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Solar Home Systems for Clean Cooking: A Cost–Health Benefit Analysis of Lower-Middle-Income Countries in Southeast Asia

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Abstract: Limited access to clean energy has long been an obstacle to livelihood improvement of populations mired in energy poverty. Cooking with traditional biomass contributes to high levels of indoor air pollution, thus imposing significant threats to public health. Due to the accessibility and affordability of clean fuels for rural residents, this study proposes that renewable solar energy be employed to supply power for induction cooking stoves (ICS) through solar home systems (SHS), and estimates both the costs and health benefits of upgrading to ICS and SHS in lower-middle-income countries (LMCs) in Southeast Asia. Disability-Adjusted Life Years and the value of a statistical life year were employed to estimate the health benefits of ICS-SHS. The results suggest that the health benefits brought by ICS-SHS alone can surpass the estimated minimum cost for an ICS-SHS in the six LMCs in Southeast Asia. This study provides a potential reference for getting other energy poverty regions involved with affordable, reliable, sustainable, and modern energy, as well as simultaneously tackling indoor air pollution caused by cooking.

Keywords: energy access; indoor air pollution; induction cooking; solar home system; Disability-Adjusted Life Years

1. Introduction

Ensuring access to affordable, reliable, sustainable, and modern energy is the aim of UN Sustainable Development Goal (UN-SDG) 7, which is also critical to improving livelihoods and fighting against poverty for billions of people around the world. In 2019, over 840 million people remained without access to electricity. Nearly three billion people still lacked clean cooking fuels as well as technologies [1], forcing them to rely on traditional biomass fuels (e.g., crop waste, dung, wood, etc.) for daily energy needs. Most such populations live in rural areas of the developing world, mainly distributed in low-income and lower-middle-income countries, especially in Sub-Saharan Africa and Southeast Asia [2]. These regions often face a similar dilemma: Weak infrastructure and low-income levels make clean energy neither available nor affordable, which, in turn, reinforces the persistence of poverty.

The primary use of energy in households in developing countries is for cooking, followed by heating and lighting. Because of geography and climate, household heating needs are minor in Sub-Saharan Africa and Southeast Asia [3], whereas cooking is the most fuel-intensive activity. Cooking begins with the process of interaction between fuels and stoves. The lack of access to clean cooking fuels forces poor people to rely on inefficient and polluting cooking systems [4], in which solid fuels (biomass, wood, and coal) are often not fully burned. Such use of low-quality fuels leads to several sustainability challenges: (1) A labour challenge because of the time-consuming collection of

biomass [5]; (2) deforestation and land degradation; and (3) most importantly, the indoor exposure to harmful gases and particles. The World Health Organization (WHO) has determined that the typical 24-h indoor PM10 (particulate matter 10 micrometres or less in diameter) concentration can reach 300 to 3000 µg/m^3 in residences using biomass in Africa, Asia, and Latin America, while the peak PM10 concentration during cooking can even reach up to 10,000 µg/m^3 [6]. The continuous use of solid fuels will increase the level of indoor air pollution, leading to issues such as respiratory tract infections, heart disease, tuberculosis, low birth weight, cataracts, cardiovascular events, higher adult mortality, and risks of premature death [7,8]. According to the International Energy Agency (IEA), household air pollution, mostly from cooking smoke, is linked to around 2.5 million premature deaths annually [2], which adds a burden on national health systems attributable to household air pollution [9], and further restricts the social and economic development of such countries.

Achieving clean cooking needs a replacement of polluting stoves and fuels with cleaner alternatives, such as cooking with Liquefied Petroleum Gas (LPG) or electricity, which has been widely analysed in empirical studies [10–15]. However, rural areas are usually remote in many lower-income countries with relatively weak infrastructure, and people living there often find it difficult to access modern energy services [16]. LPG needs specialised transportation, storage, and distribution [17], which requires the construction and maintenance of roads. Many areas have also performed experiments exploring the feasibility of cooking by electricity—i.e., utilising induction stoves given their higher efficiency and lower power consumption than electric coil stoves [4]. Still, these were not as welcomed as expected [18,19]. For people living in electrified areas, the additional electricity bills generated by cooking may be a significant burden to their family, thus forcing them to remain on multiple fuel combinations, like biomass [20–22]. Because the average cost of grid connections increases with distance [23], the extension of the grid to specific rural locations may be considered uneconomic and inefficient because of the scattered living conditions and significant transmission losses [24–26]. There are evidences that subsidies from the government are effective in encouraging the use of clean fuels, but they might not be financially sustainable [21,27]. All of these obstacles for poor people to achieve clean cooking by LPG or electricity demonstrate the great significance of the long-term accessibility and affordability of clean fuels from the perspectives of both the government and households.

