d-Lumen: A System for Cost-Effective Water Heating From Solar PV

Dominic Ó Gallachóir *Updated February 2019*

Problems With Our Current Methods of Water Heating

Approximately one fifth of energy use in households across Ireland, the UK, Canada, and the USA goes towards water heating, and much of this energy is supplied by burning oil and gas[1–5]. This is a problem for several reasons. First, heating bills are often a significant financial burden, especially for those with low incomes[6]. Second, dependence on fossil fuels exposes our economies to volatile energy markets. Third, the burning of oil and gas is a leading cause of climate change, damaging natural ecosystems and increasing the risks of floods and doughts[7]. And finally, air pollution from the burning of fossil fuels contributes to millions of preventable deaths every year[8]. Overall, a cheaper, fossil fuel-free method of heating would be very welcome.

Solar PV for Water Heating

Solar Photovoltaic (PV) panels convert daylight into electricity, and could be used to provide power for water heating. In recent years, the price of PV panels has dropped dramatically[9,10] and electricity from solar PV panels is now cheaper than fossil fuel power in many parts of the world[11]. Many households now use PV panels to contribute to their power needs, and some of the power produced by these systems may be used for water heating. However, typical residential solar PV systems include many components that are not necessarily needed for water heating. In particular, these systems are wired into the AC circuitry of the house, and must include an inverter to convert the DC output of the panels into AC for general use (*Figure 1*). In a system specially designed to heat water using solar PV panels, the inverter could be done away with and there would be no need to connect the system to the AC mains. Furthermore, by connecting all of the PV panels in parallel, the system voltage could be kept low. These factors would save on both hardware and installation costs, making the system much more affordable. Developing a system like this could speed the uptake of solar PV as a replacement for fossil fuel-based power for water heating in Irish households.

The d-Lumen: A Device for Water Heating Using Energy from Solar PV Panels

I propose a device (the d-Lumen) to facilitate water heating using the output from solar PV panels, without the need for a DC-AC inverter or connection to mains power. At its input, the device will be connected to an array of solar PV panels. At its output, the device will connect to an immersion heater with a number of resistive heating elements. The d-Lumen will use a digital maximum power point tracking algorithm to ensure that the PV array operates near its maximum efficiency, while supplying as much power as possible to the immersion heater at all times. A thermostatic sensor arrangement will also be required to ensure that the water does not overheat (*Figure 2*).

