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SMART GRID ENABLER (SGE) FRAMEWORK DEVELOPMENT FOR RESIDENTIAL SECTOR TOWARDS ENERGY CONSERVATION STRATEGIES VIA FUZZY DELPHI METHOD

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Abstract — The global implementation of smart grids has revolutionised the electricity grid, including in Malaysia, where Tenaga Nasional Berhad leads the initiative. This Smart Grid system is akin to the internet of electricity, serving as a pivotal element in the sustainable energy transition within the electricity sector. The residential sector, which heavily relies on electricity for daily activities, stands to benefit significantly from this development. Despite the numerous advantages offered by smart grids, the Malaysian residential sector has not yet fully optimised these benefits to incorporate fit-for-use components. Thus, this research aims to develop a Smart Grid Enabler (SGE) framework for the Malaysian residential sector that supports energy conservation strategies. Based on the Trias Energetica and Smart Grid Conceptual Model, the Fuzzy Delphi Method is utilised to synthesise expert consensus and establish critical components for the SGE framework and achieve the aim of this research. Subsequent future research anticipates a better refined SGE framework which explores pragmatic and practical real-world applications in the residential setting. This study contributes to ongoing efforts in sustainable energy development through smart grid system optimisation for the Malaysian residential sector.

Keywords: smart grid enabler, residential sector, energy optimisation component, framework, fuzzy delphi method

1.0 INTRODUCTION

The introduction of smart grid technologies has triggered significant shifts in the worldwide electricity utility sector. These advancements in technology are transforming the conventional electrical grid, providing improved efficiency, dependability, and sustainability. Malaysia's smart grid transformation, led by Tenaga Nasional Berhad, is a major step in modernising its electricity infrastructure [1]. The smart grid system is commonly referred to as the "internet of electricity," indicating its ability to seamlessly integrate many aspects of power generation, distribution, and demand digitally [2]. This transition is especially vital for the residential sector, as modern lifestyles depend heavily on a reliable and effective electricity supply to enable daily tasks and domestic routines.

However, the residential sector in Malaysia has yet to take full advantage of the significant benefits associated with smart grid technologies [3]. The significant challenge that remains to be addressed is the optimisation of smart grid components and their integration into buildings like residential dwellings [4]. This discrepancy, which represented the knowledge gap, emphasises the necessity for a bespoke framework that caters to the demands and scenarios of Malaysian households. The establishment of such a framework is necessary to fully utilise smart grids' potential to encourage energy conservation and improve the overall effectiveness of electricity usage in the residential sector [5]. Therefore, this study intends to fill the knowledge gap through the development of a Smart Grid Enabler (SGE) framework for the modern Malaysian households. The Fuzzy Delphi Method (FDM) was chosen as the research approach, attributed to its advantage in managing ambiguity and consolidating expert viewpoints. This methodology utilises expert consensus to identify and prioritise critical smart grid components suitable for Malaysian residential sector integration, ultimately contributing towards energy conservation strategies efforts.

2.0 THE ENERGY MODEL

The Smart Grid system operates in a complex communication network, hence the reference to "internet of energy". As the advanced electricity system of the 21st century developed to cater for the needs of the 21st-century society, suitable energy models are necessary to establish a framework identifying items of the SG components for the residential sector. As such, reference energy models are an essential basis for optimising and comprehending energy consumption, production, and distribution, especially towards establishing a theoretical framework. The proposed framework shall include a variety of technologies and strategies that are intended to improve energy efficiency, integrate renewable energy sources, and assure a reliable power supply. The following subtopic shall explain two energy models utilised in this research article, comprising of *Trias Energetica* and the Smart Grid Conceptual Model (SGCM).

2.1. Trias Energetica

The Trias Energetica is a sustainable energy strategy that originated in the Netherlands, designed to guide efforts in reducing energy consumption and environmental impact. This model, developed by the Delft University of Technology [6], outlines a three-step approach to achieving energy sustainability, as shown in the figure below.

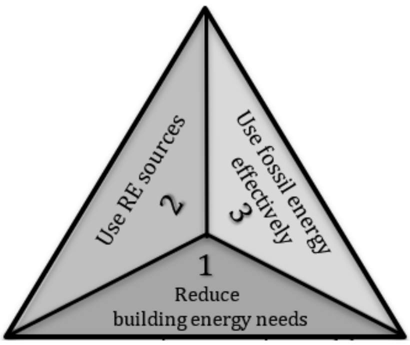

Figure 1: Trias Energetica Model

In reference to Figure 1, the concept of Trias Energetica can be explained based on the table below, characterised by its sequential application based on tiers.

Table 1: Trias Energetica sequential implementation

Tier	Sustainable energy approach
Reduce Energy Demand	The first step focuses on minimising energy consumption through energy-efficient design, technologies, and practices. This includes improving insulation, utilising energy-efficient appliances, and optimising building designs to reduce the overall energy needed.
Utilize Renewable Energy Sources	The second step emphasises the use of renewable energy sources, such as solar, wind, and biomass, to meet energy needs. By prioritising clean energy, this step aims to reduce dependence on fossil fuels and lower greenhouse gas emissions.
Use Fossil Fuels Efficiently	The final step advocates for the efficient use of fossil fuels when renewable energy cannot fully meet energy demands. This involves implementing advanced technologies and systems to maximise the efficiency of fossil fuel consumption, thereby reducing emissions and conserving resources.

