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RESEARCH PAPER

Development of Solar-Powered Mobile Battery Swap Charging Station (MBSCS) As an Environmentally Friendly Charging Station Alternative

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ABSTRACT

Electric motorcycles (EM) are promising solutions for eco-friendly vehicles, but there are some dilemmas caused by the fossil-based energy used for charging and the limited charging infrastructure. This article proposes solving these dilemmas by designing a Solar-Powered Mobile Battery Swap Charging Station (MBSCS) for EM infrastructure. MBSCS will integrate solar power plants as a sustainable energy source and using battery swap system to accommodate EM. Design thinking methodology is used to develop the initial design of MBSCS and technical indicator assessment through focus group discussions with expert panelists. Simulations are conducted using PVSyst software to evaluate various system variants defined according to the selected components. The results of this study provide the MBSCS initial design, technical indicators to assess the MBSCS system, simulation results, and optimal system variant configuration. The findings of this study will mainly contribute to a solution for EM challenges and offer an environmentally friendly charging infrastructure. This study is expected to serve as an alternative solution for future mobile charging stations designed to answer the limited charging infrastructure as well as to demonstrate the potential use of portable solar power plant to overcome dependence on fossil-based energy.

KEYWORDS: *battery swap system; Design thinking; Electric motorcycles; Expert judgement; Mobile charging station.*

1. Introduction

The technological transition from conventional motorcycles to electric motorcycles (EM) is considered a way to reduce carbon emissions. Motorcycles are considered cheap vehicles compared to cars, have high flexibility, and are adaptive to all-terrain [1]–[5]. Despite high sales of conventional motorcycles, the adoption of EM is still relatively low. EM is considered by the public to have weaknesses such as slow battery charging speed, limited battery charging station facilities, and unclean energy sources [1]–[3], [5]–[11].[1], [2], [3], [4][1]–[3], [5]–[11]

Various efforts have been made to overcome the weaknesses of EM, such as increasing the number of batteries on EM to increase mileage, using a battery swap system, and using renewable energy source to generate the electricity [10]. The battery swap system is considered as a breakthrough to speed up battery charging and also overcome expensive battery prices so that consumers do not have to pay for battery components and can reduce the selling price of EM [10]. The use of solar power plants also makes it possible to answer the problem of unclean energy sources because solar energy is one of sustainable energy that is widely used as a replacement to fossil fuel.

To accelerate the distribution of EM charging infrastructure, this research introduced the concept of Mobile Battery Swap Charging Station

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(MBSCS). This concept is expected to meet the needs of charging infrastructure, especially for EM users with the battery swap system. MBSCS will act as a complement facility to the fixed battery swap charging station (FBSCS) which is the main form of current battery swap infrastructure [2], [11], [13].

The concept of the solar-powered Mobile Battery Swap Charging Station (MBSCS) can be used to overcome the EM weaknesses and public concern about the environment. MBSCS integrates mobile charging station concept, battery swap system, and using solar power plants. The usage of a battery swap system enables a faster EM charging process by replacing an empty battery with a fully charged battery from the battery charging cabinet [1], [2], [10], [14], [15].[1], [2], [10], [14], [15] Then, by using solar power plants for charging stations as a source of electrical energy can utilize a completely eco-friendly EM.

This research uses a design thinking method that is validated through expert judgment in designing MBSCS. The design thinking method is used in this research to look at objective and subjective points of view in real system as a basis for designing MBSCS. Expert judgement was carried out through focus group discussions (FGD) to validate the research results. This research aims to provide the MBSCS initial design, technical indicators to assess the MBSCS system, and simulation results using PVSyst software. This research is expected to serve as a benchmark for future mobile charging stations design and demonstrate the potential use of portable solar power generators.