The technical progress in utilising renewable energies, especially off-grid distributed renewable energy systems, offers potential alternatives to grid electricity [25]. The Solar Home System (SHS) is one of the most promising household renewable energy suppliers, generating electricity with no air pollution or carbon emission. A basic SHS includes a photovoltaic (PV) solar panel, a battery for electricity storage, and a battery charging controller used to employ power for various end-use devices (such as fluorescent lights) [28]. In the early days of SHS, it primarily supplied complementary clean electricity to replace pollutant fuels for some low-power energy services, such as replacing kerosene for lighting in low-income countries [29]. Cases in Ghana [30], Bangladesh [24], Sri Lanka [31], Indonesia [32], and Kenya [33] have illustrated that the large-scale penetration of SHS could effectively help rural communities both in terms of alleviating energy poverty and reducing adverse environmental impacts, such as indoor air pollution. Recently, as the PV production and technology have developed greatly, costs of solar power have fallen dramatically and will fall further [34]. A case study in Sub-Saharan Africa reinforced that the cost of PV power generation within its lifecycle could drop to $0.10/kWh, and even $0.03/kWh if aggressive cost declines in PV batteries were realised. This suggests that the decentralised solar power system and centralised power grid could potentially realise basic parity in cost [35], indicating that SHS has the potential to power more household appliances. Although the initial investment for an SHS is still relatively high even with the falling price of PV panels, it is capable of paying back the initial investment within the first several years of operation through savings in electricity bills [23,24,29]. The most remarkable benefit of SHS is that once installed, the marginal cost of generation is zero [36], effectively encouraging people to use it. Therefore, many low-income

and lower-middle-income countries have been making efforts to deploy renewable solar energy as part of wider electrification programs in rural areas [37].

Traditional sources of clean fuels (LPG and grid electricity) have either accessibility challenges or affordability deficiencies in lower-middle-income countries (LMCs). Due to the potential for off-grid distributed renewable energy systems, this study proposes using SHS as the clean energy supplier for clean cooking. We thus aim to answer whether areas with energy access problems can achieve clean cooking by: (1) To cleaner cooking units utilising induction cooking stoves (ICS); and (2) to cleaner cooking fuels for such ICS utilising distributive SHS. We then proceed with a cost–health benefits analysis to estimate the cost of upgrading to this portfolio and compare the cost with the monetised health losses from indoor air pollution. The results should provide new thoughts for policymakers and other interest groups to solve the energy access problem as well as clean cooking at the same time.

2. Materials and Methods

2.1. Case Countries

As Southeast Asia is one of the regions with a rather severe energy access problem, this analysis will focus on LMCs there (Indonesia, Philippines, Lao PDR, Vietnam, Cambodia, Myanmar) given proximity and data availability. The six LMCs have marked differences in development levels (Table 1). Indonesia, the Philippines, and Vietnam are somewhat more developed, while nearly 80% of the population in Cambodia and Myanmar, as well as 94% in Laos, live without access to clean cooking in 2018 [38]. Laos and Myanmar even have greater than a 40% share of traditional biomass in their total final energy consumption (TFEC), given the unsatisfactory electrification ratio (particularly in rural areas). Fortunately, these six countries have a high potential in solar energy in terms of average Global Horizontal Irradiance (GHI). The total amount of shortwave radiation received ranges from 1600 to 1900 kWh per year in this region, allowing SHS to supply sufficient energy for ICS. This will not only improve the quality of life (especially indoor air quality), but also save on electricity bills.

Table 1. The socio-economic and clean energy access conditions of lower-middle-income countries (LMCs) in Southeast Asia.

