International Energy Agency
Photovoltaic Power Systems Programme

Task 17 PV & Transport

PVPS

VIPV as Energy Sources in Disaster Zones

2026

Report IEA-PVPS T17-9:2026

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Lithuania, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 17?

The objective of Task 17 of the IEA Photovoltaic Power Systems Programme is to investigate the interest of deploying PV in the transport sector, which will contribute to reducing the CO_2 emissions of the sector. The results of Task 17 will contribute to clarifying the potential of the utilization of PV in transport and on how to proceed towards the realization of the concepts.

Task 17's scope includes PV-powered vehicles such as PLDVs (passenger light duty vehicles), LCVs (light commercial vehicles), HDVs (heavy duty vehicles) and other vehicles, as well as PV applications for electric systems and infrastructures, such as charging infrastructure with PV, battery and other power management systems.

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COVER PICTURE

Green plant on a gray concrete floor (Credit: Nguyen Dang Hoang Nhu)

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

VIPV as Energy Sources in Disaster Zones

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Task 17
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LIST OF ABBREVIATIONS

IEA	International Energy Agency
BEV	Battery Electric Vehicle, specifically, a battery-electric vehicle without PV in this report
EV	Electric Vehicle
HDV	Heavy-Duty Vehicle
IEA	International Energy Agency
IEC	International Electrotechnical Commission
PV	Photovoltaic
SEV	Solar Electric Vehicle, namely a vehicle with integrated PV
SoC	State of Charge
SVF	Sky View Factor
V2X	Vehicle to X
VIPV	Vehicle-integrated Photovoltaic, or technology for integrating PV into a vehicle

EXECUTIVE SUMMARY

Natural disasters continue to severely and unavoidably disrupt communities. These events frequently damage infrastructure, hinder mobility, and isolate neighborhoods for days or weeks. In such situations, maintaining essential electricity is crucial for safety, communication, and health. This report demonstrates that vehicle-integrated photovoltaics (VIPV) and solar electric vehicles (SEVs) provide a highly robust and adaptable energy source in these scenarios. Their mobility, self-generation capabilities, and independence from fixed infrastructure distinguish them from traditional emergency power systems.

Conventional solutions—such as stationary PV installations, grid-connected storage, and battery electric vehicles (BEVs, a battery-electric vehicle without PV in this report)—are limited during disasters. They rely on intact infrastructure, stable logistics, and accessible charging sites. When these conditions are compromised, energy supply drops sharply. VIPV and SEVs, however, autonomously generate electricity and can move to areas with better sunlight or higher demand. As highlighted in the report, “their ability to self-generate energy, relocate to irradiance-rich zones, and transport electricity and supplies makes them indispensable in disaster environments.”

This study’s Monte Carlo simulations, accounting for shading, human behavior, and unpredictable disaster timing, produce key insights:

Community resilience is achievable through energy sharing. With approximately 13 SEVs per km²—about 1,000 vehicles within a 5 km radius—a community can sustain critical facilities such as medical shelters, cooling systems, and mobile device chargers. SEV significantly reduces the number of vehicles needed compared to BEVs.

Even when individuals prioritize their own safety, resilience remains possible. Including realistic self-preservation behavior, simulations show that 450 or more SEVs within a 5 km radius can power evacuation centers for seven days. In a city like Miyazaki, this corresponds to just 1% SEV penetration, demonstrating that increased adoption of SEVs can ensure dependable disaster response.

SEV enhances systemic resilience. Unlike fixed PV systems that can be disabled if the host building is damaged, SEV distributes risk across multiple mobile units. These vehicles can relocate, avoid shading, and maintain energy production even when parked in improvised locations.

Mobility significantly boosts operational reliability. VIPVs efficiently collect energy from sunny areas and deliver it to scattered relief points. This mobility enables them to support multiple facilities within a single day, a feat unattainable by stationary systems.