2. State of the Art

Zhang et. al. (2020) researched a novel technology that can be used to charge electric vehicles (EV) in urban areas in Xiamen, namely mobile charging stations (MCS). The research compared fixed charging stations (FCS) and MCS based on the levelized cost of electricity (LCOE). The cost comparison results show that the LCOE for MCS is lower than FCS and it is [13]recommended to use MCS as supplementary technology to fixed charging [13]. Afshar et. al. (2021) reviewed 80 research articles on MCS development. The study results reveal that using MCS services is a cost-effective technology for charging facility owners to increase the charging equipment's utilization rate and reduce adverse effects on the electricity network [11]. Afshar et. al. (2022) conducted further research on MCS management in urban areas with a case study of Chattanooga. This research compared several types of FCS and MCS through simulations using MATLAB CVX with the GUROBI solver. The result confirms the reduction in load on the electricity grid due to the use of MCS [16]. In addition, using MCS can reduce costs and travel time for electric vehicle users when charging their EV [16]. Rochani et. al. (2023) conducted a study to develop a conceptual business model canvas (BMC) design for a mobile battery swap charging station (MBSCS). The results of this study formulated an ecosystem design for the MBSCS business, defining possible stakeholders and a business canvas for MBSCS [17]. Li et. al. (2024) and Aktar et. al. (2024) also researched about MCS operational scheduling and optimization of placing the MCS. The study concludes that MCS is feasible from operational perspective to alleviate concerns about limited charging infrastructure [18], [19]. Furthermore, that study also give the insight of future MCS service framework. While these previous studies providing valuable insight about development of vehicle charging infrastructure, there remains a notable research gap regarding the specific challenges faced by electric motorcycles (EM).

From the previous studies that stated in the paragraph before, it still primarily focused on electric cars (EC) as research objective rather than EM [11], [13], [16], [18], [19]. Given the different characteristic and challenges in technology adoption between EC and EM, there is a need for research that specifically addressing EM issues. The development of MCS as stated in previous research is also limited to electric vehicles such as EC and buses. Research on developing MCS specifically for EM and integrating MCS with battery swapping systems is still limited. Previous research has acknowledged concerns regarding the environmental impact of electric vehicles, particularly regarding energy sources for charging. However, there is still lack of research about integration of renewable energy source such as solar power into MCS to address the environmental concerns and promote transportation sustainability.

This paper aims to fill the identified research gap by proposing a novel approach to address the challenges faced by electric motorcycles (EM) through designing a Solar-Powered Mobile Battery Swap Charging Station (MBSCS).

MBSCS addresses the challenges faced by EM such as slow battery charging speed, limited charging infrastructure, and concerns about unclean energy sources by integrating solar power plants and battery swap system into mobile charging station concept. Moreover, this paper uses design thinking methodology which involves a panel of experts through focus group discussions, making this paper have a holistic and user-centric approach. The design thinking method allows for a comprehensive exploration of problems and solutions, ensuring that the proposed MBSCS addresses technical challenges and considers user convenience, infrastructure development, and environmental concerns. The expert judgement process in this paper also had a pivotal role to ensure validity and the relevance of the MBSCS design and technical assessment framework into real system.

In summary, this research contributes to charging infrastructure development by proposing a novel solution to the challenges faced by EM, emphasizing the integration of solar power plants, battery swap system, and mobile charging station into charging infrastructure. The proposed Solar-Powered MBSCS is a promising and innovative concept for future mobile and environmentally friendly electric vehicle charging facilities.

3. Experimental Procedure

This study uses the framework of the design thinking method to formulate problems, solutions, ideas, and assessment indicators in designing a mobile battery swap charging station (MBSCS). The framework of this study is shown in Figure 1.

