The Emergence of PV Hot Water Systems

A Technology Brief

IEA SHC TASK 69 | Solar Hot Water for 2030

Technology Collaboration Programme
by iea

The Emergence of PV Hot Water Systems

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SHC Task 69: Solar Hot Water for 2030

Subtask C: Solar Photovoltaic Hot Water

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1 Executive Summary

As photovoltaic (PV) system costs dramatically reduce, they are becoming economically viable as a technology to replace gas, grid electricity, and even solar thermal collectors as an energy source for low-temperature heating applications. The pairing of PV electricity with domestic water heating represents an under-explored—but rapidly emerging—opportunity for innovation, self-sufficiency, and sustainable modernization. In some regions, the household domestic hot water demand is over 50% of total household energy consumption. Thus, at the residential scale, the road to a low-carbon future must include sustainable solutions for domestic hot water.

In 2023, *solar* hot water systems produced an estimated 456 TWh_{th} from an installed base of ~800 million m^2 of glazed and unglazed thermal collectors [1]. To put this in perspective, 456 TWh of the 3,750 TWh global residential hot water energy consumption [2] represents a 'solar share' of around 12%. Thus, hot water applications have plenty of capacity for increasing their solar share.

This Technology Brief outlines the PV hot water technologies that may hold the key to unlocking a much higher share of solar-derived hot water. These technologies are being supported by rapid cost reductions in PV module prices, advances in electronics, and the recent uptake in the adoption of heat pumps. This report will also touch on knowledge gains in optimized system design and operation techniques for optimizing the utilization of PV electricity. Despite these tailwinds, PV hot water technologies face product development issues, system integration issues (i.e., compatibility with other electrical demands and the electric grid), and a lag time in the development of PV-hot-water-specific policies and regulations. We conclude that for these emerging technologies to reach their full potential, they must carefully consider reliability, affordability, and their role in conjunction with smart home energy systems, peer-to-peer networks, and the electric grid.

2 Introduction

Photovoltaic (PV) solar collectors broke through the \$10 USD/W_e cost barrier in 1987 and in 2013 they started selling for less than 1 USD/W_e [3]. Throughout most of this time, solar thermal collectors were much more cost effective, at well under 1 USD/W_{th} [4]. Thus, for 30-40 years it would have been unreasonably costly to use PV electricity as compared to solar thermal collectors to create low grade thermal energy (i.e., domestic hot water). However, PV module prices are now below \$0.2 USD/Watt [3] and PV installations have well surpassed the vanguard solar technologies (evacuated tube and flat plate solar thermal collectors). In 2024, PV electricity generation was about four times (~2,000 TWh_e) the solar thermal energy produced in 2023 (456 TWh_{th}) [1].

Although the market deployment of PV hot water systems was negligible in 2025 as compared to other hot water heating options, they have the potential for rapid growth. In addition to the PV price reductions mention above, several other technological changes should enable these technologies to take up hot water heating market share. Advances in PV panel efficiencies, which are now at or above 20%, and may reach

25% (e.g., see SunDrive at https://www.sundrivesolar.com) may enable the whole energy demand of the household to be met (on net) by a typical roof area. It is possible that this trend can continue even further with the emergence of tandem perovskite-on-silicon solar cells, which holds the potential to push efficiencies beyond 30% (with a 33.9% *cell* efficiency demonstrated by Longi according to NREL's database [5]). That said, solar thermal collectors typically operate at ~60% efficiency, so for a fixed rooftop solar resource area, it may be beneficial to use solar thermal collectors together with PV modules for electric boosting. Although it is not the focus of this report, this type of integrated approach offers installation cost savings compared to using separate PV and thermal systems (i.e., common mounting structures), and it can enable high resource utilisation.

An advantage of PV water heating also is that it provides natural frost and over-temperature protection since no water needs to flow through the collectors mounted outside. Further, PV efficiency increases in low ambient temperature conditions and electricity can be generated even during times of low irradiance. Thus, on balance, PV hot water is better suited to the shoulder/winter period and to colder climates as compared to thermal collectors.

Another key driver is the widespread adoption of variable renewable electricity generation capacity on rooftops and in the grid. At times when renewable generation exceeds electrical demand, water heaters could be used provide a valuable mechanism for soaking up excess electricity. This represents a clear advantage over exporting electricity to the grid for a low price or to curtailing production. This relative advantage can be boosted even further with emerging technologies such as peer-to-peer energy trading, whereby the rooftop PV self-consumption across grid can be more than doubled (increase in grid renewable hosting capacity) with significant consumer purchased energy savings, according to a recent study [6].

PV hot water systems in China

As the largest single solar hot water market and as a strong manufacturing base, the trends in China often drive the global trends. The PV water heater market in China reached 35 billion RMB (5 billion USD) in 2023, a 10% increase over the previous year. While thermosyphon water heaters are in decline in China, PV water heaters are gradually becoming the new favorite due to their 'smart' features, such as allowing remote control and monitoring via the Internet to improve the user experience and to reduce energy consumption. In addition, there is broad Chinese government support for PV water heaters, which includes technical research initiatives as well as standardization. Agricultural, commercial, and industrial applications of PV water heaters are widespread in China and the penetration rate of PV water heaters is increasing, especially in rural areas. PV water heater exports from China are also on the rise, with international market demand rising.

Several emerging solutions are being brought to market which will increase the share of water heating that is provided by solar electricity. As shown in **Figure 1**, PV hot water systems can be categorized by how close the PV modules are to the hot water load and by how much interaction they have with the electrical grid. So called "PV2Heat" systems directly couple DC electricity from rooftop PV panels to DC resistance heating in the hot water tank (i.e., with minimal intermediary electronics). If these systems do not include a maximum power point tracker for the PV module, the PV efficiency will be low. Thus, while these systems take the hot water load off the grid, not much is possible in terms of grid interaction.

PV self-consumption technologies, represented by the middle green bubble of **Figure 1**, include a suite of emerging options for households (and local communities) which already have PV systems, including PV diverters, smart tanks, heat pumps and their associated electronic controls. These systems can be aggregated together, use price and solar forecasts, artificial intelligence to benefit the customer and the grid. In this case, PV self-consumption can be shifted from just the household level (i.e., less than 10m away), to the local low voltage grid (100s of meters). Taken a step further, peer-to-peer energy trading in the local neighbourhood may even be possible.

Grid-tied electric water heaters, the top blue bubble of **Figure 1**, will naturally use any solar electricity coming from grid's primary energy mix. Grid-powered water heating can be beneficial for grids which have high PV penetration, if controlled with timers or central control schemes, to intentionally shift their load profile to better align with high levels of renewable electricity production.

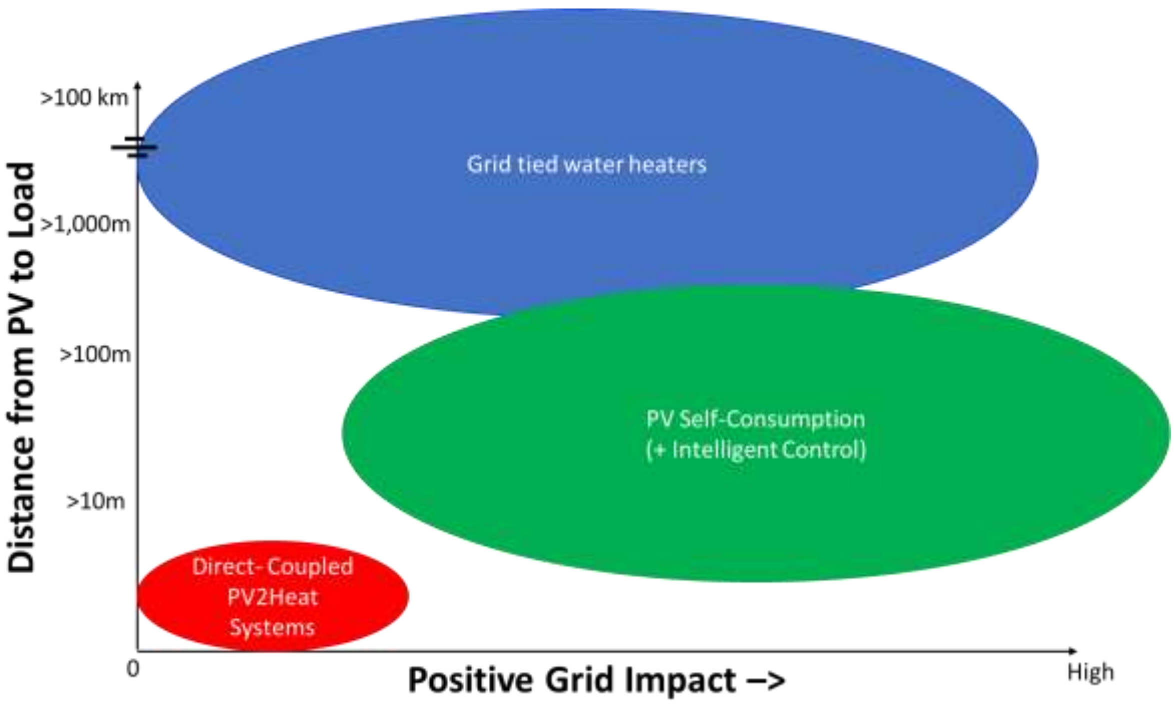

Figure 1. *PV Hot Water Configuration Overview*

3 PV Hot Water Technologies

3.1 PV2Heat Technologies

In areas with unreliable grid service, high connection costs, or low up-front capital, “PV2Heat” systems represent an ideal hot water technology. As shown in **Figure 2A**, up to the end of 2023, cumulatively there are now ~30,000 “PV2Heat” systems installed in South Africa alone. These systems are nearly indistinguishable from a PV collector system when the hot water tank is in the building, as is demonstrated in **Figure 2B**.

