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Manufacturing Strategies for a Family of Integrated Photovoltaic-Fuel Cell Systems

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Abstract: Integrated photovoltaic-fuel cell (IPVFC) systems have the potential to contribute to sustainable energy production for grid and off-grid applications. While there are studies focusing on fundamental science and designs for IPVFC systems, there are few studies that have focused on the manufacturability of IPVFC systems, which is certainly the pathway for the commercialisation of the systems. This study explores manufacturing strategies that can be considered for exploiting a family of eleven IPVFC systems. A survey and systems thinking approach were used to investigate the potential modularisation and supply chain management of the systems to achieve an optimal lean and agile manufacturing strategy. Results show that the Photovoltaic-Thermal-Separate Converter-Inverter-Battery System received 25% of the responses. The optimal manufacturing strategy depends on the overall business strategy of the firm. The 17% preference for System 1 was significant compared to four members of the family of IPVFC systems (Systems 2, 6, 8 and 9) that received only 2% of the responses, and there is a likelihood that the demand for System 1 will be among the top 42% of the total demand of all the systems. Overall, this study provides new insights into how the family of IPVFC systems can contribute to realising greater access to cleaner energy, by extension contributing to net-zero efforts using solar energy and solar hydrogen.

Keywords: renewable energy technologies; lean and agile manufacturing; modularisation; IPVFC systems; solar hydrogen; domain-based thinking; model-based systems engineering

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Citation: Ogbonnaya, C.; Hegarty, G. Manufacturing Strategies for a Family of Integrated Photovoltaic-Fuel Cell Systems. *Energies* **2024**, *17*, 4837. https://doi.org/10.3390/en17194837

Academic Editor: Philippe Leclère

Received: 14 August 2024
Revised: 12 September 2024
Accepted: 24 September 2024
Published: 26 September 2024

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1. Introduction

Renewable energy technologies (RETs) are sustainable sources of energy that operate without generating pollutants or particles unlike energy systems using fossil fuel [1,2]. Although RETs may not generate emissions during their operating life cycle phase, we have argued that a holistic view of the life cycle assessment of RETs, from cradle to grave, may reveal processes involving emissions or energy inefficiencies. For instance, before the operating life cycle phase of a RET, raw materials must have been obtained through local or global supply chains, subjected to various manufacturing processes, transported from one location to another location where value can be added to the materials and subjected to end-of-life management which may produce CO_2 and other pollutants.

Integrated photovoltaic-fuel cell (IPVFC) systems are RETs in which a photovoltaic (PV) or a photovoltaic-thermal (PV/T) module can be used as the prime mover, with a hydrogen generation module (electrolyser) and a hydrogen utilisation module (fuel cell) as classified by Ogbonnaya et al. [3]. Functionally, a PV-led IPVFC system generates electricity only, while a PV/T-led IPVFC system generates both electricity and hot fluid (air/hot water). Contextually, different configurations of the modules in IPVFC systems can be created to meet different use cases such as domestic, industrial, remote, and transportation applications, thereby creating a family of IPVFC systems. These systems have zero emissions during their operating life cycle phase, and therefore contribute to the decarbonisation of the energy infrastructure using ubiquitous solar energy, which is gaining serious traction particularly for producing blue solar hydrogen energy [4]. Nonetheless, solar energy

has the weaknesses of being intermittent due to unfavourable weather and completely unavailable at night, and it is also geographically constrained, resulting in temporal and spatial gaps between energy availability and the reliability of energy consumption by the end-users. This problem warrants the use of battery technologies and hydrogen energy technologies as energy storage components to improve the availability and reliability of IPVFC systems for all use cases [5,6]. In addition, there is a current need for devising optimal energy management strategies for IPVFC systems to enhance their durability and economic viability [7].

In Ogbonnaya [8], a domain-based systems thinking approach was shown to provide an opportunity for designers to create varieties of a system through different permutations and combinations of parts. A domain-based thinking approach aligns with the modularisation concept used in the design and manufacturing of complex systems in several world-class organisations [9]. Modularisation is a systematic decoupling of a system into modules that are independent of one another to enable customisation and mass production to meet the demands of customers for a variety of products [10]. Modularisation can enable a company to achieve engineering economy, strategic flexibility, simplification of manufacturing processes and interchangeability of modules [10]. Modularity in design is inherent in the composition of IPVFC systems because some functional modules can be manufactured by different companies across the globe whilst the final assembly can be conducted by a company leveraging global supply chains [11]. Modularity in design is applied in software design but it is very relevant in the design of complex engineered systems and in subsequent manufacturing management decisions to meet the requirements of customers [12,13].

The problem of this study is that, although applying modularisation in designing the family of IPVFC systems has benefits, a misalignment or mismanagement of the manufacturing strategy may create a wasteful inventory management approach and cost inefficiencies that may ultimately make the manufacturability of the family of IPVFC systems unsustainable. In lean manufacturing, typified by the Toyota production system, having excess inventory is gravely problematic because it will tie down cash, thereby reducing the liquidity of the firm. Carrying excess inventory may also prompt excess production of products that were not demanded, trigger a need for additional warehouse space to store excess inventory, as well as increase the cost of labour without a significant contribution to profitability [14]. Although these problems could be faced by manufacturers of the family of IPVFC systems, there are no previous studies that provide insights into how the multiple plausible configurations as well as the difficulty in determining demand can enable the lean and agile manufacturing of the systems. Considering the concept of variety-volume relationships in characterising products [15], there is a need to determine if the distribution strategy of the family of IPVFC systems will be based on a make-to-order, assemble-to-order, or make-to-stock postponement approach. Consequently, we theorise that determining the customer order decoupling point (CODP) for members of the family of IPVFC systems could offer an alignment between engineering, manufacturing and supply chains, and ultimately provide a competitive advantage to a manufacturer based on a combination of lean and agile manufacturing strategies. Jan [16] proposed that using a dual design approach in which CODP can integrate production and supply chain could improve the overall effectiveness of operations.

Furthermore, based on Marshal Fisher's matrix for matching supply chains of products to reduce demand uncertainties [17], IPVFC systems can be classified as innovative products which require a responsive supply chain strategy. Thus, by adopting lean and agile principles in the manufacturing of IPVFC systems, manufacturers and operators can achieve sustainable and profitable outcomes. A massive use of IPVFC systems for different applications will be beneficial in achieving cleaner energy access which is very important in realising several goals within the Sustainable Development Goals (SDGs) [1].

Therefore, the motivation of this study is to provide manufacturing perspectives on how to increase the contribution of the family of IPVFC systems to electrical, thermal and

hydrogen energy generations. Systematically, to determine whether modularity in design should be explored as the cornerstone of the manufacturing strategy of the family of IPVFC systems, the following null and alternate hypotheses were set forward:

- Null hypothesis (H_0): All customers prefer a photovoltaic-separate converter-inverter-battery system configuration (System 1);
- Alternate hypothesis (H_A): Not all customers prefer a photovoltaic-separate converter-inverter-battery system configuration (System 1).

The overarching aim of this research was to determine the manufacturing strategy that can be effective in serving customers who prefer different configurations among the family of IPVFC systems, based on the outcome of the hypothesis testing. The specific objectives of this research were as follows:

- Collect survey data to test the hypothesis;
- Study the modularity in the design of IPVFC systems using systems thinking approach;
- Analyse the implications of modularity in design in the context of manufacturability of the family of IPVFC systems;
- Propose the optimal manufacturing strategy for the family of IPVFC systems.

The significance of this study is that it is the first study to explore the manufacturing strategy aspect of IPVFC systems as well as provide supply chain management insights to researchers, designers, manufacturers and investors. This study advanced our previous work on design methodologies, energy and exergy analysis, modelling and simulations of PV, PV/T and thermophotovoltaic systems [5] and IPVFC systems [3,5,11,18]. This paper contributes to knowledge on the systems thinking design methodology of the family of IPVFC systems to facilitate an optimal manufacturing strategy as well as the supply chain network design that can deliver IPVFC systems to different end-users.

The overall outline of this paper is as follows. The descriptions of the IPVFC systems including potential applications are presented in the next section. This is followed by a presentation of the research methods adopted for realising the research objectives. Section 4 presents the results from the survey and a critical discussion on the implications of the hypothesis testing using model-based systems thinking. Conclusions from the study are presented in Section 5.

