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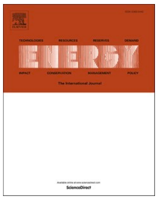

Optimal deployment of energy services for economic upliftment of low-income communities: A South African case study

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ABSTRACT

Low-income communities face a causality dilemma: A lack of energy services hampers income growth and insufficient income hampers energy service provision. Interventions delivering cost-effective energy services can address this dilemma, triggering a virtuous cycle of economic upliftment. While several studies have investigated cost-effective energy supply to low-income communities, a gap exists regarding holistic optimization of energy service deployment at different levels of economic development. Hence, a novel energy system model of a South African village is presented to optimize deployment and hourly dispatch of energy supply and energy services to recover time lost to poverty-related activities (e.g., gathering wood and water). Results showed that an optimized technology rollout can save each person over 1500 productive hours per year at an average cost below 0.2 $/hour. The model also identified the optimal order of technology deployment for driving economic development. Interestingly, an electrical grid connection was of minor importance because local mini-grids could economically supply the modest power demands of lighting, refrigeration, water pumping, and cleaning, while energy-intensive cooking and water heating can be economically performed using fuels and solar heaters. Detailed studies of individual low-income communities are recommended to outline optimal technology deployment strategies and reveal the low costs involved.

1. Introduction

Reliable access to modern energy and clean water supply is often taken for granted in the developed world. Unfortunately, this is not the case everywhere. In 2017, the global electrification rate hit 89%, which means 840 million people did not have access to any electricity [1]. This is a significant improvement compared to the 1 billion disconnected people in 2016, but under current policies an estimated 650 million people will still lack electricity access in 2030, 90 % of them living in Sub-Saharan Africa [2]. The same applies to energy supply for heating food and water, since 2.4 billion people still rely on inefficient open fires, often fuelled by wood and dung [3]. These fuels cause millions of preventable deaths annually [3] as well as ecosystem impacts from unsustainable wood harvesting.

Although the link between energy consumption and economic growth becomes complex in more developed societies, there is a clear unidirectional causality from energy consumption to growth in low-income regions [4]. However, this obvious trigger for economic upliftment is not being successfully exploited in regions like Sub-Saharan Africa [4]. Indeed, data from the BP Statistical Review [5] shows that the 15 % of the world population living in Sub-Saharan Africa consume only 1.9 % of global energy (1.1 % when excluding South Africa).

Capitalizing on the power of modern energy services (i.e., labour-saving technology powered by a reliable modern energy supply) to eradicate poverty requires a difficult causality dilemma to be overcome: Modern energy access is needed to increase economic productivity and higher economic productivity is needed to afford modern energy. When insufficient modern energy services are available, the poor must spend a major part of their productive time performing tasks that could easily be performed by technology, e.g., fetching water and wood, heating water over open flames, growing and preserving food with traditional methods, and washing clothes and dishes by hand by a river or central tap. There are also large indirect drains on the time and productivity of poor communities lacking modern energy services, such as illness from

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dirty cooking methods and insufficient light to facilitate productive activities and limit crime after sunset. Other self-sustaining effects of poverty, including substandard healthcare and health insurance [6], various debilitating diseases of poverty [7], teenage pregnancies [8] and limited reach of modern contraceptives [9], and poor educational opportunities, particularly for girls [10], further hamper low-income communities in acquiring the time-saving and productivity-enhancing energy services needed for sustained economic upliftment.

As a result of these complex and interconnected factors, the "lottery of birth" remains the primary determining factor of whether someone will live a life of material lack or abundance. For perspective, the global income disparity remains enormous [11], with the 95th percentile (80 $/day) enjoying about 70× greater income per capita than the 5th percentile (1.2 $/day). Reducing this extreme inequality of opportunity is proving very difficult due to low social mobility on the low-income side of the distribution caused by the aforementioned factors. For example, the Global Social Mobility Index report found that the average person born in the bottom 10 % in a developing country such as South Africa or Brazil would need nine generations before their descendants reach the middle of the income distribution [12]. Meanwhile, rich countries with strong social programs such as the Nordics reduce this lag in social mobility to 2–3 generations.

Although the present study is focussed on cost-effective energy service delivery, it is important to emphasize that this intervention by itself is unlikely to achieve the desired step-change in social mobility and economic upliftment. The problem of uplifting billions of people trapped in poverty is twofold: 1) Practical and cost-effective deployment of energy services is needed to free up time and initiative within low-income communities and 2) educational and other social programs are required to direct this newly freed time and initiative toward effective socio-economic development. If concurrently deployed, these two interventions can create a virtuous cycle where time freed by modern energy services creates the income growth required to purchase additional energy services to free up more time. The present study is focussed on the first part of this challenge, assuming that the second will be implemented in parallel. Although beyond the scope of the present work, strategies for effectively deploying the time and initiative freed by modern energy services in poor communities is a key area for future investigation.

Optimizing the provision of modern energy supply and energy services to low-income communities is a multifaceted problem that can be subdivided into three categories: 1) energy supply modelling, 2) energy service deployment modelling, and 3) technology prioritization across different levels of economic development. In category 1, multiple prior studies have investigated electrification with different technology mixes, e.g., solar and battery storage [13,14], solar, wind, and diesel generators [15], solar and diesel [16], or solar, hydro, and diesel [17]. Although such electrification studies provide valuable insights, the inclusion of other energy supply options, e.g., fuels and solar heat, is required for a more complete assessment of the optimal energy supply mix in low-income villages.

Regarding category 2, cooking heat is the most studied energy service. For example, the advantages and disadvantages of various clean cooking sources (electricity, natural gas, LPG, kerosene, biomass, and biogas) have been well described [18], as well as some novel fuel stove technologies [19]. Detailed modelling of the optimal deployment of various types of cooking technologies and other energy services is rare, e.g., a relatively old study of cooking technology deployment in South Africa [20]. Although sometimes considered in static demand profiles for energy supply modelling, the optimal deployment of energy services such as water supply, water heating, lighting, refrigeration, and cleaning in low-income communities still requires further study.

Considering category 3, the literature review could not identify existing studies presenting a formal methodology for prioritizing technologies at progressive levels of economic development. An additional challenge in category 3 is the need for quantitative data on increasing energy service demand with economic development. Existing demand projections focus on predominantly on electricity supply [21], often with broader scope including global or national trends [22,23].

The present work presents the first attempt at uniting all three categories into a holistic modelling framework to concurrently optimize energy supply and energy service provision in low-income communities across a range of economic development levels. The novel energy system model presented optimizes investment and hourly dispatch of a broad range of technology options for electricity, fuel, and heat supply, as well as energy services covering lighting, cooking, water supply, water heating, cleaning, and refrigeration. A key novelty is the formalized prioritization of technology deployment to ensure that the time-savings offered by energy services justify their cost across a range of economic development levels. This prioritization is ensured by placing a value on time (rising with economic development) and allowing the model to optimize for the trade-off between technology cost and time cost.

2. Methodology

The model deployed in the present study is extensive and will only be presented in condensed form below. A complete outline is available in the Supplementary Materials file attached to this study. Furthermore, the full model, programmed in GAMS, together with an Excel file containing all quantitative model input data can be downloaded online [24].

2.1. Model structure

The model was built from the foundation of prior country-level energy system models (e.g. Ref. [25]). Each hour of a chosen year (2019) is simulated, and the objective of the model is to optimize the deployment and hourly dispatch of all available technologies to satisfy predefined hourly demand profiles at the lowest possible cost. This is done by solving balance equations for all modelled energy services stating that supply must equal demand in each hour. These balance equations are subject to various constraints (e.g., a technology cannot deliver an output exceeding its installed capacity). In addition, multiple constraints are imposed describing interdependencies between different technologies as illustrated in Fig. 1.

2.2. The value of time (VoT)

A wide range of technology options are considered, ranging from the most primitive (e.g., candle light, walking to the river to fetch water, or cooking on wood/dung fires) to the most modern (e.g., fully electrified homes with all necessary labour-saving devices). The primary methodological novelty of the present study is that the time cost of every relevant technology is estimated next to its monetary cost (see the Supplementary Material for details). For example, wood for cooking is modelled to have no monetary cost but considerable time costs for gathering this fuel. Thus, if the residents' time is valued at a very low level, it will be most economic to gather wood (pay in time rather than money) instead of purchasing a more expensive fuel (pay in money rather than time). However, as economic upliftment increases the value of every hour of productive labour, there will be a point at which fuel/electricity purchases for cooking will become the least-cost option.

