conv} = \frac{incremental\ PV\ power}{heat\ gain\ from\ the\ environment\ and\ solar\ heating} \tag{1}$$

For collectible solar irradiance I_{coll}, with the PV field operating at 111 K, in contrast to ~330 K in the absence of cooling, η_{conv} is

$$\eta_{conv} = \frac{(\eta(T = 111\ K) - \eta(T = 330\ K))\ I_{coll}}{q_{conv} + q_{rad} + q_{solar}} \tag{2}$$

Reducing convective heating (e.g., via evacuation) and radiative exchange (e.g., with a selective coating on the PV glazing) could increase η_{conv} noticeably, but are not explored here because their cost would likely be unacceptably high for such systems. Nonetheless, it should be noted that the potential for improving η_{conv} by as much as a factor of ~5 is possible, in principle, with existing technologies.

The gross land area requirement (total footprint) is typically slightly more than twice the PV module area, based on spacing among the modules being sufficient for acceptably low shading losses, plus access within and around the PV field. Most ports for receiving LNG present available areas of this magnitude, provided the PV arrays form a covering structure for the port, i.e., do not require a noticeable expansion of available area (with the added benefit of shading the working areas below them).

After completing latent heat delivery, the remaining sensible heat flux needed for the NG to reach ambient temperature (50 $MW_{thermal}$ in this instance) can be provided in part from additional PV modules. However, the average PV operating temperature must then be substantially higher than 111 K. It will depend on the fluid flow rate and the properties of the insulated heat exchanger [18] attached to the back of the PV modules. Because these involve case-specific cost considerations, detailed design and performance evaluations are delegated to future individualized studies. It can be noted, however, that, because of the linearity of η with T, the PV efficiency boost will be approximately linear in the average PV temperature across this part of the PV field. For example, at an average PV temperature ~100 K below the nominal 1-sun uncooled operating value of ~330 K, the efficiency boost at 1 sun would be ~35% relative (Fig. 3a). Whatever the operating temperatures best suited to a particular installation may be, estimates for A_{PV}, the net incremental electricity delivery from harvesting sensible heat and its corresponding conversion efficiency, can be estimated as portrayed above.

6. Remaining challenges

A major challenge is avoiding frost formation on the PV panels that would be installed in systems cooled by LNG regasification. Our particular application poses a unique parameter space that does not appear to have merited prior consideration. While developing a solution for this specific issue is beyond the scope of this paper, it is worth noting that such solutions should not be intractable. Creating an evacuated space between the irradiated side of the PV panels and a transparent glazing above them would mitigate the problem (as confirmed in the experiments in our cryostat - *vide supra*). However, the incremental cost for large cost-effective commercial installations may be unacceptable. However, new generations of super-hydrophobic materials that could be applied to the PV panels and are potentially affordable could represent a viable option [19]. Future low-cost mechanical solutions tailored to such systems present additional options [20,21].

A second issue is the heat exchange hardware that would need to be bonded to the back of each PV module, and the piping through the PV field. These, however, come from mature, large-scale and affordable technologies [18], including LNG regasification installations, complemented by only small parasitic pumping energy needs above and beyond that of existing LNG regasification systems.

There is also the question of the resilience of Si PVs under extreme thermal cycling down to cryogenic levels. First, the experiments reported here revealed no perceptible worsening in PV performance after repeated cycling between 80 K and 380 K. Second, different types of c-Si modules deployed on satellite missions have not exhibited degradation under comparable extreme thermal cycling. Hence exposure to cryogenic temperatures would not appear to be an impediment.

7. Conclusions

The considerable free cold energy currently dissipated to the sea upon regasification at LNG receiving terminals prompted the exploration of ways to exploit an available temperature difference of ~200 K (from LNG's liquefaction temperature of 111 K up to ambient temperatures). Here, we have proposed a concept whereby the power output of conventional c-Si PV plants that would be installed at the receiving terminals could be boosted by close to 80% relative.

Based on today's LNG trade, the potential to be tapped is ~12 $GW_{thermal}$ from regasification (i.e., ~105 TWh/yr). The associated peak PV power generation that could be installed per annum would clearly be small relative to the global installed capacity of ~500 GW. Yet this potential, in a market where the current worldwide growth rate in the LNG trade is ~10%/yr [9] corresponding to an increase of a factor of ~2.6 per decade, could be deemed worthy of consideration.

Because this is, to our knowledge, the first time that the integration of elements and constructions from distinct PV and cryogenic technologies is being proposed, an economic analysis is premature. Preliminary indicators, however, can be viewed as favorable due to (a) PVs representing the lowest-cost electricity-generation technology today, and (b) LNG regasification being only one small cost element in the grand scheme of the mining, liquefaction, storage, shipment and regasification of NG that provides a cost-effective fuel for a considerable fraction of power plants worldwide.

Moreover, the workability of such systems is strengthened by the fact that both the PV systems and the LNG regasification systems are, separately, mature, economical technologies, the integration of which would also entail the use of existing mass-produced components (heat exchangers, pumps, piping, controls and safety procedures). As noted above, it would seem the key issue then is finding an inexpensive way to avoid frost formation on the PV panels.

It did not appear obvious that extrapolation of the equations governing temperature-dependent PV performance [8] would remain valid down to cryogenic temperatures. Rather than conjecturing the validity of this performance enhancement from extrapolations of PV specs down to the ultra-low temperatures of LNG regasification - or of basing the assessment on a small sample of different types of customized PV cells developed for satellites - we performed extensive measurements (Figs. 2–3).

Our data show a basically linear relation between all the principal PV performance parameters - most notably efficiency - and temperature over the full range of interest. The PV efficiency enhancement for cooling from a typical 1-sun PV operating temperature of 330 K down to the 111 K liquefaction temperature of LNG is close to 80% relative. Nevertheless, as shown above, the inherently high rate of heat exchange from the environment to the cooled PV modules, mainly via natural convection but also by thermal radiation and solar heating, severely limits the efficiency with which the cold thermal energy can be converted to electricity with this strategy to only a few percent.

Credit author statement

All authors contributed equally to this work.

Funding sources

This work and GM's doctoral fellowship were funded by Research Grant number 3–15970 from the Israel Ministry of Science, Technology and Space.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We gratefully acknowledge Howard Wenger (Walnut Creek, CA) for financing the purchase and shipment of all solar cells used in our experiments. JMG wishes to thank Prof. Kian Jon (Ernest) Chua of the National University of Singapore for having prompted the exploration of new ways to convert LNG regasification cold energy into utilizable power.

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