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Research Article

SWHEI: A New Approach to Measure Policy Effectiveness for Solar Water Heaters

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Abstract. In the context of the global energy transition, governments design and apply renewable energy policies as tools to replace fossil fuel sources for the heating end-use sector, which represents half of the global total final energy consumption (TFEC). In the last two decades, large deployments of solar thermal technologies, such as solar water heaters (SWH), have helped renewable energy penetrate the heating sector. To be successful, their adoption must be supported by effective policies; however, measuring the effectiveness of a particular policy is a complex task. Some studies design and propose indicators to measure this effectiveness but are difficult to replicate or adapt to specific markets. This work submits a novel policy-outcome effectiveness indicator, the Solar Water Heater Effectiveness Indicator (SWHEI), based on equipment deployment (installed capacity per capita, installed capacity growth) and the solar energy potential of each country, constructed using publicly available data to ensure replicability and universal utilization. The overall SHWEI values for the period 2003–2019 are low, reflecting the current low adoption of solar technologies, but show regional clusters of good performance, such as in Europe. Barbados achieved the maximum value of 6.9, which reflects its outstanding performance, driven by its installed capacity per capita. The analysis shows that the SWHEI is particularly useful to determine policy ineffectiveness while confounding factors could camouflage policy effectiveness. The SWHEI-active SWH policies matrix can help policymakers identify courses of action. Policymakers could 1) use market-entry policy instruments in undeveloped SWH markets (segment C, no policies in place); 2) review and improve failing SWH policies (segment D); 3) propose randomized controlled trials to study causal relationships between SWH policies and large SWHEI (segments A and B with policies in place); and 4) regulate successful markets, allowing for continued organic growth (segment A, no policies).

Keywords: Solar heating and cooling; policy design; energy transition; policy indicators; renewable energy adoption.

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1.Introduction

There are three energy end-use sectors: heat, transport, and electricity. Heat is the largest sector, representing 50% of global total final energy consumption (TFEC) and 40% of global carbon dioxide (CO_2) emissions in 2018 (IEA, 2019a). Renewable energy accounted for around 23% of the total heat consumption in 2019 (United Nations, 2022). However, solar thermal consumption did not even reach 1% of the total heat consumption (United Nations, 2022). This work seeks to contribute to the growth in the use of renewable technologies to increase solar-thermal consumption through the design of an indicator that measures policy effectiveness. This indicator, the Solar Water Heater Effectiveness Indicator, or SWHEI, is based on equipment deployment (installed capacity per capita, installed capacity growth) and the solar energy potential of each country. The indicator is constructed using publicly available data to ensure replicability and universal utilization. With an enhanced understanding of policy effectiveness, policymakers would obtain access to a realistic, data-driven, and publicly available method to evaluate the effectiveness of public policies supporting their solar water heating markets.

Among the appliance options residents can select to heat water, the popularity of solar water heaters (SWH) across the world is low. For example, a survey in Nigeria showed that while only 1.2% of respondents indicated their use of solar water heaters in households, 48% of the respondents claimed to use portable electric kettles, while a further 48% used kerosene stoves to heat their water (Ezema, Olotuah, & Fagbenle, 2016). Those that used SWH did so mostly because their dwellings already had them installed, reflecting the importance of building codes to mandate the installation of SWH in new buildings or retrofit older ones.

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A significant body of research focuses on the techno-economic and life-cycle analysis of SWH technologies (Li, Tzameret, & Onyina, 2012; Chang K. , Lin, Lee, & Chung, 2008; Chang K. , Lin, Lee, & Chung, 2009; Huang, Castán Broto, & Liu, 2018; Baccouche, 2014; Handayani & Ariyanti, 2012; Kulkarni, 2016; UNEP, 2015). However, there are fewer research papers related to measuring the effectiveness of public policies that are aimed at increasing the deployment of renewable energy, much less that of SWH (Puig & Morgan, 2013; Chang, Ho, & Hsu, 2013; Held, Ragwitz, & Haas, 2006). This study aimed to develop a novel and reliable indicator that would enhance the policymaking process and help policymakers assess the effectiveness of SWH policies.

This indicator is built at a spatial resolution of country territories and a temporal resolution of years. The design of the building blocks we used for the indicator can also be applied to other renewable energy technologies, opening the door to a variety of effectiveness indicators across countries and their technology policy mixes. The scope of this analysis was limited to solar water heaters in the household sector. The indicator uses 20 years of data (2000–19) of 216 countries or territories—resulting in 4,332 data points and yielding 3,681 SWHEI scores over the 2003–19 period. These scores were then analyzed statistically and supported with case studies to provide examples of our findings.

The rest of the paper is organized as follows: Section 2 overviews the existing policies used to support renewable technologies across the world and outlines different policy assessment techniques. Section 3 details the methodology, data inputs, and equations that comprise the SWHEI, highlighting the replicability of the indicator's design for other technologies. Section 4 uses the computed SWHEI to analyze the global performance of SWH policies. This work uses the SWHEI as the leading indicator of effectiveness through time and for 2019. Additionally, this work shows how analyzing the SWHEI can uncover hidden gains in policies or confuse policy effectiveness with other unrelated factors, such as organic market growth. Finally, in Section 5, we conclude by reflecting on how policymakers can use the SWHEI to increase the share of SWH technologies in the TFEC. We also outline some limitations of this study and open doors to potential new research that could build on this work.

2. Overview of SWH policies and assessment techniques

2.1 Renewable policy instruments

Governments use market efficiency policies to increase the market share of renewable technologies when their market has not proliferated (LSE, 2020). These policies may vary in their depth and scope and are often useful in reducing or overcoming direct economic barriers (with taxation or subsidies, for instance) or when implementing mandates and standards for more rigorous and fair market regulation. For SWH in households, fiscal incentives have encouraged household owners to install SWH to satisfy their domestic needs in countries such as Austria, Cyprus, and China (IEA, IRENA, 2020).

While renewable electricity saw increasing growth during the 2010s in terms of installed capacity (IRENA, 2022), SWH has not seen the same proliferation on a global scale. SWH is an attractive target for policy intervention because it involves three main topics from the international political agenda: renewables, climate change, and energy efficiency. Thus, an overview across around 4,400 active energy policies around the world found that only 173 policies could be explicitly related to SWH in 2019, as shown by the three policy databases from the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) databases (IEA, IRENA, 2020; IEA, 2020; IEA, 2019b).