Country	Indonesia	Philippines	Lao PDR	Vietnam	Cambodia	Myanmar
Population (thousand)	258,705	103,243	6621	92,695	15,454	52,917
GDP per capita, PPP (current international $) [1]	13,079	8951	7439	7447	4360	6674
Percentage of Urban Population (%) [2]	55	47	34	35	23	30
Healthy Life Expectancy at Birth (years) [3]	61.7	61.7	57.9	67.5	60.8	58.4
Population without Access to Clean Cooking (%) [4]	32	55.8	94	26.9	79.8	79.3
Share of Traditional Biomass in the TFEC (%) [4]	23	19	41	15	21	44
Electrification Ratio in Urban Areas (%) [5]	100	98	100	100	97	79
Electrification Ratio in Rural Areas (%) [5]	89	80	91	98	50	46
Average GHI (kWh/m^2 per year) [6]	1817	1816	1614	1781	1901	1854

[1] World Bank. GDP per capita, PPP (purchasing power parity). [2] ASEAN (Association of Southeast Asian Nations) Statistical Yearbook, 2018. [3] United Nations Development Program. Human Development Indices and Indicators 2018 Statistical Update. [4] ASEAN Center for Energy, 2017. [5] International Energy Agency. Southeast Asia Energy Outlook 2017. [6] Global Solar Atlas. https://globalsolaratlas.info/?c=22,96,9&s=22.421395,96.707535&e=1.

2.2. Cost–Health Benefit Analysis

Cost-Benefit Analysis provides the methodological framework that allows for an overall evaluation of projects and policies by taking account of all cost and benefit parameters [39]. Upgrading cooking stoves and employing SHS can bring many benefits for residents, including better indoor air quality and health conditions, savings in cooking time, reduction of emissions, and associated preservation of forests and ecosystems [40]. This analysis will only address health benefits to see if the health benefits of upgrading to ICS-SHS alone can make the investment in this portfolio worthwhile.

2.2.1. The Costs of ICS-SHS

The principal cost of upgrading to ICS-SHS (P) breaks down into three components: (1) The cost of upgrading to ICS (P_1); (2) the cost of the SHS itself (P_2); and (3) the relevant cost of cookware (P_3). As clean cooking is the major purpose, the generating capacity of an SHS will mainly be designed to meet the demands of the ICS. This analysis thus calculates the total cost of ICS-SHS with the formula:

$$P = \Sigma_{i=1}^{3} p_i \tag{1}$$

Proposition 1. *The cost of upgrading to ICS.*

ICS comes in a variety of types and prices. The most basic ICS contains a single cooktop, while more sophisticated styles may have multiple cooktops and even an oven underneath to cook more cuisines. According to the prices collected in the literature and local websites [41,42], as well as the data from Alibaba [43] (suppliers who have, in the past, exported to Southeast Asian countries), the common price for a single ICS ranges from 10 to 25 USD.

Proposition 2. *The cost of the SHS itself.*

The cost of an SHS depends on its generating capacity, which is determined by the daily electricity consumption of an ICS. Taking into account the actual energy needs and the price tolerances for these areas, this analysis selected the basic single ICS to calculate the range of its energy consumption. The wattage rating of a basic single ICS is usually between 1100 and 1600 kW [43]. According to an analysis performed in India, most households operated ICSs at wattages of 1300 W for approximately two hours a day, and the maximum cooking hours were no more than three hours [20]. This analysis will assume cooking two to three hours per day to estimate the range of electricity consumption for using ICSs for cooking purposes. Therefore, the daily electricity demand is between 2.2 and 4.8 kWh, thus roughly 803 to 1752 kWh of electricity should be supplied per year through an SHS (Table 2).

Table 2. Estimated cost and consumption of electricity of using induction cooking stoves (ICS).

Average Wattage (W)	Cooking Hours (h)	Daily Electricity Consumption (kWh/Day)	Yearly Electricity Consumption (kWh/Year)
1100–1600	2	2.2–3.2	803–1168
1100–1600	3	3.3–4.8	1205–1752

Note: A year = 365 days.