2. Description of the Family of Integrated Photovoltaic-Fuel Cell Systems

All the members of the family of IPVFC systems use solar energy, which is the most abundant renewable energy source in nature, to generate either electricity or electricity and hot air/water. This section presents the application of domain-based systems thinking and model-based systems engineering in proposing eleven IPVFC system configurations that are the focus of this study. There could be other configurations within the current design space depending on the creativity, innovation, technical ability and resources at the disposal of designers or manufacturers.

Table 1 presents the composition of the family of IPVFC systems with their reference number. To facilitate interpretation, "separate" means that the modules exist independently. Using System 1 as an example, "separate converter and inverter" is written with a hyphen (-) as a convention. The two modules can be combined into one module to create a unitised converter/inverter system as in System 2, which is written with a slash sign (/) as a convention. The purpose of unitisation is to reduce the cost and complexity of the overall system whilst increasing the efficiency. In addition, the manufacturing of the two modules from the same factory can reduce the risks of sourcing the two modules from original equipment manufacturers (OEMs) in different locations. These interpretations apply to the combination of a separate electrolyser and a fuel cell into a unitised regenerative fuel cell system that can generate hydrogen and oxygen through electrolysis as well as reverse the process to generate electricity through a redox reaction using hydrogen and oxygen, at a reduced cost and complexity [19] as in System 6. Fuel cell and electrolyser components can also exist independently [20] as in System 4.

Table 1. The family of IPVFC systems, their compositions and outputs.

Reference Systems	Functional Energy Output(s)	Module Composition
System 1	Electrical	Photovoltaic-Separate Converter-Inverter-Battery System
System 2	Electrical	Photovoltaic-Unitised Converter/Inverter-Battery System
System 3	Electrical and thermal	Photovoltaic-Thermal-Separate Converter-Inverter-Battery System
System 4	Electrical	Photovoltaic-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System
System 5	Electrical and thermal	Photovoltaic-Thermal-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System
System 6	Electrical	Photovoltaic-Unitised Regenerative Fuel Cell-Separate Converter-Inverter-Battery System
System 7	Electrical and thermal	Photovoltaic-Thermal-Unitised Regenerative Fuel Cell-Converter/Inverter-Battery System
System 8	Electrical	Photovoltaic-Electrolyser-Fuel Cell-Unitised Converter/Inverter-Battery System
System 9	Electrical and thermal	Photovoltaic-Thermal-Electrolyser-Fuel Cell-Unitised Converter/Inverter-Battery System
System 10	Electrical	Photovoltaic-Unitised Regenerative Fuel Cell-Unitised Converter/Inverter-Battery System
System 11	Electrical and thermal	Photovoltaic-Thermal-Unitised Regenerative Fuel Cell-Unitised Converter/Inverter-Battery System

Systems 1, 2, 4, 6, 8 and 10 produce electricity as their functional output. This implies that the applications of any of the systems are for the generation of electrical energy. The use of electrolyser and fuel cell serves to conserve excess electrical energy that may be generated by the PV module beyond the capacity of the batteries due to favourable weather conditions or during periods of underutilisation of energy generated from the PV or PV/T modules. Adding an electrolyser and a fuel cell also improves the reliability and robustness of IPVFC systems since the hydrogen generated during favourable weather conditions can be utilised in the fuel cell as a back-up power supply in mission critical use cases.

Systems 3, 5, 7, 9 and 11 produce both electrical and thermal energies that can be used for diverse applications depending on the end-use. Using PV/T modules improves the exergy efficiency of PV modules because more solar energy is harnessed from the same surface area and the cooling effect of the fluid increases the electrical energy efficiency of the PV/T module. As an opportunity cost, there is an increased complexity and cost associated with the extraction, transportation, storage and utilisation of thermal energy from PV/T modules. The diagrams of the eleven members of the family of IPVFC systems are presented in Appendix A.

IPVFC systems can be used for domestic and industrial applications, in electric and hydrogen cars, as a remote power source during camping, exploration and mining activities, in boats and unmanned aerial vehicles and as distributed power generators in schools, hospitals, markets, parks, religious buildings, libraries and ICT hubs in developing countries where there is often an unreliable power supply from the national grid.

3. Research Methodology

There were three approaches adopted in this study. First was a domain-based systems thinking approach which employs creative and analytic thinking processes to explore the interrelationships between the domains of design, function, use case, manufacturing, supply chain and demand of the family of IPVFC systems in a systematic way [8]. Domain-based systems and systematic thinking enabled a contextualisation of the complexities around the systems under consideration. Each member of the family of IPVFC systems is

a system with inputs, processes and outputs. The manufacturing firm that can assemble the systems is conceptualised as a system in which the modules, labour, capital, processes, information, technologies, etc. can be used to facilitate the assembly of IPVFC systems. The supply chain network design creates a system in which raw materials and information flow from one partner to another to ultimately satisfy the needs of the end-users of IPVFC system.

The second method incorporated into this study was model-based system engineering to explore a wide range of system configurations based on models of the IPVFC systems instead of using an experimental approach which would have been quite expensive for this study. The model-based systems engineering approach provided insights that can inform subsequent experimental and demonstration studies. In this study, the model-based approach focused on the modular architecture to allow design changes to be made to subassemblies [21]. An example is utilising waste heat from a PV module to heat fluid thereby creating a PV/T module. The fundamental thermodynamic principle in creating variants was based on an attempt to utilise waste electrical energy outputs to perform additional thermal work, but this has been shown to increase the complexity and cost of the IPVFC system [22]. Unitisation was used as a system design principle to merge two closely related modules into a single module as in unitised regenerative fuel cell and unitised converter/inverter modules. Table 2 shows the number of modules used to create the eleven systems from the design space containing PV, PV/T, BAT, INV, CON, UCONV/INV, EL, FC and URFC modules (see keys in Table 2).

Table 2. Number of modules required to make each member of the family of IPVFC systems.

Reference Systems	Modules								
	No. of Modules	PV	PV/T	BAT	INV	CONV	UCONV/INV	EL	FC	URFC
System 1	4	■		■	■	■				
System 2	3	■		■			■			
System 3	4		■	■	■	■				
System 4	6	■		■	■	■		■	■	
System 5	6		■	■	■	■		■	■	
System 6	5	■		■	■	■				■
System 7	3		■	■			■			
System 8	5	■		■			■	■	■	
System 9	5		■	■			■	■	■	
System 10	4	■		■			■			■
System 11	4		■	■			■			■

Keys: BAT = Battery; INV = Inverter; CON = Converter; UCONV/INV = Unitised converter/Inverter; EL = Electrolyser; FC = Fuel cell; URFC = Unitised regenerative fuel cell.

The third method used in this study was an online survey to obtain original data from respondents to test the hypothesis and gain insights into the level of demand based on the choices of the respondents. Google Forms was used to create an online survey, which contained only one question, but included all the images of the family of IPVFC systems in Appendix A. The question was:

> *"If you wanted one of the IPVFC systems to be developed for you, which one would it be?"*.

The respondents were instructed in the description to act as a customer who needed one of the IPVFC systems and choose a system that they thought would be suitable for them. The description of the outputs of the eleven systems was presented alongside the images showing the components. The images improved the visual appeal of the systems and made the systems easily distinguishable. The online survey was distributed using

various methods including asking individuals directly to complete it via email, posting the survey on LinkedIn, WhatsApp groups and Facebook.

Pareto analysis was used to rank the choices of the respondents. The result was further analysed to facilitate a discussion on the manufacturing management of the family of IPVFC systems.

4. Results and Discussion

To systematically explore manufacturing strategies for the family of IPVFC systems, the first endeavour was to examine the hypothesis in the light of the survey data to address research objective 1. The second task was to discuss the modularity in design of the family of IPVFC systems to address research objective 2. The insights from research objectives 1 and 2 were contextualised to determine the manufacturing and management principles that can facilitate the manufacturing of the family of IPVFC systems.

Hypothesis testing generally depends on the framing of the null and alternate hypotheses. In this case, the null and alternate hypothesis were stated thus:

- H_0: All customers prefer photovoltaic-separate converter-inverter-battery system configuration (System 1);
- H_A: Not all customers prefer photovoltaic-separate converter-inverter-battery system configuration (System 1).

