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SUSTAIN WATER, SANITATION AND HYGIENE SERVICES

**Sustainable water pumping in refugee camps:  
costs and benefits of over-sized solar PV systems**

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*Residents of refugee camps often face challenges to accessing efficient energy for domestic needs and livelihoods. This paper presents a case study from Nyarugusu Refugee Camp in Tanzania, where a water pumping system was powered by a solar PV / diesel hybrid system, and considers optimising energy generation and valuing surplus energy, so the surplus can be utilised to provide social benefits to residents. The results provide validation of solar energy data sources and projected PV installation costs, and show the marginal capital cost/kWh of over-sizing a solar PV system is attractive beyond 50% surplus capacity where cost/kWh levels slightly below \$0.10/kWh. The proposed sustainability assessment framework includes new parameters; Gross Productive Energy (GPe) and Productive Energy Index (PeI), which provide a means of quantifying surplus energy utilisation, and examples successfully assessed included school computers, mobile handset charging, and an 'enterprise hub' building which could support social cohesion, knowledge transfer and income generation initiatives.*

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## **Introduction**

Refugee camps in sub-Saharan Africa often face challenges to access clean, efficient energy at a reasonable cost, and often resort to diesel generators for electricity, and climate sensitive resources such as wood and charcoal for domestic cooking. As increasing numbers of water pumps within refugee camps are being converted to solar PV/diesel hybrid power it is important to consider optimising systems and oversizing solar PV arrays to provide extended pumping hours, potentially eliminating the need for diesel generators entirely. Surplus energy produced during peak solar irradiation periods can then be utilised to support other energy requirements within the refugee camp and contribute towards wider social benefits.

## **Background**

Following the analysis of a 54kWp solar PV array installation at Nyarugusu Refugee Camp, a sustainability assessment framework was developed to evaluate the technical, and whole-of-life economic and environmental considerations of generation scenarios. The framework has been labeled the *Net Energy* model (nete) and analysis is presented in a separate paper (Harkness, Guthrie & Burt, paper 2622), where a number of key outcomes were identified:

- Solar PV system design can be improved through network monitoring, by determining array size and tilt using the lowest solar month, and through careful pump selection.
- Localised economic and impact rates gave useful results, and mapping of global future projections onto local prices provided a useful sensitivity analysis and were incorporated in the nete framework.
- Fuel for generators was the largest significant recurring cost in hybrid scenarios. Hybrid economic payback was <5 years despite higher investment; and exposure to high fuel prices was reduced.
- Impact from module and inverter manufacture, and fuel combustion was significant; but compared to a diesel generator, CO<sub>2</sub>e payback was under 2.5 years and energy payback was under 5 years.
- A hybrid generation system with a 20% over-sized PV array provided 45% lower Levelised Cost of Electricity (LCOE) and annual impact than a diesel generator, reducing external resource dependence.

## Objectives

The objectives of this research are to: 1) identify opportunities to optimise energy generation and system performance; 2) value surplus energy and quantify its utilisation; 3) investigate the integration of social benefits to compliment the nete sustainability assessment framework (Harkness, Guthrie & Burt, paper 2622).

## Literature review – performance optimisation

### System Efficiency

The term ‘system efficiency’ is often used to quantify electrical losses between modules and pump motor (Bucher, 1996) or to determine the unit cost of water; the latter suggesting an inter-changeability with ‘optimisation’ (Odeh et al., 2006). Some pump manufacturers calculate ‘system efficiency’ ( $m^3/Wp$ ) by dividing daily production by system capacity (Lorentz, 2016). This is helpful when comparing systems, but doesn’t account for variations in field performance. Another measure used regularly is ‘daily hydraulic energy equivalent’, or ‘volume-head product’, measured in  $m^4/d$  (see McNelis and Derrick, 1989, Odeh et al., 2006 for instance). Again, this provides a daily average comparison at the manufacturer specified duty point, but in practice, this varies (with efficiency) under variable speed pump control.

### Storage

Energy storage is suitable for solar PV where there is a production deficit during daylight hours. Deep cycle batteries are often used, however round-trip efficiency can be as low as 80% and battery life is often 5 years (Rehman and Al-Hadhrami, 2010). Energy storage is a ‘bottleneck’ to progress (Sandalow et al., 2015) and price reductions are necessary before more efficient technologies can become viable.