These SWH policies cover 45 countries. The respective governments implemented them to overcome barriers to renewable heat deployment (IEA, 2018). Moreover, there are multiple policy types, some related to economic factors and others related to non-economic factors. Economic instruments are the most predominant policies implemented: more than half of the 173 policies belong to this type. On the other hand, a quarter of them are regulatory instruments and policy support mechanisms. The predominance of economic instruments demonstrates the need to overcome market and financial barriers in these countries. Remarkably, regulatory policies are more frequent in countries with larger economies and often enforce technology implementation.

2.2 Policy assessment methods

An energy system can be studied from different perspectives. Under the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, the international political agenda increasingly includes greenhouse gas emission mitigation strategies and objectives (UNFCCC, n.d.).

Therefore, policymakers started to design policies with the overall intention of avoiding or reducing greenhouse gas emissions as the impact of said policies. However, while the ultimate impact of these policies is clear, the outcomes and outputs may not be easily connected to the impact. Moreover, a policy's outcome can be misleading, non-comparable across countries, or unrelated to an energy system in this approach. Consequently, governments can struggle when comparing an implemented policy and its impact on avoiding/reducing emissions. Therefore, how can governments contemplate a policy as effective?

A policy is effective if it meets its targets (van Dijk et al., 2003). These targets can be measured in terms of policy outputs, outcomes, or impacts (Parsons, Gokey, & Thornton, 2013). This work focuses on outcomes. The outputs of SWH policies could be conceived in terms of an increase in installed SWH, potentially measured in installed capacity. This is a clear and measurable metric, however, it misses the bigger picture of the policy: its impact on society. Outcome is a step above output, since it is more indicative of effectiveness. For SWH policies, this could be a rise in renewable heat in the TFEC. However, this is more difficult to measure and attribute solely to SWH. While more significant, outcomes can be abstract and challenging to measure (Parsons, Gokey, & Thornton, 2013).

Therefore, to determine a proxy of the effectiveness of a policy outcome, governments and analysts opt for more accessible alternatives, such as energy indicators, which describe how human activity and energy use are related (Vera, Langlois, Rogner, Jalal, & Toth, 2005). Energy indicators can reveal energy market insights and serve as tools for supporting decision making, even when analytical data are unavailable (Patlitzianas & Psarras, 2007; Kagiannas, Flamos, Askounis, & Psarras, 2004). Furthermore, energy indicators also help monitor implemented policies (IAEA, UNDESA, IEA, Eurostat & EEA, 2005), improving communication between citizens, analysts and policymakers (Patlitzianas, Doukas, Kagiannas, & Psarras, 2008). Still, due to the simplicity of using energy indicators to measure policy effectiveness, multiple risks could introduce biases and inaccuracies during the calculations.

Because economic or energy indicators measure outcome at the system level (imagine, for instance, the TFEC of a country when trying to look into specific TFEC for technologies), it can be challenging to attribute a share of this systemic outcome to a policy targeting specific technologies or, in this case, home appliances such as SWH. Similarly, defining which policy instrument has caused a specific change in the outcome is difficult to measure precisely. Multiple organizations have attempted to standardize the measurement and analysis of energy systems. A couple of examples are the International Recommendations for Energy Statistics, from the UNSD (2018), and the Energy Indicators for Sustainable Development: Guidelines and Methodologies, from the IAEA, UNDESA, IEA, Eurostat and EEA (2005).

In some cases, public policies may not necessarily achieve the expected results planned by policymakers. Thus, two views for measuring policy effectiveness have emerged, one, grounded on policy outputs and the other focused on policy outcomes (Neij & Åstrand, 2006).

2.2.1 Output-oriented policy effectiveness

The first approach to policy effectiveness depends on the specific policy instrument (Held, Ragwitz, & Haas, 2006). Following Van Dijk *et al.* (2003), consider that each policy instrument has a specific output to be accomplished. For instance, feed-in-tariffs may have the expected output of a number of distributed electricity interconnections (number of households), or the installed capacity of distributed renewable electricity (kilowatts).

Moreover, an excessive focus on meeting individual policy instrument targets could be counterproductive. This is reflected by Goodhart's economic law, which states that a measure ceases to be effective when it becomes a target. The underlying reason for this is that trying to maximize or minimize a specific target or output may overlook the wider economic and systemic objectives at hand.

Policies can also be made effective by their features. Focusing on policy objectives or targets could help to oversee these critical features. Roulleau & Lloyd (2008) describe "successful policy features" and then compare these to case study examples to evaluate their robustness. In these cases, “good” policies are those that have the specific components of a “best case” checklist. For instance, in renewable energy auctions, the features that qualify a good policy or auction process can be related to the design components, such as having options for winner selection criteria, qualification requirements, demand detail, and so on (IRENA, 2019).

2.2.2 Outcome-oriented policy effectiveness

The second and more commonly used approach to the measurement of policy effectiveness depends on the systemic outcomes of policies. Outcome indicators have been used to evaluate policy effectiveness at least since the 1990s (Neij & Åstrand, 2006). They need to be simple, responsive to changes, reliable, and representative, as well as featuring qualified evaluators. In this vein, Neij & Åstrand (2006) proposed an outcome-based framework for evaluating policies, arguing that it offers a more favorable measure of outcomes than policy instrument outputs or features because outcomes fit within the scope of sociotechnical systems (a broader perspective on effectiveness). Moreover, they also suggested an evaluation framework for energy policy based on policy instrument outcomes through indicators that analyze overall sociotechnical effects.

Multiple authors have recommended indicators following this approach. Some focus on policy effectiveness through the cost-effectiveness of technologies when financial instruments such as viability gap funding, accelerated depreciation, and feed-in tariffs are in place (Shrimali, Srinivasan, Goel, & Nelson, 2017). For example, Pirnia, Nathwani, & Fuller (2011) measured social welfare changes and linked them to feed-in tariffs in Ontario, Canada. In addition, the UNU-WIDER (2017) argues that to qualify policies seeking to reduce greenhouse gas reductions as effective, these should be analyzed at a global scale, even when the policies are national or subnational. In addition, the Denmark Technical University (DTU) and United Nations Environment Programme (UNEP) developed a "Policy Effectiveness Indicator (PEI)" (Puig & Morgan, 2013). The PEI depends on two complex factors: energy production and the technology's medium-term potential. Other approaches compare the cumulative amount of installed capacity of a specific technology from the moment governments announce a policy to a specific target year, as seen in some IRENA and IEA reports (IRENA, IEA and REN21, 2018, pp. 23, 28-29).