The model is structured to solve this optimization problem across the wide range of available technologies, each with costs specified in terms of money and time. To enable such an optimization, a monetary value, referred to as the Value of Time (VoT), is put on each hour of productive labour associated with the different energy supply and energy service technologies considered. Formally, the VoT represents the monetary valuation of each hour that can be saved by deploying modern energy services or, indirectly, the value an average citizen can create from an hour freed up by technology. This is an important consideration linked to the two-fold poverty alleviation challenge mentioned in the

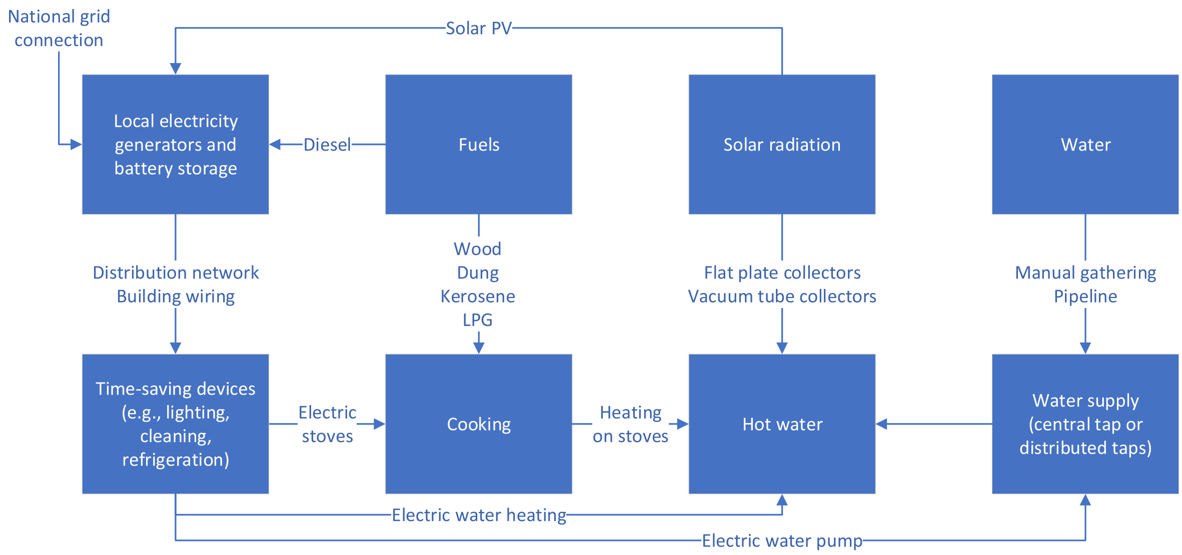

Fig. 1. An illustration of the various connections between technologies implemented in the model.

introduction: Without educational/health/entrepreneurial programs ensuring that additional time can be used productively, the VoT will remain low, and the model will find an optimum with limited deployment of time-saving technologies.

Depending on the VoT specified, the model will modify the technology mix to find the optimal balance between monetary and time costs. By gradually increasing the VoT, the transformation of the technology mix under gradual economic upliftment can be simulated. The results presented in this work illustrate this transformation of the optimal technology mix via simulations completed over a wide range of VoT assumptions, ranging from abject poverty (0.0005 $/hour) to a moderate level of economic development (4 $/hour).

Table 1
Summary of the sources for key model assumptions. Full descriptions are available in the Supplementary Material, and calculations can be viewed in the model input Excel file shared online [24].

Assumption	Source
Electricity generation	
Wind and solar generators	[14,16,17,26–29]
Diesel generators	[17,26,27]
Batteries	[14,16,26–28]
Village grid connection	[30]
Grid electricity	Own estimates of centralized generation and transmission costs from country-level modelling [25]
Village distribution grid	Own estimates based on European levelized transmission and distribution costs, adjusted for low demand.
Electrical wiring of buildings	[31] with own adjustments for cases with low electricity demand.
Wind and solar availability	[32]
Miscellaneous home and business electricity demand profiles	[13,16,28,29,33], complemented with own estimates.
Water supply and heating	
Water storage tank	Triple purchase price of [34] to account for transport and installation.
Electric pump	[35]
Hand pump	Assumed as half electric pump costs.
Water piping	[36]
Solar water heaters	[37–40], Vacuum tube collector “Thermomax DF100-30” [41], Flat plate collector model “Grant Solar Sahara” [42].
Solar heat collection profiles	[32]
Water demand profiles	[43–47], complemented with own estimates.
Cooking	
Cooking stoves	[18,19,48–50]
Cooking fuels	[18,19,48–52]
Cooking health impacts	[53–55]
Rain profile (cooking indoors)	[32]
Cooking heat demand profile	[49,56], complemented with own estimates.
Lighting	
Streetlights	[57]
LED efficiency	[58]
Home LED light and candle	Own estimates from retail websites.
Sunrise and sunset profile	[32]
Lighting demand	[13,27,33], complemented with own estimates.
Appliances	
Fridges, washing machines, dishwashers, vacuum cleaners	Own estimates from retail websites.
Outside temperature profile	[32]
Heat transfer coefficient (fridge heat losses)	[59–62]
Washing, dishwashing, vacuum demand	Own estimates.

2.3. Model assumptions

A South African village in the Limpopo province called Tshiungani, home to about 2100 people, was selected as a representative case study of a low-income community in sub-Saharan Africa. This specific village was chosen because one of the co-authors grew up there, giving him a unique perspective to help fill in the substantial gaps in the data required to provide the model with energy service demand patterns (the first section of the Supplementary Materials provides an informative description of energy services in the village). However, the model is built to apply to a broader developing world perspective, covering a wide range of economic development levels in any region with good solar resources (both for electricity and water heating), significant distances to the closest supply of wood and fresh water, and the possibility to connect to a distant central electricity network.

The sources of key model assumptions are acknowledged in Table 1, and a full description of the various technology costs (time and money) and performance assumptions can be found in the Supplementary Material. As shown, empirical data was gathered wherever possible, but own estimates had to be used in some cases.

2.4. Energy service demand growth

Another important assumption in the model is the increase in demand for energy services with economic development. Such increases can be dramatic and add greatly to the cost of reaching the next level of development. As detailed in the Supplementary Materials, data for electricity [63] and water [64] for South African households at three different income levels were used to create the trends illustrated in Fig. 2. Domestic and business electricity demand grows most strongly with income levels (a well-established trend in lower-income communities [65]), while water demand also grows steadily, although at a slower pace and from a higher base. Other energy services exhibit trends indicating a relatively steady basic necessity at low VoTs, followed by faster growth at higher VoTs when economic development reaches levels where energy services can start to be enjoyed for convenience instead of necessity.

2.5. Holiday demand

Furthermore, demand for miscellaneous home electricity, cooking heat, water, and heated water is increased by 50 % for three weeks during Easter and Christmas when migrant workers return home. These holiday demand spikes, which are common in low-income communities, represents an important capacity challenge for energy provision.

3. Limitations

The results presented and discussed in the following section must be interpreted with care due to several important model limitations:

1. There is a considerable degree of uncertainty in the demand profiles for the various services included in the model with increases in VoT (Fig. 2). Uncertainty stems from limited empirical data, uncertainties regarding behaviour and efficiency changes, and the simplification of scaling all hourly profiles linearly with total demand instead of attempting to modify the shape of every profile with varying levels of economic development.
2. Similarly, the time cost of various activities is uncertain, particularly assumptions about the indirect time savings from better lighting (to increase productivity after sunset and prevent crime) and cleaner cooking (to avoid time lost to poor health).
3. Each simulation is completed as a greenfield system sized optimally for a given VoT. In practice, certain investments such as electricity transmission networks will need to be substantially oversized in

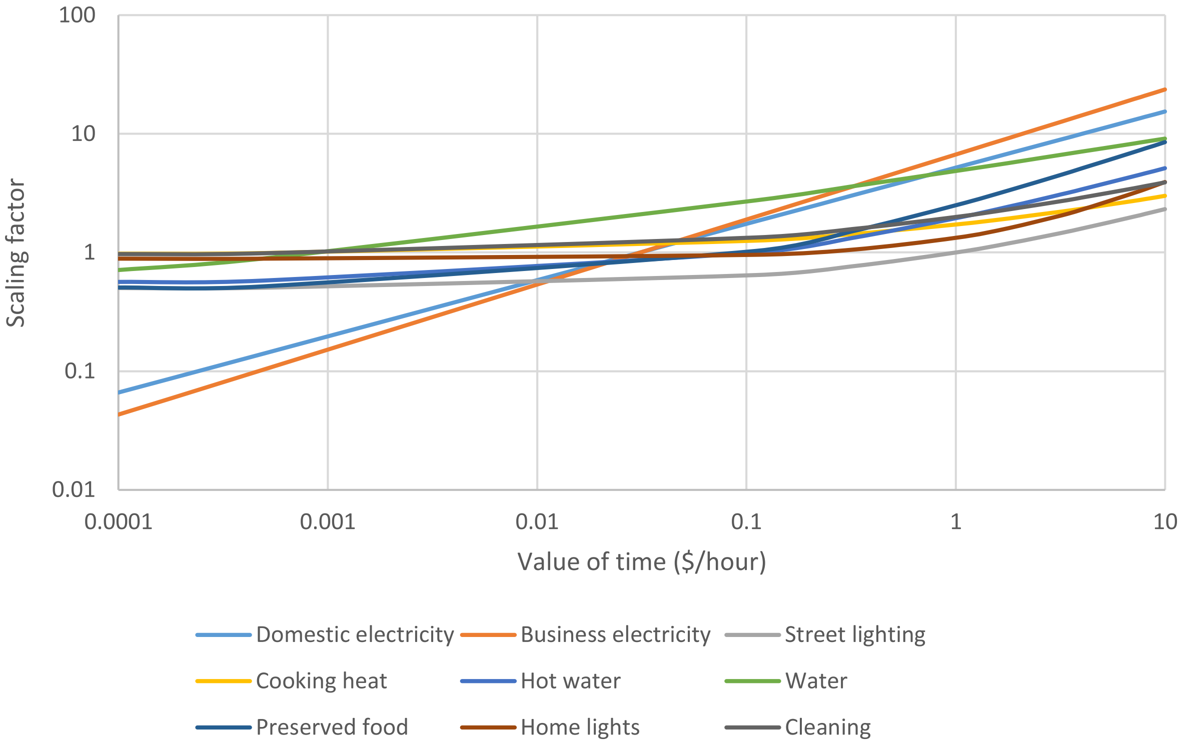

Fig. 2. Scaling of the nine different demand profiles with VoT. A scaling factor of 1 represents the following quantitative values for the whole village of 422 households (all energy units represent final energy): Domestic electricity = 51.7 MWh/year, Business electricity = 76.4 MWh/year, Street lighting = 14.9 MWh/year, Cooking heat = 127.0 MWh/year, Hot water = 273.3 MWh/year, 42.3 Ml/year, Preserved food = 211 kg/day, Home lights = 12.8 MWh/year, Cleaning = 63.3 kg/day laundry, 844 kg/day dishes, and 422 dust units per day.

anticipation of future growth because frequent incremental capacity upgrades will be too expensive and impractical.