The results clearly demonstrate that VIPV and SEVs are not just alternatives to traditional emergency power solutions—they represent a new class of mobile, self-sufficient energy assets. Their strengths include:

- continuous energy generation even when unattended
- independence from fuel supply chains
- ability to transport both electricity and physical supplies
- compatibility with community-based, voluntary energy-sharing models
- reduced risk of single-point failure compared with fixed installations

The report underscores the critical role of community behavior. Voluntary sharing of surplus energy significantly boosts resilience, and even modest participation can stabilize energy supply. Simulations clearly demonstrate that when more residents contribute small amounts of energy, the system becomes markedly more robust than relying on a few large contributors.

It is evident that VIPV and SEV technologies are essential components of a distributed, flexible, and socially supported emergency energy network. Their mobility, autonomy, and adaptability make them especially vital in regions vulnerable to earthquakes, typhoons, landslides, and extended outages. As SEV adoption grows, communities will have a scalable and practical tool to maintain essential services during disasters.

While VIPV and SEVs offer clear technical advantages, their value must also be assessed against realistic counterfactuals such as portable solar generators, stationary PV-battery systems, and conventional diesel generators. From a resilience-planning perspective, investments are justified through frequency–impact analysis and least-regret criteria. VIPV systems demonstrate a uniquely low kWh cost under disaster conditions because they combine mobility, generation, and storage in a single asset already used for transportation. Unlike portable solar kits or stationary PV systems, VIPV assets do not require pre-positioning, fuel logistics, or additional transport capacity during emergencies. Their ability to autonomously relocate to irradiance-rich areas and deliver energy directly to multiple sites significantly reduces operational costs and mitigates the risk of single-point failure. These characteristics firmly position VIPV as a complementary, least-regret option within a diversified resilience portfolio, rather than a standalone replacement for other emergency power technologies.

For individual consumers, the justification for VIPV and SEVs extends beyond disaster scenarios. Although the upfront cost is higher than that of conventional EVs, the integrated PV system reduces daily charging needs, lowers lifetime energy costs, and provides a guaranteed source of electricity during outages. In regions with frequent typhoons, earthquakes, or grid instability, the avoided fuel costs, reduced dependence on public charging infrastructure, and the ability to maintain essential household loads during blackouts significantly improve the lifetime value proposition. When evaluated over a 10–15-year ownership period, the combined mobility and energy-security benefits can outweigh the incremental cost of the PV system.

Portable solar systems are an important counterfactual and offer low-cost emergency generation. However, their effectiveness depends on storage availability, manual deployment, weather exposure, and the ability to transport them to multiple sites. VIPV systems inherently solve these constraints by integrating generation, storage, and mobility. In scenarios where roads are partially blocked or where multiple evacuation centers require intermittent support, the ability of SEVs to move, generate, and deliver energy without additional logistics provides a resilience advantage that portable solar systems cannot replicate.

While VIPV and SEVs offer meaningful advantages in mobility and autonomous energy generation, they are not universally robust to all disaster types. Like any vehicle, they may be damaged, submerged, or rendered inaccessible in severe flooding, landslides, or building collapse. Their contribution to resilience, therefore, depends strongly on the specific hazard scenario.

The resilience framework used in this report does not assume that VIPV/SEVs survive every event. Instead, it reflects a realistic disaster-recovery process in which logistics gradually resume after the initial impact. In many Japanese disasters, road access is restored earlier than grid power, enabling surviving vehicles to move, generate, and deliver energy even when the stationary infrastructure remains non-functional.

Accordingly, VIPV/SEVs should be understood not as universally robust assets but as valuable resources under particular conditions—especially in scenarios involving prolonged power outages, limited road access, and the need for distributed, mobile energy supply during the early recovery phase.

In summary, VIPV and SEVs represent a major advancement in building energy-resilient communities. By integrating solar generation, transportation capabilities, and voluntary energy sharing, they provide a realistic and powerful strategy to reduce vulnerability and support recovery in the immediate aftermath of natural disasters.

