The Design and Installation of Solar Home Systems in Rural Cambodia

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ABSTRACT: *This study contends that solar home systems (SHS) are an appropriate solution to provide affordable, reliable and clean electricity in rural Cambodia. SHS provide decentralised electricity suitable for the electricity needs of rural households and with the decreasing cost of solar energy technologies, SHS are becoming an increasingly competitive source of energy. This study details the design and installation of two SHS in a rural community in Cambodia. The SHS have replaced the use of kerosene lamps and supplemented car battery usage, which has generated a cost saving of USD$2.50-3.20 per month. The SHS have increased the hours of quality lighting making it possible for users to improve educational outcomes by studying at night and participating in private education classes as well as potentially extending their working hours that provides an opportunity to increase their income. Community involvement in the installation of SHS and participation in an education program has ensured transfer of knowledge about system operation and maintenance at a local level that has ensured economic, social and environmental were benefits. This study builds a case in support of solar energy at the household level in rural Cambodia and makes recommendations for the deployment of SHS in rural communities throughout the developing world.*

KEYWORDS: Solar energy, rural off-grid electrification, solar home systems, sustainable development

1 INTRODUCTION

Eighty per cent of the population in Cambodia lives in rural areas where access to grid electricity is as little as 18.8 % (World Bank, 2015). Due to dependence on expensive imported oil, losses in distribution and lack of high voltage transmission lines, electricity tariff in Cambodia is the highest in the Southeast Asian region (United Nations, 2007). Communities in rural areas use alternate energy sources that: are expensive, pose health risks, are potential fire hazards, and are damaging to the environment. An estimated 1.06 million rural households use kerosene lamps as their primary source of lighting and a further 1.12 million rural households (45 % of rural households) use car batteries charged at isolated battery charging stations (BCS) (International Finance Corporation [IFC], 2012).

The alternate energy sources are more costly than grid electricity and as 90 % of the poor live in rural areas, this cost disproportionally impacts rural households. The use of kerosene lamps accounts for an average 4.9 % of total expenditure for rural households (IFC, 2012). The lamps provide low illumination, which hinders activities at night such as, cooking and studying. Furthermore, the burning of kerosene emits health-damaging pollutants and can cause structural fires to houses, severe burn injuries and the unintentional ingestion of kerosene is a risk to children (Mills, 2012). The BCS emit tons of CO2 each year, are plagued with poor conditions which pose health threats to workers and due to inadequate infrastructure allow acid to spill into the public drainage system and contaminate the groundwater and surrounding soil (Ministry of Environment, 2004). The BCS rely on expensive imported diesel thus recharging batteries accounts for an average 4.5 % of total expenditure for rural households (International Finance Corporation, 2012). To give context to this lack of affordable energy access, the average expenditure on electricity in Australia is 2 % of household income (Australian Bureau of Statistics, 2013) while the average Australian electricity usage is over 300 times higher than a rural Cambodian household (10,400 c.f. 31 kWh/capita/annum).

The Royal Government of Cambodia has made progress towards extending the electricity grid however at least 30 % of Cambodian households are not scheduled to have access to the grid until 2030 at the earliest (Ferranti et al. 2016). Due to the ease of installation and appropriateness of the technology, solar home systems (SHS) are a disruptive method of improving energy access in Cambodia. The largest injection of SHS has come from two initiatives: The Rural Electrification Fund (REF) and The Good Solar Initiative. The initiatives have installed an aggregate 20,000 SHS, with an aim to roll out a further

20,000 and 25,000 respectively by 2018 (Ferranti et al. 2016). These initiatives comprise of SHS from numerous companies that have made comparatively lower private sales.

Despite the appropriateness of the technology, care must be taken in project implementation. There are many examples of electrification aid projects that have rapid cycles of installation to failure (Quoilin & Orosz, 2013). One such project occurred in the rural Secret Beach community in south Cambodia. A solar panel and battery system was installed in the community's local primary school in 2013 and was only operational for six months. The system was incorrectly sized and designed with no community consultation. Due to the absence of community involvement in implementation, there was a lack of local knowledge about the operation and maintenance of the system. This project implementation approach failed to create a sense of ownership and damaged the reputation of the technology. This study details a project completed by the author and a partner non-government organisation (NGO) in the Secret Beach community. The project rectifies previous failings by applying the principles of human-centred design and taking a participatory implementation approach.