In order to satisfy the generating capacity, the analysis then calculated the required wattages of the PV panels according to electricity consumption with the formula [44]:

$$E = A * r * H * PR \tag{2}$$

where:

E = Energy generated by the solar PV panels (kWh),
A = Total solar panel area (m^2),

r = Solar panel yield efficiency (%),

H = Annual average solar radiation on tilted panels (shadings not included) (kWh/m^2 per year), and

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75).

As r is the yield of the solar panel given by the ratio of electrical power (in kWp) of one solar panel divided by the area of one panel, A*r is the sum power of the solar panel. Normally, the nominal ratio is given for standard test conditions (STC): Radiation = 1000 W/m^2, cell temperature = 25 °C, wind speed = 1 m/s, and air mass = 1.5. The unit of the nominal power of the PV panel in the standard test conditions is called "Watt-Peak" (Wp or kWp = 1000 Wp) (Pstc) [45]. Therefore, the formula can be simplified as:

$$E = Pstc * H * PR \tag{3}$$

H is the annual average solar radiation on tilted panels. The radiation reaching the earth's surface can be represented in a number of different ways. GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground, which is generally applied to PV installations. This analysis will take the national GHI for H.

PR is a value to evaluate the quality of a PV installation because it gives the performance of the installation independently of the orientation and inclination of the panel. It includes all losses that depend on the size of the system, technology used, and the site (Photovoltaic-Software, 2019). A typical value of PR is between 0.7 and 0.8; this analysis assumes 0.75 as an appropriate value. Therefore, the required Pstc (in Wp) for an SHS is in Table 3.

Table 3. Required nominal power under standard test conditions (Pstc) for a solar home system (SHS).

Country	H (GHI) [1]	PR (%)	Required Energy PV Production (kWh/year)	Pstc (Wp)
Indonesia	1817	0.75	803–1752	589–1286
Philippines	1816	0.75	803–1752	590–1286
Lao PDR	1614	0.75	803–1752	663–1447
Vietnam	1781	0.75	803–1752	601–1312
Cambodia	1901	0.75	803–1752	563–1229
Myanmar	1854	0.75	803–1752	577–1260

[1] GHI—https://globalsolaratlas.info/?c=22,96,9&s=22.421395,96.707535&e=1.

The total cost of an SHS (P_2) consists of PV modules, balance of system (BOS), and installation costs, while PV modules typically cost between one-third and one-half of the total capital cost of an SHS [46]. Currently, solar panels are often priced in dollars-per-watt, varying from brand to brand. The average price of a solar PV panel has continued to decline, and is now below 0.32 USD/W [47]. This analysis will assume 0.32 USD/W as the price for the solar panel to estimate its costs. The total installed cost of PV systems can vary widely within individual countries, reflecting the maturity of domestic markets, local labor, and manufacturing costs. For residential and small solar systems, BOS and the installation costs may account for 55% to 60% of the total cost of an SHS [46]. Therefore, the minimum to maximum total costs of an SHS are estimated in Table 4, indicating that an SHS would have large fluctuations in costs according to the power of the ICS, panel efficiency, and installation costs in the six countries, etc.

Table 4. Total cost for an SHS.

Country	Panel Price (USD)	P_2 (USD) (BOS and Installation = 55%)	P_2 (USD) (BOS and Installation = 60%)
Indonesia	189–411	419–2857	471–3214
Philippines	189–412	419–2859	472–3216
Lao PDR	212–463	472–3216	531–3618
Vietnam	192–420	427–2915	481–3279
Cambodia	180–393	401–2731	451–3072
Myanmar	185–403	411–2800	462–3150

Proposition 3. *The relevant cost of cookware.*

As an ICS heats food through the heating coil without a flame, it needs special cooking utensils and appliances to replace the old pots that can be used directly on traditional stoves or gas stoves. Different types and styles of cooking utensils vary greatly in price. According to the price data from Alibaba and local websites, the price of a single pot or pan suitable for an ICS can be as low as 3 USD, while the more common price is around 10 USD. In the case of Ecuador, induction-compatible cookware (e.g., pots, pans) is purchased at prices ranging from 25–75 USD for a basic set (i.e., three pots with lids and a frying pan) [19], which will also be adopted in this analysis.