1 INTRODUCTION

Natural disasters profoundly disrupt daily life and expose the fragility of existing energy and transportation systems. This report focuses on how communities—particularly in Japan—can strengthen their resilience by leveraging photovoltaic (PV)-equipped vehicles. Rather than simply stating that a certain amount of energy, such as “xxx kWh,” is required, it is essential to examine how that energy can realistically be secured during an actual disaster. Without evaluating feasibility, resource availability, and operational constraints, numerical targets risk becoming abstract and detached from real-world conditions. By grounding the discussion in scientific rigor and practical assessment, this report aims to clarify the true potential of PV-equipped vehicles as a mobile, self-sufficient energy resource in disaster environments

Drawing from an insightful questionnaire administered to junior high school parents and siblings in the Kibana district of Miyazaki City (Japan) —home to the esteemed Miyazaki University—we embarked on an important analysis of how the surplus energy generated by vehicles equipped with VIPV could play a pivotal role in supporting evacuation centers during disasters. Our investigation also factored in the nuances of sunlight shadows and the distribution of weather across the local streets.

Focusing on specific communities allowed us to underscore the critical importance of self-sufficiency in isolated areas in the aftermath of disasters, a reality vividly illustrated by previous incidents in Japan. While the effects of disasters can vary greatly from one region to another and from one country to another, our thorough mathematical studies in targeted areas provide valuable insights that can be adapted to other regions with some modifications to the underlying assumptions.

By delving deeply into individual cases, we created a powerful benchmark and an exemplary learning model that guides our understanding and preparedness in diverse scenarios across different locales. The contribution of photovoltaic and storage technologies to energy resilience (in the aftermath of natural disasters) has been discussed as an advantage of energy microgrids. Transportation is essential for disaster resilience, and robust transportation systems have also been studied. The combination of electricity as an energy lifeline and transportation as a physical lifeline has been enhanced by battery-powered electric vehicles (BEVs, defined as battery-electric vehicles without PV in this report). The automobile battery in solar-electric vehicles can be seen as a form of energy resilience. However, several issues must be resolved when adding a vehicle battery to the electrical utility system. The PV charging stations act as an interface between vehicles and utilities. The connection of EVs to PV charging stations has been recognized as beneficial for resilience.

PV technology harnesses abundant solar energy worldwide. While VIPV and SEVs offer technical advantages, their value must be weighed against alternatives like portable solar generators, stationary PV-battery systems, and diesel generators. From a resilience perspective, investments are justified through frequency–impact analysis and least-regret criteria. VIPV systems have low kWh costs during disasters because they combine mobility, generation, and storage in one asset used for transportation. Unlike portable kits or stationary systems, VIPV assets don’t need pre-positioning or fuel logistics and can autonomously relocate to irradiance-rich areas, reducing operational costs and single-point failure risks. This makes VIPV a complementary, least-regret option in a diversified resilience strategy rather than a replacement for other emergency power sources. For consumers, VIPV and SEVs offer benefits beyond disaster preparedness, including reduced daily energy costs, lower lifetime expenses, and reliable power during outages. In regions prone to typhoons, earthquakes, or grid issues, they enhance energy security and can justify the higher initial cost over 10–15 years through mobility and reliability. Portable solar systems are cost-effective emergency options but depend on storage, deployment, weather, and transport. VIPV systems solve these issues by integrating generation, storage, and mobility. In scenarios with blocked roads or multiple evacuation centers, SEVs' ability to move and supply energy gives a resilience edge that portable solar cannot match.

This report provides a comprehensive quantitative analysis of resource requirements across different scenarios, enabling researchers and professionals to feel confident in adopting solar energy as a crucial solution to enhance resilience. We will thoroughly examine the characteristics of automotive solar cells as a significant energy source, including their advantages and disadvantages, optimal use strategies, and the scale of resources required for survival and recovery.

This discussion focuses on voluntary sharing of resources, based on the universal access to solar energy. Instead of merely asserting the benefits of PV technology, thorough analyses of the resources needed across various scenarios will be provided. Additionally, the potential for genuine voluntary resource sharing to substantially improve resilience will be examined.