This energy model is crucial for developing the SGE framework, as it outlines sustainable energy strategies for the residential sector. It focuses on three key areas: reducing electricity demand through efficiency in appliances and behaviour, prioritising renewable energy sources like solar and wind, and using fossil fuels in the cleanest, most efficient way for any remaining energy needs. In Malaysia, integrating electric vehicles (EVs) is highlighted as a vital strategy to reduce reliance on fossil fuels for transportation, contributing to lower carbon emissions in residential energy use. The Trias Energetica model enhances energy resilience and sustainability, supporting Malaysia's Environmental, Social, and Governance (ESG) goals and aligning with the United Nations Sustainable Development Goals (UN-SDG) 2030.

2.2. Smart Grid Conceptual Model

The Smart Grid Conceptual Model (SGCM), developed by the National Institute of Standards and Technology (NIST), offers a foundational framework for smart grid interconnection and interoperability [7]. SGCM, widely adopted globally, outlines seven key domains known as Bulk Generation, Transmission, Distribution, Markets, Operations, Service Providers, and Customers, where each is crucial for the grid's efficient, reliable, and secure operation.

The Bulk Generation domain includes both conventional and renewable energy sources, along with storage systems, essential for large-scale power production [8]. Transmission and distribution manage the high-voltage transfer and distribution of electricity, ensuring efficient flow and real-time data management [7]. Markets facilitate power trading, promoting economic efficiency [9], while operations focus on real-time grid monitoring and control [10]. Service providers, including utilities and third-party services, enhance grid functionality [11]. The customers' domain involves end-users utilising smart technologies like metres and demand response programmes to engage with the grid, thereby improving efficiency and sustainability [12].

Collectively, these domains form an integrated energy system essential for balancing supply and demand, integrating renewable resources, and enhancing grid resilience. Identifying and understanding these domains is crucial for developing the SGE framework, as they highlight key smart grid components vital for residential energy management.

2.3. Residential unit significant components

In smart grid domains, specific components are crucial for the housing sector, enhancing energy efficiency, user engagement, and system reliability. These components are essential for future housing developments, as they optimise electricity supply and demand, promote energy conservation, and encourage sustainable behaviour.

A study highlighted key Smart Grid (SG) components for residential integration, as shown in Table 2. These include renewable energy sources, energy storage systems, electric vehicles (EVs), smart metres, communication systems, feedback systems, IoT, and sensors. Each component aligns with SG domains like generation, distribution, and customer services, forming a comprehensive residential energy management strategy. Integrating these components enables the residential sector to optimise energy usage, engage users in sustainable practices, and improve the overall energy management experience. This alignment with smart grid infrastructure is critical for advancing a resilient and sustainable energy system in future Malaysian housing developments.

Under the generation, including the DER domain, households are increasingly generating their own electricity, driven by Malaysian policies like Suria 1000, FiT, NEM, MySuria, and GTFS, which have boosted solar panel installations. Globally, home battery storage systems, crucial in the energy storage domain, are recognised for reducing grid dependence, particularly where time-of-use pricing is used. However, in Malaysia, the high initial cost of these systems remains a barrier [5].

Electric Vehicles (EVs) and Plug-in Vehicles (PIVs) are key to residential energy conservation, optimising energy use and integrating renewables within the Smart Grid framework. They interact with the Customer domain for energy management, the Distribution domain for grid integration, and the Service Provider domain for load balancing, enhancing overall energy efficiency and sustainability.

Table 2. SG components are significant for residential sector integration.

Related SG Domain / Sub-Domain	Significant SG component	References
Generation (including DER), Customer, Distribution, Service Provider, Operations.	RE sources	[13]
Customer Service Provider, Markets	Energy storage	[14]
Customer, Service Provider, Markets.	Plug-in Vehicle	[15, 16]
Customer, Markets, Operations, Generation (including DER).	Smart metering system	[9]
Customer, Markets, Service Provider, Operations, Generation (including DER), Transmission, Distribution	Communication system	[17, 18]
Customer, Markets, Service Provider	Feedback System	[19]
Customer, Service Provider, Operations, Generation (including DER), Distribution	Internet of Things (IoT)	[20, 21]
Customer, Service Provider, Operations, Generation (including DER), Distribution	Sensors	[22, 23]

*DER – Distributed Energy Resources

Smart metering systems are critical for real-time energy monitoring, allowing homeowners to manage consumption and reduce waste. Within the SGCM, smart meters provide data to the customer domain for home energy management, to the service provider domain for grid optimisation, and to the distribution domain for efficient load management and fault detection.