2 SOLAR HOME SYSTEM BENEFITS

A community committee in Secret Beach identified electricity access as a priority to achieve economic development and increase quality of life (Saly, 2014). This study details a project that encompasses the design and installation of two SHS in the community to assess the appropriateness of SHS in achieving this vision. SHS consist of a solar panel, charge controller, battery and a load and the suitability of the technology is discussed below.

2.1 Affordable and suitable for small-scale, decentralised generation

The reduction in cost of solar panels (reaching less than USD$1.0 per Watt in 2015) (Fraunhofer, 2016) has increased the accessibility of solar energy technologies to low-income populations if accompanied by appropriate financing arrangements. Solar modules are sold according to the Watt-peak (Wp) and as the price does not scale with module size, they are appropriate for small-scale electricity generation (Advisory Group on Energy and Climate Change, 2010). SHS provide a decentralised energy supply, which is well suited to remote locations where grid extension is not economically viable like the Secret Beach community. Poor project implementation and lack of accessible financing options for households pose the most significant barriers preventing wide-scale roll out of SHS.

2.2 Reliabible and convenient

Car batteries, like those used in households in the Secret Beach community, are shallow cycle and are not designed for the current practice of overcharging and high depth of discharge. This practice reduces the lifetime of the battery that varies from eight to 24 months (Ministry of Environment, 2004),(Rijke, 2008). The SHS encompasses a deep-cycle battery that is more suitable for a high depth of discharge. The SHS also operates with a charge controller, which regulates the charging and discharging of the battery and thus increases the expected battery lifetime. As the battery is charged from the solar panel, the battery remains within the household. The time previously spent or cost incurred from transporting the battery to and from an external charging source (for example a BCS) can be spent on income creating or social activities.

2.3 Opportunity to implement clean and renewable energy technologies

The lack of existing electricity infrastructure in Cambodia presents an opportunity to leapfrog emissions intensive energy systems and satisfy growing demand through cleaner energy sources (United Nations [UN], 2010). Solar energy is a clean and renewable source and an energy system transformation to such technologies can support sustainable wealth creation while reducing the strain on resources and climate (UN, 2010).

3 SOLAR HOME SYSTEM DESIGN AND IMPLEMENTATION

The following sections detail the human-centred design of the SHS and participatory implementation approach in the community.