The main limitation of measuring policy effectiveness through outcome indicators is the lack of attribution of individual policy instruments to outcome performance. Since outcomes are measured systemically, their measurement includes the combined effectiveness of all policy instruments and any other confounding factors (Neij & Åstrand, 2006). Moreover, outcome indicators do not track additional variables simultaneously, often missing functional correlations between, for instance, SWH installed capacity, and other socioeconomic factors. Ultimately, it is improbable to relate an energy system's results to a specific policy instrument.

2.3 Policy assessment challenges

In the context of SWH policies, there are multiple challenges to measuring public policy effectiveness, namely 1) neglecting policy instrument externalities and 2) the complexity of policy effectiveness indicators. Without accounting for them, governments will produce biased, poorly designed, or inefficiently implemented public policies.

2.3.1 Neglecting policy instrument externalities

For SWH, policy effectiveness models have suggested a positive feedback loop between SWH installation and subsidies or research and development activities. Chang, Ho, & Su (2013) modeled simulations of how the expected SWH installation growth in given areas of Chinese Taipei reacted to various subsidy rates. However, this approach assumes that subsidies are entirely responsible for SWH installations, regardless of other externalities, which is a simplification that could result in biased recommendations to government officials.

2.3.2 The complexity of policy effectiveness indicators

Several indicators track policy progress; however, these can be impractical for SWH policies because they depend on complex factors. For example, the PEI calculation from

DTU-UNEP uses energy production and the technology's medium-term potential.

Energy production is not readily useful for SWH; the thermal energy produced by solar water heaters is not commonly available in the literature because it is not measured at all in most cases. Instead, SWH or thermal power are available in multiple records, representing installed capacity and serving as a proxy for energy production. Alternatively, SWH is measured in electricity or gas bill savings for customers. Therefore, if one were to use the PEI for SWH, one would require assumptions about thermal efficiencies and demand curves. By contrast, other SWH variables, such as absolute or per capita installed capacity, are more readily available.

The second feature of the PEI, medium-term potential, is rarely used or calculated for any kind of technology. We have not found a reasonable and easily replicable way to calculate this medium-term potential of SWH for every country in the world. In the PEI, this potential is only available for the EU, South Africa, and Brazil as an initiative from DTU-UNEP themselves, requiring economic modeling calculations for the remaining countries. An easier approach to understanding technology potential is to avoid entering the economic realm of potential and to limit the analysis to technical potential, based on theory.

One way to overcome the limitations related to calculation complexity and the potential bias resulting from assumptions is to emphasize the project level of SWH deployment. Using this approach, effectiveness calculations using financial terms such as the Net Present Value (NPV), Return on Investment (ROI), or the Internal Rate of Return (IRR) can yield policy effectiveness if these calculations consider specific policy instruments, such as grants and subsidies for SWH. If a project is financially feasible and implemented, then one could argue that the policy is effective. However, these calculations are unlikely to reflect the overall behavior of a national energy system since they only focus on the economic aspects, and their scope is limited to one project at a time.

Moreover, considering the limitations of both methods for the assessment of policy instruments, it is relevant to design a new approach to overcome these barriers and use cross-country evaluations. Furthermore, the existing indicators for evaluating renewable energy policies have general considerations for all the technologies available, lacking specificity and distinctions between renewable energy production methods.

3. Methodology

3.1 Confounding factors and design requirements of the SWHEI

What should we consider, then, to build a policy effectiveness indicator for solar water heaters? The first factor to study is the outcome of a SWH policy. In this case, since we can see that most SWH policies focus on increasing the deployment of SWHs (IEA, IRENA, 2020), let us argue that the outcome of these policies would be at least associated with an increased number of SWH installations in a country, measured in thermal megawatts (MWth) of installed capacity.

Secondly, how can this indicator isolate the effectiveness of SWH policies? We propose comparing SWHEIs between countries that do not have SWH policies in place and countries that do. We would expect to see a difference between these two groups, indicating that countries that have SWH policies return a higher SWHEI value than countries without these public policies.

The next question would be, could a higher deployment of SWH be associated with higher solar energy potential? The SWHEI must account for solar irradiance availability, that is, the amount of solar energy that countries receive within their territories. In this way, countries with larger solar irradiances, in theory, would have a higher incentive to take advantage of this untapped potential and possibly install more SWH. By contrast, countries with low irradiance may not be interested in investing in SWH deployment. To account for this difference, we could benefit from incorporating solar irradiance in the SWHEI as a handicap, similar to the adjustments that are made to the baseline performances of top golfers compared with inexperienced golfers on the same course to level the playing field.

Further confounding factors for the SWHEI are gaps in data or methodological discrepancies in parts of the indicator when building it. Statistics are not a perfect reflection of reality. Data gaps may arise from variations in the measuring and reporting methodologies between countries. To avoid this and to follow a similar approach to the PEI, the SWHEI relies on international data that follow the same methodology in their measurement, and that are published regularly in reliable public sources.

Lastly, regional and cross-country effects could influence the SWH market. For example, wars, geopolitics, international financing cycles, and other unpredictable factors could cause outliers in indicators of policy outcomes. For this reason, the indicator incorporates a cross-sectional instrument so that the SWHEI does not represent countries individually but, instead, uses "comparative" energy indicators and classifies countries through rankings. According to Patilitzianas *et al*. (2008), comparative energy indicators measure similarities between countries using necessary normalizations. Therefore, the SWHEI would have to normalize the data to account for cross-country effectiveness.

3.2 SWHEI design: assembling the building blocks.

Having reviewed the previous theoretical background and a list of challenges to overcome, we assembled the SWHEI. We present it mathematically in this section. We start from the final equation, then explain its composition through its three sub-indicators. Equation (1) shows the equation for the SWHEI.

$$SWHEI_{i,t} = w_{IC} IC_{i,t}^{cap'} + w_{CAGR} CAGR_{IC\,i,t}^{cap'} + w_{Ep} Ep'_{i,HC} \quad (1)$$

The three sub-indicators in the SWHEI help to correct some confounding factors explained in section 3.1, as well as presenting the results relative to the SWHEI performance of other countries in a given year in the form of a number from 0 to 10.

Thus, for each country (i) and year (t), where $IC_{i,t}^{cap'}$ is the scaled per capita SWH installed capacity per country per year (MW_{th} per inhabitant), $CAGR_{IC\,i,t}^{cap'}$ is the scaled 3-year Compound Annual Growth Rate (CAGR) of the SWH installed capacity per capita by country and year (%), $Ep'_{i,HC}$ is the handicap of the scaled solar energy potential per country (TWh/year), w_{IC} is the weight factor of $IC'_{i,t}$, w_{CAGR} is the weight factor of $CAGR'_{IC\,i,t}$, and w_{Ep} is the weight factor of Ep'_i in the SWHEI. Weighing the different sub-indicators is a complex analytical exercise. For simplicity, in this work, we considered the per capita installed capacity the most critical factor and assigned a weight factor of 60% as it directly reflects the adoption of SWH. Next, we assigned an equal weight factor of 20% for each, the CAGR, and the energy potential. Policymakers can choose the weighting allocation for each of the three sub-indicators as they see fit.