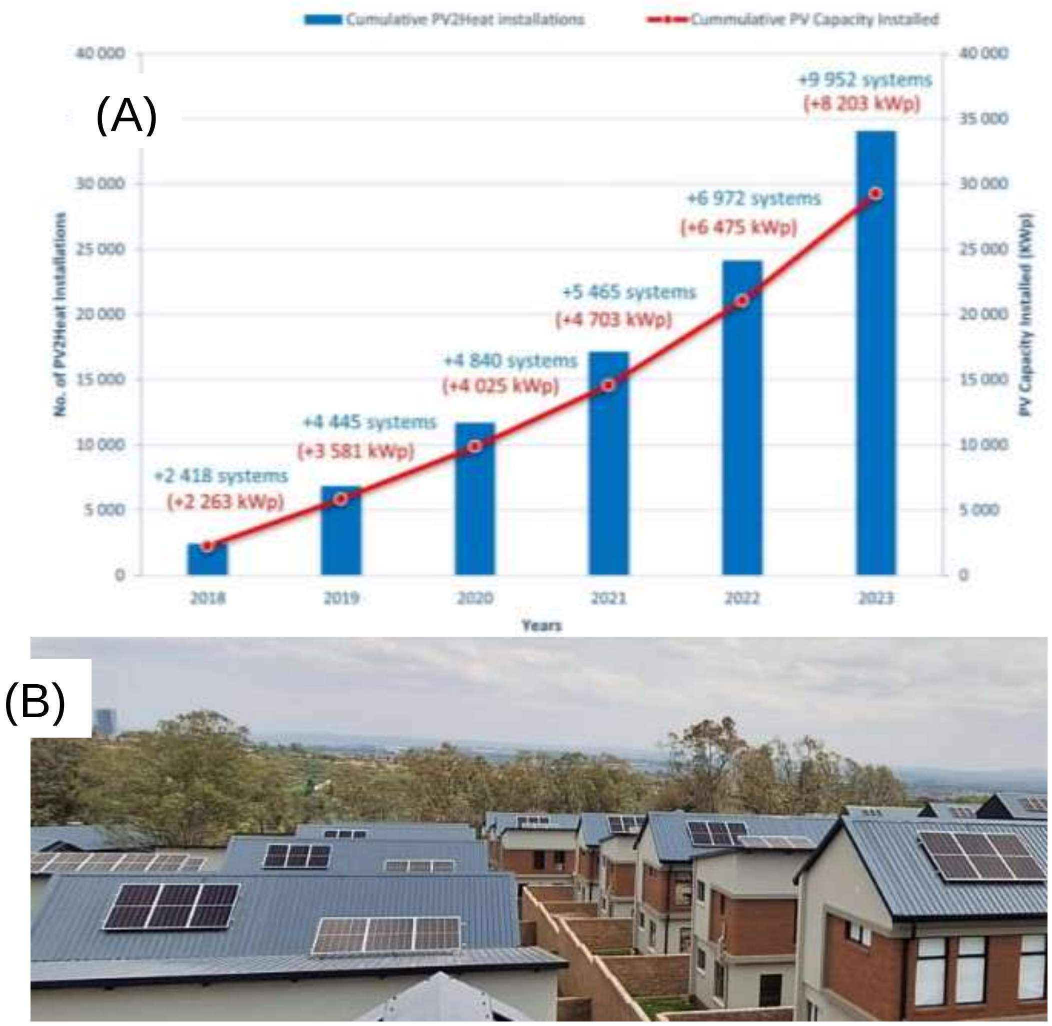

Figure 2. *PV2Heat systems. (A) Market development in South Africa between 2018 and 2023 Source: Lavhe Maluleke, Stellenbosch University, South Africa; (B) Typical PV2Heat installations in South Africa, Photo: Lavhe Maluleke, Stellenbosch University, South Africa.*

A schematic of a typical PV2Heat hot water heating system (called a PV geyser) is shown in **Figure 3**, which includes three PV panels connected in series (via a PV isolator) to a control panel. The control panel also takes tank temperature information along with back-up grid electricity to ensure safe, reliable operation. For the most basic PV2Heat systems the electrical resistance of the immersion electric heating element just needs to be sized to match with the design point voltage-current output of the PV array. However, this matching cannot be done perfectly for both cloudy and clear sky conditions. In the absence of a power point tracker and an inverter, the system may frequently slip away from operating anywhere near the maximum power point of the PV array. This is because it is impossible to design the heating element's resistance to match the maximum power point of the PV panels across a wide range of atmospheric conditions. In these systems, back-up electricity from the grid is also used to make hot water (often in a separate AC resistance heating element). However, for a bit more up-front cost, it is advantageous to use a maximum power point tracker (MPPT) along with some power conversion electronics to achieve a better electrical match between the PV output and the heating element(s).

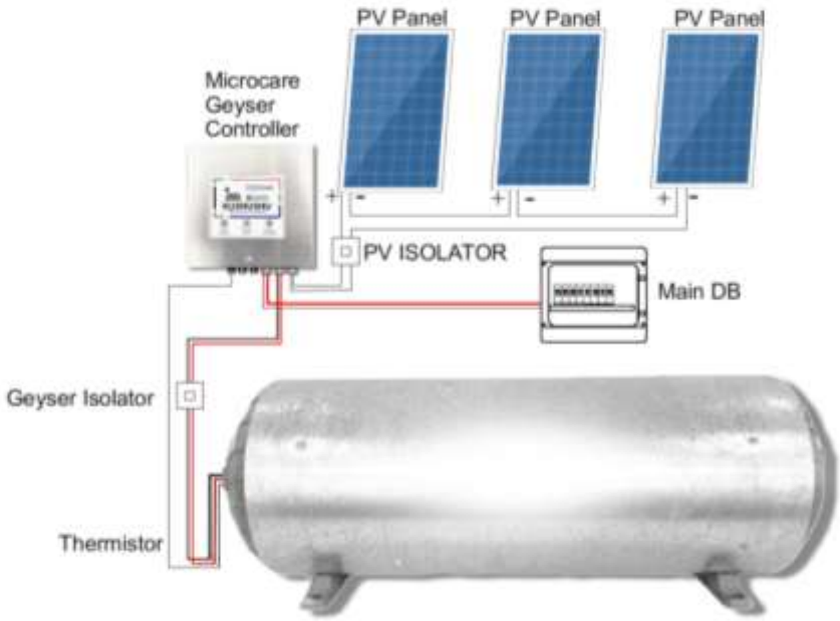

Figure 3. Schematic of a PV2Heat system from Microcare [7].

One issue with direct-coupled PV2Heat water heaters is that unlike for an AC connection, the high voltage DC connection between the PV array and the electric element cannot be broken without significant sparking. Sparking can destroy a relay, causing problems with the tank overtemperature control. This is caused by DC current arcing across control contactors (such as thermostats or relays) which can result in the contactors getting welded closed. This is a significant safety issue if it occurs because the element has no way of turning off when PV power is available, resulting in high water temperatures (scalding risk) and even explosive rupture of the water tank where pressure relief fails. It should be noted that a solution to this is to instead use AC current since the circuit can be broken at zero amps at zero crossing, but this requires an inverter (which adds to system cost). In a DC system, two solutions are commonly used: a) modest PV array size relative to the load and to the tank volume to avoid high temperatures and having to frequently break the DC connection, or b) use of an open vented tank, where the temperature control is achieved through increased evaporation from the tank. Both solutions have limitations. Solution (b) increases water consumption and heat loss. When water discharges to the atmosphere it needs to be replaced by supplementary cold water, likely to over-cool the tank after the PV power is naturally reduced at night. As another alternative, if a maximum power tracker is included in the system design, however, it is possible to gradually move the PV array off the maximum power point when the water temperature approaches a set value, thereby smoothly curtailing PV production. Ultimately, PV array size, hot water usage patterns, and system operation need to be considered carefully over the year rather than relying on one single point of energy control.

3.2 PV Self-Consumption for Hot Water

PV self-consumption systems are of particular interest in markets with high levels of installed PV on the electrical grid. These systems can take many forms, from a simple power export flow diverter/controller, as shown by the box with red font in **Figure 4**, to more advanced 'smart' systems which interface with other household appliances, the grid, and even local networks of PV systems and households. A uniting feature of these technologies is that excess PV electricity must be available after all other electrical loads are met. In this situation, it can be advantageous to heat water rather than export the electricity to the grid.

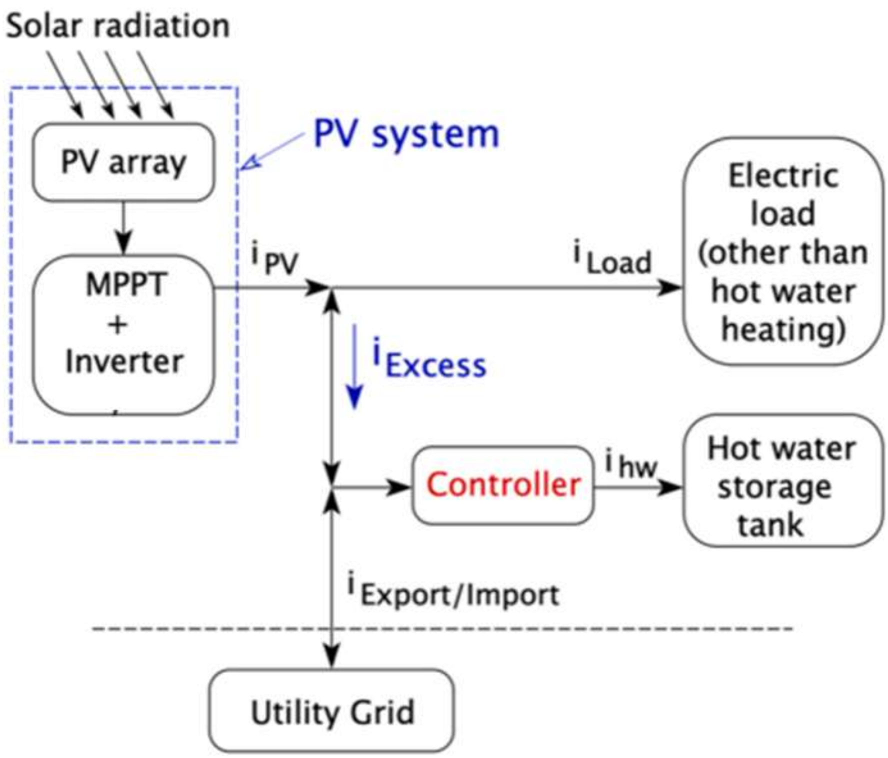

Figure 4. PV self-consumption system schematic from [8].

One big advantage of self-consumption systems is that they can help deal with a pronounced 'duck' curve, shown in **Figure 5**. This type of curve occurs in high PV penetration markets and can lead to a dramatic reduction in the export value of generated PV electricity. Hot water tanks represent a huge amount of *as-yet-untapped* energy storage, which could help to *duck-proof* the grid. This is because a typical electrical consumption of a water heater is 4-12 kWh per day [9], which means that utilizing a thermal storage tank of sufficient volume can enable this energy use to be shifted to any period of the day. As a simple estimate, if 1 billion households have hot water tanks, up to 4-12 billion kWh could theoretically be shifted to times of low energy demand. All that is technically necessary to unlock the *enormous* existing infrastructure for energy storage is some controls systems (anything from timers advanced systems which can optimize for usage patterns, real-time pricing, and by working together with other grid-connected systems, such as smart appliances). It should be noted here that to access the highest potential of water heating demand response, it requires increased power control and—crucially—two-way communication from water heater (current charge status and autonomous energy consumption) to a central aggregator to ensure grid response is proportional while also ensuring hot water availability is guaranteed.