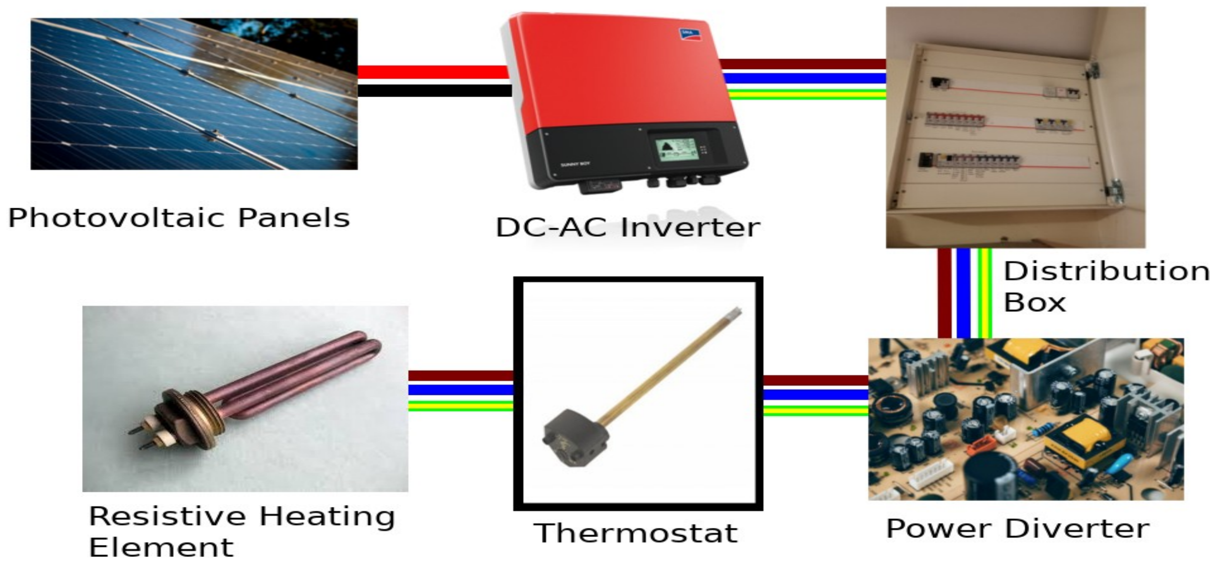


Figure 1: Standard PV System with Power Diverter Schematic

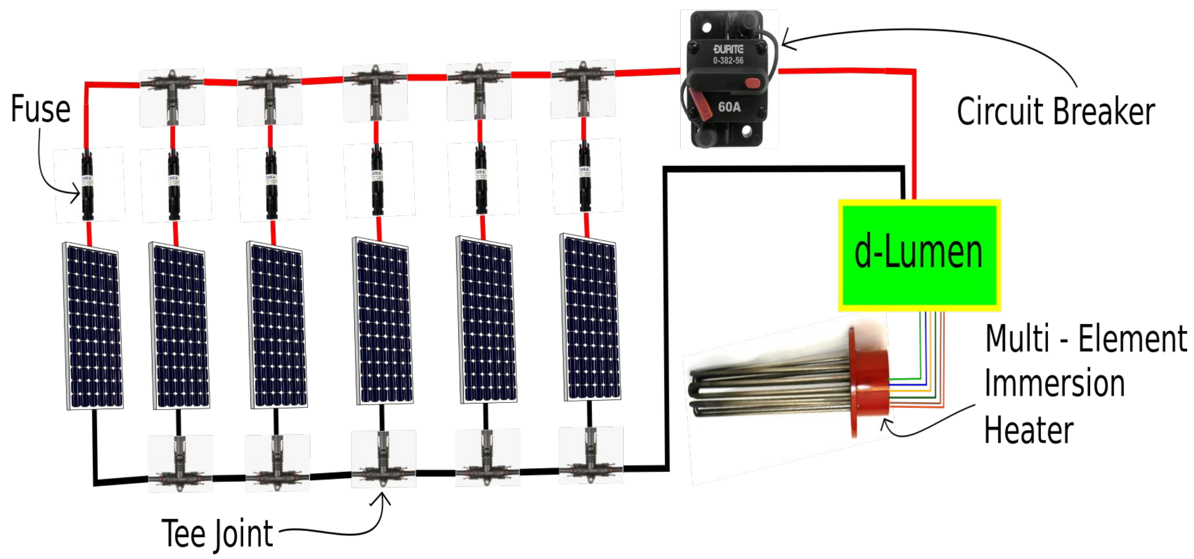


Figure 2: d-Lumen System Schematic

Some devices of this design are already available for sale but are limited to approximately 1.2kW$_{DC}$ of input power[12,13]. This relatively low power rating is likely due to the fact that the devices are being sold in warm locations such as Australia and Nevada, which have relatively high incoming water temperatures (meaning lower energy demand for water heating) and excellent conditions for solar PV. In Northern Europe, the ideal PV array size is likely to be much larger, due to cooler incoming water temperatures and lower solar irradiance levels. Furthermore, these devices use panels connected in series, increasing the system voltage and they require the use of large capacitors/inductors. The use of DMMPT architecture with multiple heating elements avoids the need for these expensive, heavy, and often unreliable components.

Solar thermal systems are another possible competitor to the d-Lumen system. Solar thermal systems use the sun's rays to heat water as it passes through tubes or panels and are an older technology than solar PV. However, solar PV-based systems have some major advantages when compared with solar thermal systems including:

- Few or no moving parts
- No risk of pipes bursting in freezing weather
- Reduced risk of corrosion
- Much less plumbing required
- No antifreeze needed
- Solar PV technology is continuing to improve rapidly and further cost reductions are expected over the coming years
- Solar PV panels are most efficient in cold weather, precisely when their output is most needed

5. Sample Application: Hot Water for a Family of Five in Ireland (With Hot-Fed Showers)

Let's examine the practicalities of the d-Lumen system by considering the financial return of installing the system for a family of 5 in Ireland. In rural parts of Ireland, kerosene is typically burned during the winter months to provide space heating and hot water. In the summer, when central heating is not required, electricity is used for water heating. Let us assume that electricity is used from April to September and kerosene is used from October to March. Let us also assume that the family uses showers that are connected to the hot water feed because this would help to make the best use of the d-Lumen. The results are summarized in Table 1. Detailed calculations can be found in Appendix 1.