4. The model implicitly assumes that people behave rationally in the exchange of money for time. In reality, factors such as tradition and momentary convenience will regularly lead to economically suboptimal behaviour. Clear communication and education to achieve efficient behavioural patterns are therefore necessary next to optimal technology deployment.
5. Technologies are dispatched on the assumption of perfect information availability across the system. For example, demand response services from electric solar water heating and water pumping are automatically employed by the model to minimize system costs, which would require relatively sophisticated IT services to be implemented in practice.
6. Due to modelling complexity, sectors such as transportation (e.g., demand response from charging small electric vehicles) and sanitation (e.g., biogas production from wastewater treatment) were neglected. Future work to include these sectors could reveal the potential for considerable additional time savings at low costs.
7. The VoT is assumed to be constant for all people in the village. Real societies include people with widely varying abilities and ambitions, which would create a broad span of VoT across the population, allowing those whose time is valued less to economically complete more time-intensive tasks for those whose time is valued more.
8. The possibility of adjustable demand in response to electricity prices is ignored. For example, the village could integrate solar more economically if the fixed hourly business and household electricity demand profiles currently imposed in the model could include some degree of flexibility to consume more power on sunny days and less on cloudy days.

Overall, limitations 1 & 2 increase general uncertainty, 3–5 will tend to underestimate the cost of saving time, while 6–8 will tend to overestimate the cost of saving time. The relatively high discount rate employed in the study (10 %) was selected to counteract the possibility that the net effect of all these limitations may skew the results to the optimistic side. If a discount rate of 5 % was employed, for example, the modelled cost of saving time would be about 20 % lower.

4. Results and discussion

Results will be presented and discussed in three subsections: 1) an exploration of how increases in the value of time influence the optimal technology mix, 2) quantification of the cost of saving each incremental unit of time, and 3) a sensitivity study to the effect of not having the possibility of a grid connection and halving the cost of green technologies.

The detailed system scale model results files for all cases are shared online [24], where deeper insights can be gained from hourly profiles of the optimal dispatch of the various technologies.

4.1. Technology evolution with the value of time

The simulated village has the possibility to deploy a wide range of technologies to save time in the form of direct labour, lost healthy life years, or lost productivity. As the value placed on each hour of time is increased, the model gradually introduces more expensive time-saving technologies, thereby saving the most cost-effective hours first. This subsection reveals the order in which technologies are deployed to optimally exchange money for time.

4.1.1. Electricity supply

As shown in Fig. 3 (top), the value of time (VoT) has a large influence on the optimal electricity mix. Connecting to the grid (here assumed to require a 10 km connection) becomes competitive around VoT = 0.03 $/hour. Below this value, the total electricity demand is too low to justify such an investment. As electricity demand grows with VoT, the connection to the national grid becomes increasingly attractive until all power is derived from the grid at VoT = 0.3 $/hour. However, beyond 1 $/hour, a small share of local solar PV returns to the optimal mix due to an increased demand for electrical appliances with daytime use patterns aligning with solar PV generation. Wind power is not deployed because the wind resource is poor relative to the solar resource in the chosen location.

Despite the good solar resource in the simulated location and a halving of solar and battery costs from literature values (see the Supplementary Material), dispatchable diesel or grid electricity still command the majority share in the optimal technology mix. At low levels of economic development, the low solar share can be explained by a demand pattern concentrated mainly in lighting and a few basic domestic appliances like radios or phones (Fig. 3, bottom). Naturally, lighting demand is misaligned with solar supply, and, under the present assumptions, running diesel generators at night was more cost effective than running lights on solar electricity stored in batteries. The daily electricity peak occurs at night up to VoT = 0.1 $/hour, preserving the role of night-time diesel generators.

As the economic development level in the village increases, the share of lighting in electricity demand declines, while electricity demand rapidly expands as a range of other end-uses become attractive. Many of these end-uses, such as water heating and electricity use by small businesses, occur in daytime that aligns better with solar. At this point, however, a connection to the grid is already more economically attractive than further expanding local solar power.

The VoT levels where electrical appliances are introduced in Fig. 3 (bottom) serves as a direct indication of how effectively various electrically powered energy services save time. Electrical water pumping and refrigeration in centralized stores are already introduced at VoT = 0.016 $/hour due to the large number of hours required to carry water and preserve food via traditional methods. Although a small fraction of electrical water heating is employed at low levels of economic development to capitalize on unused solar power available at mid-day, electrical water heating only gains real traction at VoT = 0.128 $/hour when electrically assisted solar water heaters become preferable to water heated over cooking appliances. Vacuum cleaners are introduced to replace brooms at the same level. Other electrical appliances are then introduced, including cooking stoves and public washing machines at VoT = 0.256 $/hour and dishwashers at VoT = 1.024 $/hour. Street lighting is installed at VoT = 0.512 $/hour. The following sections will provide further details about the deployment of various technological alternatives for rendering all these energy services.

4.1.2. Cooking and water heat supply

Cooking heat supply (Fig. 4, top) starts changing already at very low levels of development. At VoT = 0.001 $/hour, basic wood and dung fires are largely displaced by a more advanced wood stove that increases the conversion of fuel energy into cooking heat from 16 % to 25 %, thus reducing the time required to gather wood and the healthy life years lost due to particulate emissions. These advanced wood stoves dominate until a relatively rapid transition to a mix of electricity, kerosene and LPG at VoT = 0.256 $/hour. Beyond this level, electricity gradually displaces kerosene as the relatively small health impacts of kerosene cooking are increasingly valued. Transitions between different cooking methods are relatively gradual because of the implementation of a dependence of indoor cooking (which has 100x greater health impacts than outdoor cooking) on rainfall. Thus, a cleaner fuel is first introduced during rainy hours and then during dry hours.

The overall demand for cooking heat (line in Fig. 4, top) is initially far greater than the demand for electricity. This effect not only originates from the need for cooking, but also for hot water. However, when it becomes economical to install rooftop solar water heaters around VoT = 0.1 $/hour (Fig. 4, bottom), cooking heat demand falls rapidly.