The communication system in the SGCM is essential for real-time data exchange between smart devices and the grid, ensuring efficient energy management. It connects the customer domain for smart home integration, the service provider domain for dynamic pricing, and the distribution domain for grid stability and load management.

Feedback systems are crucial in providing real-time energy consumption insights, helping users reduce energy use. In the SGCM, they enhance the customer domain with detailed reports and recommendations and support the service provider domain by enabling tailored energy-saving programmes and promoting proactive conservation.

IoT and sensors are vital for automating and optimising energy use in homes connected to smart grids. They interact with the Customer domain for smart home technologies, the Distribution domain for precise grid management, and the Service Provider domain for enhancing energy efficiency programs and creating a responsive and intelligent energy ecosystem.

2.4. The enabling components

Based on Table 2 in subsection 2.3, further Smart Grid components were identified based on literacy publications that are depicted in Figure 2 below. Energy-efficient dwellings require many smart grid domains and subdomain-enabling components. These components optimise domestic energy usage and sustainability with modern technologies. Solar photovoltaic (PV) and vertical-axis wind turbines (VAWT) were key renewable energy sources for domestic integration [24]. Solar PV in residential installations is rising in Malaysia [25], whereas wind energy is small due to low wind speeds across the Peninsula [26].

These devices cut homeowners' energy costs and grid dependence. EVs and PIVs are growing worldwide due to their sustainability. Recent government policies and incentives are accelerating the adoption of these vehicles in Malaysia's automotive market. If this trend persists, Smart Grid (SG) systems, which include EV charging and EV batteries, will require EV and PIV infrastructure, particularly in residential regions, thereby transforming Malaysian home energy management. The role of EVs in smart grids has been studied [15]. With EVs, households save energy. Home EV charging stations and V2G technologies allow EVs to replenish the grid during peak demand, decreasing system strain.

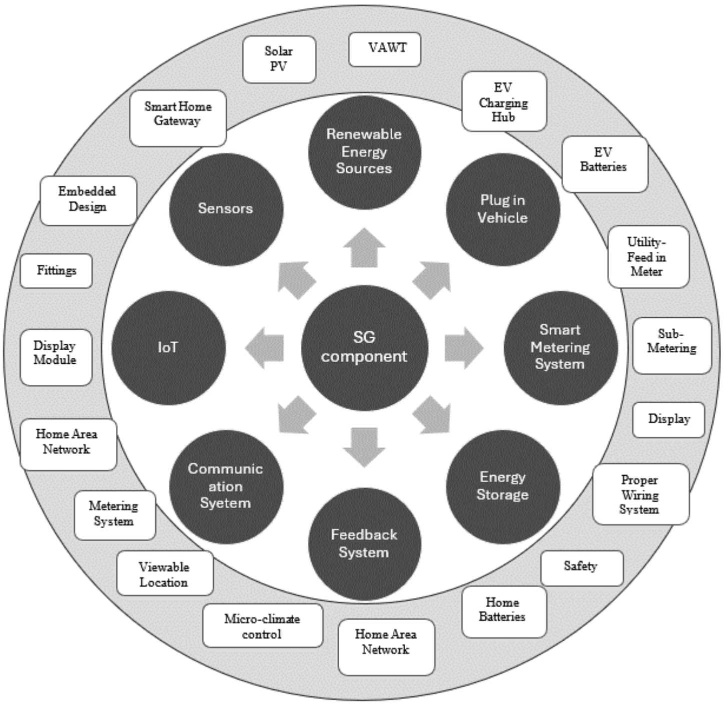

Figure 2: Initial smart grid significant components

Smart meters, real-time monitoring, and feedback-display systems are key to energy management. Smart meters let homes make energy usage decisions by providing real-time electricity consumption data [27]. Kang et al. [28] found that energy display-integrated system-informed decision-making enhances household energy efficiency. The Home Energy Management System (HEMS) can be used in conjunction with Home Automation (HA) and the Energy Services Interface (ESI) to connect key stakeholders in the Smart Grid, improve energy conservation, and improve the consumer experience. Home battery systems are another essential smart grid component for households. These systems have been thoroughly tested and demonstrated to dramatically reduce energy costs and homeowners' grid dependence [29].

Home batteries store excess energy from renewable sources like solar panels to optimise energy usage during peak demand periods, cutting electricity bills. These batteries also provide power backup during power outages, boosting energy security and resilience. Home battery systems improve grid stability and allow homeowners to control their energy use, creating a more sustainable and self-sufficient residential energy model. High costs have limited Malaysian household battery usage. However, time-of-use (ToU) pricing and falling battery prices may drive widespread adoption, allowing homeowners to optimise energy use and reduce grid reliance.

In future home developments, smart grid-connected residences will need a powerful communication infrastructure for wired and wireless networks. Key wireless gateway nodes can be strategically placed to improve communication within the home area network between display modules, microclimate control systems, IoT devices, and sensors. These modules should also include aesthetic design characteristics like electrical and lighting fittings, such as solar PV modules [30, 31].