Table 1 – Economic Return of the d-Lumen System	
Daily Hot Water Demand	220 L
Total Cost of d-Lumen System with 3kW of PV Panels	€3,350

Total Annual Savings (Electricity and Kerosene)	€491.91
Annual Rate of Return on Investment	14.68%

As Table 1 shows, the d-Lumen system has the potential to provide significant savings to Irish families on their energy bills. Furthermore, the return on investment is attractive. The economics could be even better if government incentives and future energy price increases are taken into account.

6. Conclusions

If developed, the d-Lumen system will use the output power from solar PV panels to provide hot water. This could result in significant environmental benefits by displacing fossil fuel use. Furthermore, financial calculations show that the d-Lumen could be cost-effective and economically attractive. Overall, the d-Lumen system could have significant benefits for society.

6. Next Steps

I would be happy to see the d-Lumen developed by anyone, even for commercial purposes. On the other hand, if you are interested in working on an open-source collaboration to make the d-Lumen a reality, or if you would be kind enough to offer your feedback on this proposal then please get in touch at *dlumenproject@gmail.com*.

Appendix 1: Calculation of Values for the Illustrative Use Case

Assumed Values:

General

Water temperature change from cold feed to hot output	36.7 °C[14]
Density of Water	1 kg / L
Heat Capacity of Water	4,186 J / g.K
Heat Loss Through Cylinder Walls, Pipe Work, Wires, etc.	132.1 W[15] (96.51kWh/month)
Current Method of Heating Water (April - September)	Electrical; 100% efficient
Current Method of Heating Water (October – March)	Kerosene; 90% efficient (Based on the minimum efficiency of new oil boilers required to meet part L of the Irish 2019 housing regulations[16])
Price of Electricity (inc. VAT)	€.1974 / kWh*
Price of Kerosene	€.0918 / kWh (2018 Q4[17])
Number of Days in a Month	30.44
Efficiency of the d-Lumen	98% (Based on commercially available solar PV inverters claiming greater than 98% efficency[18])

*This is based on Electric Ireland's Standard Domestic Electricity Tariff (24 hour rate, including VAT; December 2019)[19]. Electric Ireland is the largest supplier on the Irish electricity retail market[20].

Estimating Daily Hot Water Demand

An observational study in the UK found that the daily domestic hot water demand of a household can be estimated by the equation "46 + 26 N", where N is the number of occupants of the household[14]. This gives us an estimate of 176L for a family of five. However, instantaneous electric showers (with cold water feed) are popular in the UK[21]. Domestic hot water consumption is likely to be much higher in homes where showers are fed with hot water.

A study in Latvia found that apartment dwellers use 42 L of water per person per day on average[22]. This equates to 210 L/day for a family of 5.

In Bratislava, apartment dwellers were found to use on average 16.76 m^3 of hot water per year. This equates to an average consumption of 46 L/person per day or 230L per day for a family of 5.

A research article from North America draws attention to the importance of demographics in estimating hot water use. In the report, the authors estimate that two adults and one child will use 156 L/day while a single parent and two youths will use 275 L/day. Directly scaling these values to a family size of 5 gives 260 L/day and 458 L/day, respectively[23].

Another source reports substantial variation in hot water consumption between countries, from 30L per person per day in Spain, to 94L per person per day in Canada[24]. These values equate to 150L and 470L per day for a family of 5, respectively.