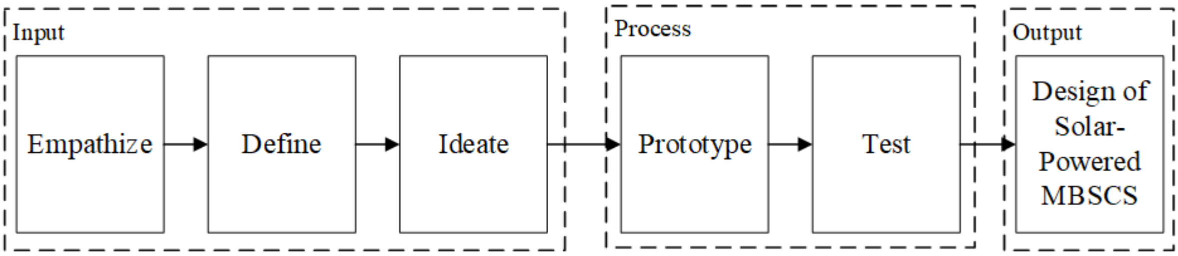

Fig. 1. Study framework

The design thinking method is a thinking process that can provide ways to interpret problems, find ideas, make prototypes, experiment, get feedback, and re-evaluate for developing ideas. [20], [21]. The implementation of the design thinking method consists of five important stages that cover the entire design thinking process, namely: empathize, define, ideate, prototype, test [22], [23], [24]. The five stages of design thinking activities in this study are described as shown in Table 1.

Tab. 1. Design thinking stage in this research

Design Thinking Stage	Definition	Activity in This Research
Empathize	Empathize is a process to position yourself from the point of view of users and stakeholders of the product to be designed [23].	Discussing related problems in the real situation regarding the infrastructure of charging stations and public battery exchange (SPBKLU).
Define	Define is a process to identify information related to problems obtained in the previous stage [24].	Categorizing the problems that have been determined at the empathize stage to find effective solutions easier.
Ideate	Ideate is the ability to think creatively and focus on problem processes [23].	Discussing the solutions to the problems to be formulated into product design ideas. Then, the research team will create a product design to fulfill the solutions discussed.
Prototype	Prototype is a real embodiment of the ideate stage which turns something abstract into something substantial [23]. This stage aims to realize the idea and test the solution ideas formulated in the previous stage [24].	Visualizing the ideas that had been formulated in the previous stage. Making product design visualization in this study using Autodesk Inventor software.
Test	The test is the stage of testing the prototype that has been made in the previous stage. This stage aims to test the prototype by predetermined indicators to get feedback for continuous improvement. [24].	Running the simulation using PVSyst software. The simulation results displayed are then summarized and adjusted to the technical indicators that have been formulated with the panel of experts.

This paper utilizes expert judgement in design thinking stages to ensure the validity and relevance of the MBSCS design and its technical assessment indicators for system evaluation. Expert judgement involves generating insight, opinions, and expertise from qualified professional or expert in a field that is relevant to the research. The expert judgement process in this research is described in Table 2.

Tab. 2. Expert judgement processes

Expert Judgement Process	Activity in This Research
Panel of expert selection	Panel of experts are carefully selected with relevant qualification and backgrounds related to electric motorcycles (EM), battery manufacturer, swap battery system provider, and renewable energy. This selection ensuring that the panel members covering various aspect of the research topics. This research appoints panel of experts as listed in Table 3.
Focus group discussion (FGD)	Panel of expert then gathered through FGD, where the panel members engaged in interactive discussions to share their knowledge, insight, and opinions about the research topic. These FGD were addressing key questions about challenges faced by EM adoption, its possible solution, the idea of MBSCS design, and the formulation of technical assessment indicators.
Validation of design thinking results	Expert judgement process in this paper has a pivotal role in validating the design thinking results. Panel members provide feedback and validation of the solutions and MBSCS design proposal. This process will ensure that the MBSCS design is addressing all key challenges effectively and met the needs in real system.
Establishment of technical assessment indicators	Panel of experts collaborating with researcher defining the technical assessment indicators for evaluating the performance of MBSCS design system variants. These indicators will provide a robust framework for assessing the feasibility and effectiveness of different system configurations.