### The benefits of energy access

A focus on fuel-efficient cook-stoves in refugee camps is appropriate, considering more than one third of the world’s population uses inefficient biomass fuel (Cullen and Allwood, 2010), and in refugee camps, efficient fuel sources are limited. The benefits of sustainable energy in refugee camps are abundant, and include improved social cohesion, gender equality and improved health (Sooriyaarachchi et al., 2015 Mishra and Behera, 2016), security, livelihoods and resilience, environmental, energy security (Gunning, 2014), knowledge transfer and income generation initiatives (Lahn and Grafham, 2015).

### UNHCR and partner energy access case studies

In Hagadera, Kenya, the installation of 20 school computers powered with an independent solar system was successfully trialed (Robinson, 2014). A typical low cost desktop computer draws 65W (Acer, 2016), so utilisation of this scale is feasible. Instant Network Schools (INS) has provided 20 refugee schools with Internet connectivity, tablets, projector and modem; requiring 6-8 h/day of device charging (INS, 2016).

## Methodology

As previously established, diesel generators can be optimised through installation of a variable speed drives, however a wide range of field variables will impact PV energy generation, so data from PVGIS, NASA, Lorentz Compass (Lorentz, 2016), and SolarGIS was analysed for Nyarugusu. Lorentz and SolarGIS provide both irradiation and predicted energy output data, while energy output for PVGIS and NASA data was calculated using variables outlined in Figure 1, with consistent losses. PVGIS also provides detailed monthly irradiation data files, which allowed more detailed analysis.

Published PV installation price data and UNHCR project cost was then collated (see Pernick et al. 2013, Chung et al., 2015, UNHCR, 2015, Epicentre, 2016) to provide clarity on PV learning rates, industry trends and to project future scenario planning rates in the nete framework – refer to Figure 4. Next, the relationship between additional capital investment for over-sized PV systems, and % surplus capacity was investigated. Because the magnitude of surplus energy is dependant on daily and seasonal impacts on generation, surplus energy was calculated for eight over-sized systems by subtracting the daily instantaneous gross energy from pump demand for each month, as indicated in Figure 2.

The derived 2016 capital PV installation rate was used (refer Figure 4); it was assumed that there were no additional maintenance costs; and total annual generated energy was discounted over the PV system life of

25 years using rates previously outlined. PV load factor was calculated by dividing the annual energy generation by 8,760 hours/year. It was also proposed that an evaluation would be best achieved by distinguishing between gross (potential) energy, and net (productive) energy.

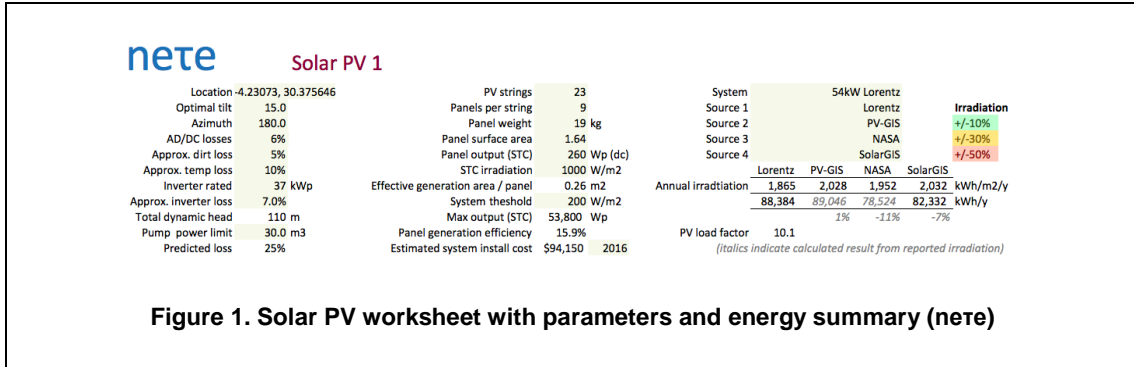


Figure 1. Solar PV worksheet with parameters and energy summary (nete)