Thus,

$$w_{IC} = 0.6;\ w_{CAGR} = w_{Ep} = 0.2$$

Moreover, after simplifying the weighted SWHEI equation, we have Equation 2 for the simplified SWHEI:

$$SWHEI_{i,t} = 0.6IC_{i,t}^{cap\prime} + 0.2\left(CAGR_{IC\,i,t}^{cap\prime} + Ep_{i,HC}^{\prime}\right) \quad (2)$$

3.2.1. Per capita SWH installed capacity

The per capita SWH installed capacity (IC) is the first sub-indicator included in the SWHEI. The SWH IC per capita is the most indicative piece of information about the SWH supply relative to a population, and we calculate it for every year and each country based on public data. If hot water demand were to remain comparable across countries (which is not necessarily the case), this indicator would show which countries could install more SWH to satisfy a larger share of their hot water demand.

The installed capacity per capita is already comparable across countries. Furthermore, we normalise this value to somewhere between 0 and 10 by using the min–max scaling method (Eremenko & de Ponteves, 2020). The value is multiplied by 10, as shown in Equation (3). If there are countries without SWH installed capacity, the minimum capacity across countries is 0 each year and thus cancelled out in the equation, resulting in a simplified Equation (4).

$$IC_{i,t}^{cap\prime} = 10\left(\frac{IC_{i,t}^{cap} - IC_{t,min}^{cap}}{IC_{t,max}^{cap} - IC_{t,min}^{cap}}\right) \quad (3)$$

$$IC_{i,t}^{cap\prime} = 10\left(\frac{IC_{i,t}^{cap}}{IC_{t,max}^{cap}}\right) \quad (4)$$

where $IC_{i,t}^{cap}$ is the per capita SWH installed capacity by country and year (MW$_{th}$/100k inhabitants), $IC_{t,max}^{cap}$ is the maximum per capita SWH installed capacity across countries by year (MW$_{th}$/100k inhabitants), and $IC_{t,min}^{cap}$ is the minimum per capita SWH installed capacity across countries by year (MW$_{th}$/100k inhabitants).

The per capita SWH installed capacity is calculated using publicly available data from *Solar Heat Worldwide*, a yearly publication from the IEA Solar Heating & Cooling Program (IEA, 2021), and the World Bank's World Development Indicators database (World Bank, n.d.a), as shown below.

$$IC_{i,t}^{cap} = \frac{IC_{i,t}}{P_{i,t}} \quad (5)$$

where $IC_{i,t}$ is the SWH installed capacity by country and year (MW$_{th}$), and $P_{i,t}$ is the population by country and year (100k inhabitants).

3.2.2. The 3-year compound annual growth rate (CAGR) of per capita SWH installed capacity

The second sub-indicator of the SWHEI is the 3-year compound annual growth rate (CAGR) of per capita SWH installed capacity. The CAGR accounts for long-term yearly growth in the overall SWH IC per capita. It represents the country's progress relative to the installation of SWH systems following population demand.

The CAGR is also normalized with min–max scaling and then multiplied by 10, and there is a minimum and maximum cross-country CAGR for every year.

$$CAGR_{IC\,i,t}^{cap\prime} = 10\left(\frac{CAGR_{IC\,i,t}^{cap} - CAGR_{IC\,t,min}^{cap}}{CAGR_{IC\,t,max}^{cap} - CAGR_{IC\,t,min}^{cap}}\right) \quad (6)$$

Where $CAGR_{IC\,i,t}^{cap}$ is the 3-year CAGR of per capita SWH installed capacity by country and year (%), $CAGR_{IC\,t,max}^{cap}$ is the maximum 3-year CAGR of per capita SWH installed capacity by year (%), and $CAGR_{IC\,t,min}^{cap}$ is the minimum 3-year CAGR of per capita SWH installed capacity by year (%).

Ordinarily, the first step in the determination of SWH growth would be to calculate the annual SWH installed capacity growth rate, but swings in annual changes could be very large and statistically noisy. Hence, we use the CAGR to measure IC growth as a constant rate during the evaluation periods, using Equation (7).

$$CAGR_{IC\,i,t}^{cap} = \left(\frac{IC_{i,t}^{cap}}{IC_{i,t-3}^{cap}}\right)^{1/n} - 1 \quad (7)$$

where $IC_{i,t}^{cap}$ is the per capita SWH installed capacity for each country and year (MW$_{th}$/100k inhabitants), $IC_{i,t-3}^{cap}$ is the 3-year behind per capita SWH installed capacity for each country and year (MW$_{th}$/100k inhabitants), and n is the number of years for the growth rate; in this case, $n = 3$ (years).

3.2.3. Solar energy potential

The third and final sub-indicator for the SWHEI is the handicap for solar energy potential. This handicap is positive for countries with a smaller solar energy potential than the global average and negative for countries with larger solar energy potential than the average.

$$Ep_{i,HC}^{\prime} = \overline{Ep^{\prime}} - Ep_{i}^{\prime} \quad (8)$$

where $\overline{Ep^{\prime}}$ is the average of scaled solar energy potential for all countries (TWh/year), and $Ep_{i}^{\prime}$ is the scaled solar energy potential by country (TWh/year).

We calculated the scaled solar energy potential by country by transforming the country's solar energy potential with min–max scaling, which converts each solar energy potential value to a number between 0 and 1. Next, we multiplied the value by 10 to obtain values from 0 to 10.