2.2.2. Health Benefit Analysis

There are several methods for evaluating the economic loss of air pollution to health. The dose-response relationship between air pollution and diseases must be established first, i.e., the mortality and morbidity caused by these air-quality-related diseases. The value of such health effects can thus be monetised. Currently, the mainstream methods to monetise health benefits include:

- Human Capital Method: Estimate the value of human capital, assuming that the economic loss due to morbidity and mortality is equal to the value of the individual's future contribution to production if he or she continues to work healthily [48];
- Cost of Illness: Measure the direct cost of a disease to the whole society, including the loss of income caused by the disease and medical expenses, such as hospital care, household health care, the services of doctors and nurses, and other related expenses [49]. This method has been criticised because it may ignore the willingness to pay of individuals, which is different in different subgroups [50];
- Willingness to Pay: Estimate how much a person is willing to pay for reducing the risks of illness or death [51]. This method is greatly influenced by subjective factors, which makes it difficult to attain an objective value of death risk;
- Disability-Adjusted Life Years (DALYs): Refers to all of the loss of healthy life years, including the loss of life years caused by premature death and diseases. This method not only considers the value of life, but also takes the non-fatal consequences of diseases into account, such as the decline in patients' life quality [52]. DALYs continue to be monetised using the value of a statistical life year (VSLY). VSLY is the annualised equivalent of the value of the statistical life (VSL), which is the common method for calculating the cost of mortalities by transferring a base VSL from the United States calculated labour market estimates from Census of Fatal Occupational Injuries data, coupled with utilising income elasticity to demonstrate adjustments for differences in income between the United States and the country of interest [53,54]. DALYs enable the comparison with estimates of different diseases and foreign countries in monetary expenditures, where the lack of morbidity data may lead to an underestimation of the actual impact [55].

As economic costs of health often include both direct costs and indirect costs, the above methods are often used simultaneously or crosswise to make more reasonable cost estimates. This analysis chose to estimate the health benefits that upgrading to ICS-SHS can bring by monetising the national household air-pollution-attributable deaths and Disability-Adjusted Life Years from the WHO's Global Health Estimates 2016. Given that VSLY is the annualised equivalent of VSL, people of different ages place different emphases on reducing their risks of death. VSLY thus changes with age and reaches a peak about two-thirds of the way through life expectancy [56]. By yielding 133 unique VSL estimates published between 1995 and 2015, Schlander et al. transformed these estimates into VSLY, using WHO life expectancy tables, a 3% discount rate, consumer price indices for inflation adjusting, and purchasing power parities for currency conversion. This analysis utilised their median VSLY estimates in North America (271,200 EUR, approximately 304,500 USD) as the base VSLY [57] (Table 5).

Table 5. Total economic cost of household air pollution.

Country	Income Elasticity (Compared to U.S.) [1]	VSLY (Million USD) (Baseline = 0.3045 Million USD)	Household Air Pollution Attributable DALYs (Years) [2]	DALYs per Capita	National Statistical Health Loss (Million USD)
Indonesia	0.062	0.02	4,426,747	0.017	83,123
Philippines	0.064	0.02	2,857,357	0.028	55,376
Lao PDR	0.031	0.01	237,432	0.036	2252
Vietnam	0.036	0.01	936,483	0.01	10,159
Cambodia	0.019	0.01	372,442	0.024	2174
Myanmar	0.021	0.01	1,589,945	0.03	10,086

[1] Schlander, M., et al. New estimates of the willingness-to-pay for a statistical life year: A systematic review of the empirical economic literature. [2] World Health Organization (WHO) Global Health Estimates 2016, available online at https://www.who.int/healthinfo/global_burden_disease/en/.

This benefit assessment has two important limitations: (1) It is oriented only towards health without attempting to quantify other values that typically require contingent valuation estimates; (2) VSL and VSLY data are not readily available in the six countries, and, thus, data collected in other areas were modified to represent the situation in this analysis. The collection of site-specific data is considered to be an essential need for improved environmental benefit assessment in the future, but the approach employed nonetheless provides a preliminary estimate of the magnitude of such benefits.

3. Results

3.1. Cost Calculation

Based on the above analysis, the total cost of an ICS-SHS portfolio (P) contains the cost of an ICS (P_1), an SHS (P_2), and cookware (P_3) (Table 6). As this analysis set P_1 and P_3 in fixed ranges, the total cost is mostly influenced by P_2.