Solar water heaters use cheap flat plate collectors instead of more

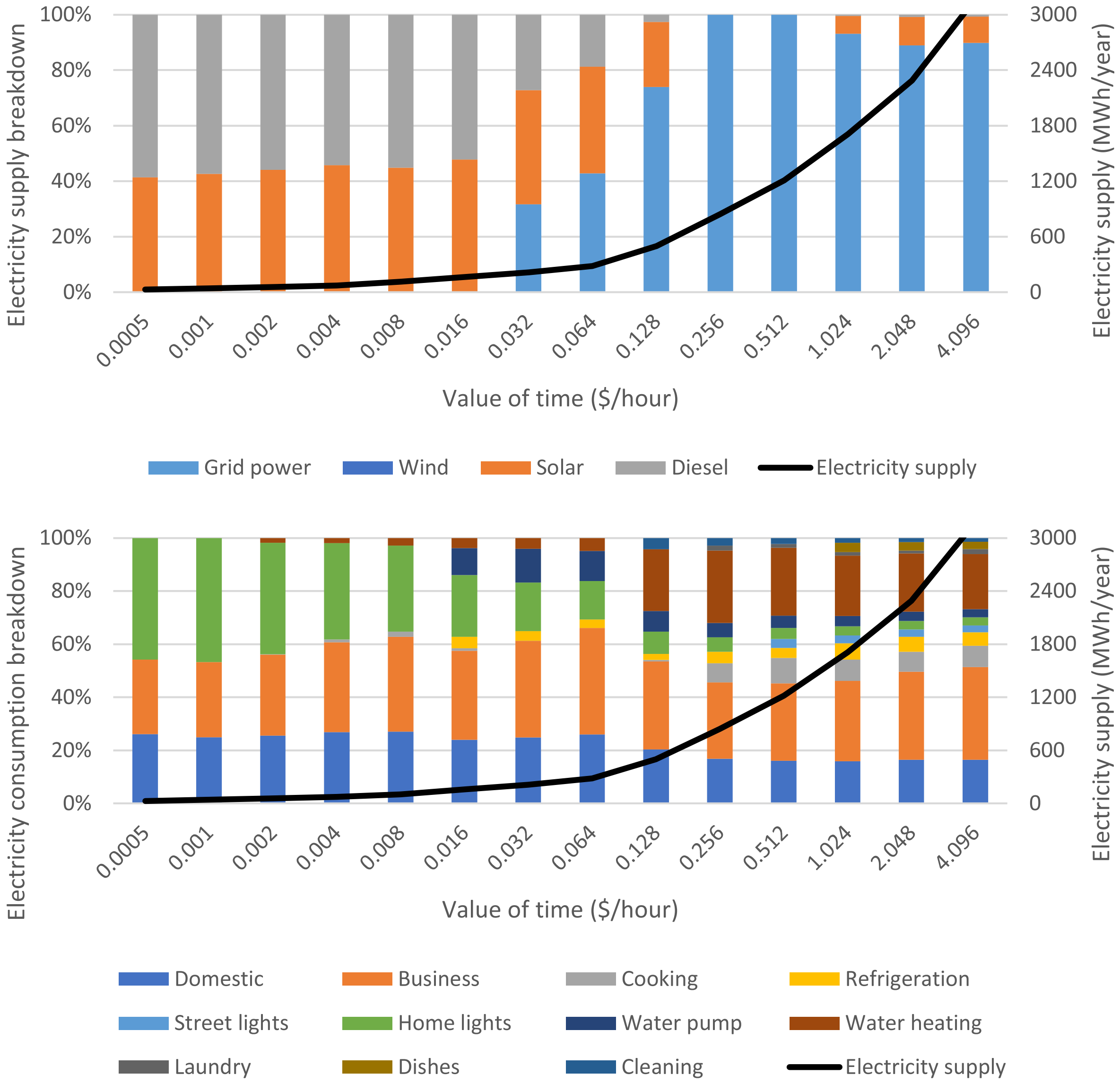

Fig. 3. Evolution of the optimal electricity supply mix and consumption breakdown with consecutive doublings of the VoT.

expensive vacuum tubes that enable more solar heat to be collected during less sunny periods. However, these solar collectors never supply more than 65 % of hot water. Flat plate heaters cannot generate sufficient heat during cloudy days. In addition, holiday periods during Easter and Christmas when many migrant workers return home increase the demand for hot water by 50 %, and it is not optimal to oversize solar water heaters to supply sufficient hot water also during those few weeks. Heating energy during cloudy spells and holiday periods is initially mainly supplied via cooking stoves, but it gets increasingly displaced by electricity as the VoT increases due to the time cost of supplying hot water via cooking relative to having an automatic electric heating element in the hot water tank.

4.1.3. Water and lighting

Water supply is broken down into supply and distribution. Water can be supplied by walking to the river, laying a pipeline operated by a hand pump, or installing an electric pump, whereas distribution can occur from a central tap or a water distribution network sending water to individual homes. The model also has the option to install a water storage tank to allow for mismatches between supply and distribution, which can allow the electric pump to run when electricity is relatively cheap.

As shown in Fig. 5 (top), walking to the river to fetch water is only optimal at very low levels of development. Installing a pipeline with a hand pump for water supply already becomes economical when VoT = 0.002 $/hour and switching to an electric pump happens at VoT = 0.016 $/hour. In contrast, the shorter walk to collect water at a central tap only starts to be displaced by a more expensive water distribution network to individual homes around VoT = 0.032 $/hour. At VoT = 1 $/hour, the water supply system is fully modernized with electrically pumped supply and distribution to individual homes.

Fig. 5 (bottom) shows that lighting is dominated by candles at very low levels of development when electricity distribution and wiring of individual homes to facilitate electric lights is still uneconomical. However, as the VoT increases, grid connections are gradually expanded to drive out candles which are assumed to cost 10 % of each hour in productive output relative to electric lighting (e.g., people can study or perform various household tasks more effectively by electric lights). A gradual transition is shown because the model tends to install only the level of LED lighting that will not increase peak electricity demand (and thus the required distribution and connection capacity). Lighting is an important contributor to total electricity demand at low VoT values with large morning and evening peaks, but further economic development creates many other forms of daytime electricity demand that facilitate full LED lighting without significantly increasing peak load.

The installation of streetlights becomes economical around VoT = 0.5 $/hour. Streetlight infrastructure is relatively expensive, and the assumed crime reduction effects of streetlights (30 % of the 10 % of total time lost to crime) only become worthwhile at this level of economic development.

4.1.4. Food preservation and cleaning

As shown in Fig. 6 (top), traditional food preservation methods (here represented by salting) remain preferable to electric refrigeration up to VoT = 0.008 $/hour. Beyond this point, the time cost involved in traditional food preservation drives the optimal technology mix to refrigeration, which was modelled to occur in three levels. The first level, preferred from VoT = 0.016 $/hour to VoT = 0.128 $/hour only uses large-scale fridges and freezers at a centralized convenience store. This arrangement minimizes electricity consumption for refrigeration, but still involves considerable time costs as people need to walk to the store at regular intervals to buy preserved food. Private fridges become economical at VoT = 0.256 $/hour and private freezers (which consume more power due to their lower operating temperature) at 1 $/hour. Such private food preservation capacity allows people to reduce their shopping frequency to once per week, thus saving additional time.

Fig. 6 (bottom) shows that cleaning is broken down into clothes washing, dishwashing, and house cleaning. Walking to the river to wash clothes and dishes is only viable at a very low VoT, and it quickly gets displaced by handwashing within the village using water conveyed from the river using a pipeline (Fig. 5, top). However, the VoT must increase to 0.256 $/hour before electrified cleaning is introduced via a central laundromat (which uses washing machines at a high utilization factor). Electric vacuum cleaners become preferable to sweeping a little earlier at VoT = 0.128 $/hour. Only when VoT reaches 1 $/hour does the additional time saving facilitated by electric dishwashers become viable and private washing machines only outcompete the laundromat beyond 4 $/hour. These private devices are used at very low utilization factors, making the effective cost of washing a load of clothes or dishes relatively high.

4.2. System costs analysis

The total system cost involves the monetary costs of all technologies and the time costs (product of the number of hours and the VoT) of performing various activities. The latter component becomes increasingly important as the level of development improves and people become capable of creating more value from each hour of work (higher VoT). This section explores the trade-off between these two cost components as the VoT is increased.

4.2.1. Breakdown of total system costs

Fig. 7 shows large changes in the breakdown of total system costs as the VoT changes. The figure is best viewed by considering that the model deploys the range of energy services at its disposal to optimally limit monetized time costs that are directly proportional to the assumed VoT.

Initially, lighting (mainly candles) is the dominant cost. All other

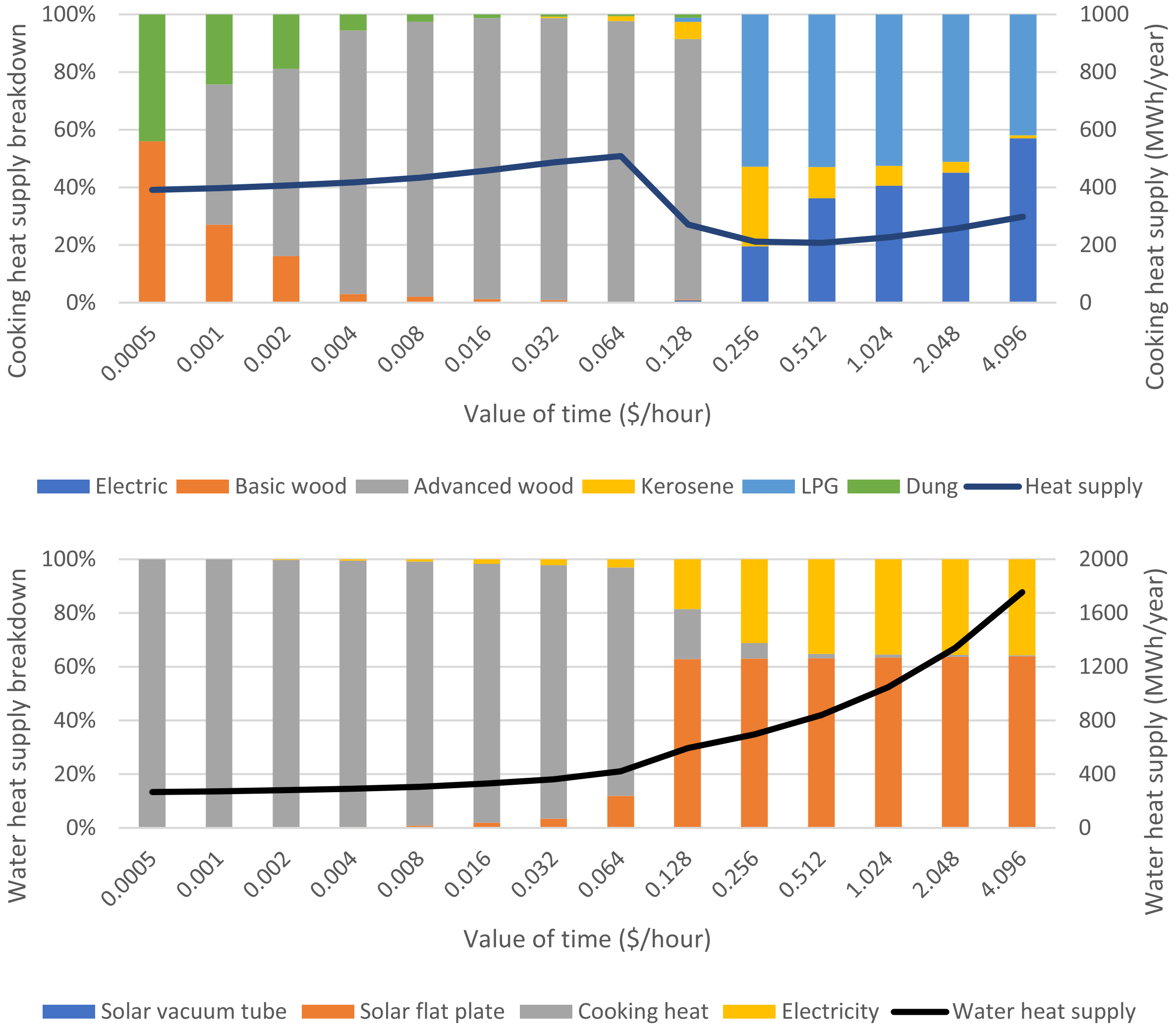

Fig. 4. Evolution of the optimal cooking and water heat supply mix with consecutive doublings of the VoT.