Creating energy-efficient houses with a smart grid framework requires integrating critical components that optimise energy use and sustainability. Smart grid-optimized buildings (SGOB) and smart grid-connected houses use energy utilisation, demand management, and distributed resources to improve efficiency and conservation [4]. Future homes can cut energy expenditures, reduce dependency on non-renewable energy, and promote an energy-conscious lifestyle by incorporating renewable energy sources, EVs, home batteries, and advanced communication networks. This integration improves energy independence, resilience, and sustainability without compromising quality of life.

3.0 METHODOLOGY

This research article uses the Fuzzy Delphi Method (FDM) to identify the significant Smart Grid Enabling (SGE) components for the Malaysian residential sector. In this research context, FDM gathers expert perspectives concerning suitable smart grid components for the SGE framework development, which identifies items that have been enlisted in sub-sections 2.3 and 2.4. This strategy has helped expert-based validation researchers overcome ambiguity and inaccuracy for decades [32]. The advantages of FDM have been widely discussed in several pieces of research in similar fields [33, 34]. In short. FDM has been presented and adopted in various studies as the better approach to its predecessor, the Delphi Method [32, 35].

FDM improves the previous DM approach in terms of a shorter timeframe and enhanced accuracy for empirical data synthesis based on the linguistic scale of the fuzzy number set. Due to the limitations of the Delphi Method, which uses verbal expressions that can represent and measure experts' viewpoints with varied linguistic meanings and vague descriptions, fuzzy numbers provide accurate outputs in many real-world decision-making scenarios.

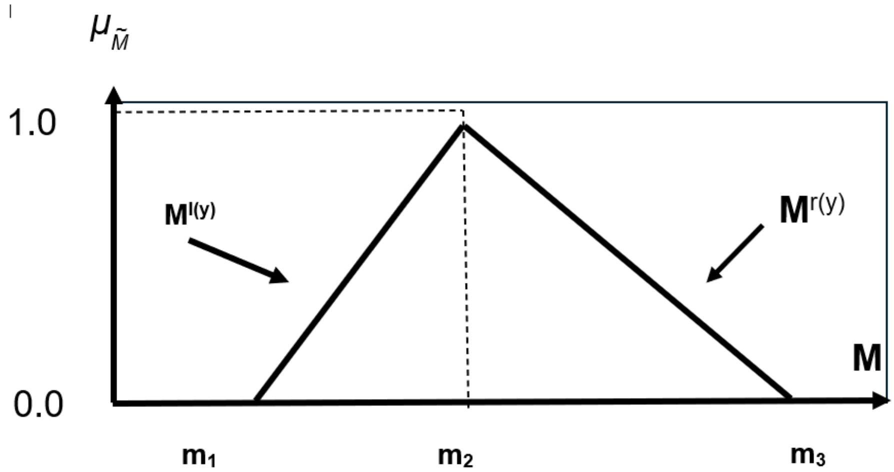

Figure 3: Triangle min versus Triangular value

Defuzzification and Triangular Fuzzy Number (TFN) are fundamental to FDM. Figure 3 shows that the TFN, m, has three values: m_1, m_2, and m_3. The least appropriate value is m1, the most appropriate is m2, and the largest is m3. The curve in Figure 3 shows that all three TFN values are between 0 and 1. An initial pilot FDM survey provided useful feedback for questionnaire and SGE framework changes. The fuzzy triangular series is ranked according to two expert agreement criteria. First, a threshold value (d) is required, followed by expert consensus on each piece. A pre-established equation determines the threshold value (d). The following subsections describe how these investigations used the Fuzzy Delphi Method (FDM).

In the analysis, each construct, component, element, problem, variable, and sub-variable is classified by defuzzification. This approach examines relevant variables and subvariables. The review items are ranked and prioritised. This grading approach generates data based on expert opinion among sample respondents. A_{max} is a fuzzy evaluation or scoring symbol. Triangular fuzzy numbers are denoted as m_1 (smallest), m_2 (likely), and m_3 (biggest). In three scenarios, FDM data validation evaluates and validates items, issues, element variables, and expert-approved acceptance or rejection criteria.

These three scenarios allow for potential data-driven research. The first and second conditions are linked by the Triangular Fuzzy Number (TFN), which measures expert consensus on a construct or item. The final fuzzy evaluation condition ranks identified constructions or objects by score. Using fuzzy scores and α-cut values, the third condition can indicate expert consensus acceptance or rejection of a construct or item. The next part explains how to calculate the α-cut value. The first condition is determined by the threshold value (d), employing the formula below, followed by the interpretation of the first condition (threshold value, d).

$$d(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]} \quad (1)$$

Table 3 The α-cut value calculation for the threshold value-d

Threshold value, d	Description	Interpretation
$d \leq 0.2$	If the threshold value is less or equal to 0.2	Accept item
$d > 0.2$	If the threshold value is more than 0.2	Reject item OR initiate another round of survey sessions with non-consenting experts only.