Table 6. Total cost of an ICS-SHS in Southeast Asia.

Country	P_1 (USD)	P_2 (USD)	P_3 (USD)	Minimum P (USD)	Maximum P (USD)
Indonesia	10–25	419–3214	25–75	454	3314
Philippines	10–25	419–3216	25–75	454	3316
Lao PDR	10–25	472–3618	25–75	507	3718
Vietnam	10–25	427–3279	25–75	462	3379
Cambodia	10–25	401–3072	25–75	436	3172
Myanmar	10–25	411–3150	25–75	446	3250

3.2. Health Benefit Calculation

This analysis collected data addressing the population without access to clean cooking from the IEA and estimated the number of households without access to clean cooking in the six Southeast Asian LMCs based upon average household size data collected from UN Population. The corresponding health benefits assessment per household is identified in Table 7.

Table 7. Health benefit assessment per household.

Country	Population without Access to Clean Cooking (Million) [1]	Average Household Size (Number of Members) [2]	Estimated Number of Households without Access to Clean Cooking (Million)	Health Benefit Assessment (Million USD)	Health Benefit Assessment per Household (USD)
Indonesia	82.7	4	20.68	83,123	4020
Philippines	62.1	4.7	13.21	55,376	4191
Lao PDR	6.6	6 [3]	1.10	2252	2047
Vietnam	37.4	3.8	9.84	10,159	1032
Cambodia	13	4.6	2.83	2174	769
Myanmar	50.8	4.2	12.10	10,086	834

[1] Population without access to clean cooking, International Energy Agency (IEA)—Energy access database, https://www.iea.org/energyaccess/database/. [2] Average Household Size, UN Population—Household Size and Composition 2018, https://population.un.org/Household/index.html/. [3] Average Household Size of Lao PDR, WHO—Country Profile of Lao PDR, http://www.wpro.who.int/laos/about/lao_country_profile/en/.

3.3. Cost–Health Benefit Analysis for ICS-SHS

Acting as a fundamental power provider in unelectrified areas or a supplement in electrified areas, the expenditure on an SHS is usually one time. The results in Table 8 show that the yearly health benefits brought by ICS-SHS alone can at least surpass the estimated minimum cost for an ICS-SHS in the six LMCs in Southeast Asia. The benefits can even exceed the estimated maximum cost for an ICS-SHS in Indonesia and the Philippines.

Table 8. Comparison of cost and health benefits for an ICS-SHS.

Country	Minimum Cost for an ICS-SHS (USD)	Maximum Cost for an ICS-SHS (USD)	Health Benefit Assessment per Household (USD)
Indonesia	454	3314	4020
Philippines	454	3316	4191
Lao PDR	507	3718	2047
Vietnam	462	3379	1032
Cambodia	436	3172	769
Myanmar	446	3250	834

4. Discussion

4.1. Uncertainties of Cost

From the results, we can see a significant gap between the minimum and the maximum costs for the ICS-SHS portfolio. The cost calculations are subject to considerable uncertainties, especially the cost of SHS. For example, the price of PV modules, balance of system (BOS), and installation costs may vary largely in different countries, while the total cost is highly dependent on the price of PV modules. In this study, the costs of BOS and installation are estimated according to the fixed ratio to the PV modules given local data unavailability. This analysis also uses the national GHI to estimate yearly electricity generation, without taking into account the factors like rainy days, SHS transmission loss, etc. Besides, the GHI is the average level across a country, regardless of regional differences. Each individual datum has its uncertainty, which leads to more significant uncertainty when these data are calculated together. However, this analysis aims to provide a rough range of the cost, as well as offering references for those interested in clean cooking, such as households, sponsors, and policy makers.

4.2. Financial Options to Support SHS

It is worth noting that in the poorer LMCs in Southeast Asia, such as Laos, Vietnam, Cambodia, and Myanmar, although households in these countries have the most severe clean cooking access problems, the estimated health benefits they can obtain from upgrading to ICS-SHS are smaller and much closer to the estimated minimum cost of the upgrade. Given the benefits that upgrading to clean cooking may bring, in practice, however, renewable power generation is historically characterised by high initial capital [58]. Although the upgrade to ICS-SHS is most needed in these countries, given the estimated relatively minor gap between the health benefits and cost, it may prove difficult to persuade these households with limited payment ability to invest in ICS-SHS. The question of whether this portfolio could be used as a solution to clean cooking also depends on how and who to pay for an SHS when it is beyond the direct beneficiaries' affordability, and who might help bear such costs.