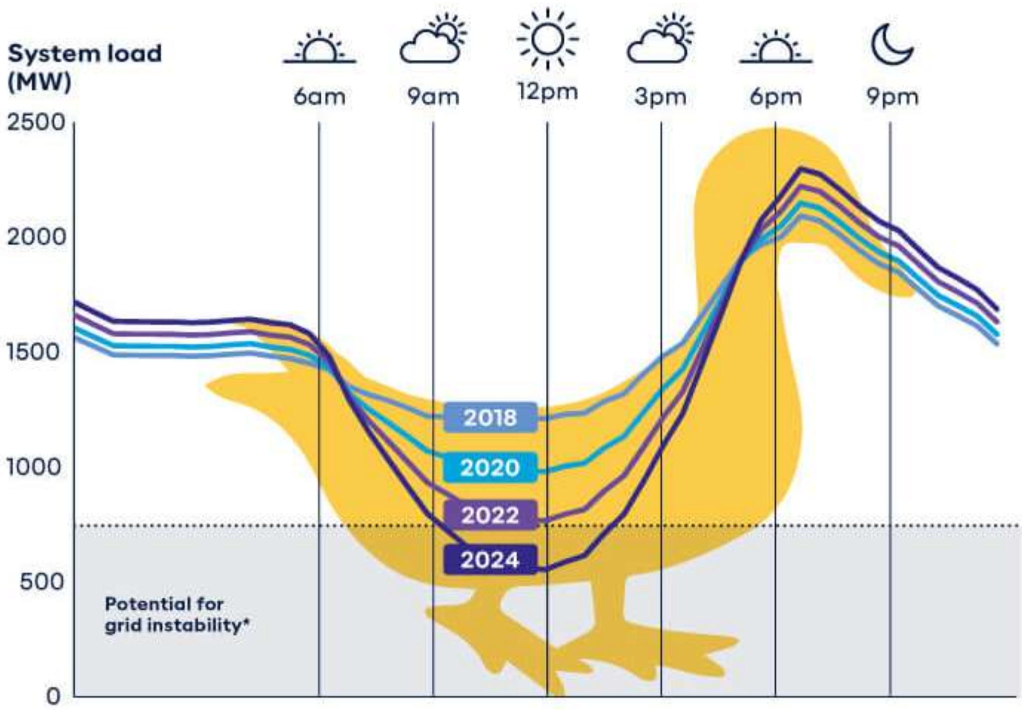

Figure 5. *A graphical representation of the 'Duck Curve' in Western Australia, created with 2020 data from* ***AEMO*** *[10]*

Australia, for example, is a leader in household PV penetration with a total installed capacity of 1.38 kW_e per person in 2024 [11]. **Figure 6.** Australian solar hot water market. Data from: [12] & [13]. shows that, despite healthy incentives for solar systems and heat pumps, electric water heaters still represent more than one-third of the Australian hot water market. In 2024, there were a total of 1.1 million installed solar thermal water heaters, 0.58 million air source heat pump water heaters, and 3.42 million rooftop solar PV systems installed in Australia

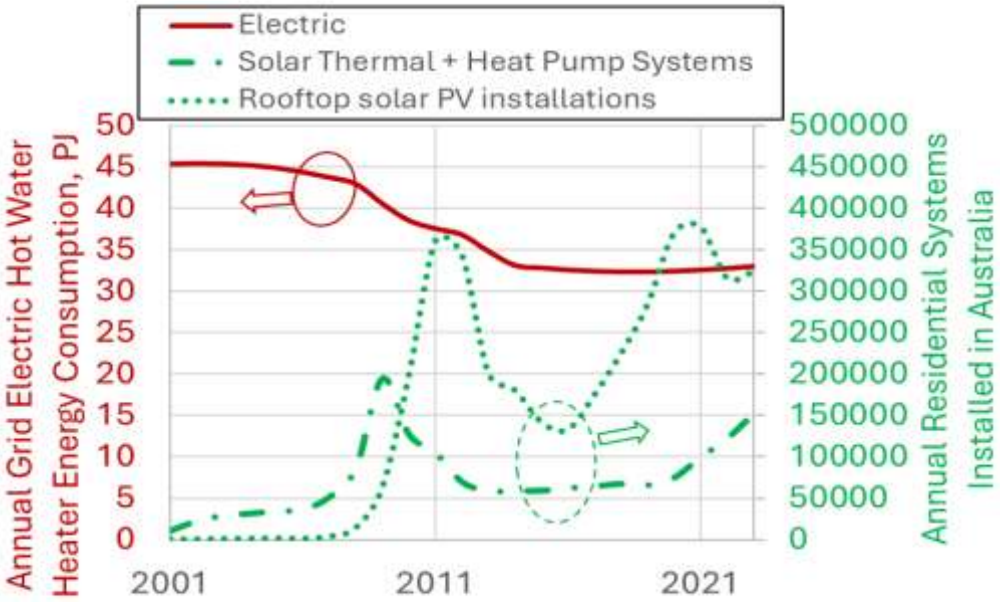

Figure 6. Australian solar hot water market. Data from: [12] & [13].

Without additional forms of energy storage, an obvious requirement of an optimised self-consumption system is that the overall excess PV capacity should not exceed the available loads, otherwise the PV electricity will be sold back to the grid (perhaps at very low rates in a variable tariff scheme). Less obviously, the state-of-charge of the tank and the power draw requirements should be controlled so that the system is able to effectively soak up excess PV. This less obvious point is illustrated in **Figure 7** which depicts the power drawn from a thermostatically controlled electric storage tank against the available excess PV power [8]. In this example, the electric element is activated across 1-hour periods. In this example, over a 24-hour period, only about 13% of the electric element power is covered by excess PV power. With proper design and control, it is possible to utilise much more of the area under the excess PV power curve, more than 80% according to Clift et. al. [8].

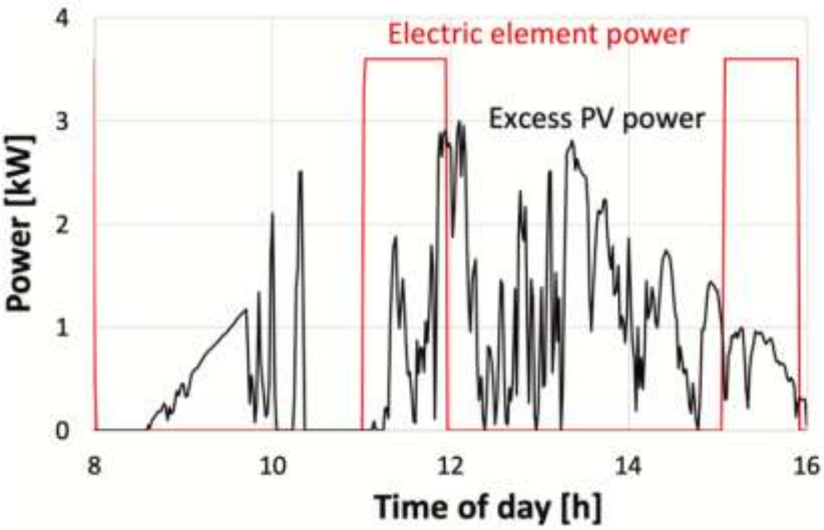

Figure 7. Electric element power (3.6 kW) compared to the available excess PV power when the water heating is only controlled by a tank thermostat (from [8]).

3.2.1 PV Diverters

PV diverters are an emerging category of home energy products designed to ensure excess rooftop PV electricity is directed to thermal loads at times when PV generation exceeds other home energy demands. Some examples of commercially available products developed by manufacturers in the United Kingdom are depicted in **Figure 8**. These products are relatively low cost (500-1000 USD) and can connect to existing resistance heating element(s). Most of these products are not suitable for connection with induction loads (i.e., heat pumps).

PV diverters can have a fast economic payback for households facing a large gap between import and export prices (e.g., at 0.2 USD/kWh price difference it only takes 2,500 kWh of self-consumption to break even). Sophisticated products can even coordinate with other internet-connected devices in the household and can be aggregated to help manage the grid. If used effectively aggregated systems can be used as demand-side response systems offer ancillary services that may help avoid grid infrastructure upgrades.

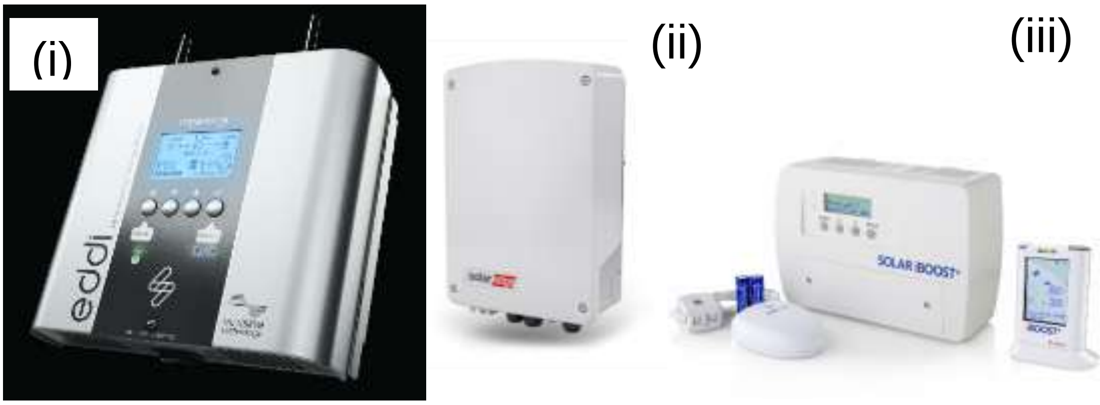

Figure 8*. Commercial PV Diverters*, including: *(i) the Eddi from MyEnergi, (ii) the Solar iBoost from Marlec, and (iii) the Home Hot Water Controller from SolarEdge*

However, simply connecting a PV diverter to an existing electric resistance heater (not designed for a variable power input) may create less PV self-consumption than anticipated due to the instantaneous power mismatch. To fix this issue, the tank heating elements may also need some redesign/modification.