The assumption behind the hypothesis construction was that System 1 might be preferred by a significant number of respondents based on factors including ubiquity, familiarity, cost, complexity, efficiency, functionality and sustainability. System 1 is the most used member of the family of IPVFC system, and it is the cheapest as well. All customers are aware that it does not use fossil fuel and, therefore, it is a sustainable energy system which uses solar energy as its primary source of energy to achieve certain functionalities. Determining the overall efficiency of the system is a technical decision and our previous study clearly concluded that increasing the complexity of IPVFC system will increase the cost but it must not necessarily increase the efficiency [22].

The second point that needs to be contextualised is that applying central limiting theorem to generate more data was not necessary in this study because the construction of the hypothesis sought to establish the level of deviation of demand of other systems from System 1 to inform the manufacturing strategy. In other words, if a significant number of respondents chose System 1, it is justifiable not to explore manufacturing strategies to cater for the family of IPVFC systems. Alternatively, if respondents chose significantly different IPVFC systems, it becomes justifiable to seek manufacturing strategies that are appropriate for low volume and high variety IPVFC systems.

Table 3 presents the survey data, based on the Pareto principle, to show the top 20% of systems selected by the respondents. The percentile was calculated using the cumulative number of respondents who selected each system. Based on the Pareto 80/20 rule, 20% of the systems selected by the respondents should be the configurations that the manufacturers can prioritise for development. From Table 3, System 3 (Photovoltaic-Thermal-Separate Converter-Inverter-Battery System) alone received 25% of the responses and constituted over 20% of the respondents based on the Pareto principle. Although the survey did not require respondents to give reasons for their choice of system, System 3 appeared quite popular among the respondents. Only 17% of respondents chose System 1. Although System 1 ranked second, which tends to validate the assumption that respondents may have chosen it because of its ubiquity, familiarity, simplicity and cost-effectiveness, the percentage falls significantly below average. This implies that the null hypothesis should be rejected whilst the alternate hypothesis should be accepted that "Not all customers prefer photovoltaic-separate converter-inverter-battery system configuration (System 1)" even with its perceived ubiquity, familiarity, simplicity and cost-effectiveness. Although a 17% preference for System 1 is significant compared to four members of the family of IPVFC systems (Systems 2, 6, 8 and 9) that received only 2% of the responses, it only indicates that

there is a likelihood that the demand for System 1 will be among the top 42% of the total demand for the eleven IPVFC systems.

Table 3. Results of the survey on the family of IPVFC Systems.

Systems	Module Composition	Respondents	Cumulative	Percent
System 3	Photovoltaic-Thermal-Separate Converter-Inverter-Battery System	13	13	25%
System 1	Photovoltaic-Separate Converter-Inverter-Battery System	9	22	42%
System 7	Photovoltaic-Thermal-Unitised Converter/Inverter-Battery System	8	30	57%
System 11	Photovoltaic-Thermal-Unitised Regenerative Fuel Cell-Unitised Converter/Inverter-Battery System	7	37	70%
System 10	Photovoltaic-Unitised Regenerative Fuel Cell-Unitised Converter/Inverter-Battery System	5	42	79%
System 5	Photovoltaic-Thermal-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System	4	46	87%
System 4	Photovoltaic-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System	3	49	92%
System 2	Photovoltaic-Unitised Converter/Inverter-Battery System	1	50	94%
System 6	Photovoltaic-Unitised Regenerative Fuel Cell-Separate Converter-Inverter-Battery System	1	51	96%
System 8	Photovoltaic-Electrolyser- Fuel Cell-Unitised Converter/Inverter-Battery System	1	52	98%
System 9	Photovoltaic-Thermal-Electrolyser-Fuel Cell-Unitised Converter/Inverter-Battery System	1	53	100%
Total			53	

An interesting result that emerged from this study was that respondents chose Systems 3, 7, 11 and 5 that contained PV/T modules. What makes this result interesting is that four out of the top six IPVFC systems contained PV/T modules (4/6 = 67%) (i.e., out of the top six IPVFC systems, four are PV/T-led while two are PV-led). This has a supply chain management implication because agile manufacturing requires responding speedily and flexibly to customer demands, which depends on the availability of the components to initiate the assembly of a system for an assemble-to-order distribution strategy. Thus, understanding that the systems with PV/T modules could be among the top six systems demanded could inform the overall inventory management strategy and the optimal design of the assembly of PV/T-led systems. This is also important in making speculations on the buffer inventory to be maintained to achieve lean principles by avoiding excess inventory beyond the actual demand from customers. The buffer inventory to be held should reflect the proportion of demand for PV-led and PV/T-led systems. This has decision-making value from a lean manufacturing perspective. For instance, for every six prime movers (PV and PV/T modules) held as buffer inventory, four can be PV/T modules while two can be PV modules. This will enable the manufacturer to respond to demand from the customers using the buffer inventory which will be replenished based on the reorder quantity level.

If the demand for PV/T-led systems is juxtaposed with our previous findings, that indicated that IPVFC systems with PV/T had higher energy and exergy efficiencies compared to equivalent systems with PV modules [22], this may explain why System 3, which was described as having the capacity to produce electricity and hot water/air, ranked first. This suggests that the respondents may have considered the functionality of each system in terms of generating electrical and thermal energy since PV/T-led Systems 7, 11 and 5 trail System 3. System 9 has a PV/T component, but the perception of complexity may have affected how respondents evaluated it. It is reasonable to think that the acquisition cost

and the operating cost of a complex IPVFC system should be higher than that of a simpler IPVFC system [22].

The alternate hypothesis in this study supports a modularisation strategy to achieve the interchangeability of modules for different IPVFC systems to meet customers' needs. Grouping the systems based on the prime mover (PV or PV/T) can facilitate a speedy assessment of the requirements of the configuration demanded by the customer. During assembly operation, not all the stations where the modules are stored will be visited every time a customer's order is being fulfilled. Table 4 presents the PV-led and PV/T-led systems for streamlining internal processes within the manufacturing firm. Notably, the systems require battery storage as a common denominator. This information is of strategic relevance because a company assembling IPVFC systems may decide to invest in battery manufacturing since all the systems need a battery module. For every demand of any of the IPVFC systems, battery module will be demanded, thereby creating a dependent demand scenario in which the demand for batteries varies with the number of systems demanded and the capacity of the IPVFC system. This vertical integration strategy to manufacture batteries can be embedded into a manufacturer's facility depending on the strategic choices of the firm. It may be more profitable and efficient to outsource the manufacturing of the battery while the firm focuses on the downstream part of the supply chain. Currently, efforts are directed towards investigating different types of battery technologies, including Li-ion batteries, that can be incorporated as the energy storage component in RETs [23].

Table 4. Streamlining system composition with internal supply chain.

Reference Systems	Modules									
	No. of Modules	PV	PV/T	BAT	INV	CONV	UCONV/INV	EL	FC	URFC
System 1	4	■		■	■	■				
System 2	3	■		■			■			
System 4	6	■		■	■	■		■	■	
System 6	5	■		■	■	■				■
System 8	5	■		■			■	■	■	
System 10	4	■		■			■			■
System 3	4		■	■	■	■				
System 5	6		■	■	■	■		■	■	
System 7	3		■	■			■			
System 9	5		■	■			■	■	■	
System 11	4		■	■			■			■

Keys: BAT = Battery; INV = Inverter; CON = Converter; UCONV/INV = Unitised converter/Inverter; EL = Electrolyser; FC = Fuel cell; URFC = Unitised regenerative fuel cell.

There are two scenarios considered in this study—a layout to facilitate assemble-to-order distribution and a warehouse layout in which components are stored and dispatched to meet customer orders onsite. These scenarios are presented with an acknowledgement that the assembly layout or warehouse layout is not cast in stone. As such, the overall layout depends on the existing manufacturing system or the strategic objectives of the firm. In this study, the assumption was that the firm uses assemble-to-order onsite. In other words, a facility is used as a warehouse to store the components such that the modules can be picked and quality-checked before they are delivered and installed at the end-user's location. This can also serve a scenario where the customer wishes to install the system using their engineers. The supply chain implication is that some modules can be sent to the site from the OEM thereby reducing the required warehouse capacity and the logistic implications of moving the modules to the warehouse first, storing them before moving them to the location of installation.