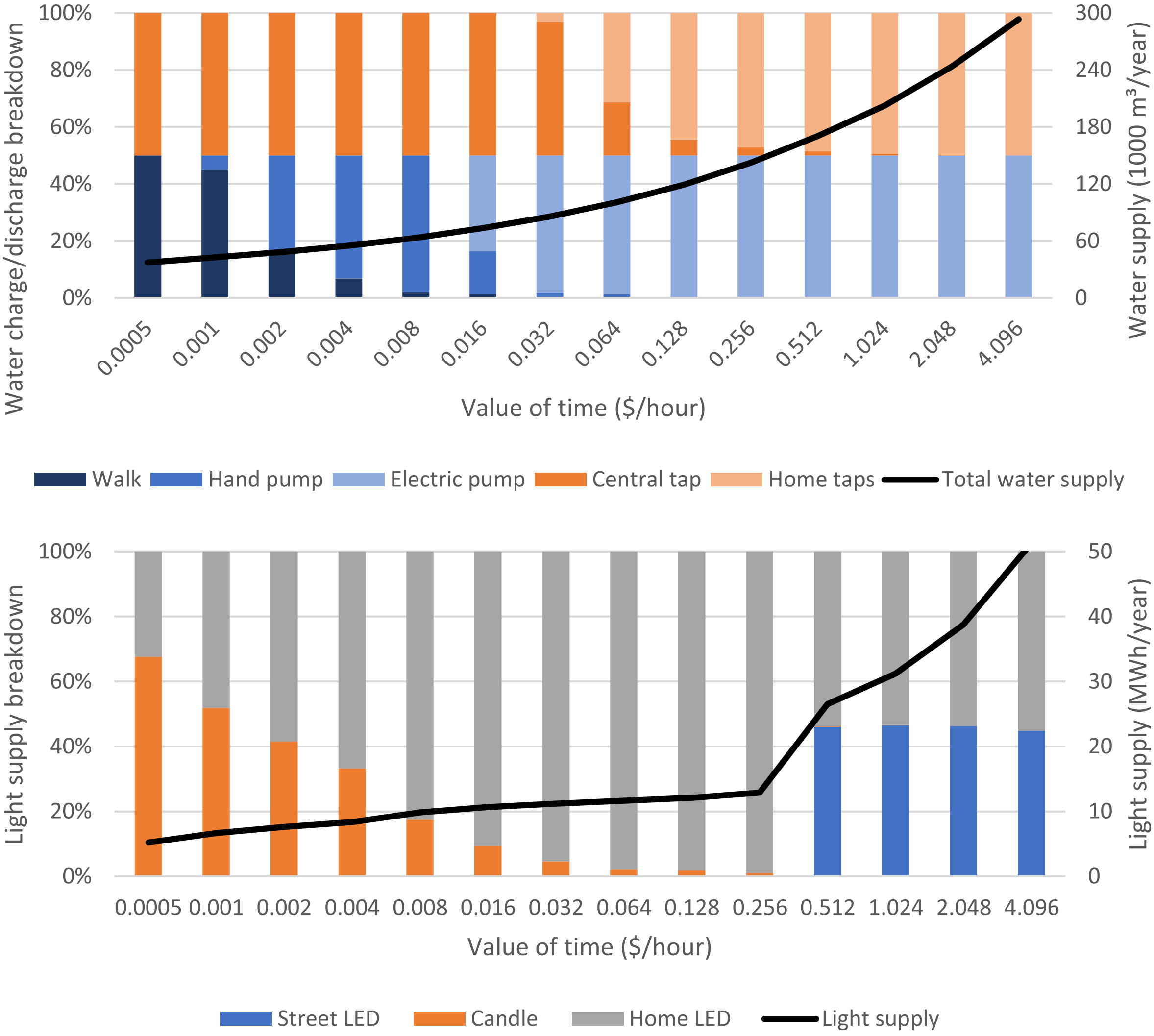

Fig. 5. Evolution of the optimal water and light supply mix with consecutive doublings of the VoT.

services such as heat and water supply, food preservation, and cleaning is done using time-intensive traditional methods because time is valued close to zero. The cost of candles is gradually displaced with electricity and electrical grids powering LEDs as the VoT increases (Fig. 5, bottom). Water supply using a pipeline, storage tank, and electric pump also start contributing significant costs at low levels of VoT (Fig. 5, top).

Cooking, hot water, and cleaning only start to impose significant monetary costs beyond VoT = 0.1 $/hour. Below this level, these services are performed using wood stoves and brooms where time is essentially the only modelled cost. The introduction of modern energy services in these categories halts the increase in the monetized cost of time in the range of VoT = 0.064–0.256 $/hour because the decrease in hours spent on primitive cooking and cleaning methods cancels out the increase in the VoT. However, monetized time costs drop sharply at VoT = 0.512 $/hour when streetlights are installed to reduce time lost to crime at the cost of substantial additional lighting expenses. The introduction of electric dishwashers and home freezers at VoT = 1.024 $/hour serve to further reduce the monetized cost of time. At this point, time saving devices are essentially exhausted (aside from private washing machines introduced at VoT = 4.096 $/hour) and monetized time costs increase steadily with VoT.

4.2.2. *The time-money trade-off*

Despite the gradual introduction of time-saving technologies, Fig. 7 shows that the total cost of time grows to almost 40 % of the entire system cost at VoT = 0.064–0.256 $/hour before the final available time-saving technologies are deployed. Fig. 8 gives a better representation of the trade-off between technology costs and time savings. Most notably, development up to VoT = 0.512 $/hour can save up to 1570 productive hours/person/year using simple technology that costs only 296 $/person/year (an average cost of $0.19 per hour saved). As a rough global impact estimate, if the ~2.5 billion people living on less than 4 $/day [11] could each save an average of 1000 h/year at 0.2 $/hour, the world can gain 2.5 trillion productive hours for $0.5 trillion (about 0.3 % of world GDP [66]).

Fig. 8 (top) shows that close to half of the time costs originate from indirect sources, mainly low productivity and crime resulting from poor lighting and lost productive life years from dirty cooking methods. Direct time costs reach almost 1000 h/person/year at low levels of economic development. Since not all citizens are of working age (although it is common for children to perform time-consuming tasks like water carrying), these hours that can be saved by simple and commonly available technologies equate approximately to an entire working year in the developed world.

The breakdown of time costs (Fig. 8, bottom) shows that lost productivity and increased crime from poor lighting have the largest effect. These indirect costs are not possible to quantify accurately, so they must be interpreted with caution. The key assumptions employed are 1) having to rely on candles rather than electric lights costs 10 % of every hour that lighting is needed at home and 2) streetlights reduce crime,