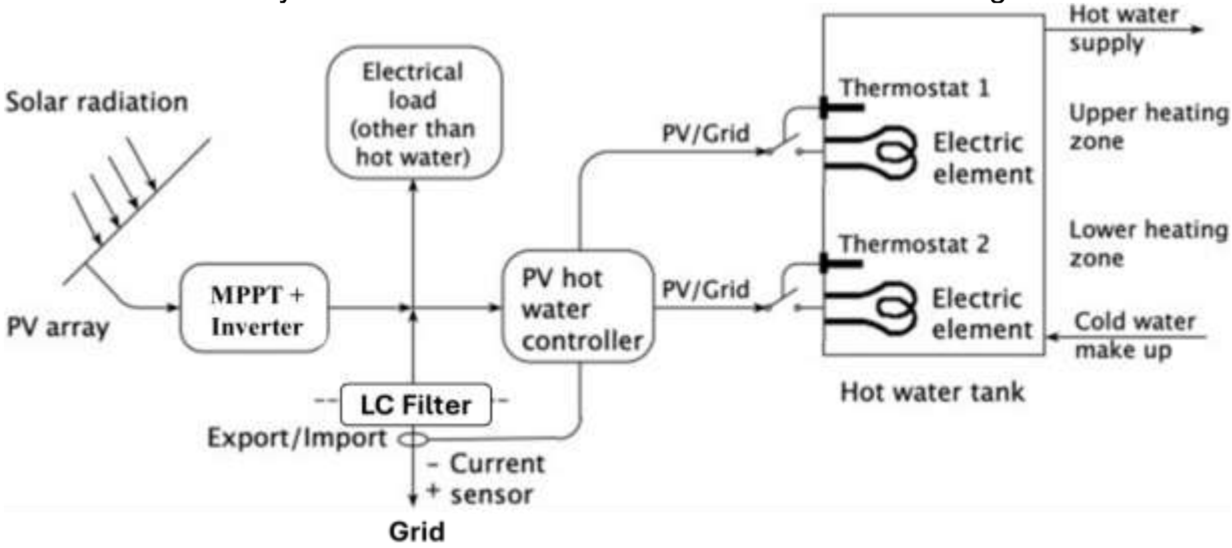

Figure 9 illustrates a proposed system design which can more effectively divert and utilise excess PV electricity. It includes multiple heating zones/elements and power modulation.

A PV controller is crucial for power modulation and water tank temperature control. Since a relay has a fast response, easy installation, and a low price, using a relay with a programmable logic controller (PLC) is an economical and reliable choice for PV hot water controller. The relay turns the element "on" and "off" by collecting signals from the water tank thermostats, current transformer, inverter (if present), and the electrical load. When the water tank's temperature is higher than the set temperature, the relay (and electric element) is turned off. When the tank thermostats' temperature goes lower than the set temperature AND the current transformer detects grid-connected current flow (i.e., excess PV), the relay is closed, which starts the heating element to consume excess PV power. This continues until the temperature of the tank thermostats are higher than the set temperature. When the temperature of thermostats are lower than the set temperature AND the inverter output power is less than the electrical load, if the demand for hot water heating in the water tank occurs, the relay will let the heating element take power from the grid until the water tank temperature reaches the set temperature.

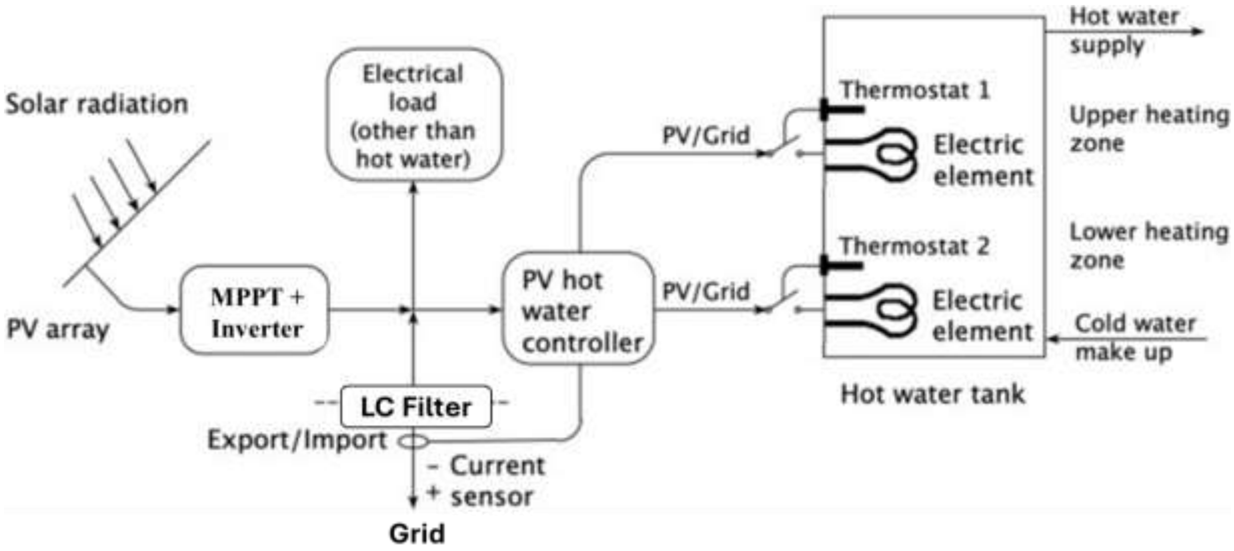

Figure 9. An electric storage heater with a controller sensing the PV export and modulating the electric element power across heating zones to achieve a better match to available excess PV power (as proposed in [8]).

As of the start of 2025, several PV inverter and electronics product manufacturers have begun to make PV diverter products. As shown in the non-exhaustive **Table 1**, the retail price for these products ranges from $800-1700 USD and they can achieve power output of 3.6 kW to 12 kW, depending on whether single phase or three phase power is used. It should be noted that a critical concern with all PV diverters is the impact on power quality that they may have on the grid. At present their uptake is minimal, so their impact is small and may only have a small effect locally (i.e., via light flicker), a larger proliferation of them could impact appliance life expectancy and other grid synchronisation issues, so incremental power quality standards may need to be mandated in the different operating environments.

As a power quality control method for a PV hot water system, a suitable low-pass filter can be connected in series at the grid-connected point for harmonic attenuation and suppression. At the same time, the inverter itself can be better controlled to reduce harmonics through technologies such as pulse-width modulation (PWM), control algorithms, and multi-level inverters to reduce harmonics to a minimum. Through these measures, problems such as malfunctions of relay protection and automatic devices, as well as disruptions in electric energy metering of PV hot water systems can be reduced.

Table 1. Comparison table of commercially available PV Diverter products.

Manufacturer	Product	Retail Price (AUD)	Maximum Power Capacity	Control method	Product Website
myEnergy	Eddi	$995	3.68kW	Pulse Width Modulation	Eddi Typical Install Cost & Payback - myenergi

SOMA Energy	SunMate	$960-$1,400 (3 phase)	3.6kW to 12kW	Pulse Width Modulation	SunMate PV Diverter | SOMA Energy
Catch Power	Green Catch Gen 1 &3	$795	4.8kW	Burst Fire	Green CATCH Power | CATCH Power
Solar Edge	Home Hot Water Controller	$850	4.8kW	Pulse Width Modulation	SolarEdge Home Hot Water Controller | SolarEdge
Fronius	Ohmpilot	$1,700	3kW (single phase) 9 kW (three phase)	Pulse Width Modulation	Fronius Ohmpilot
My-PV	AC Thor	$1,430	2 x 3kW	Pulse Width Modulation	AC•THOR (my-pv.com)

3.2.2 Chinese Manufacturing Examples

A PV self-consumption example from a large Chinese manufacturing is the SUNRAIN system, which is designed to be installed on the balcony or roof and includes a water tank which can be installed in or near each family bathroom. In high-storey buildings, split wall-mounted photovoltaic hot water systems are used, while in low-floor buildings, photovoltaic collection and distribution systems are used. **Figure 10** below illustrates the SUNRAIN PV self-consumption hot water product, and

Table 2 lists the specific parameters related to the tank and PV module.

Figure 10. SUNRAIN PV Water Heater

Table 2. Configuration parameters sheet for the SUNRAIN PV Water Heater

Tank Data	Model	GW-60-2/0.4-2	GW-80-2/0.4-2
	AC Rated Voltage	220V	
	AC Rated Power	2000W	
	DC Rated Voltage	42V	
	DC Rated Power	400W	
	Rated Pressure	0.7MPa	
	Inner liner Material and Thickness	SPCC/2.0mm	
	Housing Material and Thickness	painted steel plate/0.4mm	
	Insulation Materials and Thickness, Density	PU/ 50mm, 32-38Kg/m^3	
	Protection Level	IPX4	
	Size	Φ468*730	Φ468*920
PV Module Data	Component Type	monocrystalline silicon	
	Rated Power	550W	
	Optimum Operating Voltage	41.96V	
	Optimum Operating Current	13.11A	
	Open-circuit Voltage	49.9V	
	Short-circuit Current	14A	
	Size	2278*1134*35mm	
	Weight	29.4kg*1 PCS	

Another Chinese manufacturer, MICOE, has developed an intelligent switching PV diverter which uses DC electricity directly supplied to a storage tank but also uses utility power to compensate when PV electricity is not available. It consists of an advanced maximum power point tracking (MPPT) solar water heating controller (efficiency > 99%) which can maximize the use of solar energy to save purchased electricity and implement triple leakage protection and a two-stage over-temperature protection to protect the water heater from damage. For this system, PV heating is prioritized when the PV voltage is within the operating range of the controller; if the solar voltage falls below the controller's operating range, the controller will switch to mains heating until the water temperature reaches the maximum set temperature and stops heating. The hot water output rate exceeds 70%. The MICOE PV and grid combined hot water heating with intelligent switching is illustrated in **Figure 11** showing the components and wiring paths in the system and the detailed specifications are provided in **Table 3**.