On the other hand, the assembly layout requires a complete or a partial assembly and testing of the components of a system before they can be transported to the location of the end-user for final installation and quality assurance testing. Overall, the business strategy and performance objectives of the organisation will determine how the assembly layout will be configured. The schematic diagram in Figure 1 shows the highest level of abstraction of the possible U-shaped warehouse layout of the storage of the modules. It does not show the detailed flow of parts of the modules, wiring requirements, system health monitoring devices (temperature, pressure, humidity, flow rate, etc.), instrumentation, piping, storage systems, etc. These details can be provided and possibly standardised by the manufacturer to facilitate lean and agile manufacturing processes. This will require manufacturing systems engineering and additional research to plan the value stream mapping to achieve a lean and agile operation.

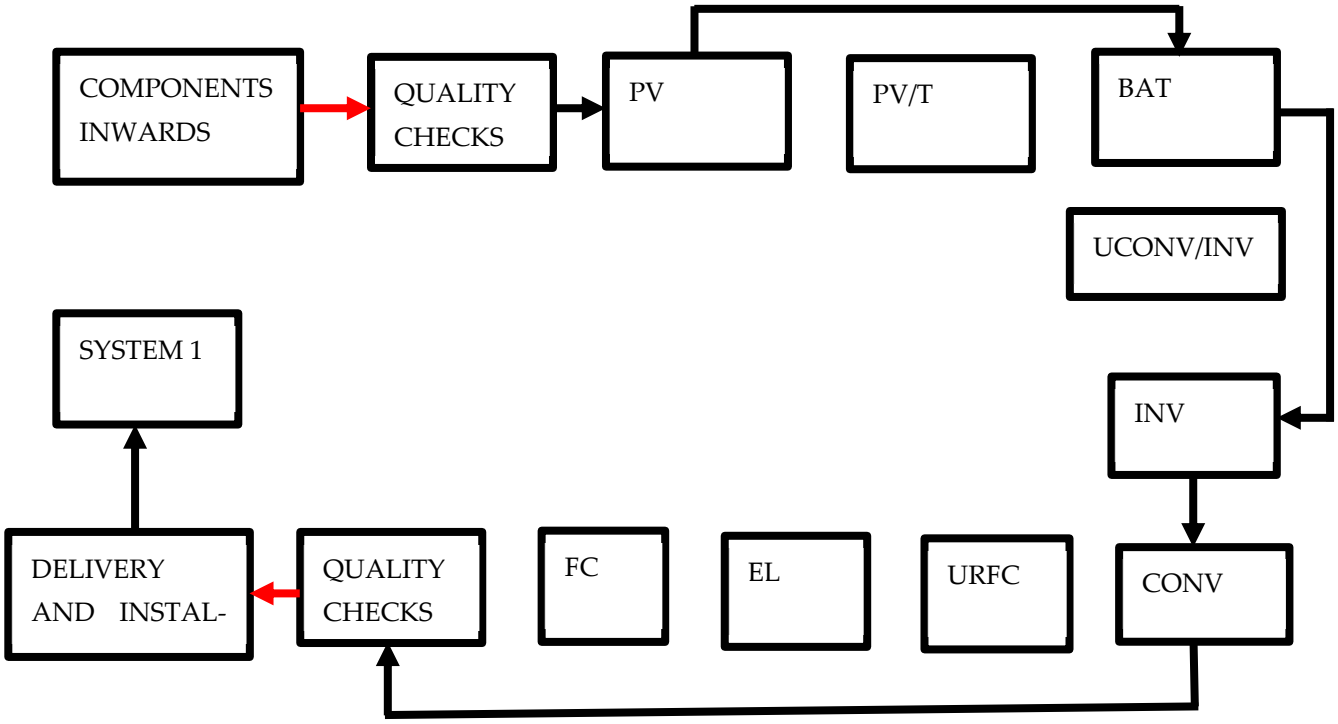


Figure 1. Proposed warehouse layout for onsite installation.

The proposed layout was designed to manage the assembly of all the members of the family of IPVFC systems. An example of how an order for System 1 can be fulfilled has been illustrated. Initially, modules received from OEMs are checked for quality assurance. The modules can then be stored at clearly marked stations or storage areas. When an order is placed, the relevant modules required to configure the system are picked up and checked for quality. Again, the modules can be assembled onsite or within the facility depending on the nature of the operation. Although the manufacturer may adopt assemble-to-order, to reduce inventories at the stage of tier 1 supplier, OEMs may need to adopt a make-to-order strategy based on the dependency of the demand for the modules on the demand for the IPVFC systems from the customers. To manage the supply chain effectively and remove the Forester effects due to uncertainties in the demand of each member of the family of IPVFC systems, there is a need to adopt a collaborative planning approach and information sharing mechanisms with all the partners in the supply chain to maintain supply chain visibility, and efficient and stable supply chain dynamics.

The findings from this study contribute to the investigation of the manufacturability of the family of IPVFC systems but the limitation is that the scope does not cover the cost-complexity-efficiency information on the eleven systems. This limitation of scope is being

addressed in our ongoing study focusing on the trilogy of cost-complexity-efficiency of IPVFC systems so that the systems can be ranked in terms of the cost-complexity-efficiency model for assessing RETs [5]. Addressing this limitation is necessary considering that we have already established that increasing the complexity of IPVFC systems in an effort to reduce exergy destruction in some components does not always translate into increasing the overall energy and exergy efficiencies of an offspring system, but it can translate into increase in total cost of the systems [22].

5. Conclusions

This study explored how the family of Integrated Photovoltaic-Fuel Cell Systems can be manufactured based on lean and agile manufacturing principles, leveraging the inherent modularity in the design of the systems. To achieve this, model-based systems engineering, domain-based systems thinking and the use of an online survey were employed. In this study, the Photovoltaic-Thermal-Separate Converter-Inverter-Battery System (System 3) received 25% of the responses while 17% of respondents chose the Photovoltaic-Separate Converter-Inverter-Battery System (System 1). Although System 1 has the characteristics of ubiquity, familiarity, simplicity and cost-effectiveness, the percentage of responses fell significantly below average, thereby necessitating the alternate hypothesis that supported modularisation. Comparing System 1, that received 17% of the responses and ranked second, with Systems 2, 6, 8 and 9 that received only 2% of the responses suggested that there was a likelihood that the demand for System 1 will be among the top 42% of the total demand for the family of IPVFC systems.

Overall, the manufacturing system configuration preferred by a manufacturer will depend on the nature of the company, the strategy of the company and the performance objectives of the company. Finally, modularity in design, which is inherent in the family of IPVFC systems, should be managed through appropriate supply chain management and a manufacturing operation that is inclined to lean and agile manufacturing.

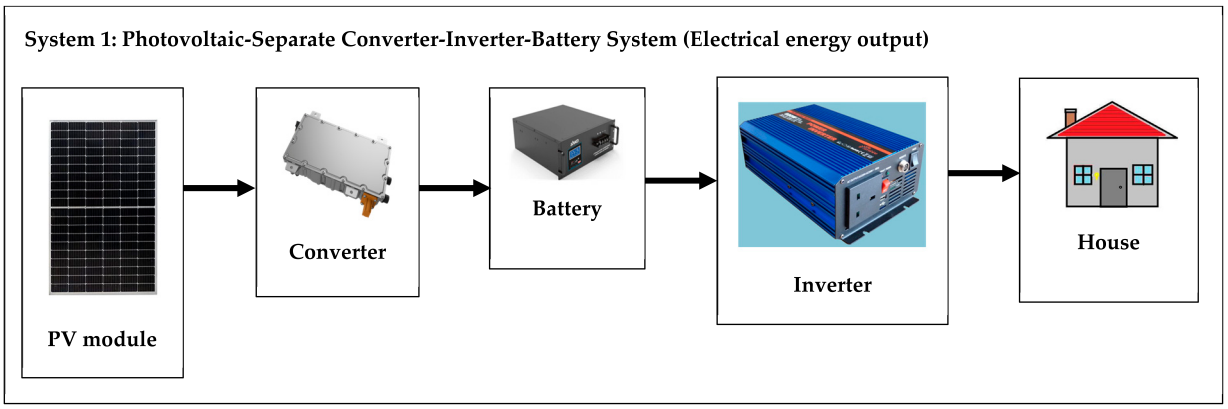
Author Contributions: Conceptualisation, C.O. and G.H.; methodology, C.O. and G.H.; software, G.H.; validation, C.O.; formal analysis, C.O. and G.H.; investigation, G.H.; resources, C.O.; data curation, G.H.; writing—original draft preparation, G.H.; writing—review and editing, C.O.; visualization, G.H.; supervision, C.O.; project administration, G.H. All authors have read and agreed to the published version of the manuscript.