Taking all of these studies into consideration, I have estimated that a family of five in Ireland with hot-fed showers will use **220L** of hot water per day. This is higher than the estimated use for families in the UK (who are likely to use showers fed with cold water) and Spain, but lower than the estimated use in the USA and Canada. It is mid way between the water usage values for Bratislava and Latvia, respectively.

d-Lumen Estimated System Costs

d-Lumen	€250
Other Hardware (PV panels, wiring, brackets, etc.)	€1,900
Installation Cost	€1,200
Total	**€3,350**

Available DC Output Power from a 3.0kW$_p$ Solar PV Array in Ireland*

Month	**Available Output Energy (KWh)**
January	93
February	145
March	239
April	311
May	395
June	394
July	378
August	345
September	250
October	196

November	109
December	76

*Values from the NREL PV Watts calculator (2019-12-11)[25]. The parameters used were: Location Dublin, Module Type Premium, Array Type Fixed (roof mount), Array Tilt 36°, Array Azimuth 180°, System Losses 6.35%, Inverter Efficiency 98%, DC to AC Size Ratio 1.2, Inverter Efficiency 98%.

Calculated Values:

Monthly Energy Requirement for Water Heating

The energy required to bring incoming cool water up to the hot output temperature is calculated as:

(Number of Days in a Month) X (Daily Hot Water Demand) X (Density of Water) X (Required Temperature Change) X (Specific Heat Capacity of Water)

Substituting in the values we get:

(30.44) X (220) X (1) X (36.7) X (4,180) = 1,027,329,301 J = 285.37 kWh

To this number, we must add heat loss through the walls of the tank and pipework to get the total energy requirement:

Total energy requirement = (Energy to Bring Water Up to Temperature) + (Heat Losses)

Total energy requirement = 285.37 kWh + 96.51 kWh

Total energy requirement = 381.88 kWh

Cost of Useful Energy From Kerosene

Typical kerosene burners are not 100% efficient. Therefore, we must take energy losses into account in order to calculate the true cost of energy from kerosene. The cost of providing energy to the water is given by the cost of kerosene's chemical energy divided by the efficiency of converting that chemical energy into heat energy stored in the hot water cylinder:

Cost of useful energy in water from kerosene = (chemical energy cost) / (efficiency)

Cost of useful energy in water from kerosene = (€.0918) / (90%)

Cost of useful energy in water from kerosene = €.1020 / kWh

Estimated Electricity and Oil Savings

The following table shows the calculations for financial savings from a d-Lumen system. Data in the second column are taken directly from the assumed values (performance of a 3.0kW_{DC} solar PV system in Ireland). Data in the third and fourth columns are based on the assumption that power from the d-Lumen will replace purchased electricity during the summer months and purchased kerosene during the winter months, up to a maximum of the total monthly energy required to provide hot water.

Month	**Available Energy (kWh)**	**Energy from Electricity Saved (kWh)**	**Energy from Kerosene Saved (kWh)**	**Value**
January	93		93	€9.49
February	145		145	€14.79
March	239		239	€24.38
April	311	311		€61.39
May	395	382		€75.46
June	394	382		€75.46
July	378	378		€74.62
August	345	345		€68.10
September	250	250		€49.35
October	196		196	€19.99
November	109		109	€11.12
December	76		76	€7.75
Total				**€491.91**

Financial Metrics

The annual rate of return on investment is estimated by dividing the annual savings by the cost of the system:

annual rate of return on investment = (annual savings) / (system cost)

annual rate of return on investment = (€491.91) / (€3,350)

annual rate of return on investment = 14.68%

Appendix 2: Design Considerations

System Voltage

The vast majority of solar PV panels on the market today are manufactured using either 60 or 72 silicon cells wired in series, giving approximately 40 or 48V DC $_{oc}$, respectively. This means that if all the panels were to be wired in parallel, then the entire d-Lumen system might have a voltage of no more than about 48V DC $_{oc}$ – an appealing design feature from a safety point of view.

Mitigating the Risk of DC Arcs

DC arcs present a serious fire hazard even at moderate voltages because DC arcs can self-sustain at much greater separation distances than equivalent-voltage AC arcs. Locations where DC arcs could be a problem include:

1) Inside the d-Lumen itself

Careful design of the d-Lumen will be required to ensure that it is not susceptible to DC arc faults.