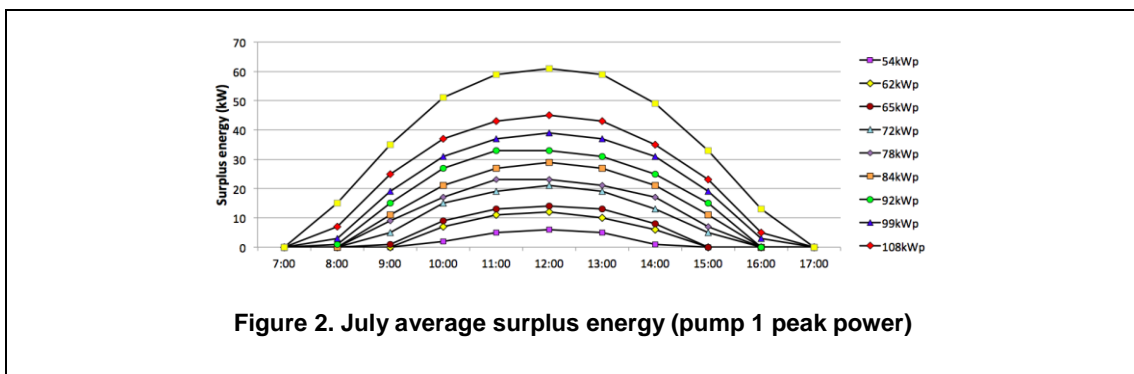


Figure 2. July average surplus energy (pump 1 peak power)

Initially, a new parameter, ‘Gross Productive Energy’ (*GPe*) - in kWh/m<sup>3</sup> - measured the gross energy embodied in water produced (after Ashby, 2013); calculated by dividing instantaneous gross electrical energy (kW) by production rate (m<sup>3</sup>/h). A proxy for efficiency, this approach was considered more appropriate for system optimisation and comparing generation options in refugee camps than the inverse parameter ‘system efficiency’ (m<sup>3</sup>/Wp) previously discussed, as *GPe* identifies the most/least energy-intensive time to produce water on any given day.

Finally, a dimension-less parameter, ‘Productive Energy Index’ (*PeI*) was developed to promote the concept of *effectiveness*. Since instantaneous PV power is typically expressed as an average per hour, it becomes energy (kWh), so each variable was measured over the same time period (kWh), and we calculated *PeI* by adding  $E_{Productive}$  and  $E_{Utilised}$ , and dividing the total by  $E_{Potential}$ .  $E_{Productive}$  is the energy required for water production (pumping),  $E_{Utilised}$  is energy utilised concurrently in another productive manner, and  $E_{Potential}$  is the total gross energy generation potential. Finally, these approaches were applied to the generation scenarios (Harkness, Guthrie & Burt, paper 2622), and a number of ‘Energy Access’ concepts were analysed to determine their feasibility. A new assessment map is therefore proposed in Figure 3.