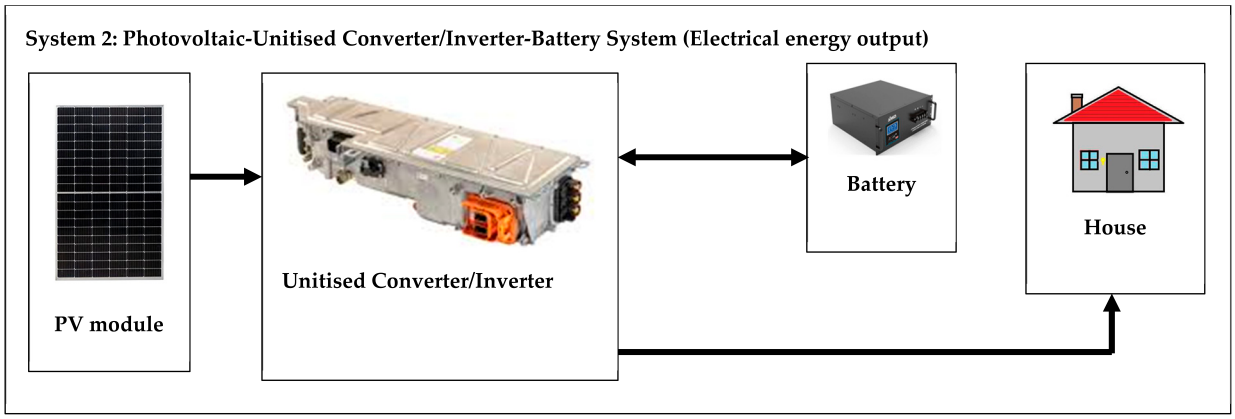
Funding: This research received no external funding.

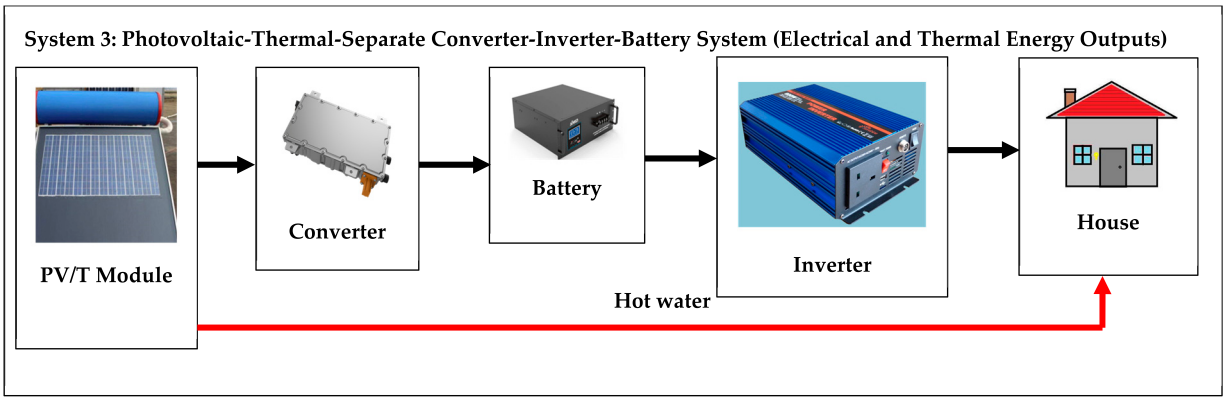
Data Availability Statement: Data are contained within the article.

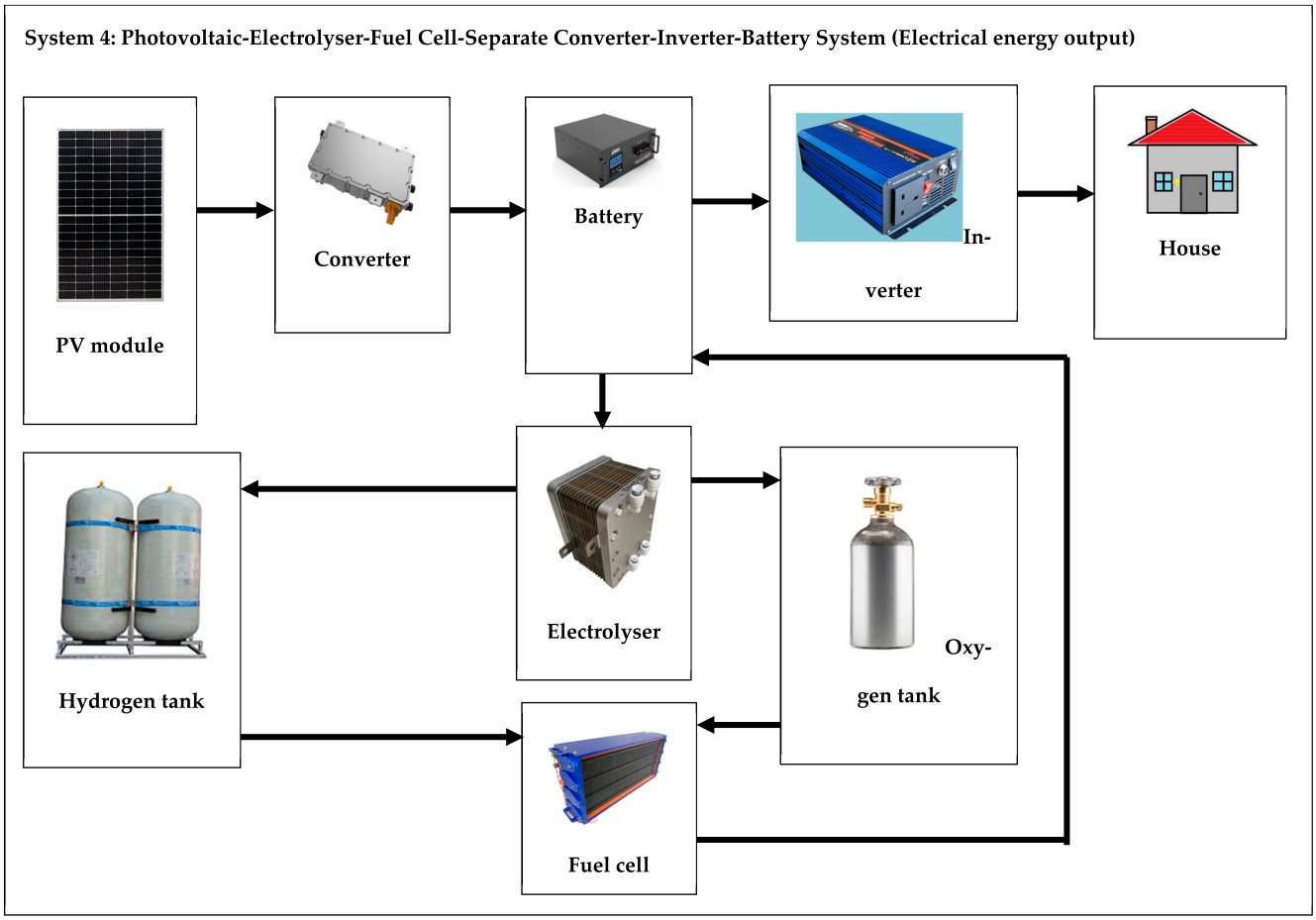
Conflicts of Interest: The authors declare no conflicts of interest.