Tab. 3. List of expert panelists

Panel Members Name	Panel Qualification
RWA	Executive of a lithium battery manufacturing company and electric motorcycle dealer
TSR	Executive of electric vehicle conversion company
PWB	Engineer team of lithium battery manufacturing company
RMI	Engineer team of renewable energy company

4. Results and Discussion

4.1. Results of design thinking

Focus group discussions (FGD) were held to collect data needed for design thinking. The FGD was carried out as part of an expert judgment with several panelists who were deemed to have expertise relevant to this study. The number and qualifications of a panel of experts in this study are shown in Table 2. The results of design thinking in this study are shown in Table 4.

Tab. 4. Summary of design thinking results

Design Thinking Stage	Activities	Results
Empathize	The FGD was carried out by asking the following core questions: 1. What are the problems driving and hindering the development of electric vehicles? 2. Are there any problems related to the charging station facility?	[FP-1]: Fossil fuel energy source dilemma (not eco-friendly) [FP-2]: Limited charging station [FP-3]: Battery charging time is relatively long [FP-4]: Difficult placement of charging station due to limited space [FP-5]: Implementation of government regulation
Define	The research team categorized the problem findings to make it easier to formulate solutions.	[C-1]: Environmental concern → FP-1 [C-2]: Infrastructure development → FP-2; FP-4 [C-3]: User convenience → FP-3 [C-4]: State program implementation → FP-5

Ideate	The FGD continued with the search for solutions to the problem findings at the *Empathize* stage. Then, after the solution is obtained, the discussion is continued by determining the idea for making a prototype that adapts to real conditions.	Solutions [S-1]: Use of renewable energy → C-1 [S-2]: Equitable distribution of charging facilities → C-2; C-3; C-4 [S-3]: Charging station that can move easily or mobile → C-2; C-3 [S-4]: Use of different charging systems → C-2 Prototype Idea [PI-1]: Use of solar power plant → S-1 [PI-2]: Use of trailer truck concept to accommodate the mobility of charging station → S-2; S-3 [PI-3]: Use of battery swap charging system → S-2; S-4 And the technical indicators as stated in Table 9
Prototype	The input from the previous stage was then formulated by the research team into a prototype. The prototype in this study is shown in a three-dimensional model.	Three-dimensional model of solar-powered MBSCS and its feature
Test	The research team conducted a simulation using PVSyst software with predetermined specifications. The displayed results will be adjusted to the technical indicators for assessment purposes.	The simulation results of solar-powered MBSCS operational, according to the technical indicator assessment

4.2. Three-dimensional design of solar-powered MBSCS

The results of the prototype stage were in the form of a three-dimensional model and the components that make up the MBSCS which were visualized through the Autodesk Inventor software by the researcher. The results of this stage are shown in Figure 2 and the feature or component in the MBSCS design is shown in Table 5. The blue color of the three-dimensional design depicts the PV panel as part of the solar power plant used in MBSCS.