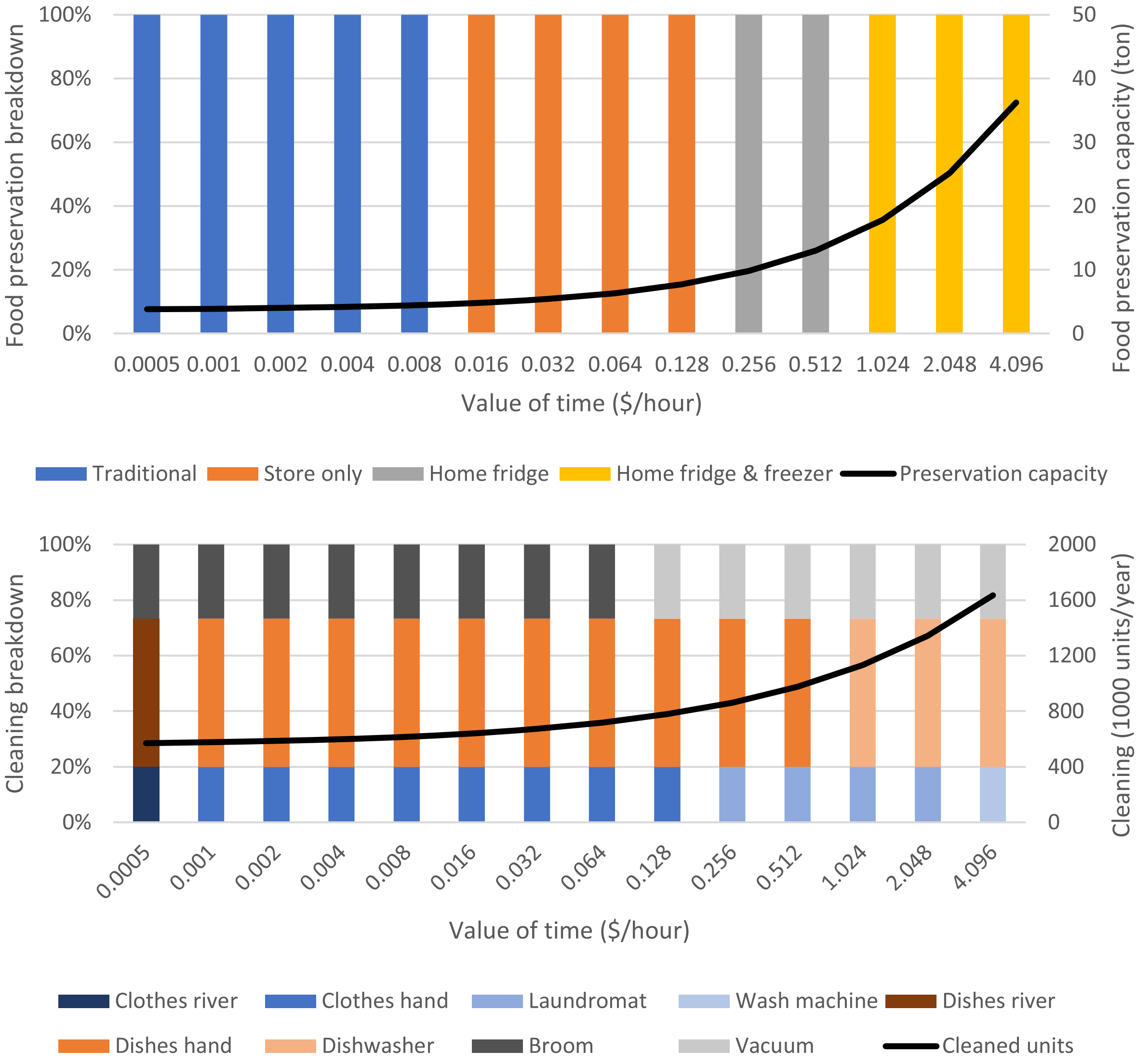

Fig. 6. Evolution of the optimal mix of food preservation and cleaning technologies with consecutive doublings of the VoT.

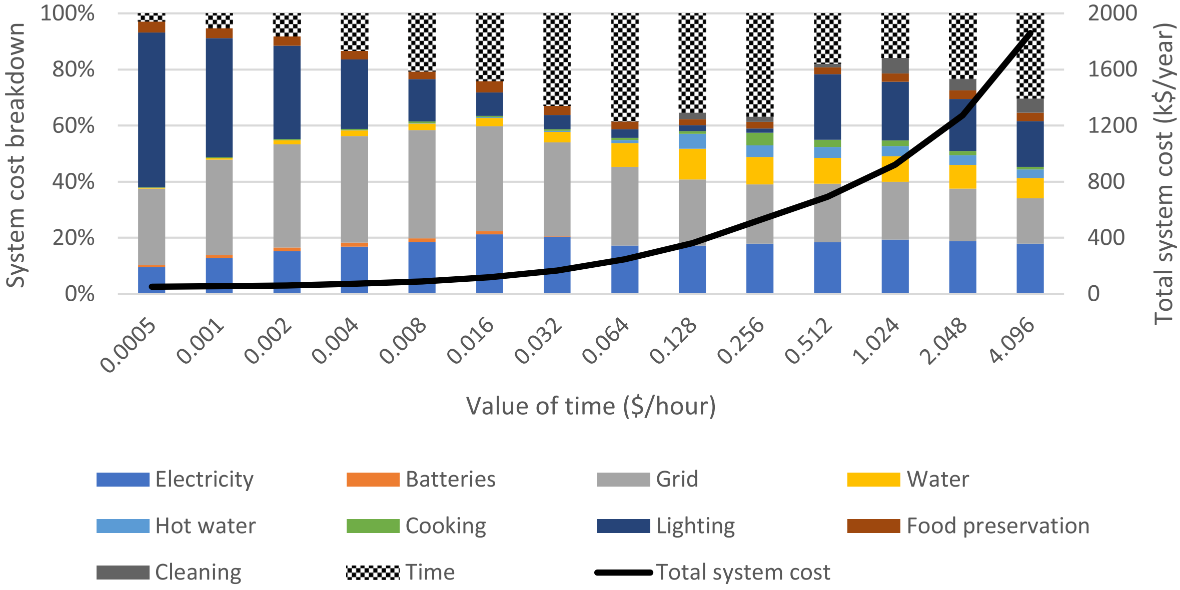

Fig. 7. Evolution of the total system cost with consecutive doublings of the VoT.

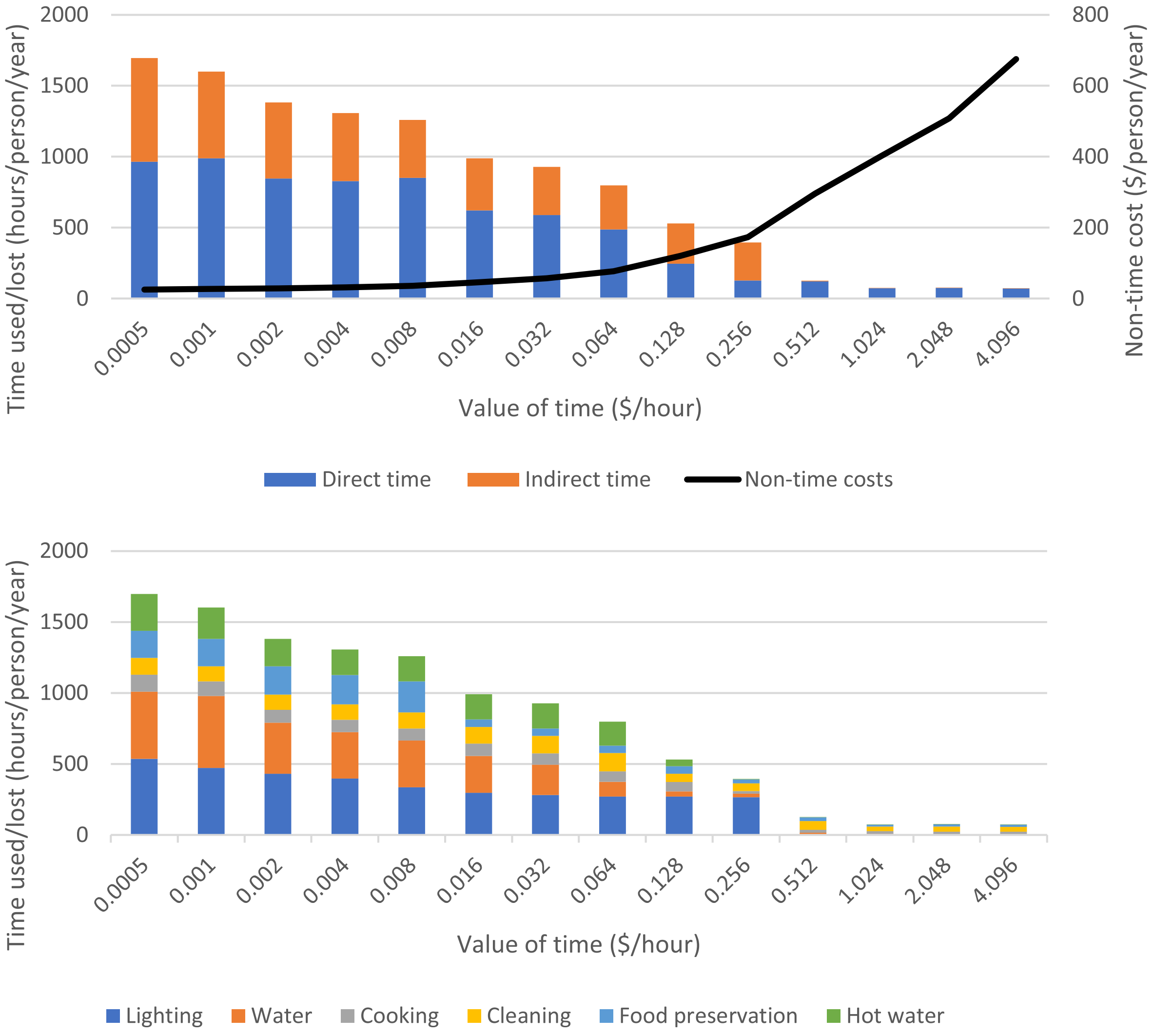

Fig. 8. The trade-off between increased technology costs and reduced time use (top) and the breakdown of time used/lost (bottom) as the VoT is increased.

which costs the society 10 % of their time, by 30 %.

Water carrying has a similarly large time cost to lighting. Walking to the river or well, assumed to be 1 km away, to get an assumed 15 L of water is a very low-value and time-intensive activity, and walking to the central tap, assumed to be 0.2 km away, still imposes a significant time cost.