2) Along the wires that run from the PV array to the d-Lumen

Conventional PV inverters include arc-fault detection and suppression to avoid problems here. This technology could be adapted for use in the d-Lumen.

3) The circuit from the d-Lumen to the resistive heater.

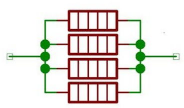
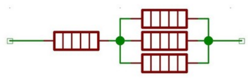
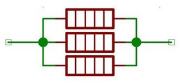
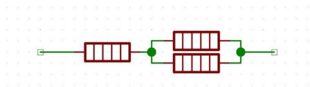
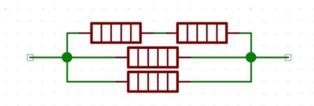
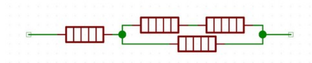
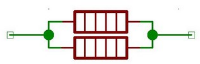
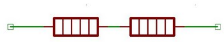
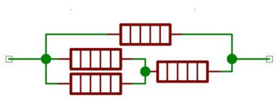
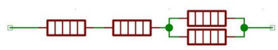
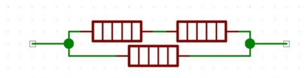
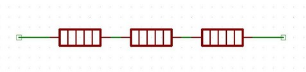
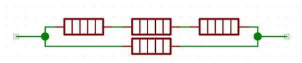
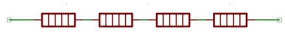
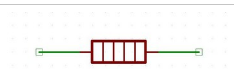
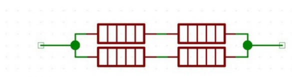
This part of the circuit presents a special problem because typical thermostats and switches designed for use with AC are not suitable for breaking DC. This means that instead of simply connecting the thermostat in series with the immersion heater, it will be necessary to come up with another method. One option might be to connect the thermostat to the base of a transistor so that power is cut off from the d-Lumen once the maximum water temperature is reached.

Rated power output of the solar PV array

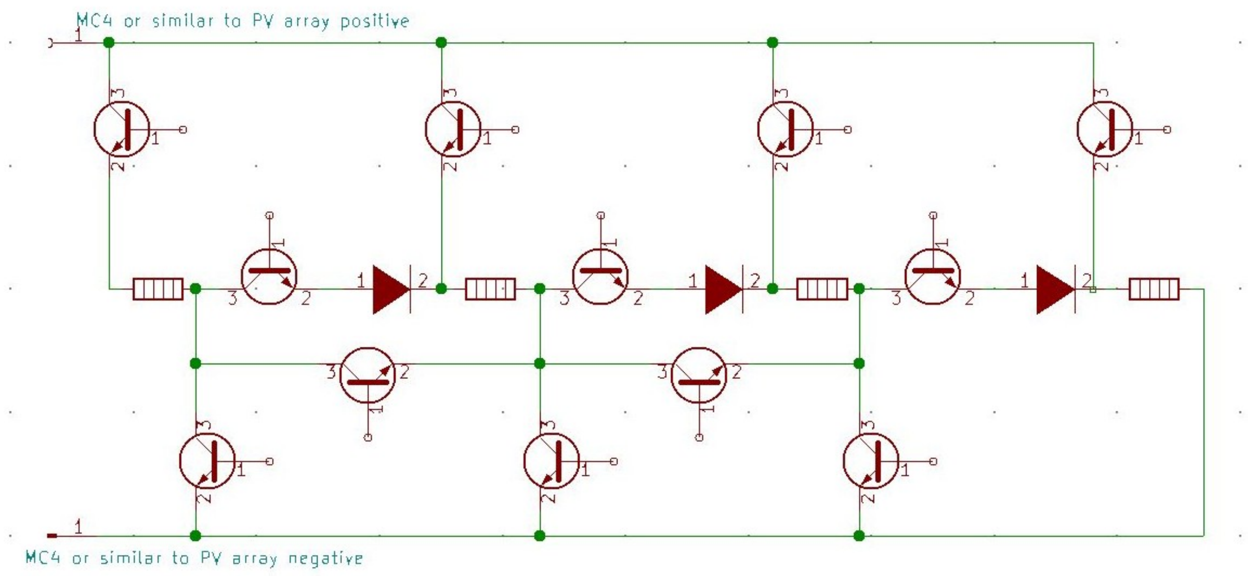
Ideally, the solar PV array should be large enough to provide a substantial portion of the household's energy needs for water heating. On the other hand, an excessively large array would be overly expensive and wasteful. Most likely, the appropriate size will be large enough to provide a significant proportion of the winter heating needs and all or almost all of the heating needs in the summer, with perhaps a small surplus at times. As an example, my financial calculations (not shown) indicate that 3kW of panels would be about optimal for a family of 5 in Ireland.