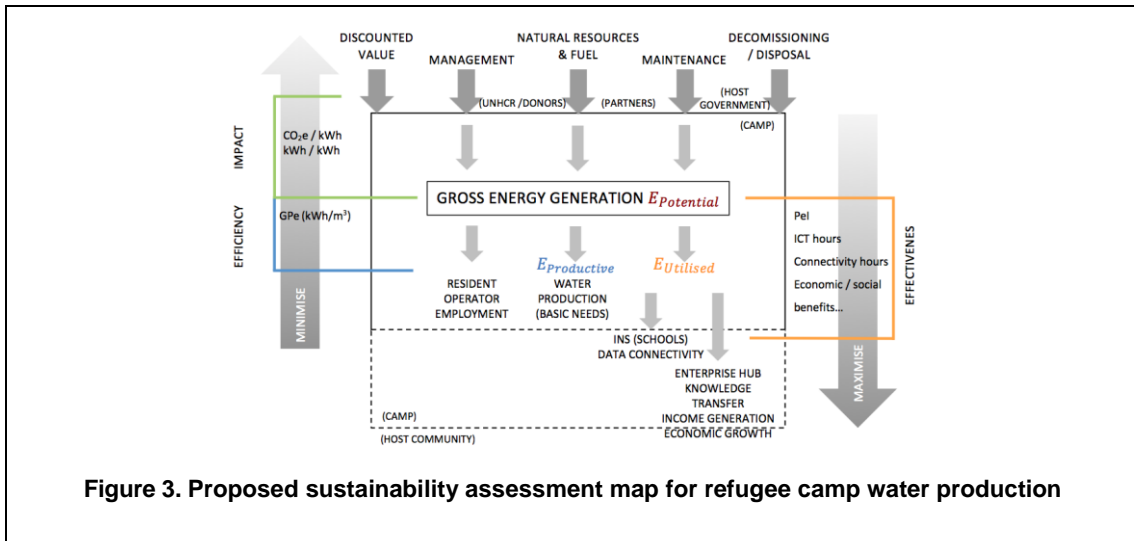


Figure 3. Proposed sustainability assessment map for refugee camp water production

## Results / discussion

### Data analysis

Lorentz irradiation data was found to average 5% below NASA data, and 9% below PVGIS and SolarGIS data, as outlined in Figure 4. The NASA calculated energy and was 11% below Lorentz, particularly over peak months of May to September. The PVGIS calculated energy closely followed Lorentz energy data and was only 3% lower over the peak months of May to September, excluding November to January. Limited field performance data has been provided since the June 2016 field visit, however, generated energy between July and August 2016 appears to match Lorentz and PVGIS energy data.

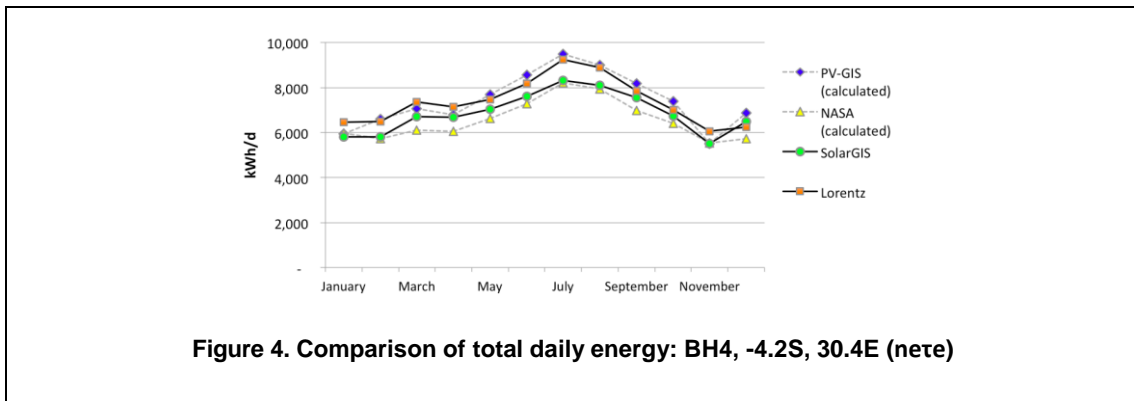


Figure 4. Comparison of total daily energy: BH4, -4.2S, 30.4E (nete)

Historic PV installation data shown in Figure 5 indicates learning rates during earlier years but various trends converge well prior to 2012, and the CEGlobal projected rates beyond 2013 indicating the maturity of the current generation technology (Pernick et al. 2013). The actual Dadaab 45kW (UNHCR, 2015) and BH4 54kW installation prices (Epicentre, 2016) are consistent with these projected prices.

The marginal cost of surplus system energy for both pumps indicated declining trends as outlined in Figure 6, but the rate of decline is more noticeable with the less-efficient pump 1. At 50% surplus capacity, the marginal cost for pump 2 is only \$0.10/kWh and the rate of decline begins to level for both pumps beyond this point. At higher levels of surplus, pump efficiency is less critical to achieving low marginal cost as the convergence of the two pump trends indicates.