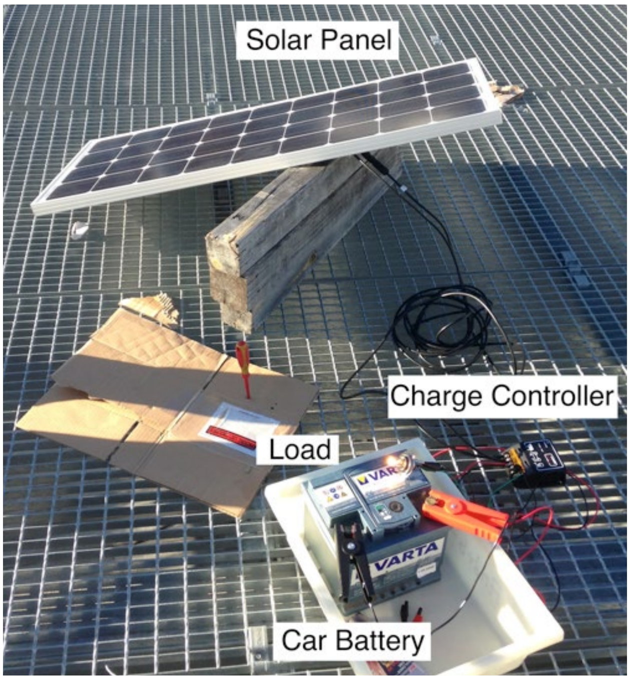
3.1 SHS design and prototype

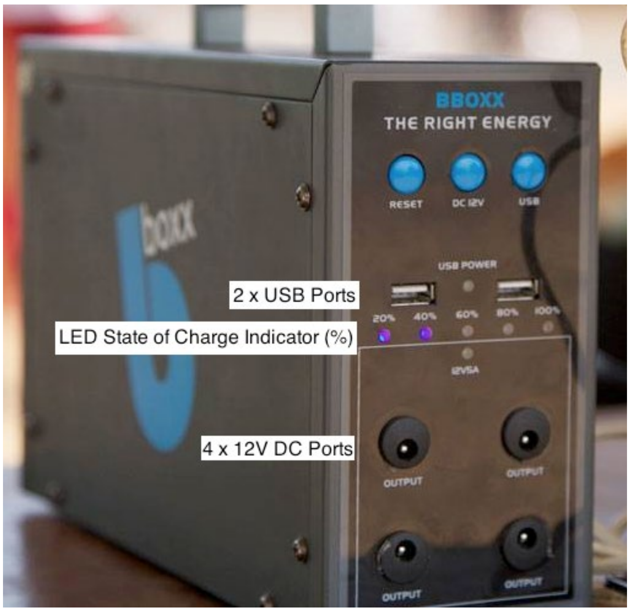
The human-centred design process starts with understanding the user (IDEO, 2015). Data about energy consumption, expenditure and the aspirations of the families in Secret Beach was gathered through a field visit by the author and community consultation (see Appendix 2). This consultation uncovered that the end-users prioritised: lights, phone charger, TV and fan and with main influencing factors being reliability and affordability. Based on this information, a SHS was designed to satisfy the user requirements and prototyped and tested, illustrated in Figure 1.

Assembling the prototype highlighted considerations for the final system configuration. Purchasing components individually allows for system customisability however requires a multistage wiring process and the system is vulnerable to tampering. Testing the system uncovered information to be communicated to the community, for example the decrease in panel output from shading and the importance of correct panel orientation.

3.1 SHS design and prototype

Based on an assessment of the usability, quality and price of the systems available in the market, the author, community and partner NGO decided the most appropriate SHS was the Bboxx BB7 (including a 15 Wp panel and 7 Amp-hour battery). The system satisfies the user





Top to bottom:
Figure 1: Photo of the model system
Figure 2: Control unit of Bboxx BB7 (Bboxx, 2015)
Figure 3: Solar energy workshop

requirements and is supplied by a suitable local supplier. The supplier provided the most comprehensive after sales support and importance was placed on this due to the lack of such support for the system installed in 2013.

Pictured in Figure 2, the Bboxx BB7 has an integrated control unit, which removes difficulties and complexities in system wiring. The infused casing reduces the chance of tampering or removal of the charge controller, which was an issue in previous SHS projects in Cambodia (Rijke, 2008). The battery (sealed lead-acid) is suitable for the generation and consumption profile of solar power and requires minimal maintenance (Power Sonic, 2009) which reduces health and safety concerns. These features address concerns identified in the prototyping stage, thus the final system design improved before reaching the end-user.

Based on community consultation, the two locations for the SHS were decided to be:

- At a household (HH1) whose family had expressed a desire to access solar energy; and
- At the local primary school (HH2) to provide electricity to teachers and students and the family who lives in the school office.

3.3 Economic viability

In 2011, 72 % of the population in Cambodia lived on less than US $3 per day (Asian Development Bank, 2014). The upfront cost of SHS like the Bboxx BB7 (RRP US $129) is unattainable for the majority of the population. Through further cost reductions in solar technologies and establishing efficient financing, SHS are becoming increasingly affordable for communities in rural areas. Appendix 1 indicates the affordability by investigating three hire-and-purchase arrangements. The arrangements are based on the model used to analyse the REF initiative (World Bank, 2012) and have similar payment periods currently offered in the SHS market.

3.4 Education and training

Education workshops (illustrated in Figure 3) were conducted with community members to raise awareness about solar energy and create user understanding about the operation and maintenance of the SHS. This education rectifies the shortcomings of the approach for the system installed in 2013. The workshops encompassed activities supported by visual tools, with material developed from research and learnings from the prototyping stage.

The activities included practical learning, for example participants practiced the operation and maintenance of the systems. Importance was placed on the communication method, as it is the process through which knowledge is shared, and determines whether learning occurs (Cummings, 2003). Through an open floor discussion, the participants shared their experiences with current energy sources and discussed the advantages of solar energy and the benefits of SHS. Development experts have identified that activities, which focus on facilitating knowledge sharing, are more likely to be successful than those focusing on transmitting Northern knowledge to South

Figure 4: Community involvement in installation

(Ellerman, Denning, & Hanna, 2001). The discussion both facilitated knowledge sharing and also indicated which information had been understood during the workshop. Thus, gaps in knowledge were explained to ensure a comprehensive understanding.

3.5 Community involvement in installation

With relevant training, community members were involved in installing the systems to develop local capacity for further SHS installation and create a sense of ownership. Community involvement also facilitated technical knowledge sharing. For example, the site for installation of the panel (Figure 4) was decided based on discussion about the importance of an unshaded location and the panel placed at the correct orientation.