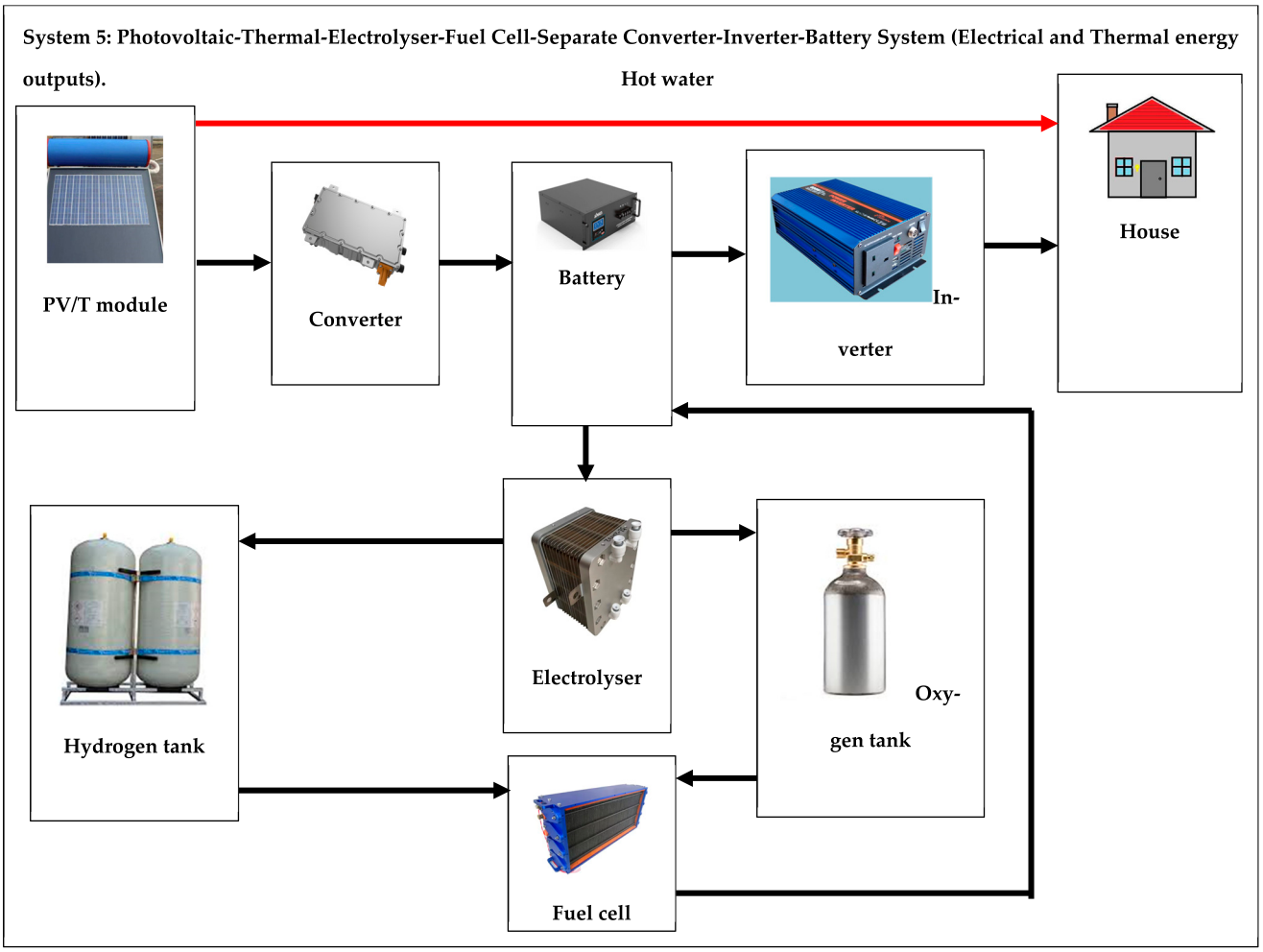
Appendix A. Configurations of the Family of IPVFC Systems

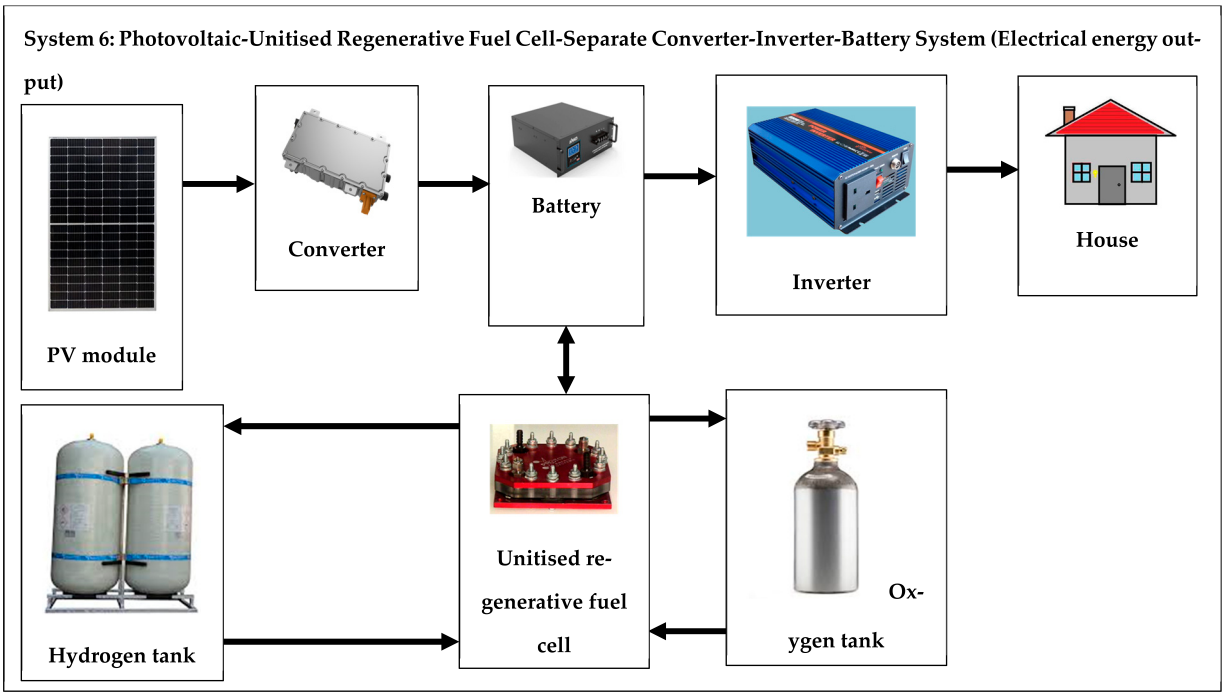



System 2: Photovoltaic-Unitised Converter/Inverter-Battery System (Electrical energy output)
PV module
Unitised Converter/Inverter
Battery
House

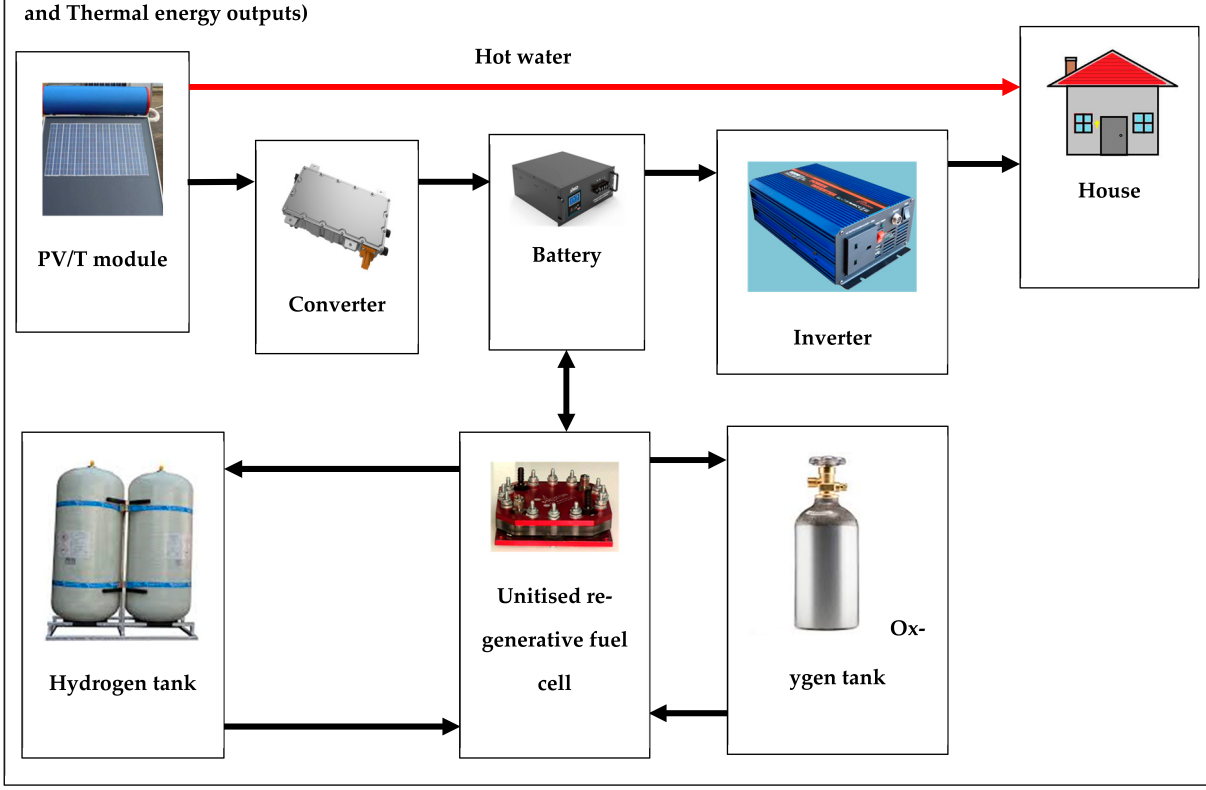

System 3: Photovoltaic-Thermal-Separate Converter-Inverter-Battery System (Electrical and Thermal Energy Outputs)
PV/T Module
Converter
Battery
Inverter
House
Hot water