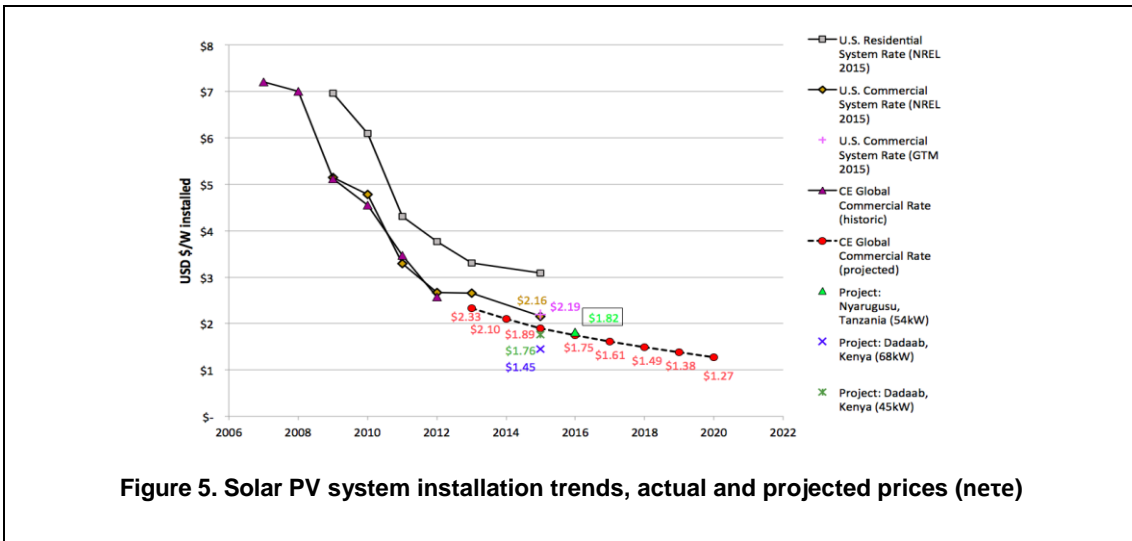


Figure 5. Solar PV system installation trends, actual and projected prices (nete)

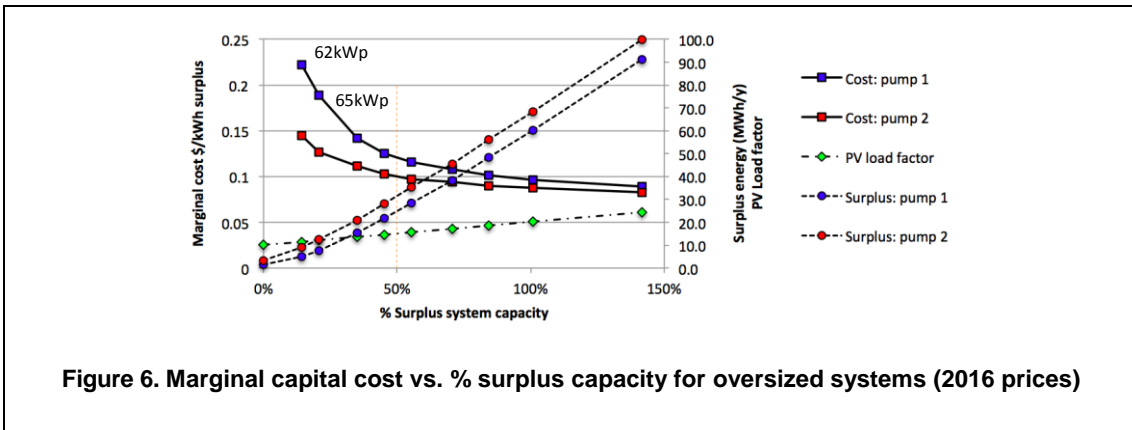


Figure 6. Marginal capital cost vs. % surplus capacity for oversized systems (2016 prices)

**New assessment parameters**

The proposed new parameters (GPe and PeI) were applied to the generation scenarios (Harkness, Guthrie & Burt, paper 2622), and results for the July peak are displayed in Figures 7 and 8. Scenario A (85kVA diesel generator) provides no energy surplus, and while both figures suggest optimal performance, there is no opportunity for improvements in utilisation. GPe results (refer Figure 7) for scenario C (60kVA generator / 65kWp PV) are higher than scenario A, due to the generation of surplus solar PV energy, despite low pump efficiency. Peaks are evident during overlaps between solar PV and generator energy.