Table 1
Construction of the solar thermal energy potential. Source: (NREL, 2008)

Metric		Units	Method
DNI	Direct Normal Irradiance	kWh/m^{2}day	Measured and modelled
A_P	Productive Land	m^2	Estimated 1.5% of the total land available
n_{th}	Solar thermal efficiency	%	Estimated at 10%
t	Period	days/y	Assumed 365 days/y
Ep_i	Solar thermal energy potential	TWh/y	Calculated

Table 2
Indicators required for the SWHEI and their publicly available data sources. Source: Authors

Indicator	Source
SWH IC (MWth)	IEA Solar Heating & Cooling Programme Annual reports (IEA-SHC, 2021)
Population (number of inhabitants)	World Bank Group, indicator SP.POP.TOTL (World Bank, n.d.a)
Irradiance (kWh/m²day)	NREL Solar resources by class and country (NREL, 2008)
Solar Thermal Energy in Households (TJ)	UNSD Energy Statistics Database (UNSD, n.d.)
Land area (km²)	World Bank Group, indicator AG.LND.TOTL.K2 (World Bank, n.d.b)
SWH policies	IEA & IRENA, Renewable Energy Policies database (IEA, IRENA, 2020)

$$Ep_i' = 10\left(\frac{Ep_i - Ep_{i,min}}{Ep_{i,max} - Ep_{i,min}}\right) \tag{9}$$

where Ep_i is the solar thermal energy potential by country (TWh/year), $Ep_{i,max}$ is the maximum solar thermal energy potential across countries (TWh/year), and $Ep_{i,min}$ is the minimum solar thermal energy potential across countries (TWh/year).

The National Renewable Energy Laboratory (NREL) (2008) measured and modeled solar thermal energy potential by country from 1961 to 2008; these values reflect the theoretical potential of each country to provide solar thermal energy. NREL reports this potential in terms of TWh/year. The potential is constructed as follows:

$$Ep_i = A_P DNI n_{th} t \tag{10}$$

Table 1 shows the solar thermal energy potential components, their units, and their quantification methods. In this methodology, the irradiance value corresponds to the direct normal irradiance (DNI) needed for solar concentrators, such as SWH (Louineau, 2018), while considering a conversion efficiency of 10% from solar energy gathered to thermal energy produced by a given converting equipment. For the calculation of the SWHEI, we divided the solar thermal energy potential by each country's surface area, yielding units of MWh/m²y. Because of the handicapped nature of this sub-indicator, countries with ample solar resources but little to no SWH installed capacity could present a negative SWHEI value. Table 2 presents the inputs necessary to calculate the SWHEI for each country and year.

4. Results and Discussion

Following the methodology used to construct the SWHEI, the results yielded a SWHEI value for 216 countries over the 17 years between 2003 and 2019, which we present in section 4.1. Next, an analysis for the year 2019 shows the best-performing countries; this analysis is presented in section 4.2. Finally, the SWHEI unveils the low effectiveness of SWH policies in specific countries in section 4.3.

4.1 Cross-country SWHEI for multiple years

Plotting the average SWHEI (blue dot) against the number of active SWH policies in Fig. 1 shows that the SWHEI value is independent of the number of SWH policies in place. The horizontal grey bars on top of and below the blue dot represent the range of SWHEI values within two standard deviations. Hence, around 95% of the SWHEI values fall within the vertical grey line for each blue dot, but this does suggest the even spread of these values following a normal distribution.

One can derive some insights from this graph. First, there is an association between the application of policies and a larger average SWHEI. If there are no policies in place, the average SWHEI is 0.4 —a smaller value than in countries with at least one SWH policy in place (differences of 0.3 to 1.6, or 75% to 400%). However, there is no linear correlation between the SWHEI and the number of active SWH policies, showing that if countries have more than one SWH policy in place, their SWHEI does not increase significantly. Thus, the SWHEI value is independent of the number of active SWH policies (case by case for each country–year pairing).

Considering the scatter plot of historical SWHEI against active SWH policies shown in Fig. 2, we plotted the distribution of different countries according to their number of policies and drew four segments to analyze this distribution. The segments in Fig. 2 are divided in quadrants to form a SWHEI-active SWH policies matrix. The SWHEI is halved at the global median of 2.75 and the policies at 5 in place.

The **top half** shows the leading SWH deployment performances, where SWHEI scores are high (larger than 2.75). For SWHEI values larger than the global median of 2.75, more active SWH policies are associated with a lower SWHEI (as shown by the more frequent top performers in segment A compared to segment B of the SWHEI policy matrix).

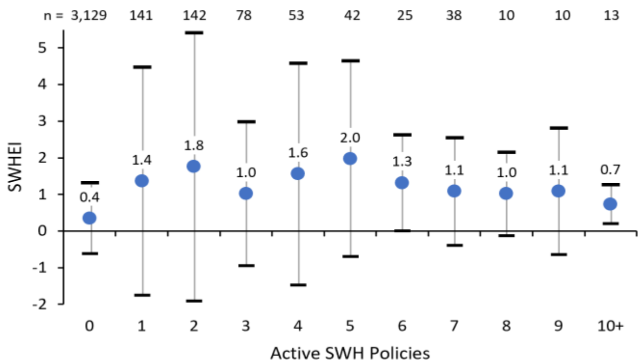

Fig 1. Average SWHEI by the number of active SWH policies. Source: Authors

Fig 2. SWHEI-policy matrix showing SWH performance segments, 2003-2019. Source: Authors

- **Segment A** includes countries with or without SWH policies and a relatively large SWHEI of 2.75 or more. The points in grey, denoting a large SWHEI with no policies, represent countries where market forces positively drive SWH deployment. The blue points are countries with a reduced number of SWH policies but with a large SWHEI. This analysis makes it impossible to determine the causal link between policies or a mix of other confounding factors, such as market forces, and the SWHEI performance of these countries. Therefore, it is challenging to narrow down these "best-case" policies based on this analysis alone.
- **Segment B** includes the least amount of country performances. This segment includes countries where there are multiple SWH policies in place and where there are relatively large SWHEI performances. This signals inefficiencies in the policymaking process, since multiple policies are needed to maintain high SWHEI scores. Nonetheless, the results indicate that there is an association between the collective group of policies and the markets, due to the effective deployment of SWH.

The **bottom half** of the graph shows low SWHEI scores, where SWH deployment is relatively small (lower than 2.75) for these countries and years.

- **Segment C** includes countries that need public policy action. Similar to segment A, segment C is subdivided by countries with or without SWH policies. The countries without policies in place (grey) feature SWH market failures. If the SWH market had been enough to deploy SWH in these countries, their SWHEI would be relatively higher. These countries require public policies to identify these market failures and intervene to solve them. Moreover, the points with active policies (blue) and relatively low SWHEI could reflect a lack of good policy design or implementation, or other barriers.
- **Segment D** includes countries with ineffective SWH policies. These points suggest relatively low SWH performance, together with a relatively large amount of SWH policies in place. If these policies were adequate, the SWHEI would theoretically be larger.

Because SWH is not widely spread as a mainstream technology globally, most countries have very low or 0 SWHEI, as seen visually in Fig. 3.