Digital Maximum Power Point Tracking

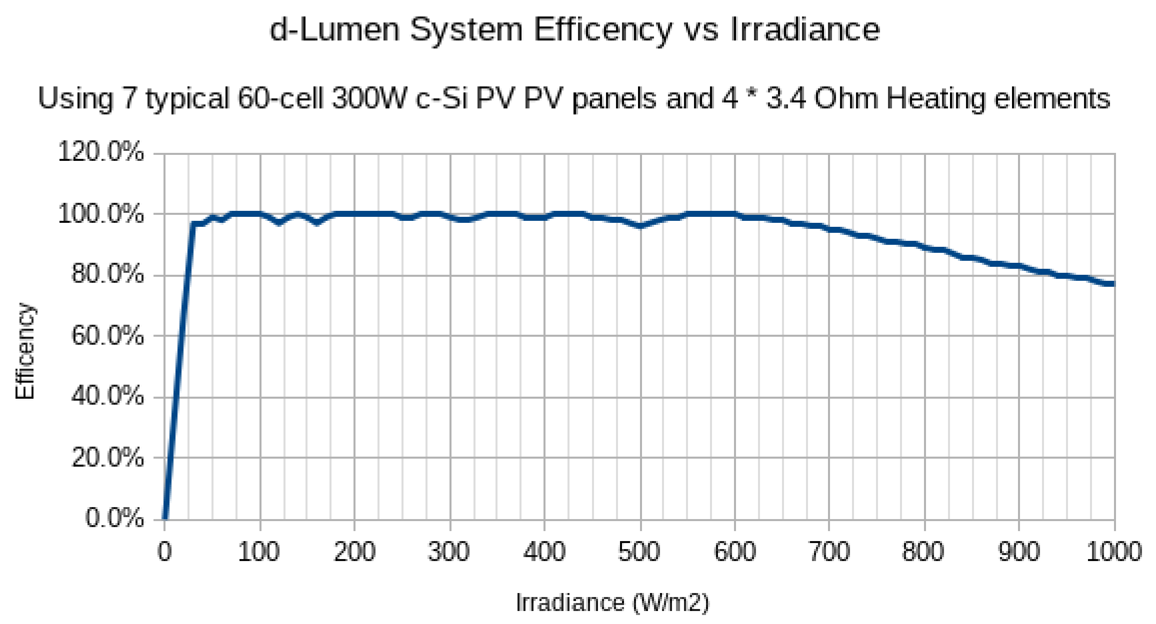
Taking four equal resistors with an impedance of 1 Ohm each, it is possible to assemble 15 different loads by connecting the resistors in various configurations:

Config No	Diagram	R (Ohms)		Config No	Diagram	R (Ohms)
1		1/4		9		1 1/3
2		1/3		10		1 1/2
3		2/5		11		1 2/3
4		1/2		12		2
5		3/5		13		2 1/2
6		2/3		14		3
7		3/4		15		4
8a/8b	 	1				

The following diagram shows the basic circuitry that could be used to control the resistors so that they can be configured in any of the above ways:



The figure below gives a simulation of the performance of such a setup. In this case, the PV array is of 7 * 60-cell 300W c-Si panels, and the immersion heater has 4 * 3.4 Ohm elements.



Legionella

Legionnaires' disease is a serious illness caused by *Legionella* bacteria, which grow in warm water[27]. Hot water systems are at risk of becoming breeding grounds for *Legionella* if poorly designed[28]. Therefore, any implementation of the d-Lumen system needs to be designed carefully to protect hot water users from this risk.