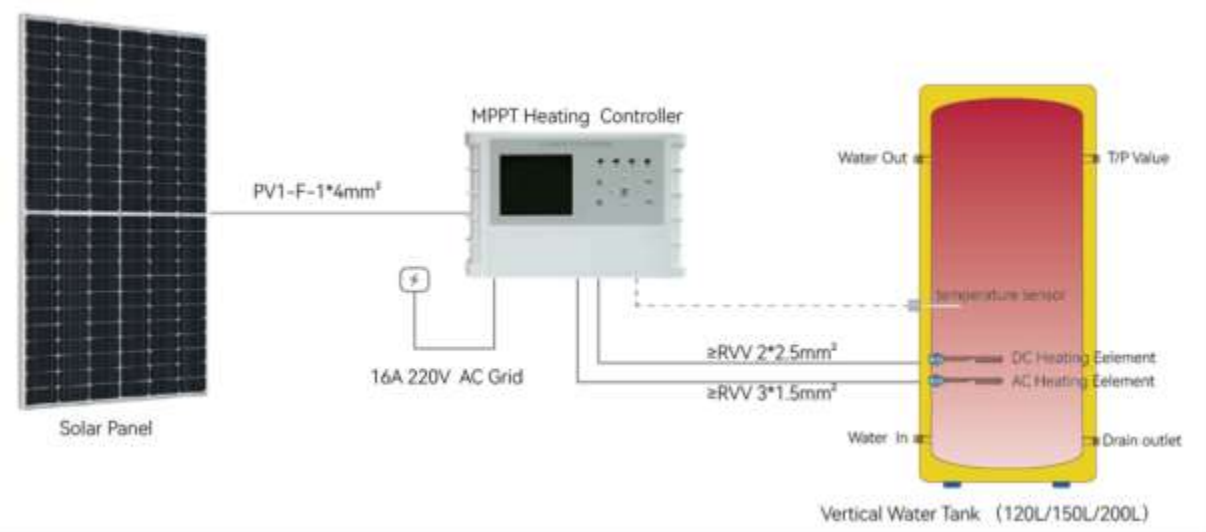

Figure 11. MICOE PV and Grid Combined Heating Hot Water Systems.

Table 3. Specification sheet for the MICOE products

Model	GL-120-2/2-1	GL-150-2/2-1	GL-200-2/2-1
Capacity	120L	150L	200L
PV Input Data			
Recommend PV Input Power	1100W	1650W	2200W
MPPT Operating Voltage Range	$36V_{dc}$~$150V_{dc}$		
PV numbers	550W*2 PCS	550W*3 PCS	550W*4 PCS
AC Electric Heater Data			
AC Rated Power	2000W		
AC Rated Voltage	230V		
DC Electric Heater Data			
DC Rated Power	2000W		
DC Rated Voltage	120V		
Tank Data			
Size	Φ450*1290	Φ520*1190	Φ520*1540
Temperature Setting Range	55℃~80℃		
Protection Function	Leakage protection, Over temperature Protection		
Inner Liner Material	Enamel		
Rated Pressure	0.7MPa		

3.2.3 Smart Hot Water Tanks

Another solution is smart hot water tanks, as shown in the images of **Figure 12**, which are installed in the UK. A similar example of this is the Powerstore supplied by Solahart, Australia. Smart hot water tanks mitigate some of the issues of PV diverters because they represent a wholistic (albeit more costly than PV diverters) solution where the tank itself is designed to monitor the state of charge and would typically contain modulated heating capacity (e.g., between 30 and 3000 Watts). This allows higher PV utilisation as the thermocline moves up and down in the tank to act as a thermal battery. Advanced hot water tanks can also use machine learning to maintain this thermal stratification through predicted household draw patterns and to predict dynamic PV generation inputs (via weather forecasts) and price trends. These systems can also be aggregated as a large demand side management tool and to provide ancillary services to the grid. Although smart water tanks can be considered as an emerging technology, this technology has recently been recognised in the UK Building regulations to reduce primary energy and carbon for dwellings further down compared to a standard PV diverter.

Figure 12*. Images from a smart PV hot water solution for 15 new-build flats and 23 existing homes at William Angie Court in Welshpool, Mid-Wales (supplied by Mixergy)*

3.2.4 PV-Driven Heat Pump Water Heaters

With generous rebate schemes in over 30 countries, heat pump installations are increasing exponentially at ~11% growth globally in 2022 [14]. Hot water heat pumps represent a small ~3% of the overall heat pump market, but this equates to ~6 million units sold in 2022 alone (from 200 million total heat pumps sold) [14]. Hot water heat pumps commonly use an air-source wherein two to three times more heat is pulled from the surrounding air than the input electricity. Thus, the benefit of a PV-powered heat pump system is that the overall solar-to-hot water efficiency can meet or exceed the conventional solar thermal collector efficiency, albeit at a relatively higher cost. As a simple example, a heat pump water heater with an annual average coefficient of performance (COP) of 3 combined with a PV system efficiency of 16.7% will provide a solar-to-hot water efficiency of over 50% (which is notably still below the 60% achievable with a solar thermal collector). Of course, the PV system has the advantage that it can be used to meet other electrical loads and would not just serve the hot water system.

As one example, the use of heat pumps (including water heating) in Germany has seen a dramatic increase in recent years (see **Figure 13**). In Europe, this growth may be attributed to a reduced gas supply and the subsequently volatile prices. Meanwhile, in several other countries regulatory changes (i.e., banning the use of gas for new residential buildings in some states in Australia) and more energy efficient building construction requirements contribute to this trend.

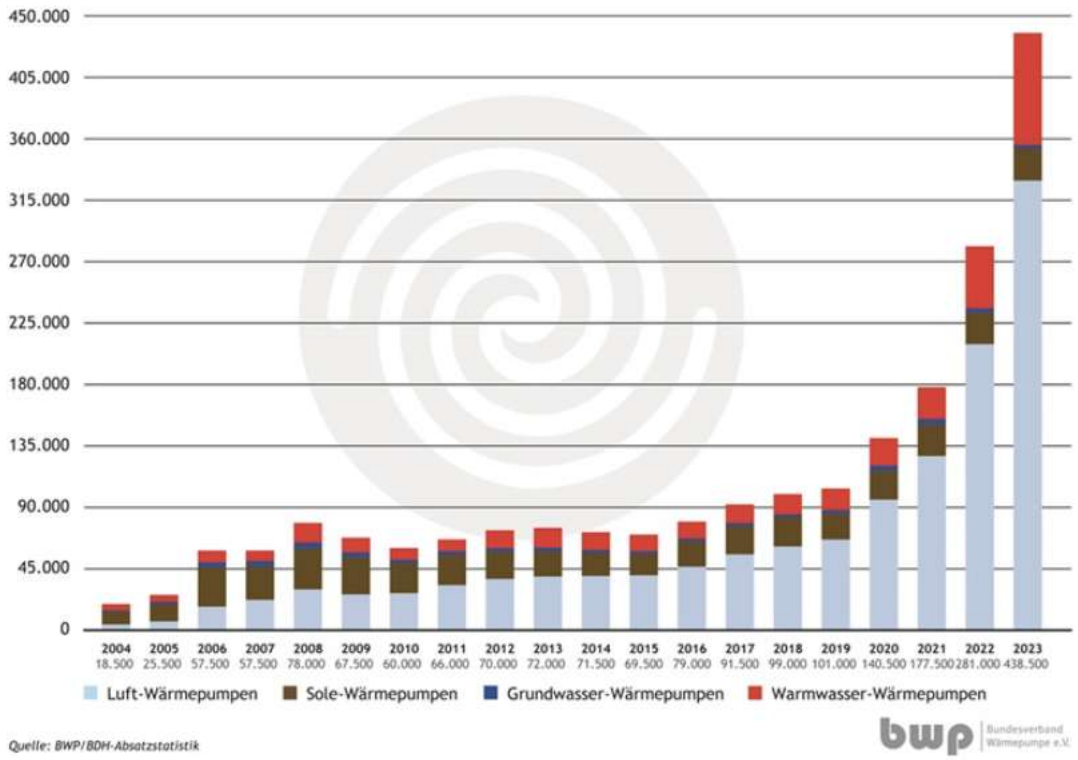

Figure 13: Sales development of heat pumps in Germany 2004-2023. Note the red part of the bar graph represents hot water heat pumps. (Source: PV Magazine [15])

In theory, when heat pumps are installed on a dwelling with a sufficiently large rooftop PV system, a significant portion of the electricity can come from the locally produced solar electricity. Unlike resistance heating elements, simple power electronics are not sufficient to match the power requirements for the high voltage inductive load of a compressor in a heat pump. Nevertheless, if designed and sized properly, research has shown that grid electricity consumption for water heating can be reduced by approximately 90% in a PV-household [8]. To achieve such substantial energy savings, it is necessary to limit the heat pump operation to the daylight hours (e.g., by starting the daily water heating at 10 am using a timer) and ensure the tank is large enough for only one tank reheat per day (for more details refer to Clift and Suehrcke in [8]).

It should be noted that PV-driven heat pumps are not without their challenges. Solar availability and demand patterns can substantially impact how much PV can usefully contribute to overall domestic hot water supply. The default control system for hot water heat pumps involves maintaining temperature and Legionella control, without regard to operation time. Limiting heat pump operation to daylight hours requires manufacturers to consider the added complexity of how much PV-electricity is available and whether customers would like to maximize PV-self consumption. Another potential option Is to utilize variable capacity heat pumps (i.e., inverter compressor speed control) to match available PV output. A recent study found that while this will enable an improvement in PV self-consumption, the incremental capital expense does not provide a lifetime cost benefit when compared to a fixed speed compressor with a simple timer control [16].

3.2.5 PV Self-Consumption Technology Comparisons

It is informative to compare the three major technological options for PV self-consumption to create hot water. In terms of cost, the options range from as low as 500 USD (PV diverters) to 1,500-2,500 USD (smart hot water tanks) to 5,000 USD (heat pump water heaters). In terms of how much of the PV electricity can ultimately be converted into hot water, all of them can achieve high levels of self-consumption (>>50%), if designed correctly. However, heat pumps benefit from the COP multiplier (i.e. 3) so a smaller amount of excess PV electricity can achieve a much higher solar fraction for the hot water load. Recent research by Clift et al. [16] proposed a novel approach to evaluate and define the performance of a heat pump (HP) based on various operational parameters such as ambient temperature, humidity, stored water temperature, and compressor speed. In this study, the HP characteristics were then used in yearly time series simulations to demonstrate an optimized compressor speed control that aims for the highest coefficient of performance (COP) in real-time. This method showed that it is feasible to decrease the annual energy consumption of the HP from 867 kWh to 628 kWh (a reduction of 28%) without the need for rooftop photovoltaic (PV) or a battery. Surprisingly, a variable speed compressor control took over 10 years to pay back and the advantages only became apparent when a relatively large 6.6 kW_p rooftop PV system was installed. It was demonstrated that adding electrical storage (a battery) may not add much value to the hot water system since the inherent storage within the water heater could be effectively utilized with appropriate design and controls, which would be significantly cheaper than the battery capital expense. Thus, the current lowest net lifetime cost was achieved with a 6.6 kWp PV system and a fixed speed HP with timer control, which was shown to reduce a typical household electricity lifetime cost by 27%.