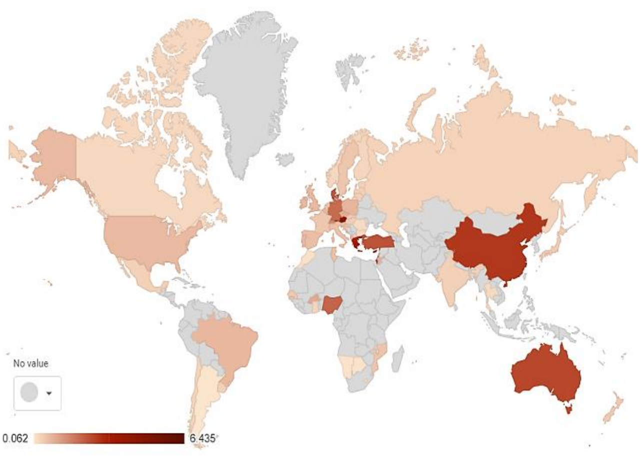

Fig 3. SWHEI global atlas, 2019. Source: Authors

The SWHEI global atlas represents the SWHEI score for 65 countries for 2019 as a heatmap and identifies the high-performing countries/areas as those with darker red tones. The generally low cross-sectional SWHEI values for countries in 2019 indicate that most countries have an undeveloped SWH market, and that policymakers could benefit from this untapped potential through market-entry policy instruments. Europe showed a regional cluster of larger SWHEI compared to other regions in 2019. Other high performers were outliers within their regions, such as Nigeria, Australia, China, Brazil, the United States, Turkey, Israel, and Palestine.

4.2 Top SWHEI performers

Table 3 shows the ten top-performing countries in 2019, based on their SWHEI scores. It also shows the three scaled sub-indicators constituting the SWHEI and a bar chart to visually contrast the values. In most cases, the largest per capita SWH installed capacity yields the largest SWHEI. Nevertheless, the heterogeneity in the top ten countries suggests the minor influence of natural resources, level of development, or country/population size, as evidenced by the CAGR and solar thermal potential handicap for each country.

For some nations, the strength of their SWH markets is reflected in their SWHEI scores. Moreover, most of the top 10 countries have negative solar thermal energy handicaps, pointing to the association between solar irradiance and SWHEI. Despite the impossibility of separating market forces from policy effects, as seen in segment B of Fig. 2, an overview of the top three SWHEI performers of 2019 across time, considering their SWH markets and policies, is presented below.

Barbados had the top SWHEI performance in 2019 and top performance for this indicator since 2015. Barbados belongs to segment A in the SWHEI policies matrix. Its government has adopted two SWH policy instruments since the beginning of the SWH industry in the 1970s and 1980s, which could have boosted the installation of new SWH units during these decades (Rogers, 2016).

In 1974, the government introduced a 20% import tax exemption for materials used in SWH fabrication, lowering the installation costs by between 5 and10%, along with a 30% tax on conventional water heaters. In 1977, the government introduced a mandatory building code that required the installation of SWH in new buildings under a government housing program. Later, in 1980, a tax amendment was passed for deducting the total costs of solar water heaters from income tax. The amendment lasted until 1993, and it was reintroduced in 1996.

Table 3
Top 10 SWHEI performers in 2019. Source: Authors

Country	SWHEI	$IC^{cap'}_{i,t}$	$CAGR^{cap'}_{IC\,i,t}$	$Ep'_{i,HC}$	Segment
Barbados	6.4	10	1.3	0.9	A
Cyprus	4.7	7.9	1.3	-1.6	A
Austria	4.3	7	1	-0.3	A
Israel	3.8	6.4	1	-1.0	A
Greece	3.3	5.3	1.2	-0.7	B
State of Palestine	2.9	4.6	0.8	-0.2	A
China	2.8	4.2	1.1	0.3	B
Australia	2.6	4.4	0.9	-1.3	D
Turkey	2.4	3.6	1.4	-0.4	C
Denmark	2.3	3.5	1.1	0.1	C

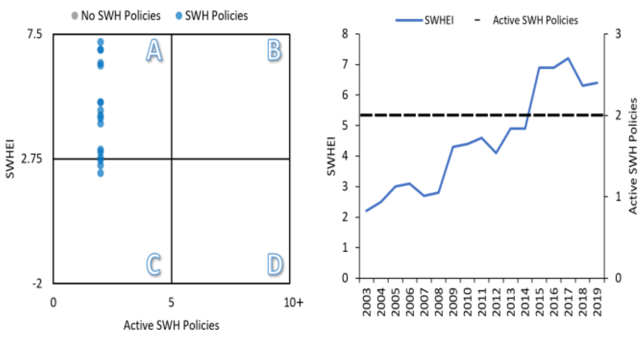

Fig 4. SWHEI policies matrix: SWHEI vs. active policy trends (Barbados), 2003-2019. Source: Authors

Recently, Barbados has been the SWH market leader in the Caribbean Community (CARICOM) region, with over 80% of its households equipped with SWH in 2015 (UNEP, 2015). Figure 4 displays a matrix showing the relationship between the SWHEI performance and the SWH policies applied in Barbados over the years.

Furthermore, the SWHEI has consistently increased in Barbados over the last two decades suggesting that the SWH market has grown successfully. However, what is not clear is whether this success is due to market forces, or whether it is related to policies, especially as we did not analyze each policy individually. Moreover, another factor could be that Barbados' market forces have already been reshaped, possibly through the influence of the Fiscal Incentives Act and the 1977 building code. The Fiscal Incentives Act pushed forward instruments to support SWH implementation. For example, a 70% reduction in gas consumption was achieved through a SWH pilot installation at the Prime Minister's home (Rogers, 2016). On the other hand, although Cyprus has the lowest solar thermal energy handicap across the top ten performers, it still had the second largest SWHEI in 2019.

Cyprus is highly effective at developing its SWH markets, with one of the largest per capita SWH installed capacities in the world and an impressive 3-year CAGR. The use of negative handicap for Cyprus was fair in order to make it comparable to other countries with lower solar irradiance. In this case, the SWHEI is almost analogous to the per capita SWH installed capacity. Figure 5 displays a matrix showing the relationship between the SWHEI performance and the SWH policies in Cyprus through the years.

Cyprus belongs to segment A, where there is a high SWHEI with a low number of SWH policies in place, indicating that either the market or the policies effectively promote SWH usage. Some policies recently applied in Cyprus include a mandatory solar water heater installations in new dwellings since 2009 (Energy and Water Agency, 2018) and a 2015 financial support scheme that covered the installation or replacement of solar water heaters with ten or more years of installation. The scheme granted around €350 for the complete system and €175 for the replacement of its panels (Republic of Cyprus, 2015). From Figure 5, it is not evident that the policies have a significant correlation with the SWHEI, perhaps because Cyprus has had a large SWHEI since 2003. In fact, Cyprus was one of the world's earliest adopters of SWH.