4 MONITORING AND EVALUATION

As the SHS were purchased to trial the appropriateness of the technology, members of HH1 and HH2 (the users) committed to the author and partner NGO to provide feedback about user experience and system performance. The users were surveyed one, three and five months post installation to capture the initial and ongoing impact of SHS usage. There is often a lack of ongoing monitoring on similar projects. Survey results indicate the SHS have provided a reliable source of electricity and reduced usage of car batteries and kerosene lamps. The users have independently operated and maintained the systems and are able to explain to other community members how to the use systems. This information implies the workshops were successful in transferring knowledge. In addition, the workshop material was repeatedly used by community members for further training and increased the awareness of solar energy in the community.

The Most Significant Change (MSC) in behaviour is a method of participatory evaluation (Davies & Dart, 2005) that assesses the impact of technology through user stories. The MSC in behaviour for the SHS users and the associated economic, health/social and environmental benefits are described in Table 1.

5 RECOMMENDATIONS

There is significant potential for SHS to replace emissions intensive and expensive energy sources in rural households throughout Cambodia. Small-scale systems can have a significant impact on the lives of users by generating economic, social and environmental benefits as demonstrated in this study. This study provides insight into the design and implementation process of a SHS project and from this, recommendations for SHS projects in rural communities in Cambodia and other developing countries are outlined below.

5.1 Design considerations

- The SHS should be tailored to the user and the community should be involved in the decision-making throughout the project. This ensures the design is appropriate and community is empowered by the project.
- The SHS design and implementation process should be iterative, starting small scale and involve prototyping. This allows for user-feedback that ensures the design is constantly improving.

5.2 Implementation considerations

- Education should be provided to ensure systems are operated and maintained correctly. This will enable associated benefits to be generated and create user satisfaction.
- A local technician should be trained to provide local support and facilitate the expansion of SHS usage. This will assist in longevity of the SHS and create employment opportunities.

5.2 Project considerations

- A suitable user pays arrangement (see Section 3.3 and Appendix 2) should be established to provide access for low-income households and assist in the financial sustainability of the project.
- The project should leverage on existing strengths in the community, for example engaging organised groups and leaders within the community.
- Effective monitoring and evaluation tools should be established to capture user feedback and influence each iteration of the project. This ensures the project design implementation approach is constantly improving.

6 CONCLUSION

The project presented in this paper demonstrates the economic, social and environmental benefits SHS can generate for rural households in Cambodia. By taking a human-centred design approach, the project designed SHS that were suitable for users. Involving the community in project implementation built capacity and ensured technical knowledge was embedded locally. Successful monitoring and evaluation tools captured feedback from the users ,which validated that SHS can replace emission intensive and expensive energy sources. By providing

Table 1: MSC in behaviour for the SHS users and the associated economic, health/social and environmental benefits

MSC1: Members in HH1 have reduced the frequency of recharging their car battery and now charge mobile phones in their home rather than at a neighbour’s home.	
Indicator	**Benefit**
Economic	Cost saving ($3.20 per month) due to reduced frequency of battery recharging. Increased productivity as the time previously spent taking the battery and phone to charge at external sources can be spent on income creating activities.
Health/social	Reduction in exposure to toxic gases and toxic effects of lead absorption from the battery.
Environmental	Reduction in emissions from BCS due to reduced frequency of battery recharging.

MSC2: Members in HH1 have run private education classes at night due to the increased hours of quality lighting.	
Indicator	**Benefit**
Economic	Extended working hours and potential to increase income.
Health/social	Increased education opportunities for children in the community.

MSC3: The teachers have charged their mobile phones at the school (HH2) rather than at their respective houses or at a café.	
Indicator	**Benefit**
Economic	Cost saving from previous charging source (either from café purchases or reduced frequency of battery recharging). Increased productivity due to increased connectivity from higher access to mobile phones.
Health/social	Increased awareness of solar energy as students and teachers at the school are exposed to the SHS. The ability to charge phone at the school has incentivised teachers to attend classes, which has in turn increased education for students. Increased access to information due to increased access to mobile phones.
Environmental	Reduction in emissions from BCS due to reduced frequency of battery recharging (as car batteries were used to charge mobile phones).