The second condition is based on the traditional Delphi approach, which denotes that if the expert group consensus exceeds more than 75%, each of the items is "Accepted", whether it is included or omitted in the research. Accepted items that meet the FDM conditions shall be utilised in the SGE framework development.

3.1. Prior SGE framework and questionnaire improvements

An initial pilot survey was conducted to refine the proposed SGE framework (see Figure 4) and questionnaire structure before the actual expert focus group. This pilot FDM survey involved two experts selected for their expertise in energy and the built environment. The first expert was a professor at a local academic institution with vast experience in architecture, sustainability and the built environment. The second pilot survey expert is an energy efficiency specialist that is attached to the Sustainable Energy Development Act (SEDA). The survey included three sections: respondent information, smart grid components, and the proposed SGE framework. The primary goal was to ensure clarity, relevance, and consistency in the questionnaire, identify potential issues, and improve the survey's effectiveness. Additionally, the pilot allowed for an initial assessment of data quality and the reliability of the survey instrument, leading to the development of a more robust final version.

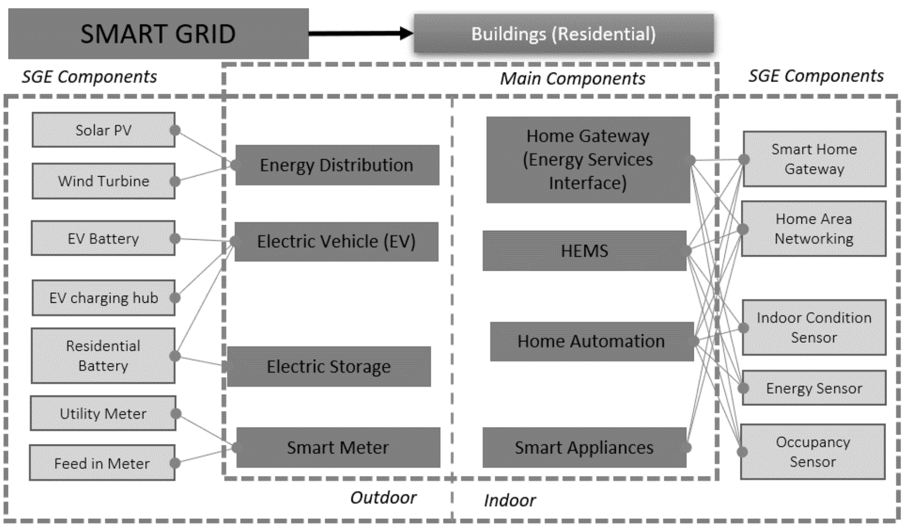

Figure 4: Initial SGE Framework for Pilot FDM

Due to time, availability, and distance constraints, both sessions were conducted online, using the Miro Board programme for synchronous, graphical discussions. Through these discussions, the pilot experts identified and addressed uncertainties or misunderstandings in the enquiries, ensuring effective and efficient data collection relevant to the research context. The pilot also confirmed the appropriateness of the measurement scales, ensured accurate comprehension and interpretation by the expert panel, and refined the fuzzy logic parameters to better capture expert perspectives. The initial SGE framework above was subsequently changed and improved.

3.2. Expert group Fuzzy Delphi Process

Selection of 11 expert panellists was exercised by delivering fifteen (15) expressions of interest (EOI) to the initially identified experts. According to Mohd Jamil et al. [32], ten (10) to fifteen (15) expert respondents are sufficient to arrive at a reliable data acquisition. Eleven (11) expert respondents agreed to participate in the FDM process. Table 4 below describes the brief information of the appointed experts.

The process of data acquisition was carried out utilising the FDM approach comprising focus group interview sessions for the Delphi technique, while the questionnaire results were analysed via fuzzy numbers. A 7-point scale was used in the questionnaire, as it is the best to reduce the fuzziness gap between the acceptance value and expert consensus [32].

Table 4 Expert respondents' background

Category	Affiliation	Position	FDM Role
Academic	Universiti Teknologi Malaysia	Professor Ts. Dr.	Pilot and Focus Group
Industry-Government	Sustainable Energy Development Authority (SEDA)	Director / Energy Efficiency Specialist	Pilot and Focus Group
Industry - GLC	Tenaga Nasional Berhad (TNB)	Resident Engineer (C&S)	Focus Group
Academic / Industry	Arkitek Azman Zainonabidin	Senior Lecturer UiTM / Principal Partner (Ar.)	Focus Group
Industry	KUEE Architect	Principal (Ar.)	Focus Group
Industry - GLC	Tenaga Nasional Berhad Energy Services (TNBES)	General Manager	Focus Group
Industry - GLC	Tenaga Nasional Berhad Energy Services (TNBES)	Senior Engineer	Focus Group
Industry - GLC	Property Services Department, Tenaga Nasional Berhad (TNB)	Resident Designer	Focus Group
Industry - GLC	Advanced Metering Infrastructure (AMI) Department, TNB	Project Management Officer (Ir.)	Focus Group
Academic	School of Electrical & Electronic Engineering, UiTM	Senior Lecturer (Ts. Dr.)	Focus Group
Industry - GLC	Asset, Facilities & Infrastructure Management, Alam Flora Sdn Bhd.	Energy Management Engineer (Ir. Ts.)	Focus Group

Table 5 depicts the linguistic translation of the 7-point Likert scale into a fuzzy score, therefore iterating the TFN achievements, as earlier discussed in section 3 and Figure 3.