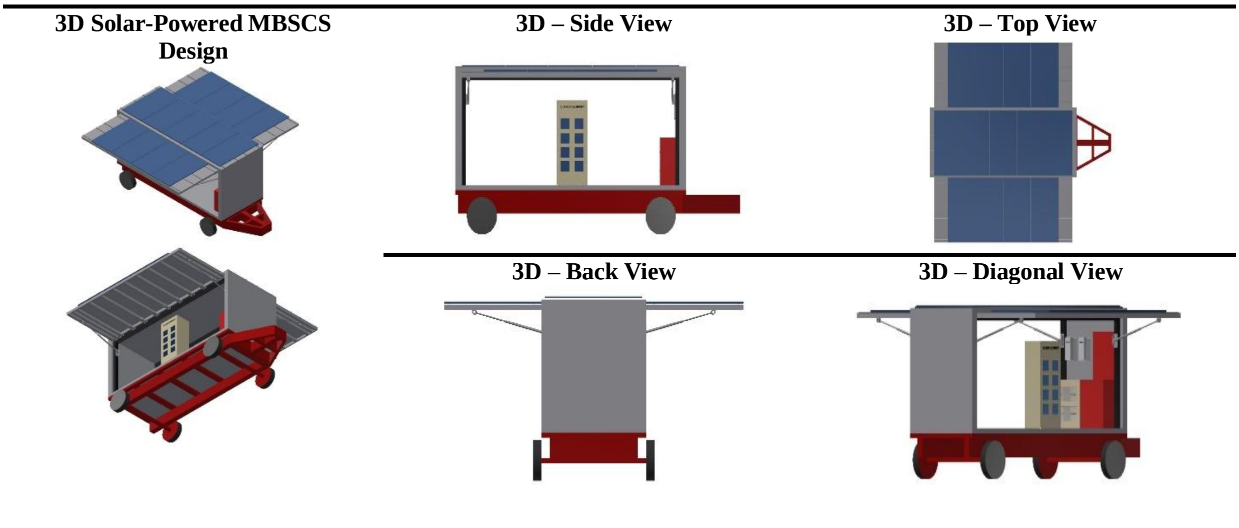

Fig. 2. Three-dimensional design prototype of solar-powered MBSCS

Tab. 5. Features in the solar-powered MBSCS design

MBSCS Feature	Description
Solar panel (Photovoltaic	The MBSCS designed in this study uses off-grid PLTS as a power source for

panel)	charging station operations. Off-grid PLTS allows MBSCS to become a charging station that is self-sustaining while being environmentally friendly.
Battery swap charging station (BSCS)	The MBSCS designed in this study uses a battery swap charging station. The use of the BSCS system at MBSCS is to meet the increasing demand for electric vehicles and to help equalize the infrastructure for public electric vehicle battery charging stations.
Chassis	The MBSCS designed in this study uses a carrier chassis as a means of transporting containers which is the framework of the charging station. The use of the chassis in MBSCS is for mobility purposes and is the core of the meaning of "mobile" in MBSCS.
Hydraulic system for door	The MBSCS designed in this study uses a hydraulic door mechanism as a means of expanding the solar panel installation area. The hydraulic door mechanism allows the right and left sides of the MBSCS container to open 90 degrees, so that the right and left side surfaces of the container face upwards.

4.3. Results of simulation

The simulation was carried out using the PVSyst software. All simulation results are according to the site of this study, namely Surakarta City with a latitude of -7.55°S and longitude of 110°E located at an altitude of 94 meters. There are three main parameters as the main input to define system variants, namely orientation, user's needs, and system.

The main parameter for orientation used in this study is 0 degrees in both plane tilt and azimuth (horizontal fixed tilted plane). For user's needs are according to the load calculation shown in Table 6. For system in this study simulates nine possible variants as shown in Table 9. The specification of parts used in the system variant of this study–for the PV module is shown in Table 7, the battery set is shown in Table 8, and the charge controller uses using universal controller MPPT converter of 1000 W and 48V having a maximum charging-discharging current of 152 A-55 A.

Tab. 6. Load calculation for user's need

Appliances	Power (W)	Quantity	Daily Use (hour/day)	Daily Energy Required (Wh/day)
Lamp	20	1	12	240
EV swap battery	300	8	12	28800
Standby consumer	200	1	24	4800
Total daily energy required				33840 Wh/day
Total monthly energy required				1015.2 kWh/month

Tab. 7. Detailed specification for PV module used

Model	JKM415M-54HL4	JKM490M-7RL3	JKM550M-72HL4
Manufacturer	Jinko Solar	Jinko Solar	Jinko Solar
Cell type	P-type mono	P-type mono	P-type mono
Dimension	1722x1134x30 mm	2182x1029x35mm	2274x1134x35 mm
Total PV module quantity	17	16	13
Module power	415 Wp	490 Wp	550 Wp
Max. power voltage (Vmpp)	28.88 V	43.68 V	40.90 V
Open-circuit voltage (Voc)	37.31 V	52.54 V	49.62 V
Max. current (Impp)	13.48 A	11.22 A	13.45 A
Short-circuit current (Isc)	14.01 A	12.04 A	14.03 A
Module efficiency STC	21.25%	21.82%	21.33%