In Cyprus, the adoption of SWH in households increased from 60% to 90% between 2003 and 2009 (Enerdata, 2012). Considered a pioneer country in SWH technology, Cyprus had over 90% of the country's households and 50% of its hotels equipped with solar water heaters, reaching an installed capacity area of around 650,000 m^2 in 2018 (Republic of Cyprus, 2019). In this case, the implementation of SWH was more likely to have been driven by market forces than by policy instruments. Indeed, the Mediterranean island started manufacturing SWH in the early 1960s, forced by both a lack of natural resources and its dependency on importation to satisfy its energy needs. Furthermore, the oil crisis and the increasing interest in renewable technologies boosted the industry in the mid-1970s.

Another excellent example of SWH implementation is Austria, the third best-performing country of SWHEI in 2019. Austria's performance is an exciting showcase of the effects of SWH policies. The SWH market in this country has not developed organically due to economic and non-economic barriers to SWH. However, despite the country's unfavorable solar resources, Austria's SWH market started growing in the 1980s, driven by high energy prices and public environmental awareness. Some years after the second oil shock, energy cooperatives started manufacturing affordable "do-it-yourself" SWH. The idea gained popularity, and by 1986, energy cooperatives were producing more SWH than commercial suppliers in Austria (Solarray, 2014). Fig. 6 displays a matrix showing the relationship between SWHEI performance and the SWH policies in effect in Austria.

Moreover, for Austria, there is a correlation between installed SWH policies and the SWHEI. The SWHEI performance increases by 0.65 for each additional active SWH policy, as shown in Fig. 6. The IEA SHC argues that the multi-level design of SWH policies (sub-national and national) is one of the key drivers of Austria's SWH market (IEA-SHC, 2020). Nonetheless, there is a risk that most of this correlation is present due to confounding factors or randomness.

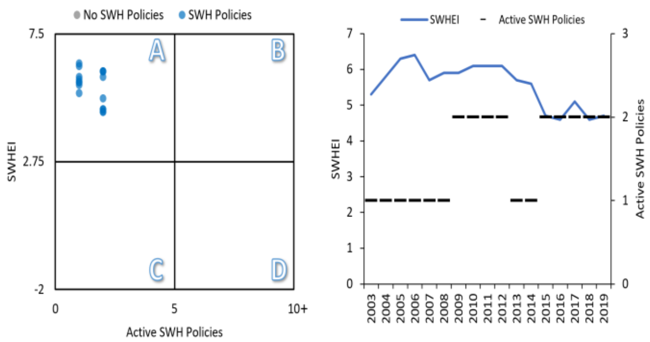

Fig 5. SWHEI policies matrix: SWHEI vs. active policy trends (Cyprus), 2003-2019. Source: Authors

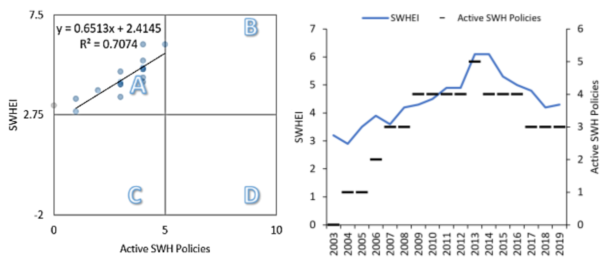

Fig 6. SWHEI-policies matrix; SWHEI vs. active policy trends (Austria). Source: Authors

Two examples of Austria's SWH policy instruments are a 2001 tax relief instrument that allowed the deduction of €2,920 of income tax per year for ordinary taxpayers who purchased solar or biomass energy production technologies for residences (IEA, IRENA, 2020), and a direct grant scheme for solar plants in single-family households from 2003, providing 25% (€4,650 for an 8m^2 solar-power system) of SWH investment costs on average. These SWH grants were a sub-program within the klima:aktiv program, which, running until 2012, aimed to promote renewable energy use in all sectors of the economy through financial incentives, information, and advice (IEA, IRENA, 2020).

While SWHEI cannot isolate policy effectiveness for high-performing countries (top half of the SWHEI policy matrix), specific country-case studies could identify effective policy instruments, as shown in Austria's linear regression coefficient of determination (R^2 = 0.7).

4.3 Ineffective SWH policies.

It is also essential to analyze the countries with a low SWHEI to evaluate, if possible, the policies that are not as efficient at increasing the SWHEI. By plotting the 2019 SHWEI performances against the number of policies and filtering out anything in the top half of the matrix, the most recent low-performing countries were outlined (Fig. 7).

Among the countries with an SWHEI lower than 2.75, segment C includes those with less than five active SWH policies. Analyzing those with a single SWH policy helps to compare in a non-experimental way the pre-test and post-test effects of the policy on the SWHEI. Two examples are Poland and Finland (Fig. 8).

Fig 7. SWHEI-policy matrix, 2019. Source: Authors

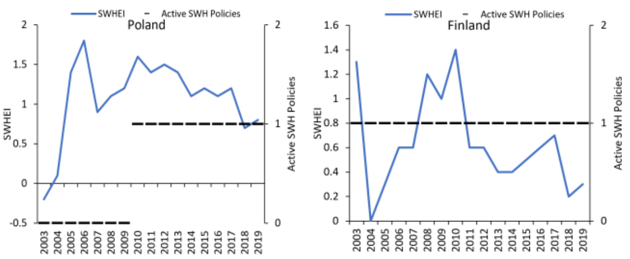

Fig 8. SWHEI and active SWH policies through time (Poland, Finland). Source: Authors

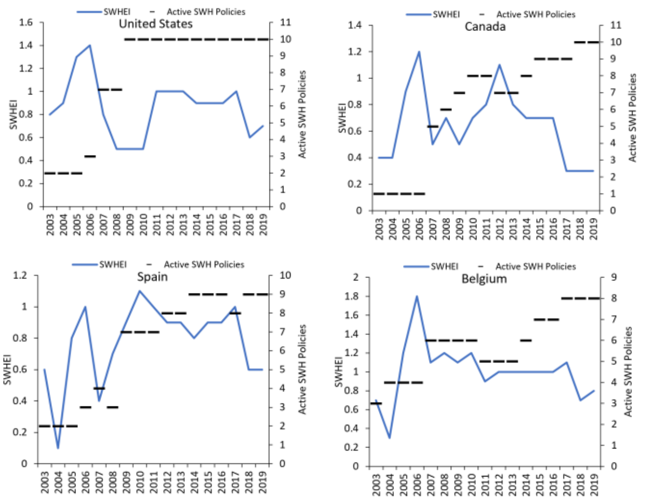

Fig 9. SWHEI and active SWH policies through time (United States, Canada, Spain, and Belgium). Source: Authors

The policies of Poland and Finland exclusively focused on increasing the deployment of SWH in their markets. However, the effect of these policies is not evident in their SWHEI. Either the markets influenced the SWHEI, the policy failed, or there were other unaddressed barriers in governance.