3.3 Hot Water from Grid PV

As another category of PV hot water, conventional electric water heaters can utilize PV electricity from the grid. This is non-negligible in most markets *today* and is set to dramatically increase as global PV penetration increases. In 2022, about 4.6% of global electricity was produced from solar generators [17], so by default there is some solar share for conventional electric water heaters. Unfortunately, it is *well below 4.6%* since conventional water heaters predominately consume electricity in the early morning, late evening, and at night—times when little solar generation is being produced for the grid. However, this can be significantly boosted by selectively running heating cycles when PV electricity *is* available. This can be done locally or through centralized control mechanisms.

Local control can be achieved by simple on/off timers integrated on the tank to allow heating elements to operate during the day (not at night), but a recent study found that this could only increase the PV supply to 38% [8]. More advanced control schemes can be designed to consider the grid and to optimize for consumer usage patterns and preferences (i.e., balance pricing structures with the risk of running out of hot water). On the other hand, centrally controlled water heaters represent an 'old' technology that might be adapted to a new electricity market. So-called 'controlled loads' have a long history of use to provide customers with low cost 'off-peak' electricity from fossil fuel generators. It may be possible to repurposed and modernized these systems, where available, to instead selectively consume 'peak' solar generation of electricity.

3.3.1 An Australian Example of "Solar Soaking" via Centrally Controlled Electric Waters

In markets where PV penetration on the grid is high (i.e., Australia), it may make sense to use smart timers and energy management systems--perhaps implemented centrally and orchestrated by retailers or aggregators--to boost the solar share in conventional electric storage water heaters. Considering the increasing installations of smart meters (i.e., in Australia all households will own a smart meter by 2030 [18]) and the abundance of excess solar generation in the middle of the day in Australia, new control strategies are being developed to leverage these trends to shift the electric hot water demand into times when solar resources are most available.

In Australia, a project called "SolarShift" is looking into the potential of optimizing the existing fleet of controlled load Australian electric storage water heaters (SolarShift) to utilize distributed solar PV, starting with a comparative trial on 2,850 systems. The promise of this approach is that controlled load hot water represents a significant flexible demand on the Australian grid (i.e., 10.8 GW of flexible demand as compared to the Australian National Electricity Market's peak generation capacity of 48 GW). In fact, more than 50% of Australian water heating is done through electric systems which makes up around 25 MWh of *daily* flexible demand in Australia's National Electricity Market. Traditionally, a great majority of these electric water heating systems were controlled by Distribution Network Service Providers (DNSPs) through using ripple control and mechanical timers where systems were installed on a dedicated electric circuit/meter separate to the general supply of the households. Ripple control works by superimposing a high frequency signal, usually between 100 and 1600Hz onto the standard 50-60 Hz main power signal. When devices which are attached to the non-essential loads receive this signal, they shut off the load until the signal is disabled. DNSPs historically used this mechanism to schedule electric water heaters to work during off-peak demand periods such as between 10pm-7am. This scheme is also known as controlled load.

With growing popularity of advanced metering infrastructure there has been increasing uptake of smart meters installed in households to be used for monitoring and billing purposes to replace the older meter technologies. Smart meter uptake is supported by federal; state governments and policy makers (https://www.aemc.gov.au/news-centre/media-releases/aemc-smart-meters-100-2030-new-customer-information-real-time-data-and-protections) and all households are expected to own a smart meter by 2030. In contrast to ripple or mechanical timer control via DNSPs through network signals, smart meters can be controlled by internet/cloud communications and currently this control is mostly done by retailers in Australia, except for the state of Victoria where smart meters are mostly controlled by DNSPs.

There are two ongoing flexible demand trials focusing on shifting electric water heating into the middle of the day to soak up excess PV generation in the network through smart meters. Project SolarShift, a Cooperative Research Australia RACE for 2030 project in partnership with Endeavour Energy, Ausgrid, NSW DCCEEW, Solar Analytics, Energy Smart Water and UNSW, and PlusES South Australia Flexible Demand Trial Project, an ARENA project in partnership with PlusES, AGL and UNSW. The aim for these projects is to assess the potential of flexible electric water heating demand into the middle of the day soak-up excess PV generation and quantify potential financial and environmental benefits for different stakeholders such as DNSPs, retailers and households.

Figure 14 below demonstrates example daily water scheduling operations for around 20,000 households in South Australia on the 1st and 2nd of January 2024. The households are clustered into ten groups represented with distinct colors and the total water heating demand can be seen via the dark blue line. It is seen on both days, around 50% of total water heating demand is shifted into the middle of the day to soak up excess solar in the network. A random demand scheduling is implemented over the night period on both days as seen by time differences of individual group peak demand, whereas an un-randomized demand scheduling is implemented during the daytime as all groups reach peak demand around the same time. On the 2nd of January, the randomized scheduling reduced daily peak electric hot water demand from ~15 MW to 11 MW which represents a ~27% reduction of peak water heating demand. The randomized schedule also resulted in a more balanced demand curve. The randomization and control strategies were determined by the wholesale market price and weather forecasts. Throughout both trials, the percentage of daily shifted electric water demand ranged between 35% to 65% depending on smart meter control decisions, fleet's hot water usage patterns and ambient temperature.

An important finding was that the average daily electric water heating demand per household increased ranging between 5% to 10% during the trial. This is because the new controlled load window includes the solar window in addition to the night-time off-peak heating window, therefore there are more hours/day where the electric circuit is on and, as a result, the average water temperature in storage tanks is higher compared to the traditional controlled load window.

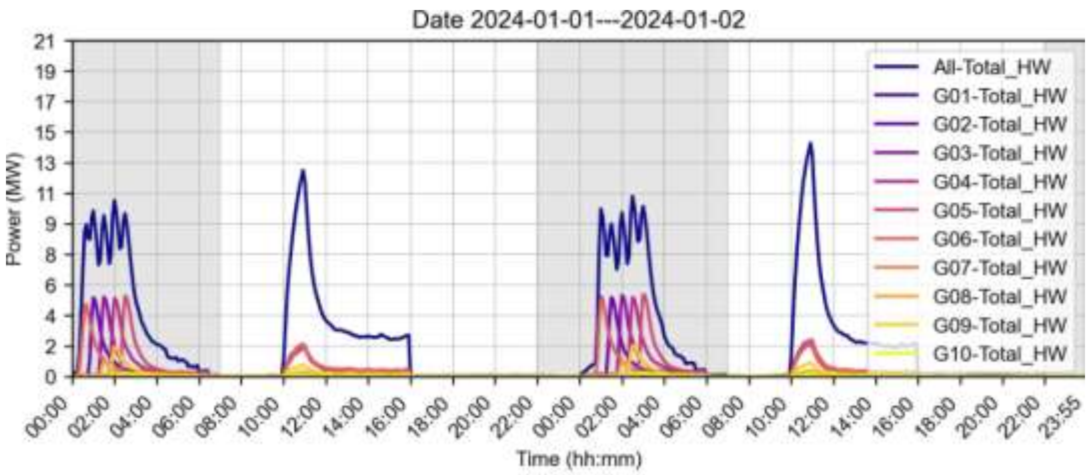

Figure 14. Daily water scheduling operations for around 20,000 households in South Australia on the 1st and 2nd of January 2024.

Increasing day-time PV exports have increased voltages for customers within low voltage networks contributing to the rising levels of PV curtailment and increased electricity bills. Shifting electric water demand into the middle of the day can soak-up excess PV generation and lower voltages. **Figure 15** below shows the distribution of voltage drop achieved by shifting electric water demand into the middle of the day. The voltage drop is calculated as the difference of voltages during water heating operations and 15 min before/after starting the water heating in the middle of the day. The median voltage drop is 2.6 V and for some households, voltage drop is much greater. This is promising as shifting water demand into the middle of the day can help in DNSPs voltage management and lowering PV curtailment The value of voltage drop depends on the power of the electric water heating system where majority of the households owns either a 3kW or 3.6kW system as well as the strength of the network depending on the length and X/R ratio. The results from the trials have shown that voltage drop is highly dependent on the timing of water heating operations depending on the control randomization and can be intermittent at times. Therefore, having a coordinated and smoother voltage drop across low voltage transformer which will benefit a wider range of households is not an easy task. Trials will continue testing different control algorithms to achieve this objective.

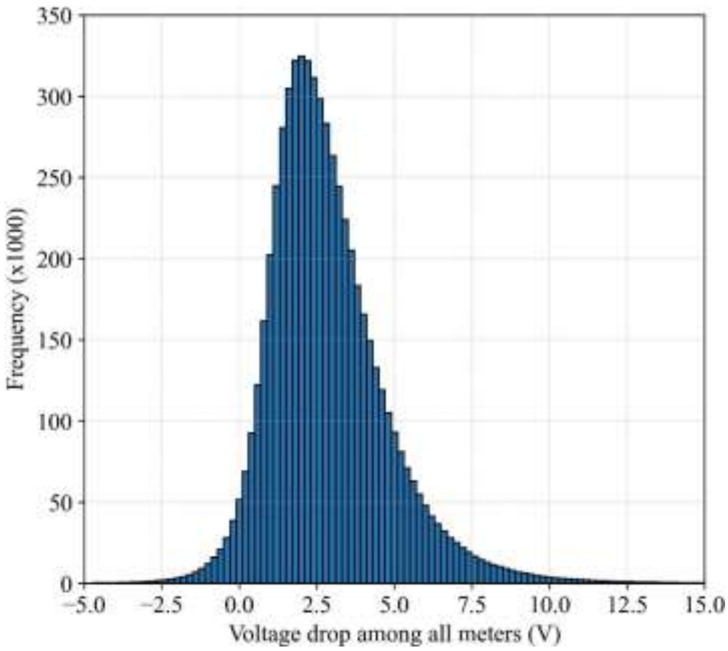

Figure 15. Distribution of voltage drop achieved by shifting electric water demand into the middle of the day

The ongoing trials have revealed that there has been a reduction in the number of controlled load fleet in the order of 20 to 30% depending on the region over the last years. This is mainly because the current controlled load scheme and newly installed smart meters don’t allow households to self-consume their solar generation for water heating, simply because the general supply (where solar is installed) and the controlled load (where hot water system is installed) are physically separate circuits. Since households get a much lower value for their solar exports (feed-in tariffs), they change their controlled load water heating onto general supply and install timers or diverters to use their solar generation to heat water at the household level. Another reason for the reduction in controlled load fleet is the increasing heat-pump installations where most manufacturers do not recommend installing heat-pumps on the controlled load circuit that my over-ride its inherent control strategies.