PV systems can generate different amounts of energy based on their location. Additionally, the types and densities of disaster-prevention equipment and facilities needed can vary by location. Unlike simulations that calculate the energy output of PV systems on vehicles or the charging operations of electric vehicles (EVs) at PV charging stations, the energy supply at resilience centers must be estimated using worst-case scenarios. This means considering unanticipated events and sometimes challenges arising from selfish human behavior. Resilience scenarios can differ based on the severity and type of natural disasters, as well as regional constraints.

Previous studies on the use of PV systems for resilience, which relied on fixed-tilt installations, focused on estimating energy supply for facilities using typical and representative climate and irradiation datasets. In contrast, VIPV and SEVs should be regarded as uncertain and variable energy sources. The Monte Carlo method, known for its effectiveness in complex, probability-based modeling, is the most suitable approach for these mobile systems.

Additionally, an advanced 3D solar irradiation model was developed to assess the energy yield of VIPV under non-uniform shading conditions. This model was validated by monitoring solar irradiance on five orthogonal sides of the vehicle. The energy yield from VIPV was calculated by accounting for the distribution of shading probability across three zones: open areas, residential zones, and building zones.

Voluntary contributions to the common good enhance SEV and VIPV's resilience. The likelihood and potential impacts on resilience were quantitatively analyzed using the Monte Carlo method.

1.1 Resilience studies using PVs

The role of photovoltaic and storage technologies in enhancing energy resilience following natural disasters has been recognized as a significant advantage of energy microgrids across diverse contexts and configurations. For instance, [1] Zhang evaluated resilience potential based on battery capacity; [2] Laws investigated microgrid applications at the building level; and [3] Galvan focused on rooftop deployments.

Effective transportation plays a crucial role in disaster resilience, and researchers have examined resilient transport systems—Elluru et al. (2019) studied robust logistics networks [4], while Murray-Tuite (2006) quantitatively assessed transportation recovery after major events [5]. The integration of electricity as a vital energy source and transportation as a key physical lifeline has been further strengthened by the use of battery-powered electric vehicles (BEVs).

The traction battery in solar electric vehicles serves as a source of energy resilience [6]. Nonetheless, integrating a vehicle battery into electrical utility systems presents several challenges, as outlined by Mohammad et al. (2022) [7]. These include how charging stations affect the grid [8], shifting peak loads with car batteries [9], reducing negative consequences from PV integration into the grid [10], and optimizing the way vehicles are integrated to the grid, an approach proposed by Slavatti et al. (2020) [11].

BEVs can also be connected to smaller systems, such as residential buildings, through vehicle-to-home (V2H) setups. Recent advances include cost optimization for load management (Abdalla et al., 2020) [12], improved EV charger inverters (Ali et al., 2021) [13], and better V2H scheduling (Wang et al., 2022) [14].

Vehicle resilience increases with PV charging [15]. Studies have compared AC and DC building power systems with PV and storage [16], and projected PV generation's role in enhancing building energy systems [17]. The "Internet of Energy" concept, similar to IoT, can be applied to electric vehicles in distributed energy systems [18].

Energy balance analysis is effective for small networks. Studies, such as Cieslik et al. (2021) [19], highlight the role of electric vehicles in addressing PV supply imbalances, with further research exploring low-voltage networks [20] and community-based models [21].

Connecting EVs to PV charging stations improves resilience and supports system performance by lowering carbon emissions and balancing grid demand. Research has focused on optimizing operations and addressing related challenges, including comparisons with VIPV.

Recent studies address optimal planning of PV charging stations [22], financial considerations in the US [23], and ecological optimization algorithms [24]. Mohammed et al. (2022) used weather forecasts for efficient PV station operation [25], while Petrusic and Janjic (2021) applied these concepts to hybrid vehicle charging stations [26].

Other notable advancements include the development of a multi-agent particle swarm optimization algorithm [27], efforts to reduce the cost of battery integration [28], and new methods for forecasting electric vehicles [29]. Zhang et al. (2019) introduced PV charging stations for e-bikes [30], while Ghosh highlighted EVs' smaller CO2 footprint as a significant benefit [31].