4.2.1. Public Policies and Finance

The universal access to clean energy through innovative public-private partnerships is possible, but will initially require substantial investments in capacity development and market-motivating policies. Public funds can account for a significant proportion of the total cost of decentralised energy investments, especially in the early stages [59]. Rural electrification is not generally considered a lucrative market, especially in developing countries [60]. It therefore requires the promotion and input from the government. In terms of public policy frameworks, the most powerful incentives for developing countries to deploy renewable energy are clear national targets for renewable energy [61]. A review of 17 energy access initiatives for the poor in the Asia-Pacific region by the United Nations Development Program (UNDP) concluded that countries that were able to achieve significant expansion benefited from the strong commitment reflected in policy documents and supported by budgetary allocations of their national governments [62]. Uncertainty about whether governments would continue to provide financial support for specific clean energy opportunities might discourage investors from investing or require higher returns to compensate for this risk [63]. Therefore, the government should consider setting national goals for the development of renewable energy, making full use of public policy tools, and providing more fiscal resources in order to improve the feasibility of rural electrification.

Appropriate subsidies are crucial, although the subsidies themselves do not necessarily guarantee the success of the project. For example, the terms and conditions of rural electrification projects often do not align with commercial loans [64]. Poor rural residents may be unable to obtain loans without collateral or guarantors, etc. In rural areas, income usually depends upon the harvest or other irregular activities, and more flexible payment times may therefore be required [65]. At this point, the government needs to step in and provide financing channels or subsidies to commercial banks or private enterprises that provide loans or instalment payments for the SHS project in order to encourage such development in the rural energy sector. The eventual policies may be likely to be a basket, containing tax and tariff elimination on clean energy installations [66], subsidy reduction on fossil fuels, and promotion of income-generating activities for end-users of SHS services [67].

4.2.2. Market-Driven Finance

There are two main financial models for large-scale development of rural electrification: Pay-for-service models and microcredit schemes.

One problem for SHS users in remote rural areas is the lack of maintenance services. The pay-for-service model, first adopted in the Pacific region, is one in which energy companies remain the owners of installed equipment and, if necessary, are responsible for maintenance or repair (for a fee) [68]. As remote residents have limited access to technical resources and bank loans, the pay-for-service model is realistic for overcoming such obstacles in rural electrification by SHS.

Many rural SHS financing projects based on microfinance institutions have successfully expanded rural electrification, primarily in South Asian countries, such as Sri Lanka, Bangladesh, and India [69].

Currently, the innovative microfinance model Pay-As-You-Go (PAYG) has become one of the most commercially viable solutions to provide decentralised energy to rural and remote communities in developing countries. Household affordability is a key challenge for energy companies, and PAYG's simple payment scheme makes solar power affordable and allows households to gradually own these systems [70]. The PAYG model also provides user training, ongoing maintenance, and minimisation of investment risk. PAYG has seen enormous success in Sub-Saharan Africa, and Kenya has pioneered this model as a cost-competitive modern alternative to kerosene. With modern information technology and mobile connectivity, PAYG can offer online payments flexibly, making the system more affordable. The ability to remotely block SHS without payment reduces the transaction cost of collection and investment risks for microfinance companies [71].

4.2.3. Non-Governmental Finance

Since the 1990s, the World Bank has recognised that SHS can contribute to rural electrification. For the past 20 years, the World Bank and Global Environment Facility (GEF) have approved 12 SHS projects to provide basic energy services, such as lighting, broadcasting, television and the operation of small electrical appliances, to rural households that cannot be connected to the grid [72].