Next, cooking takes considerable time, both from gathering wood and from lost healthy life years. It should be noted that the health effects are reduced by about a factor of 4 from the actual amount of lifetime lost in this estimation. Since the time use is measured as productive time, only 25 % of the lost life years are taken as lost productive hours.

Time costs for cleaning and food preservation reduce relatively slowly across the range of VoT as the introduction of more sophisticated time-saving devices is offset by increases in demand. Specifically, the demand for energy services related to cleaning and food preservation is assumed to increase by factors of 3 and 10, respectively, across the investigated VoT range.

Finally, hot water time costs also show a slow decline until solar water heaters take over the market at VoT = 0.128 $/hour (Fig. 4, bottom). Up to this point, water is heated using cooking technologies with the associated fuel gathering and health costs.

Even at the highest VoT investigated, some time costs related to cooking (direct time costs of preparing meals), cleaning (vacuuming and doing the laundry in private washing machines), and food preservation (a weekly shopping session for stocking home fridges and freezers) persist. It is striking to observe that even these minor tasks represent a third of the total system cost when the value of each productive hour rises to $4 (Fig. 7).

4.3. *Sensitivity to electricity supply costs*

Electricity is a key enabler of time-saving and productivity-enhancing technologies. Thus, this section explores the effect of limiting electricity supply to off-grid technologies and the benefits of having access to cheaper wind, solar, and battery technologies.

4.3.1. *Off-grid development*

When a connection to the centralized electricity network is impossible due to factors such as excessive distance, inhospitable terrain, or unreliable centralized electricity supply, electrification must proceed via a local mini-grid of solar, wind, batteries, and diesel generators. When contrasting Fig. 9 with Fig. 3, it is clear that the share of solar starts increasing at the point where grid electricity became feasible when a 10 km grid connection is possible (Fig. 3). Higher solar shares are favoured at higher levels of development as electricity demand expands from predominantly lighting (which is needed when the sun is not shining) to other daytime demands such as businesses, water pumping, and water heating. Water pumping and heating also offer demand-response services by concentrating electricity use during sunny periods (an optimistic assumption as outlined in point 5 of the limitations).

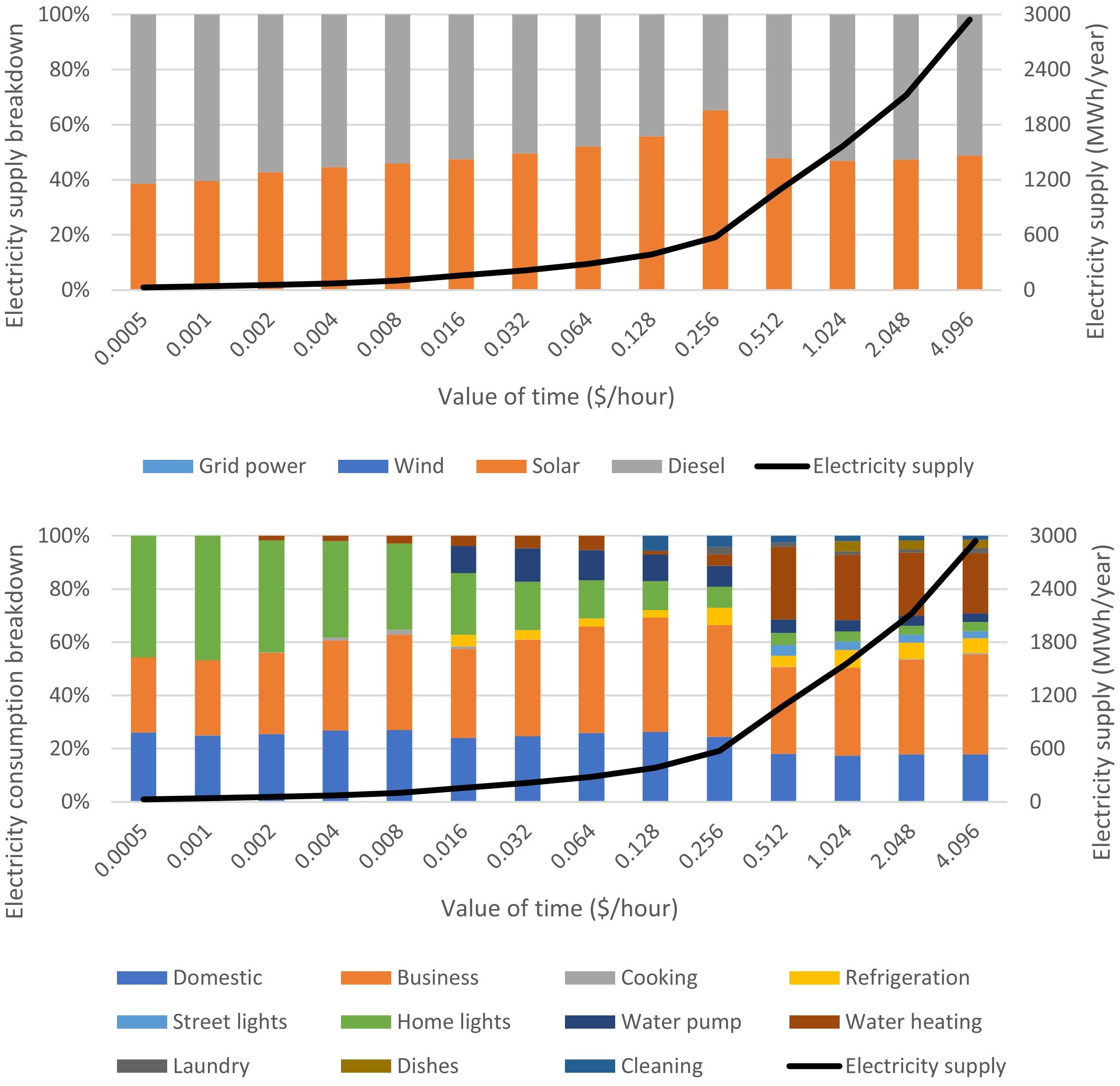

Fig. 9. Evolution of the optimal electricity supply mix and consumption breakdown with changes in VoT for a fully off-grid development path.

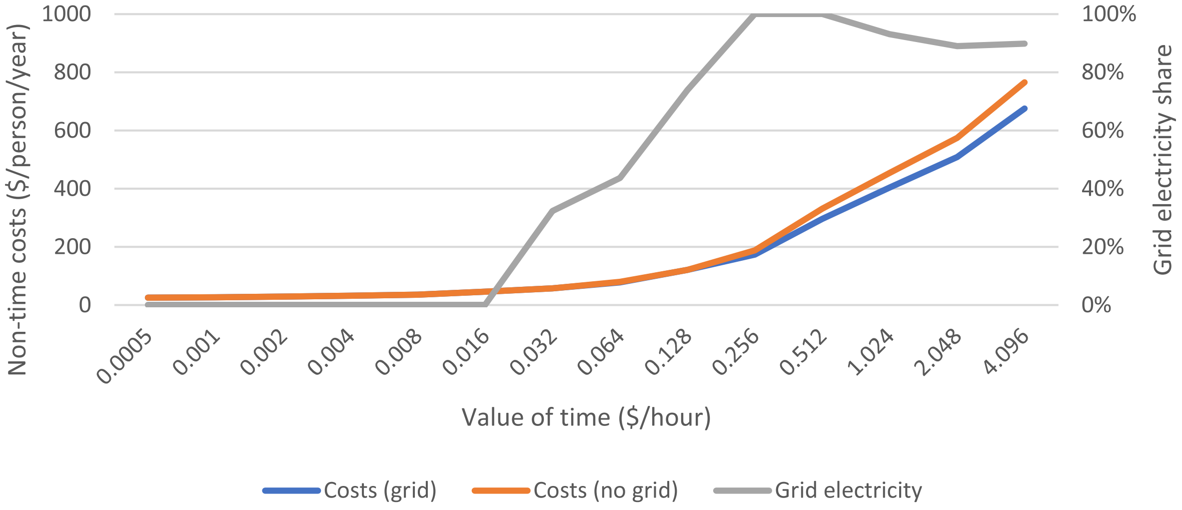

Fig. 10. Comparison of technology costs in the cases with and without a grid connection. For perspective, the share of grid electricity in the case with a grid connection is also shown.

The primary difference in terms of electricity consumption breakdown in an off-grid system (Fig. 9, bottom) is that the emergence of electrically assisted water heating to displace water heating on cooking stoves happens at a higher VoT (0.512 $/hour instead of 0.128 $/hour). The more expensive electricity in an off-grid system means that the time costs of water heating via cooking fuels remains competitive for longer. This water heating transition also corresponds with a significant fall in the optimal solar market share because electrical water heating is required primarily during extended periods of low sunshine when solar collectors cannot provide sufficient heat.

Another important difference from the grid-connected case is that there is almost no deployment of electric cooking stoves. Since cooking demand profiles are concentrated in the morning and evening when solar power generation is low, LPG cooking stoves with their moderate health impacts remain preferable to electric cooking stoves with no health impacts up to the highest VoT level investigated.