Subsequently, a group of eleven (11) expert panels were interviewed to verify items and constructs that underpin the SGE Framework in FDM via seven-point scale questionnaires. Triangular Fuzzy Numbers (TFN) were used to enhance data reliability acquired from the survey process. The defuzzification process acknowledges their responses, therefore validating the proposed framework. In addition, comments and feedback attained during the FDM session were also acknowledged to make final changes to the framework.

In this Fuzzy Delphi Method (FDM) study to design the SGE (Smart Grid-Enabled) framework, a questionnaire is the major quantitative data-gathering method. The questionnaire is carefully structured to elicit expert consensus using FDM criteria and parameters, including Equation 1 mathematical calculations. The questionnaire was based on the proposed SGE framework, which contains smart grid components and their enabling features for Malaysian residential use. The SGE-based questionnaire items were validated through a pilot survey. The final structure was developed and validated using FDM. Two expert panellists helped create the FDM questionnaire in Table 6. Their ideas for improving the proposed SGE framework were discussed in Subsection 3.1, as shown in Figure 4.

Table 5 Seven (7) Point Fuzzy Scale.

Linguistic Variables	QSF Likert Scale	FDM Likert Scale	Fuzzy Scale		
Highly Significant	3	7	0.9	1	1
Significant	2	6	0.7	0.9	1
Slightly Significant	1	5	0.5	0.7	0.9
Neither nor	0	4	0.3	0.5	0.7
Slightly Not Significant	-1	3	0.1	0.3	0.5
Not Significant	-2	2	0	0.1	0.3
Highly Not Significant	-3	1	0	0	0.1

Table 6 FDM Questionnaire Structure

Element	Code	Questionnaire
Outdoor Component	OC1	How significant are solar photovoltaic modules (including BIPV, roof, and photovoltaic shading devices) to a smart grid-connected house?
	OC2	How significant are automated shading devices as a component of the future smart grid-connected homes?
	OC3	How significant are Vertical Axis Wind Turbines (VAWT) as a component of the future smart grid-connected homes?
	OC4	How significant are home batteries or similar energy storage systems (ESS) as a component of the future smart grid-connected homes?
	OC5	How significant is electric vehicle charging infrastructure as a component of the future smart grid-connected homes?
	OC6	How significant are smart metering and submetering systems as components of the future smart grid-connected homes?
Indoor Component	IC1	How significant are Internet of Things (IoT) devices as a component of the future smart grid-connected homes?
	IC2	How significant are consumer-side sensors as a component of the future smart grid-connected homes?
	IC3	How significant are integrated automated windows as a component of the future smart grid-connected homes?
	IC4	How significant are aesthetically designed fittings, fixtures, and casings (electrical, sensors, devices, and switches) as a component of future smart grid-connected homes?

4.0 RESULTS AND DISCUSSION

The data analysis in this research follows the methodology used in similar studies [32, 35. 37], adhering to the conditions of the Fuzzy Delphi Method (FDM) as previously discussed (refer to subsection 3 and Equation 1).

The distance between two fuzzy numbers is determined by calculating the average deviation between experts' responses. Consensus among the expert group is assessed based on a degree of agreement exceeding 75%. FDM data were analysed using FDMv2.0, developed by Mohd Jamil et al. [32], which was previously used for FDM-related studies in Malaysia [35, 37, 38]. Findings of the FDM analysis are listed in Table 7, and expert consensus output is detailed in Table 8 below.

Table 7 FDM output of SGE components based on expert responses.

Expert	OC1	OC2	OC3	OC4	OC5	OC6	IC1	IC2	IC3	IC4
1	0.056	0.156	0.541	0.149	0.644	0.049	0.063	0.076	0.139	0.196
2	0.097	0.156	0.079	0.149	0.611	0.049	0.063	0.076	0.139	0.059
3	0.097	0.156	0.742	0.149	0.333	0.106	0.063	0.078	0.028	0.197
4	0.097	0.156	0.079	0.535	0.611	0.049	0.063	0.076	0.256	0.196
5	0.097	0.236	0.263	0.043	0.333	0.343	0.092	0.078	0.028	0.059
6	0.056	0.046	0.079	0.149	0.644	0.049	0.330	0.317	0.028	0.197
7	0.056	0.156	0.360	0.043	0.073	0.049	0.092	0.078	0.028	0.059
8	0.056	0.236	0.714	0.043	0.644	0.049	0.063	0.076	0.139	0.197
9	0.056	0.236	0.714	0.043	0.333	0.049	0.063	0.076	0.256	0.197
10	0.056	0.236	0.360	0.243	0.644	0.049	0.063	0.076	0.028	0.059
11	0.056	0.156	0.742	0.149	0.333	0.049	0.063	0.076	0.139	0.196
Threshold value (d)	0.071	0.175	0.425	0.154	0.473	0.081	0.092	0.099	0.110	0.147
Percentage of each item d ≤0.2	100.0%	100.0%	36.4%	90.9 %	9.1%	90.9%	90.9%	90.9%	100.0 %	100.0 %
Average fuzzy score	0.930	0.861	0.485	0.864	0.530	0.933	0.924	0.915	0.873	0.833