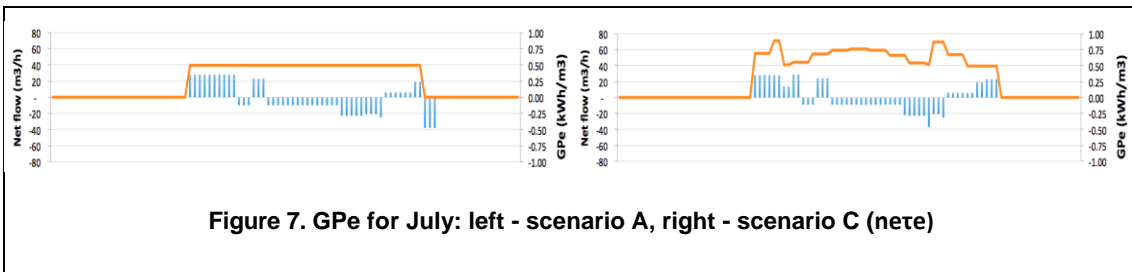
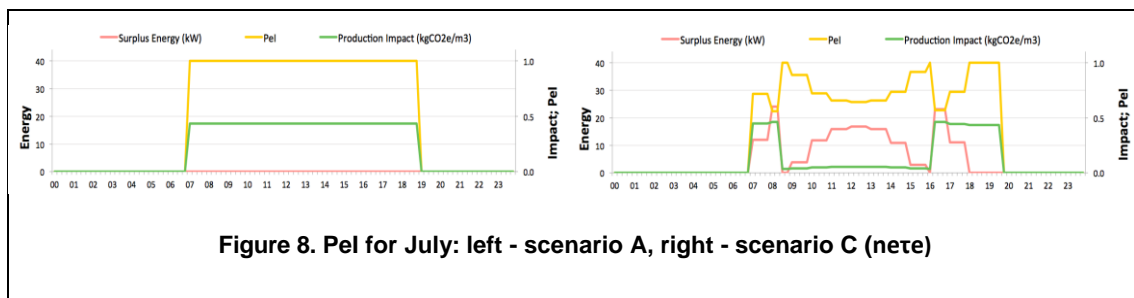


Figure 7. GPe for July: left - scenario A, right - scenario C (nete)

Scenario C shows a reduction in PeI (refer Figure 8); indicating potential energy benefits that could be realised through increased utilisation. Although not indicated here, PeI does not reduce over the lowest months because the system energy output remains below the pump power limit.



### Opportunities for energy utilisation

Scenario C (20% oversized solar PV system) resulted in a marginal cost of \$0.13/kWh, and has potential to provide power to the following applications during the daily surplus period.

#### Desktop computers

A low cost desktop computer draws 65W (Acer, 2016), and the 1.3kW demand from 20 units would result in a marginal increase in PeI. It should be possible to provide power in all but 2 months of the year, costing \$0.03 per/unit/day to run.

#### INS

An ipad charger draws 12W and a laptop charger draws 85W so the total draw of 385W over 4 hours is easily achievable during the daily surplus period, at a total energy cost of \$0.20/day. A projector and modem could be operated in the same period, or by 12V inverter and cycle-charged batteries.

#### Mobile device charging

Local handset and smartphone device purchase prices are low enough to be accessible to many refugees, but few Nyarugusu residents have charging capability. At 6W each, hundreds of devices could be charged all year round. For reference, 100 smartphones would cost \$0.31 per day.

#### Enterprise hub

The cleanliness of panels has been identified as critical to module output, however the BH4 modules are 3m off the ground to deter theft, so operators have no safe cleaning method. The structure (an estimated 4,000kg of steel), provides the skeleton of a mono-pitched building, so we propose it could be feasible to build a lightweight building structure at the desired module tilt - longer and narrower to reduce peak roof height - with a corrugated iron roof and platforms between panels to allow for cleaning. The facility could operate as a powered 'enterprise hub', supporting livelihoods, including the repair of electronic devices, household solar panels, or to run workshops on the construction of fuel-efficient stoves, for instance.