Tab. 8. Detailed specification for battery set used

Model	FERPHOS 18650 48V	FERPHOS 18650 48V	FERPHOS 18650 48V

	100Ah	150Ah	200Ah
Manufacturer	Batex	Batex	Batex
Cell materials	$LiFePo_4$	$LiFePo_4$	$LiFePo_4$
Battery in series	15	15	15
Battery in parallel	56	84	112
Total battery pack quantity	7	5	4
Battery pack voltage	48 V	48 V	48 V
Global capacity	700 Ah	750 Ah	800 Ah
Stored energy (80% DOD)	30.5 kWh	32.7 kWh	34.8 kWh
Total weight	277 kg	296 kg	316 kg
Number of cycles at 80% DOD	800	800	800
Total stored energy during the battery life	21.97 MWh	23.54 MWh	25.11 MWh

Tab. 9. System variant in this research

System Variant	**PV Panel Variant**	**Quantity**	**Battery Set Variant**	**Quantity**
System variant 1	415 Wp	17	48V 100Ah	7
System variant 2	415 Wp	17	48V 150Ah	5
System variant 3	415 Wp	17	48V 200Ah	4
System variant 4	490 Wp	16	48V 100Ah	7
System variant 5	490 Wp	16	48V 150Ah	5
System variant 6	490 Wp	16	48V 200Ah	4
System variant 7	550 Wp	13	48V 100Ah	7
System variant 8	550 Wp	13	48V 150Ah	5
System variant 9	550 Wp	13	48V 200Ah	4

To assess the simulation results, the technical indicators that have been formulated by researchers alongside with panel of experts were used. Technical assessment indicators are used as a reference in selecting the best alternative. Explanations regarding technical assessment indicators are shown in Table 10.

Tab. 10. Technical assessment indicators

Technical Indicators	Definition	Preferable Condition
E_Avail	Electrical energy available from the PV panel	Expected to be bigger
E_Unused	Unused electrical energy (because the storage battery is full)	Expected to be lower
E_Miss	Unfulfilled electrical energy needs	Expected to be lower
Technical Indicators	Definition	Preferable Condition
E_User	The electrical energy distributed to the user's system	Expected to be bigger
%SolFrac	The percentage of electrical energy that meets energy needs ratio	Expected to be bigger
%PR	The percentage of system performance ratio	Expected to be bigger

The computational modeling for E_Avail, E_Unused, E_Miss, and E_User has been done within PVSyst software, so only simulation results are discussed in this paper. The %SolFrac is the percentage of E_User and E_Load ratio. The %PR is the percentage of the final PV system yield (Y_f) and the reference yield (Y_r) ratio. The formula for %SolFrac is shown in Equation 1 and %PR is shown in Equation 2.

$$\%SolFrac = \frac{E\_User}{E\_Load} \times 100\% \qquad (Eq.1)$$

$$\%PR = \frac{Y_f}{Y_r} \times 100\% \qquad (Eq.2)$$

The simulation results in this study are summarized in Table 11. The results are presented based on the technical assessment indicator. Based on the results, system variant 6 was considered as the best alternative according to technical assessment indicators.

Tab. 11. Simulation results for each system variant

System Variant	E_Avail (kWh/yr)	E_User (kWh/yr)	E_Miss (kWh/yr)	EUnused (kWh/yr)	%SolFrac	%PR
System variant 1	10,277	10,038.50	2,313.10	46	81.27%	80.41%
System variant 2	10,277	10,054	2,303.10	31.56	81.40%	80.48%
System variant 3	10,277	10,054	2,297.20	24.82	81.40%	80.53%
System variant 4	12,112	11,082	1,269.60	793.40	89.72%	75.18%
System variant 5	12,111	11,113	1,238.40	760	89.97%	75.39%
System variant 6	12,110	11,129	1,222.50	738	90.10%	75.50%
System variant 7	10,209	9,984.60	2,367	32.32	80.83%	80.46%
System variant 8	10,209	9,985.90	2,365.70	27.70	80.84%	80.47%
System variant 9	10,208	9,993.40	2,358.20	18.12	80.91%	80.53%