Fig. 10 illustrates the effect of removing the possibility of a grid connection on the cost of all deployed technologies to achieve the large time savings illustrated in Fig. 8 (time savings proceed almost identically to Fig. 8 when no grid connection is possible). As Fig. 10 illustrates, the difference in system costs only becomes significant beyond VoT = 0.256 $/hour when the majority of time savings have already been achieved (Fig. 8). This is a clear indication that a relatively modest electricity supply driving energy services like LED lighting, water pumping, refrigeration, and cleaning appliances save a lot of time, while energy-intensive cooking and heating can be done using fuels instead of electricity. As an illustration, the off-grid case at VoT = 0.256 $/hour uses 577 MWh/year of electricity, 408 MWh/year of final cooking heat from LPG and kerosine, and 438 MWh/year of heat collected for hot water by solar water heaters. If electricity had to be used to satisfy the high energy demands of cooking and water heating, costs would increase considerably.

Fig. 10 also shows that the share of grid electricity rises rapidly in the range of VoT = 0.016–0.256 $/hour when a grid connection is possible, but savings in overall system costs caused by this grid connection are minimal. There are two primary reasons for this small effect: 1) a grid connection only offers modest electricity supply cost reductions in this range because of the improving alignment of demand with solar power output (described at the start of this section) and 2) electricity supply contributes less than 20 % to total system costs (Fig. 7), limiting the effect of a slightly cheaper electricity supply.

It is encouraging that almost all possible time savings can be achieved at a similarly low cost when no grid connection is available. For example, about 97 % of potential time savings are already realized at VoT = 0.512 $/hour directly after the deployment of streetlights. As mentioned earlier, the case with a grid connection can save each person 1570 h/year at a cost of 296 $/year at this VoT. Without a grid connection, time savings amount to 1569 h/year at a cost of 331 $/year,

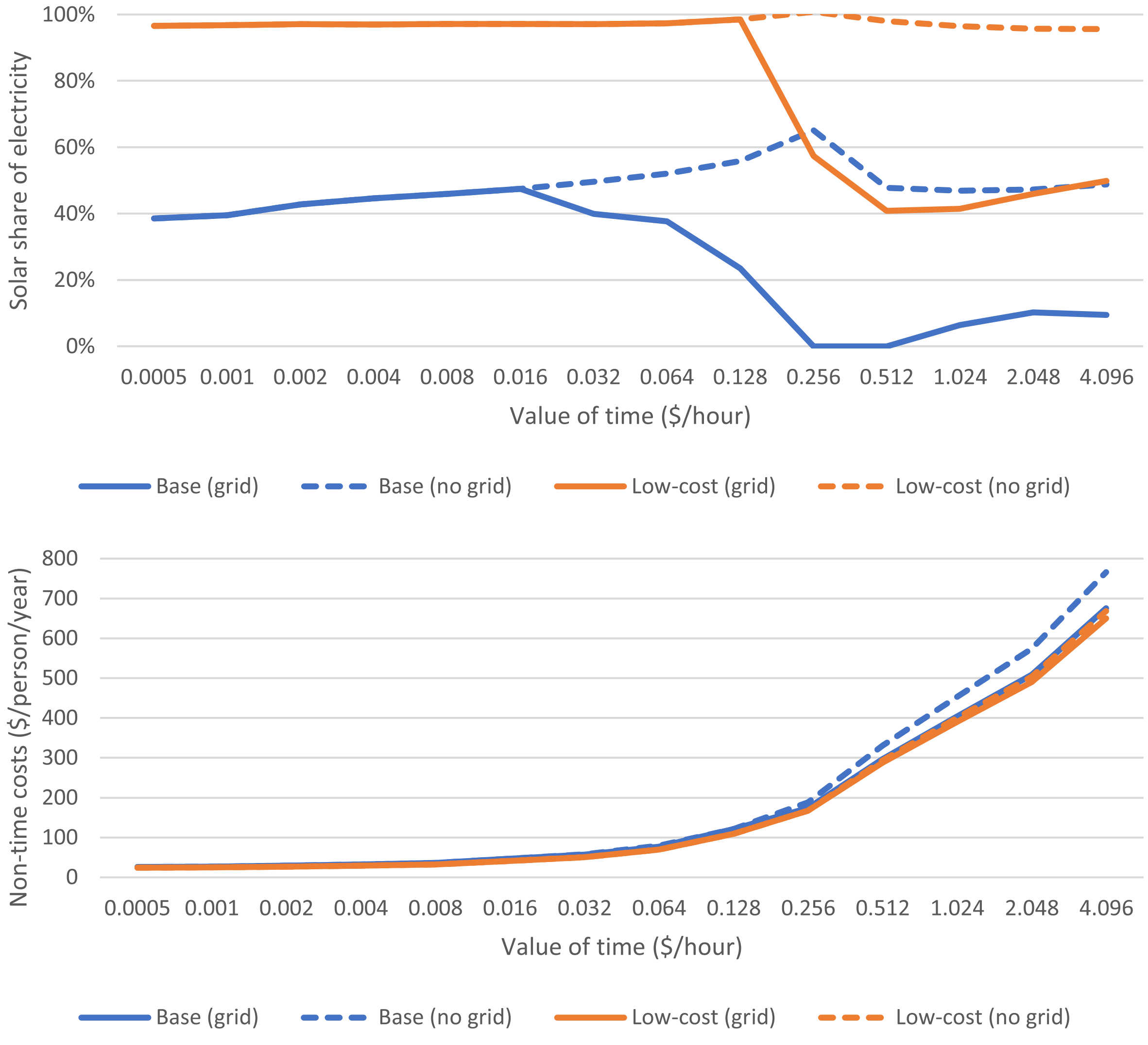

Fig. 11. A comparison of solar market share (top) and total technology costs (bottom) for the cases with regular solar and battery costs (base) and halved costs (low-cost).

only 12 % additional cost for essentially the same time saving. Beyond this point, growth in energy service demand is driven more by convenience than necessity, so a grid connection is not necessary to deliver essential energy services in a cost-effective manner.

4.3.2. *Cheaper green technologies*

Solar and battery technology has the potential to achieve considerable cost reductions in the future. Furthermore, there is potential to reduce the cost premium of technology installation in rural communities via well-organized and standardized rural electrification programs executed at scale. To investigate the effect of such advances, the cases with and without a grid connection were repeated with solar, wind, and battery costs are halved to reach levels of 601 $/kW, 1015 $/kW, and 149 $/kWh, respectively.

Fig. 11 illustrates that halving green technology costs strongly increases the solar market share and delays the transition to grid electricity. However, when the grid is available, grid electricity still grows to a market share of 60 % by VoT = 0.5 $/hour. As a result, the availability of cheap solar and battery technology makes no significant difference to the system cost when a grid connection is available (system costs are almost identical in the grid-connected case with base and low-cost green technologies in Fig. 11, bottom). However, cheap green technologies make a significant difference in the case where a grid connection is not possible, achieving similar costs to the base grid-connected case. Thus, a halving in green technology costs can enable cost-effective off-grid growth up to relatively high levels of economic development.

When considering only the essential energy services enabling 97 % of available time savings up to VoT = 0.5 $/hour, however, cheap green technologies have a minimal impact. Thus, similarly to a grid connection, green technology cost is not a meaningful impediment to the upliftment of rural communities. It is only when reaching levels of economic development where energy services are deployed more for discretionary consumption than necessity where large reductions in green technology costs start to make a significant difference.

5. Conclusions

The main conclusion from the current study is that optimal deployment of simple energy supply and energy service technologies can give the world's poor trillions of hours each year at a low cost. Basic lighting, water supply, cooking, cleaning, and food preservation services can save poor communities more than 1500 h/person/year, split about 60/40 between direct and indirect savings. The average cost of an hour saved via optimal deployment of these technologies is approximately $0.2. These findings apply fully to almost a billion people living in extreme poverty (<2 $/day) and partially to another 2 billion living below 5 $/day.

Importantly, these large and low-cost time savings can be achieved using local mini-grids powered by solar and diesel generators, supported by clean cooking fuels and solar water heaters. Improvements in electricity supply through a connection to the central electricity grid or large solar/battery cost reductions only start showing significant system benefits at higher levels of economic development where energy service demand growth is driven more by discretionary consumption than necessity.

Due to various modelling limitations and the case-specific nature of the simulation, it is not possible to draw additional generalized conclusions from the study. However, further model development and empirical data collection efforts can overcome the aforementioned limitations to devise detailed, quantitatively accurate, optimal development pathways for individual low-income communities. Such model-informed energy service deployment efforts are recommended both to motivate investment (by revealing the low cost at which time can be saved) and to maximize returns (by optimizing technology deployment and dispatch).

Finally, it must be acknowledged that cost-effective energy-service provision is not sufficient for effective poverty alleviation. Parallel efforts are required to ensure that the large amount of productive time freed up by optimal energy service deployment is used effectively by the community. Educational and business development opportunities are particularly important to replace the causality dilemma described in the introduction with a virtuous cycle where more available time leads to increased economic productivity, allowing the community to afford additional energy services to free up more time. Kickstarting this virtuous cycle is key to addressing the global challenge of poverty.

CRediT authorship contribution statement

Bart Tulkens: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Schalk Cloete:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Pfunzo Muvhali:** Methodology, Writing – original draft, Writing – review & editing. **Rob Bastiaans:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used and generated by the model (as well as the model itself) is available online as indicated in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.129444.

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