MSC4: The family that resides at HH2 have replaced kerosene lamp usage with high quality light-emitting diodes (LEDs). This has increased the hours of lighting and the quality of lighting, which has enabled the teacher (father of the family) to write his lesson plan and allowed the children read at night.	
Indicator	**Benefit**
Economic	Extended working hours and cost saving of US$2.50 per month due to the elimination of kerosene use.
Health/social	Increased education for the children. The extended work hours for the father has increased recreational activities and time spent with children during the day.
Environmental	Reduction in indoor pollution and reduced risk of burns and indoor fires caused by the kerosene lamp.

affordable, reliable and clean electricity SHS are thus an appropriate energy solution for rural households.

Given the lack of existing electricity infrastructure, the high and volatile price of electricity and remoteness of rural communities, SHS have huge potential in transforming energy usage in rural households. Rural communities comprise almost 80 % of the population in Cambodia and with the limited successful market penetration; there is a significant market for SHS. Increasing access will translate the benefits demonstrated in the project into widespread economic growth, poverty reduction and environmental sustainability. The author encourages prospective entrepreneurs, NGOs and the public and private sector to consider the recommendations made in this paper and increase the deployment of SHS.

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APPENDICES

Appendix 1: Community survey

The partner NGO provided a survey of 19 households in Secret Beach on energy usage and sources of energy (Saly, 2014). The households were a sample selected as a representation of the entire community. Consistent with the research presented in Section 1, the households use a variety of energy sources. For lighting, the households use a combination of lights powered from disposable batteries (700 riel USD $0.175 per set), kerosene lamps (USD $0.875 per litre) and/or car batteries. The usage and expenditure on kerosene was not captured in the survey and will not be included in calculations. Car batteries were the predominant source of energy for the households and will be included in the economic analysis.

As a representation of the survey, Table 1 details the expenditure on recharging a battery and appliances used by three households. Based on the data the assumed usage in Watt-hours (W?hrs/day) and associated levelised cost of electricity (LCOE) were calculated.

Appendix 2: Economic analysis

As there were only two systems installed, one being at the school (a public place and with public usage), it was not viable to establish a user-pays financing arrangement. To provide insight into affordability and potential financing arrangements, the following section investigates scenarios for the repayment of the Bboxx BB7 (USD $129). To cater to the different financial capacity of rural households, three scenarios were investigated and described in Table 2. Scenario 1 is for the total cost to be paid upfront, whereas scenario 2 and 3 hire-and-purchase arrangements. This model is based on the model used to analyse the SHS initiative under the REF initiative (World Bank, 2012).

Key considerations to incentivise households:

- Repayments are interest free as the cost of financing is borne by the provider.
- A subsidy provided under scenario 3.
- The households are no worse off in any year as the repayment amount is equal to or less than the recharge and replacement savings, with the O&M cost deducted.
- Assumptions: The Bboxx BB7 is used in conjunction with the car battery; it therefore reduces the reliance on the battery. This in turn reduces the recharging and replacing frequency, with a cost saving of USD $19.50* and USD $8.33* respectively.
- The Bboxx BB7 battery would be replaced every 10 years. The long lifetime is due to the high quality battery and support services provided by the supplier.

Table 1: Household (HH) energy usage and expenditure in the Secret Beach community (Saly, 2014)

HH	Cost per charge (USD $)	Frequency of charging	Cost per day (USD $)	Capability	Approximate usage (W-hrs/day)	LCOE (US$/kWh)
1	0.75	Every week	0.11	TV, phone, lights	84	2.25
2	2 batteries, 0.50 each	Every week	0.14	Lights, 3 phones	42	3.62
3	0.8	Every four days	0.20	TV, Video player, lights, 2 phones	118	2.49

Table 2: Costing of SHS repayments for various scenarios

		Scenario 1	Scenario 2	Scenario 3
Initial Capital	Initial capital cost required by provider	USD $129	USD $129	USD $129
	Subsidy	USD $0	USD $0	USD $32.25
	Cost owing at year 0 for household	USD $0	USD $129	USD $96.75
Benefit for household	Avoided costs (from battery recharging)	USD $19.50 per year	USD $19.50 per year	USD $19.50 per year
	Avoided costs (from battery replacement)	USD $8.33 per year	USD $8.33 per year	USD $8.33 per year
Costs for household	Periodic installments	N/A	Year 1 - 4: USD $25.33 Year 5: USD $25.67	Year 1 - 3: USD $25.33 Year 4: USD $19.25
	O&M cost	USD $2 per year	USD $2 per year	USD $2 per year