As shown in Table 11, system variants 4, 5, and 6 have simulation results that are quite close and better than the other 6 alternative system variants. The E_Avail indicator shows that the difference between the three systems is only 1 kWh/year so they are considered to have the same results. Then in the E_User indicator, system variant 6 has higher results than variants 4 and 5, with results of 11129 kWh/year, which indicates that system variant 6 is able to convert solar energy better. The E_Miss indicator also shows that system variant 6 has the lowest results with 1222.50 kWh/year, which indicates that system variant 6 is able to meet electricity needs better than other variants. The EUnused indicator shows that system variant 6 has the lowest results with 738 kWh/year, which indicates that system variant 6 has a more balanced component configuration compared to other variants. In the %SolFrac indicator, system variants 4, 5, and 6 are only fractionally different, however, system variant 6 has the highest ratio with 90.10%, which indicates that system variant 6 is more capable of meeting electricity needs than other variant systems. Although, in the %PR indicator, system variants 4, 5, and 6 are among the lowest, a ratio of 75% is still considered feasible to be implemented. We can conclude that all system variants are technically feasible with system variant 6 deemed the best system variant alternative in this study.

4.4. Managerial insight

Implementing a Solar-Powered Mobile Battery Swap Charging Station (MBSCS) presents a new strategic opportunity for businesses and government to address the challenges of electric motorcycles (EM) adoption while developing sustainable transportation initiatives. Integration of renewable energy source using solar power plant with charging infrastructure offered by MBSCS design will not only meet the growing needs for eco-friendly transportation but also contribute to net zero emission programs. Furthermore, the development of MBSCS should be prioritize to optimize MBSCS performance, enhancing charging efficiency, utilizing unused energy, and reduce investment cost. Innovation in battery swap technology, solar power integration, and mobile charging infrastructure will be crucial to maximize the impact of MBSCS and EM adoption. Government regulation and incentives also has a pivotal role to accelerate the development and implementation of MBSCS into the real system. In summary, embracing the concept of Solar-Powered MBSCS represents a forward-thinking strategy to lead the transitions towards eco-friendly transportation, capitalize on emerging EM market opportunities, and contribute to greener future.

4.5. Discussion for future research

Future research can focus on testing the economic feasibility of the mobile battery swap charging station (MBSCS). Future research is also needed regarding the business scheme for MBSCS as an effort to reach public businesses. Research can also focus on developing the technology of each component of the MBSCS. Research related to design using an external framework other than a 20-foot container can also be considered for further development.

5. Conclusions

This study aims to provide the Mobile Battery Swap Charging Station (MBSCS) initial design, technical indicators to assess the MBSCS system, and simulation results using PVSyst software. This study successfully developed an initial design for Solar-Powered MBSCS by using design thinking methodology and expert judgement. MBSCS design in this study integrates the use of solar power plants, battery swap system, and mobile charging concept as shown in Figure 2 and its feature in Table 5. This study also shows the simulation results using PVSyst software by evaluating the performance of multiple system variants as shown in Table 11, considering technical indicators as stated in Table 10. System variant 6 was found as the most promising alternative, demonstrating high energy availability and high energy needs fulfillment ratios, albeit still with some unfulfilled energy needs. The application of design thinking methodology with expert judgement in this study is a success and validates the effectiveness of this approach in addressing complex challenges and developing innovative solutions. The findings of this study mainly contribute to a solution for electric motorcycles (EM) challenges, offering an environmentally friendly charging infrastructure, validation of the design thinking approach in addressing complex challenges, and providing insights for future research and implementation of sustainable transportation. This study contributing to deliver solution for EM challenges, such as limited charging infrastructure and offer an environmentally friendly charging infrastructure. This study also expected to serve as an alternative solution for future mobile charging stations designed to answer the limited charging infrastructure as well as to demonstrate the potential use of portable solar power plant to overcome dependence on fossil-based energy.

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