Poland has a clear diminishing trend away from a high SWHEI after 2010, when its National Renewable Energy Action Plan (NREAP) was implemented (IEA, IRENA, 2020). The lack of positive results indicates that the policy did not manage to sustain a competitive SWH market in the country and had little to no effect on its behaviour. Moreover, the multi-technological approach of this national policy may have led to the SWH potential being overlooked.

On the other hand, Finland shows erratic SWHEI scores for the last two decades. In 2003, the country registered one of its best performances, matching the year its Energy Grant for Residential Buildings was implemented, providing between 15% and 25% of some SWH systems (IEA, IRENA, 2020). However, in 2004, it hit an all-time low, before recovering over the course of 2005–2010. This increase may have been a delayed effect of the 2003 policy. However, there has been a consistent decline in Finland's SWHEI since 2011, particularly when some of these grants stopped in 2008 (Government of Finland, 2017). Finland's heat end use in residential markets was dominated by heat pumps in one-third of all homes by 2018 (Sovacool & Martiskainen, 2020), which may partially explain the low SWHEI.

The great advantage of SWHEI is that it helps identify the types of pitfalls discussed above so that policymakers can use them for research and make more informed decisions. Considering segment D, where there are five or more active SWH policies but an SWHEI lower than 2.75, countries such as the United States, Canada, Spain, and Belgium can be highlighted (Fig. 9). One would expect both a continuous increase in the SWHEI and the consolidation and maturation of the SWH market as more policies are applied in the nations shown in Fig. 8. However, this was not the case in many countries, and the SWHEI did not respond positively, indicating the poor design or implementation of these policies. These results do not come as a surprise; energy policies have usually been characterized by "some modest successes and a large tranche of unintended consequences; internal contradictions; and suboptimal policies, measures, and investments" (Jefferson, 2018).

Canada and Belgium can be used as illustrations of low policy effectiveness. After 2004, Belgium made a significant investment in SWH, with incentives of up to 35% of the investment cost to purchase and install SWH (IEA, IRENA, 2020). Shortly afterwards, Belgium increased its SWHEI, which peaked in 2006. However, between 2007 and 2017, similar, additional policies were implemented without creating the same effect. Nevertheless, this lack of SWHEI increase does not necessarily reflect poor policy design but, rather, simple ineffectiveness since other external factors could have undercut the effects of these policies. For instance, Belgium experienced a period of economic and political imbalance that started after the 2008 financial crisis (IMF, 2008). The SWHEI evidenced a marginal recovery in 2017, which is the same year Brussels installed its zero-interest green loan for the residential sector, which allowed eligible parties to borrow between €500 and €25,000 at preferential rates to install SWH (IEA, IRENA, 2020)

Canada is another example of how market trends can outweigh or practically negate the effects of policies. Canada implemented financial incentive policies (IEA, IRENA, 2020) that did not achieve the desired effect, possibly due to several market externalities. One effect was the increased natural gas consumption for both space and water heating uses (Ostovar & Nassar, 2019). The natural gas uptake could be attributed to an increase in oil exports to the US between 2010 and 2014 (CERI, 2016), possibly leading to lower natural gas prices (Government of Canada, 2020).

5. Limitations

While this study proposes an indicator with a sound methodology, data, and analysis, the authors recognize a few limitations in the extent of the paper. First, this study does not determine causality between the SWHEI and the number of active SWH policies for each country–year pairing. Randomized controlled trial studies for specific policy instruments would be needed to prove causality, especially for segments A and B of the matrix. Second, individual policy effects cannot be isolated by the SWHEI or its analysis for high-performing countries. Third, the quality of the SWHEI depends on the quality of the input data, namely the accuracy of SWH installations, population data, and irradiance. Finally, the SWHEI could show inherent biases because most of the world's countries have no SWH installation capacity. Data availability limited the number of data points that could be analyzed over a given period with the SWHEI.

6. Conclusion

A novel Solar Water Heater Effectiveness Indicator (SWHEI) was presented. The SWHEI normalizes three country-specific parameters from readily accessible data, unlike other more complex and non-scalable indicators available in current literature.

The SWHEI serves as a pre-feasibility parameter for evaluation and use in SWH policy development in all countries. Policymakers could use the SWHEI to overcome the plateau in the increase in solar water heating in the household sector. To achieve this, policymakers could: (a) identify their SWH policies; (b) evaluate their SWHEI performance; (c) identify suitable SWH policy options; (d) review SWHEI for countries with these policies in place; (e) evaluate failed cases and successes involving with these policies; and (f) decide whether to apply these policies or continue with an in-depth study.

Our analysis shows that the SWHEI is particularly useful to determine policy ineffectiveness, while confounding factors could camouflage policy effectiveness. The SWHEI-active SWH policies matrix can help policymakers identify courses of action. Policymakers could 1) use market-entry policy instruments in undeveloped SWH markets (segment C, no policies in place); 2) review and improve failing SWH policies (segment D); 3) propose randomized controlled trials to study causal relationships between SWH policies and large SWHEI (segments A and B with policies in place); and 4) regulate successful markets, allowing for continued organic growth (segment A, no policies).

The authors acknowledge the possibility of engaging in further research to add validity to the SWHEI as a policy effectiveness tool. This would include: a) refining the methodology of the SWHEI to correct for other confounding factors; b) running a sensitivity analysis to refine the weighting factors for each sub-indicator in the SWHEI; c) validating the SWHEI as a PEI by comparing it with policy-instrument-based effectiveness. (i.e., measuring the effectiveness of building codes by counting the number of buildings that follow the law); d) considering other publicly available sub-indicators to include in the SWHEI that would reduce confounding factors, such as GDP and energy intensity, among others; e) considering specific regional analyses by income group, geographic regions, geopolitical status, and renewable share in the energy mix; and f) adding further dimensions to the policy-type analysis, such as financial instruments, educational, building codes, and fiscal measures, among others.

This work consolidates data from multiple sources. The consolidated file, along with the calculations and SWHEI global map, can be found in the following online spreadsheet: https://tinyurl.com/vj79cu2

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