Retailers can make financial profit through wholesale arbitrage via shifting water demand from night-time to daytime where prices are much lower (or even negative in some regions) during low demand and high solar generation periods. For Australia, this benefit was estimated to range between $50 to $100 per year per household. As explained above, networks can also benefit from this type of control through lower voltages, increasing the minimum demand during the daytime, and a reduction in curtailment. Although hot water can 'soak-up solar' at the network scale and provide value to the grid, it is not yet clear the best way to pass on this value to consumers. New value propositions and innovative tariff designs may be needed since current controlled load tariffs do not reflect these benefits in real time. The responsibility may fall onto retailers or regulators to come up with more equitable tariff structures. A concern with this control approach is that it is not very individualized or adaptable since the schedule of electrical consumption for each water heater relies on the historical water heating electrical consumption. For example, if the household consumed ~8 kWh each day, then they can schedule the 8 kWh at the most opportune time in the next 24 hours. The problem arises under abnormal usage of hot water (i.e., hosting visitors) and the thermal load for that day is significantly increased to, say, 30 kWh. As the control algorithm does not know that there has been a large increase in the thermal load, the water heater does not respond, and the household can run out of hot water. One instance of hot water depletion can result in the consumer withdrawing from aggregated control. Hence to guarantee consumer hot water amenity, further controls and two-way communication is needed.

4 Market Survey Results

4.1 Task 69 PV Hot Water Stakeholder Survey

A market survey was conducted during the last quarter of 2023 among the participating task experts and their networks. The aim of the survey was to gauge expert sentiment on what the state of play for PV hot water systems is today and the trends going forward.

4.1.1 Survey Results

There was a total of 44 respondents from a range of market actors and experts, with around half from industry, 43% from academia and research, and 7% from policy or certification bodies. **Figure 16** shows the profile of the respondents.

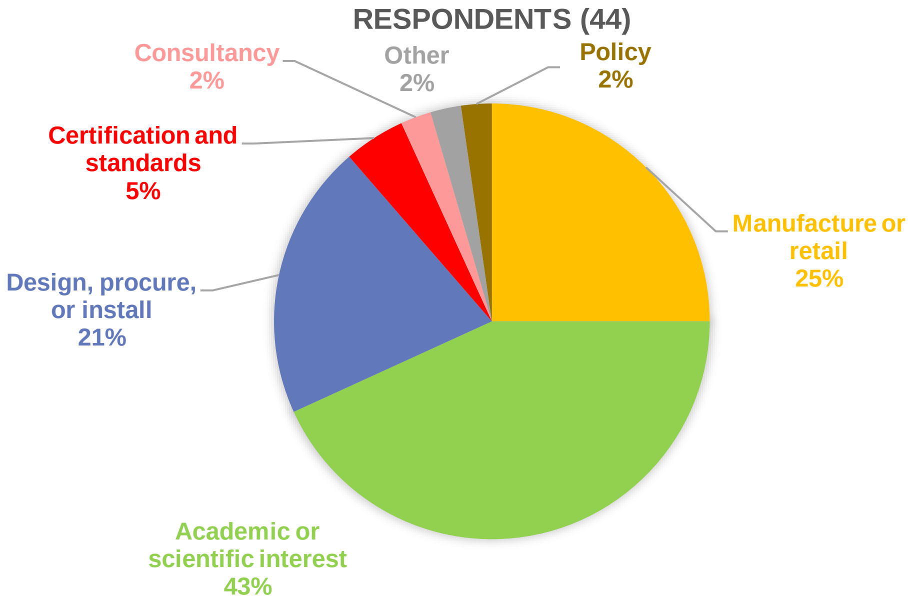

Figure 16. Survey respondent profile

The industry offerings vary by technology and service, as shown in **Figure 17A**, while the size of the offerings is shown in **Figure 17B**. Note that most of the manufacturing responses stated a 1 – 10 kW range of water heating capacity, while three design and install respondents reported > 10 kW system capabilities.

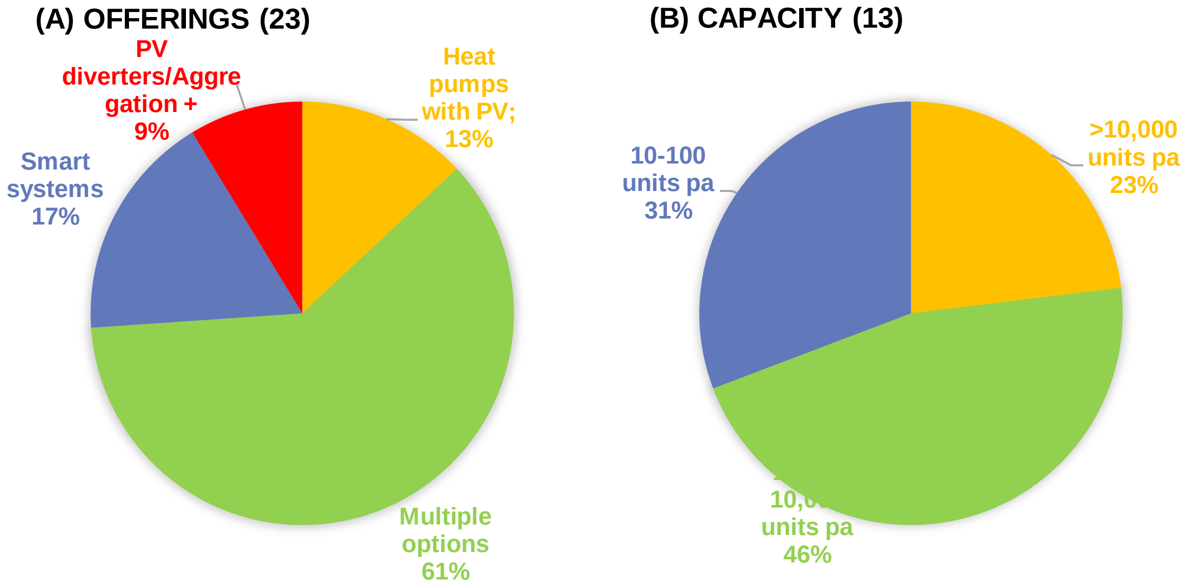

Figure 17. Manufacturing characteristics. (A) System offerings, (B) Manufacturing/installation capacity

Installed costs range from $100 to >$2500 (see **Figure 18A**), with the largest share reporting costs above $500. These costs appear high, and it is uncertain what the competing and base system costs are. In comparison, over 60% of respondents estimated annual savings to be less than $500/year (see **Figure 18B**).

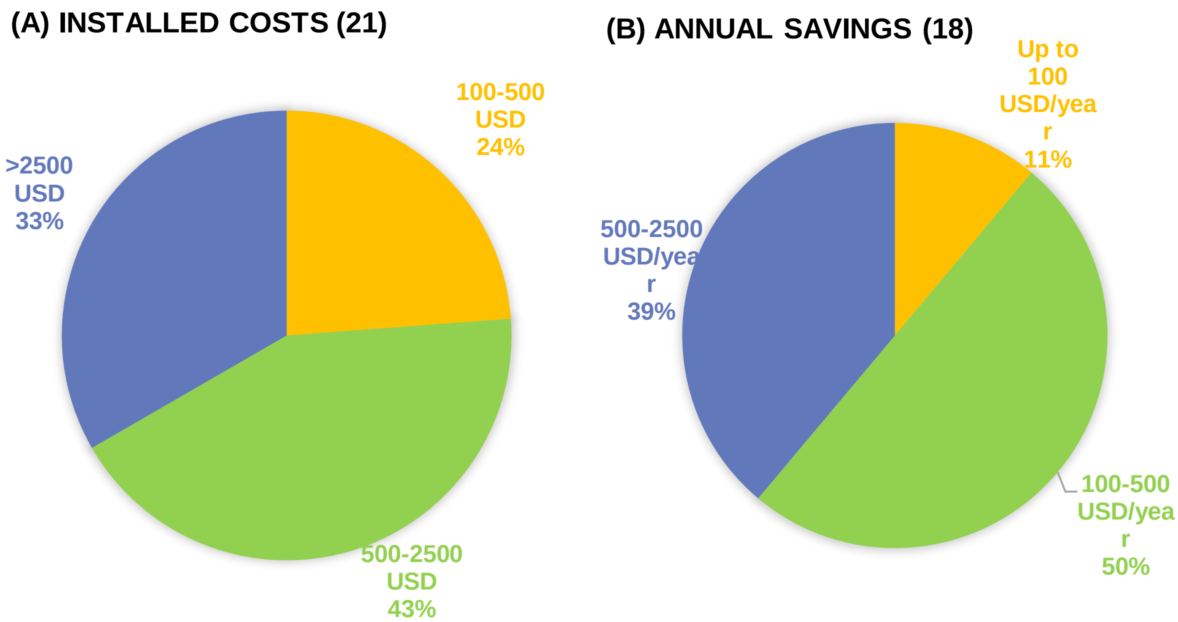

Figure 18. Reported economic indicators. (A) Reported installed cost of technology, (B) Reported typical annual savings attributable to the technology

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Figure 19A below shows the perceived market potential. This is overwhelmingly positive (medium to high growth rates) among manufacturers and some academics. The more pessimistic views are not confined to non-commercial actors (academic or policy) but include a couple of manufacturers. Most respondents included comments on market barriers, as shown in **Figure 19B**. About half of the perceived barriers to market growth fall into the categories of installation cost and the closely related value of the service. This suggests that it is difficult under existing market conditions to persuade people to employ these systems, whether as a new installation or a replacement system. This may also be closely related to the issue of technology competition, as the relative costs or understanding of the technology may not be sufficient to make the systems attractive. Another major perceived barrier is lack of skills and knowledge on the part of potential installers, although this segment includes lack of end-user knowledge. Penetration of markets that have entrenched practices appears to be difficult. However, for some markets (e.g., South Africa), there seems to be a growing acceptance that PV2Heat is a relatively simple and low-cost solution. This becomes a harder sell in more established markets with mature fossil fuel infrastructure.