System 4: Photovoltaic-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System (Electrical energy output)
PV module
Converter
Battery
In-
verter
House
Hydrogen tank
Electrolyser
Oxy-
gen tank
Fuel cell

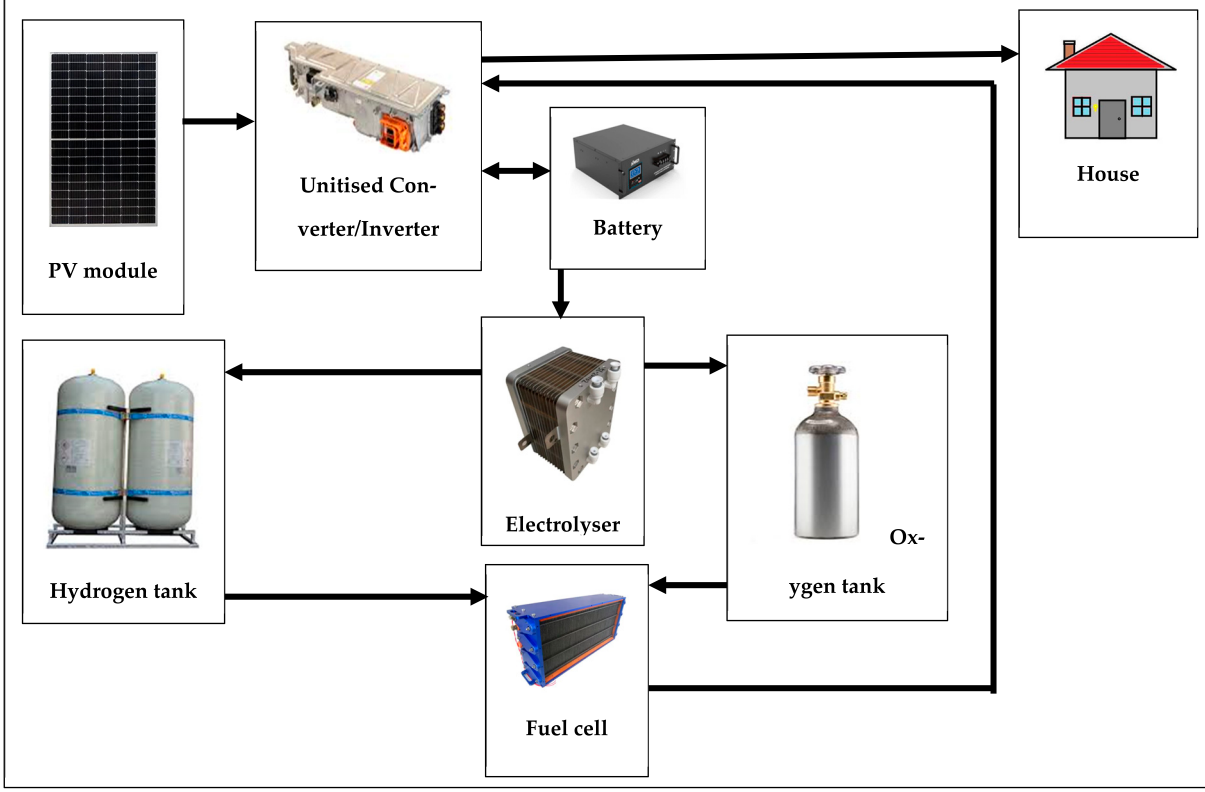

System 5: Photovoltaic-Thermal-Electrolyser-Fuel Cell-Separate Converter-Inverter-Battery System (Electrical and Thermal energy outputs).
Hot water
PV/T module
Converter
Battery
Inverter
House
Electrolyser
Hydrogen tank
Oxygen tank
Fuel cell

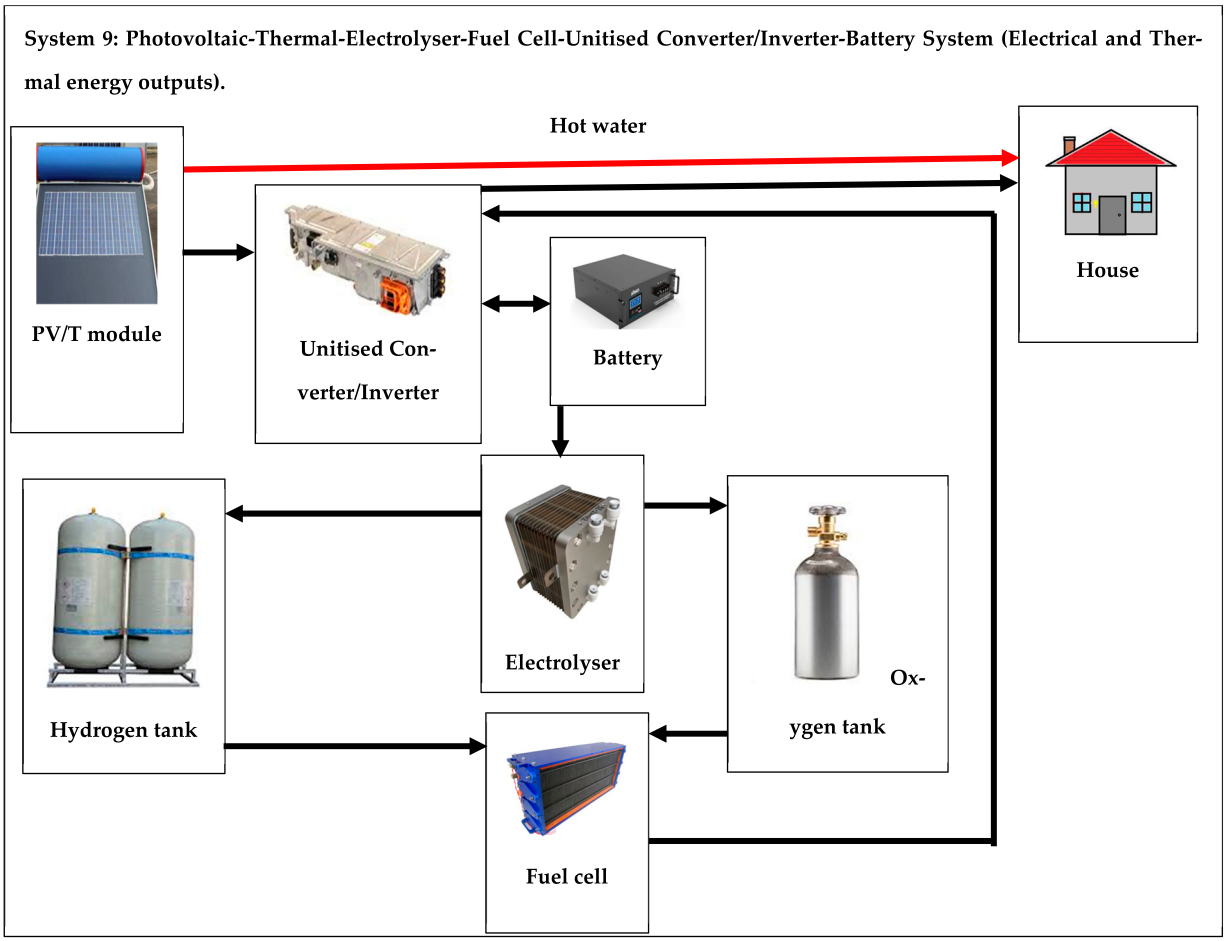

System 6: Photovoltaic-Unitised Regenerative Fuel Cell-Separate Converter-Inverter-Battery System (Electrical energy output)
PV module
Converter
Battery
Inverter
House
Unitised regenerative fuel cell
Hydrogen tank
Oxygen tank