- The O&M cost is USD $2 per year (includes $1 for a cloth and $1 for 2 litres of water).
- The increased productivity due to longer working hours and the reduction in time involved with transporting the battery and/or phones to external sources to be charged has not been included as a benefit.
- Evaluation Period is 10 years.
- Subsidy was one quarter as this was the subsidy proportion provided to households in the World Bank SHS initiative (World Bank, 2012).
- Discount rate is 12 % as this was the rate used in the World Bank SHS initiative (World Bank, 2012).
- According to the datasheet, the Bboxx BB7 provides up to 60 W-h/day. This is over half current of current electricity consumption from households (ranging 48 W-hrs/day-118 W?hrs/day). Therefore, it was estimated the batteries are charged half as often, saving half the recharge cost which equates to USD $19.50 per year. Furthermore, the reduced usage of the batteries means the batteries are to be replaced less frequently, it is estimated as every 2 years rather than every 3, saving one third of the replacement cost which equates to USD $8.33 per year. These figures are used to calculate the net benefits in Figure 5.

Figure 5 graphs the present value of the accumulated benefits under the various scenarios. In scenarios 2 and 3 the systems are paid off within five and four years respectively, after which the systems generate economic benefits and essentially “free” electricity (not including replacement costs). For scenario 1, the household would be worse off until year seven and only then reap benefits, illustrated by a negative present value of accumulated benefit in Figure 5. As no interest rate is charged, the NPV is higher under scenario 2 and 3 than under scenario 1.

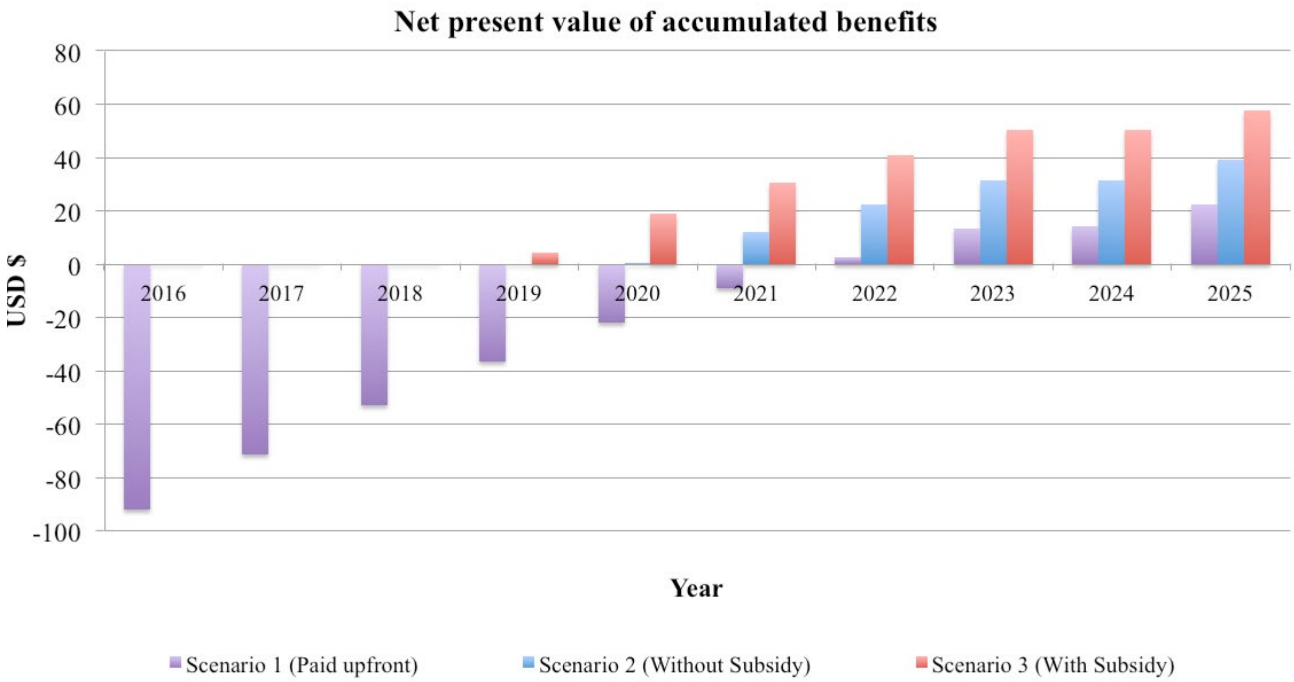

Figure 5: Net present value of accumulated benefits