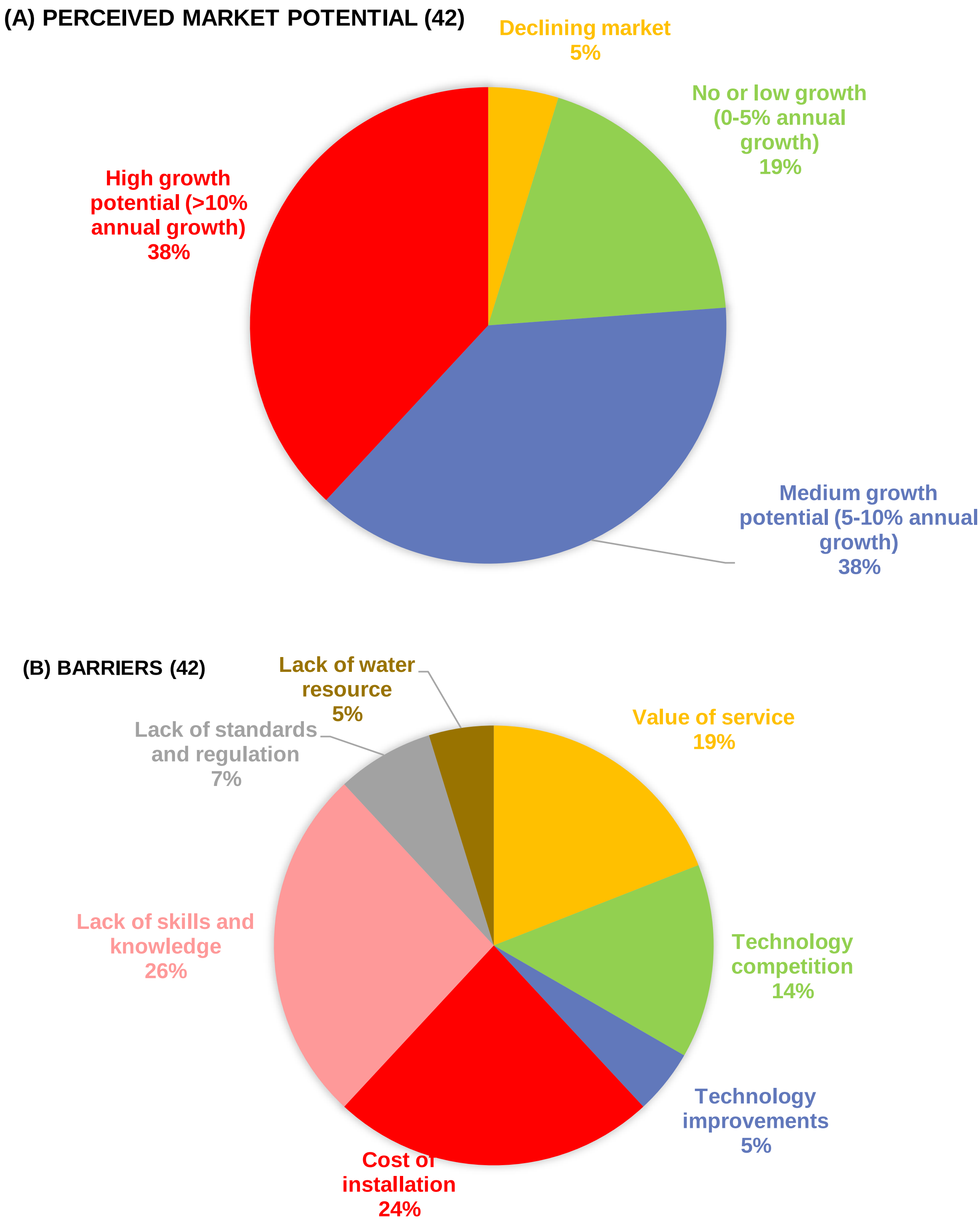

Figure 19. Perceived market for PV to DHW technology. (A) Potential market growth rates, (B) Barriers to market growth.

Some specific barrier issues based on respondent comments are summarised below:

- The value of the service to stakeholders in aggregated offerings.
- Uncertainties in the value proposition for customers due to this being a relatively new technology

- In some regions where there are new builds if there is solar PV electricity combined with hot water tanks, then the true carbon abatement potential is not fairly considered, as surplus PV electricity is diverted to the tank. Furthermore, some subsidies (for DHW) still focus on solar thermal systems rather than systems specifically designed with PV.
- Emphasis on heat pump water heaters as the only "green water heating" solution.
- Skills crossovers and responsibilities where plumbers may be expected to install the tank and the PV
- Lack of technical knowledge, regulations, frameworks, and standards.
- Concerns around the competing efficiencies and costs of PV with resistance heating as opposed to heat pumps and the need for smart controls.
- For Australia, high levels of PV may lead to system voltage imbalances, which could disadvantage PV installations. Household and community batteries may become more used, so the issues of PV export may reduce the incentive for hot water self-consumption.
- Current rebate schemes do not recognise PV water heating. As such whilst the capital installation is comparable between smart water heaters and heat pumps, for instance, the cost to the consumer is significantly different. A level playing field that is not technology specific is needed.

The market for PV2Heat is well below its potential, even though some companies are selling reasonable volumes of the technology. It will be necessary for a greater understanding of the advantages of using these technologies to be conveyed to specifiers, installers, and end-users. The uptake will largely depend upon local market conditions, existing practices, and the emergence of clear regulations and standards about where and how these technologies can and should be deployed at scale.

5 Future Technology Trends

5.1 PV2Heat systems

PV2Heat is likely to gain traction in areas with unreliable access to grid services of electricity and water and in regions where up-front costs can be a major barrier to entry. Cutting out the need for an inverter and any mechanical failure points (pumps and temperature-related failures of freezing and stagnation) will be a big selling point in these markets.

5.2 PV Self-Consumption Hot Water

In the emerging partially coupled systems, significant local savings are possible due to ensuring as much self-consumption as possible through installing PV diverters and/or smart tanks. It may also be possible to get even more out of these technologies through enabling aggregated control which could unlock the value of providing ancillary services to help manage the grid. However, an aggregator will need to collect multiple MW of capacity before a network contract would be available for this service. At a smaller scale, local peer-to-peer energy trading may provide significant pooled value in a connected community. However, care must be taken to design our future PV hot water ecosystem. We conclude that it may look different in different markets and that, in practice, the ecosystem will likely evolve to incrementally adopt technologies at different levels of sophistication to utilize excess PV.

5.3 Grid-tied PV Hot Water Systems

For the uncoupled systems, it is possible to dramatically reduce grid consumption for hot water. Retailers can make a financial profit through wholesale arbitrage via shifting water demand from night-time to daytime, where prices are much lower or even negative at low demand and high solar generation periods. In some markets, like Australia, where feed-in tariffs have dropped to sub 5c/kWh values, this may unlock up to $100 value for a typical household, but in Europe and the UK, it may still make more sense to sell excess PV electricity back to the grid. However, as more PV penetration increases on the grid, this arbitrage opportunity should become increasingly valuable. For example, Australia has seen a dramatic 4 fold increase in the occurrence of negative spot price events in the past few years [19], so households could *theoretically* get paid (e.g., reverse expense) to generate hot water at these times [19], especially under innovative retailer tariffs like Amber Electric [20] which directly passes the wholesale market prices onto customers [19] Ancillary services (e.g., frequency control) also offer some value. One of the main challenges for this participation is to coordinate enough storage tanks and operate them in a quick manner to comply with the frequency control markets. Another key challenge is how this frequency market revenue can be passed on to households. For the older controlled load schemes (i.e., where the hot water tank is directly controlled by the DNSPs), a headwind is that this fleet is reducing over time as the ripple control technology phases out. Thus, new value propositions and innovative tariff designs may be needed. One option is for hot water to be sold as a service by aggregated suppliers such as hot water tank and heat pump manufacturers. As larger players, these companies can develop and use sophisticated algorithms via cloud interfaces to maximize the value of this type of demand-side management, especially via the use and control of smart meters.

6 The Policy Context for PV Hot Water

6.1 Emerging Energy Markets

A key emerging market for PV hot water is being developed via the SOLTRAIN+ (The Southern African Renewable Heating and Cooling Initiative). This regional initiative on capacity building and the installation of demonstration systems focuses mostly on solar thermal but has also installed PV2Heat systems. The initiative runs until December 2026 and is in cooperation with partner countries - Botswana, Lesotho, Namibia, South Africa, and Zimbabwe. The lessons learned from these initial installations on the performance, reliability, and durability of PV2Heat systems are expected to drive further uptake of these systems in sub-Saharan Africa going forward.

6.2 Transitioning Mature Electricity Networks

In many advanced economies, decarbonising electricity networks is beginning to happen at pace. This is resulting in a push to decarbonise heating of buildings and processes using electricity. In general, this encourages the uptake of heat pumps for both new builds and retrofit applications, which can reduce the consumed energy requirement while also benefiting from reduced carbon intensity of the energy source. As electricity networks decarbonise, the heat pump solution provides some future-proofing and delivers rapid carbon reductions. However, heat pumps also bring some challenges to the electricity network (as noted by Chartered Institution of Building Services Engineers work on TM67 “Electrification of buildings for net zero”). Without controls and design requirements to try to selectively utilize renewable generation periods, the massive installation of heat pumps around the world is likely to increase the peak demand on the grid rather than soak up renewables.

The first is that they transfer very high energy loads onto the electricity network from other traditional heat networks, e.g., gas grids or oil systems. Most grids have not been designed for these volumes or the peak power requirements that these can introduce. For example, the peak gas grid can deliver up to five times more heating power than the peak electricity load in many areas, such as the UK. This will require significant system upgrades and/or better demand management. Secondly, heat pumps are less efficient when delivering higher heating temperatures, as are required for DHW systems and, particularly, while meeting anti-legionella pasteurisation requirements. The adoption of PV2Heat systems can help to alleviate both issues when used in conjunction with heat pumps.

Overall, we conclude that we need a well-planned energy transition to exploit the inherent benefits of both PV existing electric storage water heaters (e.g., large and very fast controllable loads to offer grid stability services) and heat pumps (ideally systems with sufficient thermal storage & controlled to selectively operate in opportune times that are "typically" present in the peak sun times). However, to ensure these advanced technologies *help rather than hurt* the electrical grid, we need regulatory recognition of the potential benefits and robust financial mechanisms to encourage consumers to take up water heating solutions which can respond to the grid and PV generation conditions in real-time.

7 Appendix

7.1 Abbreviations

DIR-FLAT	Direct system with flat plate collectors
DIR-ETC	Direct system with evacuated tube collectors
IND-FLAT	Indirect system with flat plate collectors
IND-ETC	Indirect system with evacuated tube collectors
OTH	All other systems, e.g., storage collectors

7.2 List of Figures

7.3 List of Tables

7.4 References

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