The Dutch Development Organization (SNV), a non-profit international development organisation from the Netherlands, has implemented a technical assistance program in Cambodia aimed at promoting the development of a sustainable off-grid solar industry locally to improve access to energy for rural households, which is the largest domestic solar market development to date. By September 2016, 1387 rural households had purchased certified solar products from one of six certified solar suppliers. Fourteen of Cambodia's 25 provinces had provided high-quality products and related customer services. Half of those sales used one of 687 solar loans, totaling 355,524 USD, from four microfinance partners. The implementation of the first 12 awareness-raising campaigns helped educate some 12,000 rural Cambodians. Generally, governmental and non-governmental organisations have been playing an essential role in rural electrification [73,74].

4.3. Limitations of SHS

Admittedly, SHS is a clean household energy supplier with great potential, especially as the price of PV panels has kept declining in recent years. There are several reasons that SHS has not been as popular as expected even with several financing modes in developing countries. Firstly, solar energy is an intermittent energy source susceptible to weather, implying its weaker reliability than grid electricity. As SHS cannot generate electricity at night or on cloudy days, batteries are thus needed for energy storage. If a household relies solely on SHS to electrify their home, there may be insufficient power at night and in the rainy season. While energy storage batteries help reduce load and stabilise the system, they also push costs up further. Secondly, the substantial upfront cost has always been a disadvantage hindering SHS. Although the cost–health benefit analysis in this study proves that the health benefits brought by the adoption of SHS are far higher than the investment in the long run, the initial cost may be a real obstacle for poor people; after all, health is something that can be squandered in the future. This is why this study has emphasised the diversification of financing models. However, considering that many countries still provide subsidies for the consumption of traditional energy, a further challenge to SHS will be the chronically low prices of fossil fuels, which may push back its ability to compete.

4.4. Long-Term Motivations

Regarding the health benefit assessment, every family in these six countries can enjoy significant health benefits during the year from upgrading to clean cooking. The reduction of cooking-attributable indoor air pollution may be directly reflected in fewer illnesses and lower medical expenses. In the long term, improving indoor air quality will bring better health conditions and longer lives for whole families, especially women and children who spend longer times indoors and are thus more vulnerable

to indoor air pollution [5]. In particular, the investment is basically one-off, while the health benefits will exist throughout the entire utilisation of ICS-SHS, which makes the portfolio more attractive to motivate the willingness to pay.

Meanwhile, SHS provides clean energy access to unelectrified households, the impacts of which will not be limited to replacing fuel itself, but also diffuse to the equality, opportunity, and future of these households. For instance, women and children are almost always responsible for household fuel collection in undeveloped countries, given their lack of educational opportunities and inability to generate income. However, with available clean energy, women can devote time to other productive activities with higher returns, and children can have more time for education [75]. Although the power generation of the SHS in this study was designed for induction stoves, the excess power can be stored in a battery and used in other appliances. Electricity brings more possibilities for people to enjoy modern conveniences, which are also helpful in lifting poor people out of poverty.

5. Conclusions

This study proposes that renewable solar energy be employed to supply power for induction cooking stoves (ICS) through solar home systems (SHS), thereby realising clean cooking, improving indoor air quality, and solving the energy access problem simultaneously.

Based upon data availability and proximity, this analysis selected lower-middle-income countries in Southeast Asia (Indonesia, Philippines, Lao PDR, Vietnam, Cambodia, Myanmar) as the research targets for conducting a cost–health benefit analysis of such an approach, estimating both the costs and health benefits of upgrading to ICS and SHS. In the analysis, the cost of upgrading to the ICS-SHS mainly consists of the cost of an ICS, an SHS, and cookware. The Disability-Adjusted Life Years (DALYs) and the value of a statistical life year (VSLY) were calculated to estimate the health benefits. The results suggest that the health benefits brought by ICS-SHS alone can at least surpass the estimated minimum cost for an ICS-SHS in the six LMCs in Southeast Asia. Although the relatively high initial cost of an SHS tends to be an obstacle in its popularisation, there are financial supports available from governments, international organisations, non-governmental organisations, and private companies that have multiple experiences in solely or jointly funding the installation and operation of SHSs in rural areas. These cases have enlightened late-comers to pay attention to the motivation from national strategies, the cooperation within different institutions, demand-creating, and relevant risks. This study thus reveals the feasibility of ICS-SHS in achieving clean cooking and addressing indoor air pollution as well as energy access problems in the six LMCs of Southeast Asia, providing a reference for other countries facing similar problems.

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