References

1. Sustainable Energy Authority of Ireland. Energy in the Residential Sector: 2018 Report. (2018).
2. Aguilar, C., White, D. J. & Ryan, D. L. Domestic Water Heating and Water Heater Energy Consumption in Canada. 82.
3. U.S. Energy Information Administration. 2015 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables. (2015).
4. Eurostat. File:Share of fuels in the final energy consumption in the residential sector for water heating, 2017 (%).png. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_fuels_in_the_final_energy_consumption_in_the_residential_sector_for_water_heating,_2017_(%25).png (2017).
5. Yao, R. & Steemers, K. A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings* **37**, 663–671 (2005).
6. Healy, J. D. & Clinch, J. P. Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy-saving measures in Ireland. *Energy Policy* **32**, 207–220 (2004).
7. Intergovernmental Panel on Climate Change. Global Warming of 1.5 ^{o}C: Summary for Policy Makers. (2018).
8. Landrigan, P. J. Air pollution and health. *The Lancet Public Health* **2**, e4–e5 (2017).
9. Fraunhofer Institute for Solar Energy Systems, ISE. Photovoltaics Report. (2019).
10. Feldman, D. & Margolis, R. Q1/Q2 2019 Solar Industry Update. 40.
11. International Energy Agency. Global Energy & CO2 Status Report: Electricity. https://www.iea.org/geco/electricity/ (2019).
12. SunHotWater. Sunflux Next-Gen. https://www.sunhotwater.com.au/product/sun-flux/.
13. Solar Hot Water The Easy Way! *TechLuck* http://techluck.com/.
14. Energy Monitoring Company & Energy Saving Trust. Measurement of Domestic Hot Water Consumption in Dwellings. (2011).
15. Simpson, A. & Castles, G. Measurements of heat losses from an insulated domestic hot water cylinder. *Building Services Engineering Research and Technology* **13**, 43–47 (1992).

16. Department of Housing, Planning and Local Government. Part L and European Union (Energy Performance of Buildings) (No. 2) Regulations 2019 Technical Guidance Document. (2019).
17. Sustainable Energy Authority of Ireland. Prices. https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/ (2019).
18. Solar Edge Technologies, Ltd. Single Phase Inverter with HD-Wave Technology. (2018).
19. bonkers.ie. Electric Ireland Standard Domestic Electricity. https://www.bonkers.ie/compare-gas-electricity-prices/electric-ireland/LEGJH2/standard-domestic-electricity/ (2019).
20. Commission for Regulation of Utilities. Electricity and Gas Retail Markets Report Q2 2019. (2019).
21. Tsagarakis, G., Collin, A. & Kiprakis, A. A Statistical Survey of the UK Residential Sector Electrical Loads. *ijeeps* **14**, 509–523 (2013).
22. Tumanova, K., Borodinecs, A. & Geikins, A. The analysis of the hot water consumption and energy performance before and after renovation in multi-apartment buildings. *IOP Conf. Ser.: Mater. Sci. Eng.* **251**, 012058 (2017).
23. Parker, D. S., Fairey, P. & Lutz, J. D. Estimating Daily Domestic Hot-Water Use in North American Homes. *ASHRAE Transactions* **121**, (2015).
24. Fuentes, E., Arce, L. & Salom, J. A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. *Renewable and Sustainable Energy Reviews* **81**, 1530–1547 (2018).
25. National Renewable Energy Laboratory. PVWatts® Calculator. https://pvwatts.nrel.gov/index.php (2019).
26. Enphase Energy Inc. Technical Brief: Why Is My PV Module Rating Larger Than My Inverter Rating? (2019).
27. *Legionella and the prevention of legionellosis*. (World Health Organization, 2007).
28. Health Protection Surveillance Centre, Ireland & Health Service Executive. *National guidelines for the control of Legionellosis in Ireland 2009: report of Legionnaires' disease subcommittee of the Scientific Advisory Committee*. (Health Protection Surveillance Centre, 2009).
29. Health and Safety Authority of Ireland. Legionnaires' Disease. (2008).