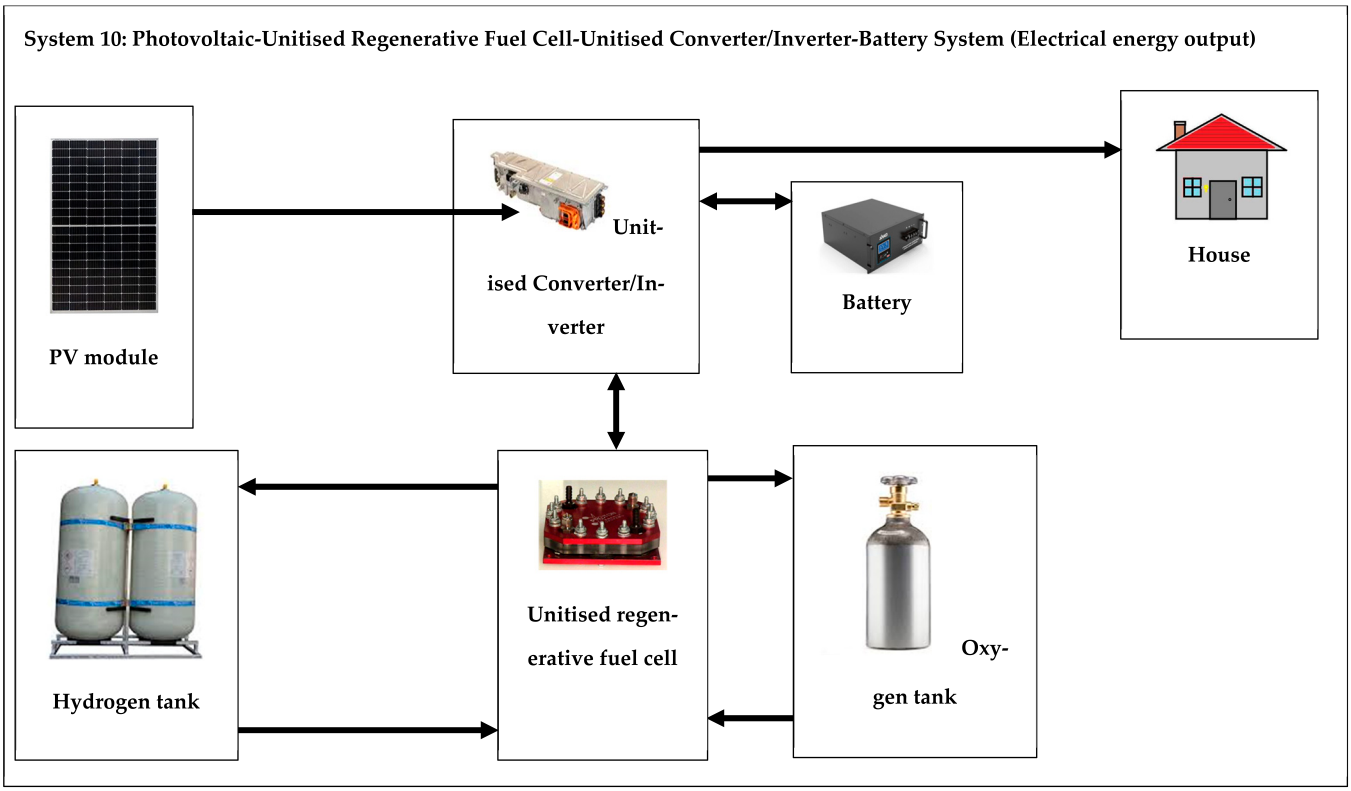
System 7: Photovoltaic-Thermal Unitised Regenerative Fuel Cell-Separate Converter-Inverter-Battery System (Electrical and Thermal energy outputs)

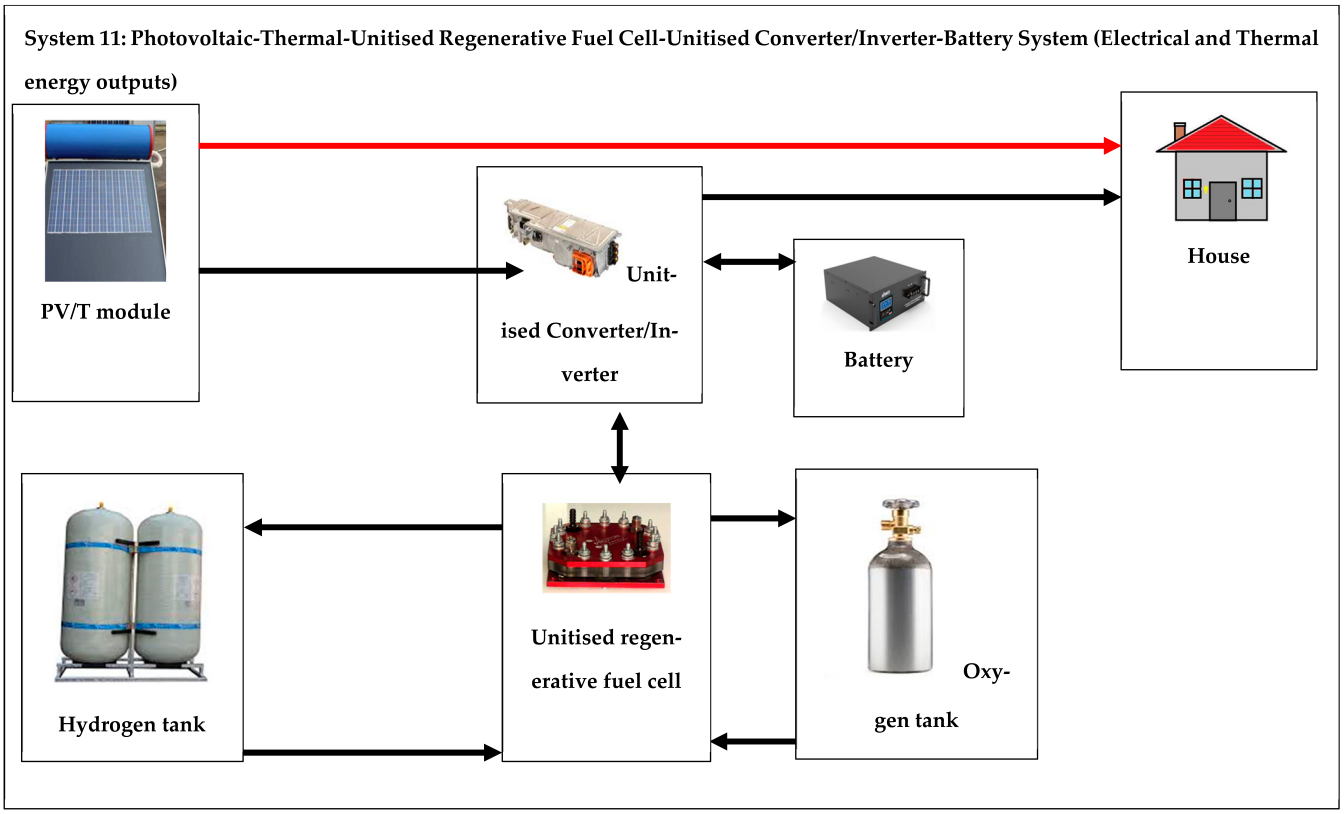


System 8: Photovoltaic-Electrolyser-Fuel Cell-Unitised Converter/Inverter-Battery System (Electrical energy output)




System 9: Photovoltaic-Thermal-Electrolyser-Fuel Cell-Unitised Converter/Inverter-Battery System (Electrical and Thermal energy outputs).
Hot water
PV/T module
Unitised Converter/Inverter
Battery
House
Hydrogen tank
Electrolyser
Oxygen tank
Fuel cell


System 10: Photovoltaic-Unitised Regenerative Fuel Cell-Unitised Converter/Inverter-Battery System (Electrical energy output)
PV module
Unitised Converter/Inverter
Battery
House
Hydrogen tank
Unitised regenerative fuel cell
Oxygen tank



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