Referring to both Table 7 and Table 8, Smart Metering and Sub-metering Systems (OC6) were identified as the most significant outdoor components, achieving the highest defuzzification score of 0.933 with 90.91% expert consensus. This reflects the critical role of smart metering in optimising residential energy consumption [39]. Solar Photovoltaic (PV) Modules (OC1) also received strong support, with a score of 0.930 and 100% consensus, highlighting the importance of renewable energy integration in reducing reliance on non-renewable sources [40]. Conversely, Vertical Axis Wind Turbines (VAWT) (OC3) and Electric Vehicle (EV) Charging Infrastructure (OC5) were rejected due to low consensus (36.4% and 9.09%, respectively), suggesting their limited applicability in the Malaysian context.

Among indoor components, Internet of Things (IoT) Devices (IC1), Consumer-side Sensors (IC2), and Integrated Automated Windows (IC3) were highly rated, with scores of 0.924, 0.915, and 0.873, respectively, indicating their importance in achieving energy efficiency through real-time monitoring and automation [41]. Aesthetically Designed Fittings, Fixtures, and Casings (IC4) were also accepted, reflecting the value of user-friendly and visually appealing designs in encouraging the adoption of smart technologies [42].

Overall, the Fuzzy Delphi Method results emphasise the importance of prioritising components like smart meters, solar PV modules, IoT devices, and automation in the Smart Grid Enabler (SGE) framework for the Malaysian residential sector. The final SGE framework established based on the FDM process is described in Figure 5. The rejection of VAWT and EV charging infrastructure suggests the need for further adaptation or technological advancements before these components can be effectively integrated into Malaysia's residential energy strategy. This study underscores the necessity of a tailored approach to smart grid implementation. considering Malaysia's unique energy consumption patterns, environmental conditions, and technological readiness.

Table 8 Result of the SGE framework item expert consensus.

Item / Elements	*Triangular Fuzzy Numbers Conditions*		Defuzzification				Expert Consensus	Ranking
	Threshold value, d	Percentage of Expert Consensus, %	m1	m2	m3	*Fuzzy Score (A)*		
OC1	0.071	100.0%	0.827	0.964	1.000	0.930	ACCEPT	2
OC2	0.175	100.0%	0.736	0.882	0.964	0.861	ACCEPT	7
OC3	0.425	36.4%	0.345	0.482	0.627	0.485	REJECT	#N/A
OC4	0.154	90.91%	0.736	0.891	0.964	0.864	ACCEPT	6
OC5	0.473	9.09%	0.391	0.536	0.664	0.530	REJECT	#N/A
OC6	0.081	90.91%	0.845	0.964	0.991	0.933	ACCEPT	1
IC1	0.092	90.91%	0.827	0.955	0.991	0.924	ACCEPT	3
IC2	0.099	90.91%	0.809	0.945	0.991	0.915	ACCEPT	4
IC3	0.110	100.00%	0.736	0.900	0.982	0.873	ACCEPT	5
IC4	0.147	100.00%	0.682	0.855	0.964	0.833	ACCEPT	8