### Conclusions

- A strong correlation was observed between solar energy data provided by Lorentz, and that calculated in the nete framework from PVGIS irradiation data, and although a full years field validation is not possible, generated energy observed at BH4 between July and August 2016 matches these sources.
- UNHCR PV project costs from comparable arrays are consistent with global trends, and projected prices have been incorporated into the nete framework for scenario planning.
- The marginal capital cost of surplus system energy was calculated, and at 50% surplus, was shown to be \$0.10/kWh, which is <50% of hybrid LCOE and <20% of diesel LCOE, as previously established.
- The proposed assessment map provides new parameters; Gross Productive Energy (GPe) and Productive Energy Index (PeI), which captures surplus energy and quantitative social benefits through increased utilisation.
- The 20% oversized 65kWp system (scenario C) was shown to provide potential benefits, including power for desktop computers, INS device and mobile handset charging; at a marginal rate of \$0.13/kWh.
- A solar PV array support structure could constitute a powered building roof - an 'enterprise hub' - with potential to support social cohesion, knowledge transfer and income generation initiatives.

- At current industry capability and cost, hybrid systems can provide low cost, low impact and self-reliant (sustainable) energy supplies, and the capital investment for over-sized systems results in low marginal cost, which can provide significant social benefits in typically energy-deprived refugee camp contexts.

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### References

- Acer (2016). *DC221HQ BWMICZ Specifications*.
- Ashby, M. (2013). *Materials and the Environment*. Burlington: Elsevier Science.
- Bucher, W. (1996). *Aspects of solar water pumping in remote regions*. E. for Sust. Dev., 3(4), pp.8-27.
- Chung, D., Davidson C., Fu, R., Ardani, K., and Margolis, R. (2015). *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*.
- Cullen, J. and Allwood, J. (2010). *Theoretical efficiency limits for energy conversion devices*. Energy, 35(5), pp.2059-2069.
- Epicentre (2016). *Quotation for Solar Pumping System for Nyarugusu Borehole*.
- Gunning, R. (2014). *The Current State of Sustainable Energy Provision for Displaced Populations: An Analysis*. London, UK.
- Harkness, B., Guthrie, P., Burt, M. 2017a (Paper 2622). *Sustainable Water Pumping in Refugee Camps: Solar PV / Diesel hybrid scenarios at Nyarugusu, Tanzania*. WEDC International Conference, Loughborough.
- INS (2016). *Instant Network Schools*. Available at: <http://www.vodafone.com>
- Lahn and Grafham, (2015). *Heat, Light and Power for Refugees: Saving Lives, Reducing Costs*.
- Lorentz (2016). *Lorentz Compass solar pump sizing software V3.1.0.65*.
- McNelis, B., and Derrick, A. (1989). *Solar water pumping: clean water for rural areas*. Proc. 2nd ASEAN Science and Technology Week (1989), pp. 607–625.
- Mishra, P. and Behera, B. (2016). *Socio-economic and environmental implications of solar electrification: Experience of rural Odisha*. Renewable and Sustainable E. Reviews, 56, pp.953-964.
- NASA, (2016). *NASA Surface meteorology and Solar Energy – Location*.
- Odeh, I., Yohanis, Y. and Norton, B. (2006). *Economic viability of photovoltaic water pumping systems*. Solar Energy, 80(7), pp.850-860.
- Pernick, Wilder, and Winnie, (2013). *CLEAN ENERGY TRENDS 2013*.
- PVGis, (2016). *Photovoltaic Geographical Information System - Interactive Maps*.
- Rehman, S. and Al-Hadhrami, L. (2010). *Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia*. Energy, 35(12), pp.4986-4995.
- Robinson (2014). *Protracted Situation of Displacement: Options Beyond Camp Assistance, Kenya*. NRC.
- Sandalow, McGormick, Rowlands-Rees, Izadi-Najafabadi, and Orlandi, (2015). *Distributed Solar and Storage - ICEF Roadmap 1.0*. Innovation for Cool Earth Forum, Bloomberg New Energy Finance.
- Sooriyaarachchi, T., Tsai, I., El Khatib, S., Farid, A. and Mezher, T. (2015). *Job creation potentials and skill requirements in, PV, CSP, wind, water-to-energy and energy efficiency value chains*. Renewable and Sustainable Energy Reviews, 52, pp.653-668.
- UNHCR (2015). *The Supply And Installation Of Solar PV Powered System For Borehole 1 In Dagahaley Refugee Camp, Dadaab Sub County - Garissa County*.
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