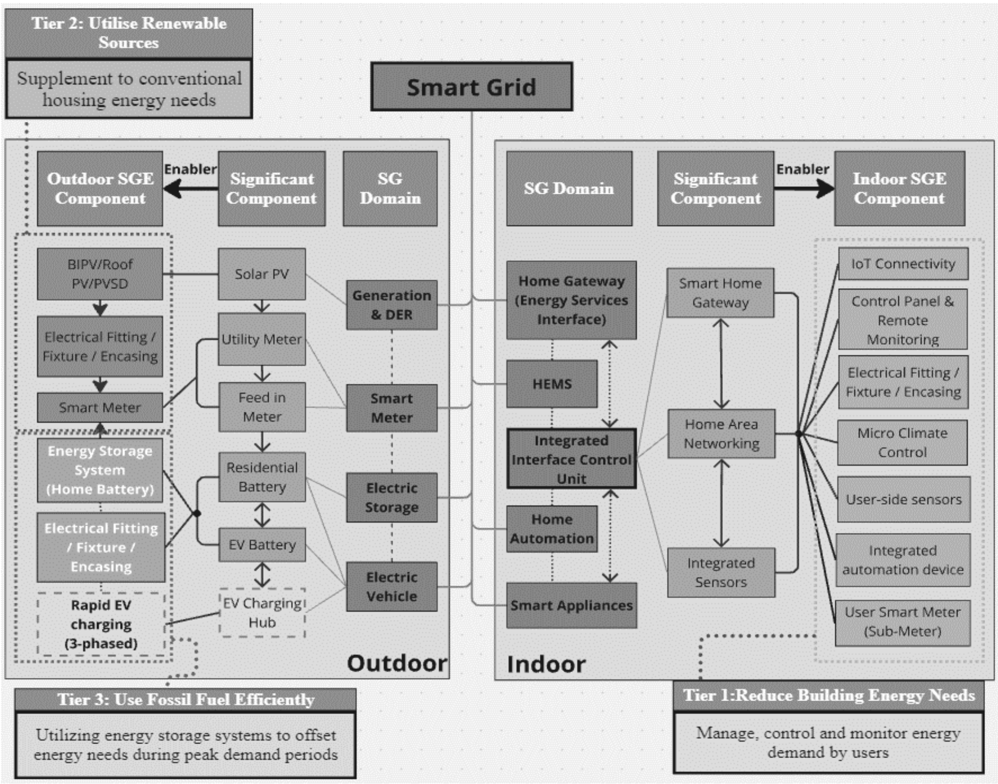

Figure 5: SGE Framework comprising the SGCM and Trias Energetica model.

Although EV charging infrastructure was initially rejected in the FDM process, experts, particularly from utilities, recommend its inclusion in the framework as a communal rather than a unit-specific component. Consequently, Figure 5 depicts EV charging infrastructure in a distinct format. For convenience, domestic charging could still be incorporated as a rapid charging system for personal use.

4.1. Government policy and incentive implications

The successful implementation of the Smart Grid Enabler (SGE) framework in Malaysia's residential sector relies on both technological viability and supportive government policies. Strengthening existing policies, such as the Renewable Energy Act 2011 and the Net Energy Metering (NEM) scheme, is crucial to promote the adoption of key components like Smart Metering (OC6) and Solar Photovoltaic (PV) Modules (OC1). Specifically, setting a target to cover 80% of households with smart meters by 2025 and expanding solar PV deployment to reach a capacity of 5 gigawatts (GW) by 2030 would align with national energy efficiency goals [40, 43].

Ensuring new residential developments are smart grid-ready would further support this initiative. Financial incentives, including subsidies and low-interest financing, are essential to overcome the cost barriers of installing technologies like Home Batteries (OC4) and IoT Devices (IC1). Expanding existing programs like the Green Technology Financing Scheme (GTFS) to include these smart grid components would support Malaysia's national goals for sustainable energy by alleviating the financial burden on consumers and promoting broader implementation. By making smart grid technologies more affordable, these incentives can accelerate their deployment, enhance energy efficiency, and contribute to Malaysia's commitment to reducing carbon emissions and progressing towards a more sustainable energy future

The study's rejection of Vertical Axis Wind Turbines (VAWT) (OC3) and Electric Vehicle (EV) Charging Infrastructure (OC5) indicates a need for further research and development (R&D) to adapt these technologies for local conditions. Government support for R&D and pilot projects could help make these technologies more viable in Malaysia [24].

Public awareness campaigns and educational initiatives are critical for increasing understanding and acceptance of smart grid technologies. These technologies are able to provide detailed, real-time energy usage to the public, thus increasing transparency and helping elevate energy literacy among consumers, enabling them to make informed decisions about their energy consumption and adopt more sustainable practices. The government could partner with civil societies and industry stakeholders to promote the benefits of smart grid adoption through media campaigns, workshops, and community outreach programmes. These initiatives could ensure that 80% of households are equipped with smart meters by 2025, aligning with Malaysia's target to increase renewable energy to 31% of the energy mix [43].

The adoption of the SGE framework aligns with Malaysia's commitment to international climate agreements, such as the Paris Agreement, and its own National Renewable Energy Policy (NREP) and Action Plan, which aim to increase the share of renewable energy in Malaysia's energy mix by 31% by 2025 and enhance energy efficiency across various sectors. By integrating smart grid technologies into residential energy conservation strategies, Malaysia can make significant progress toward its goals of reducing greenhouse gas emissions and increasing the share of renewable energy in the energy mix.

5.0 CONCLUSION AND FUTURE RESEARCH

This research contributes to the development of a Smart Grid Enabler framework by identifying and prioritising key components that align with Malaysia's smart grid system and national energy conservation objectives. The high level of expert consensus on certain components provides a solid foundation for future implementation strategies. However, the study also indicates areas where further research and development are needed to ensure that the smart grid framework is both practical and effective in the Malaysian context.

In addition to the technological aspects, this research paper emphasises the value of supportive government policies and incentives in driving the adoption of smart grid technologies. Strengthening the policy framework, providing financial incentives, and encouraging R&D via private and public engagement are all crucial steps towards realising the full potential of the SGE framework. Future research will focus on refining the SGE framework, incorporating feedback from residential pilot implementations, and exploring its practical applications in real-world residential environments. These efforts will contribute to a more sustainable and efficient energy future for Malaysia, in line with national and international energy and climate goals.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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