1.2 Lesson from natural disasters – case study in Japan

Japan, though covering just 0.28% of the world's land area, accounts for 18.5% of global earthquakes of magnitude 6 or higher, 1.5% of disaster-related deaths worldwide, and 17.5% of global disaster damage [32]. Major recent disasters include the 1995 Great Hanshin-Awaji Earthquake, the 2011 Great East Japan Earthquake, and the 2016 Kumamoto Earthquake, as well as severe rainfall and typhoons that have caused significant loss of life.

Disasters often result in extended isolation for residents of islands with collapsed bridges or mountainous regions where landslides block roads. During the Great East Japan Earthquake, many villages—including Sanriku—were cut off, hindering emergency rescues. With ongoing depopulation in rural mountain areas, such risks are rising. A 2009 Cabinet Office survey found that about 30% of agricultural and fishing villages could become isolated during disasters like earthquakes and tsunamis, affecting over half of all prefectures.

Many agricultural and fishing villages lack sufficient earthquake-resistant evacuation facilities, adequate food and water stockpiles, and functioning communication systems due to financial constraints. To address these challenges, it is essential to maintain evacuation facilities, stockpile essential supplies, ensure diverse emergency communication methods, and properly manage vital community roads.

In isolated regions, individuals must independently secure food and water until external assistance becomes available. In the event of a power outage, it is critical to ensure an electricity supply for at least 72 hours to protect lives, with provisions to extend this supply to approximately seven days if outages persist. Furthermore, elderly evacuees may experience adverse health effects resulting from stress and inadequate electrical resources while residing in evacuation centres, even when evacuation is possible.

2 METHODS

Important clarification on system boundaries:

The resilience scenarios analyzed in this report assume a complete grid outage and the physical isolation of communities, as frequently observed in mountainous regions and island areas of Japan following major earthquakes and typhoons. Under these conditions, shelters and community facilities operate as stand-alone loads without any connection to the utility grid.

Consequently, VIPV and SEVs are not required to perform grid-synchronised AC injection, frequency matching, or power aggregation with other generators. Instead, each vehicle functions as an independent mobile power source, supplying isolated AC or DC loads through dedicated off-grid inverters or V2L/V2H-type interfaces.

This operational mode differs fundamentally from grid-connected V2G applications. The focus of this report is therefore on off-grid, stand-alone emergency power supply, where simplicity, mobility, and rapid deployability are more critical than grid-integration capabilities.

In the field of natural disaster countermeasures, the concept of resilience for systems can be classified into two types: (1) the concept of resilience as the stability of the system, and (2) the concept of resilience as the ability to adapt to the reconstruction of the system. (1) The concept of resilience as system stability is influenced by the concept of engineering resilience in ecological systems. On the other hand, (2) the concept of resilience as the ability to adaptively reconstruct the system is influenced by the concept of resilience in socio-ecological systems. In this section, we first describe the systems that are subject to the concept of resilience in the field of natural disaster countermeasures. Next. The conceptual framework of resilience is described.

2.1 Cities and communities as systems

In the systems approach, cities and communities are regarded as systems (urban systems) that have functions that support the lives of residents and the activities of companies. Cities and communities are considered systems composed of subsystems: physical, socio-economic, and institutional/organizational. Cities and communities are formed by the complex interactions among their subsystems and components [33-37].

A physical system is the environment that underpins city or community activities. It includes both natural elements (like terrain, water, weather, plants, and soil) and built elements (such as utilities, infrastructure, buildings, equipment, and farmland).

Social and economic systems function as subsystems built upon physical infrastructure and shaped by the activities of residents and businesses. Within these systems, individuals and companies facilitate the exchange of goods, services, capital, and labor that are essential to daily operations. Moreover, artificial environments—including buildings—are constructed through actions within social and economic frameworks. These activities are influenced by various demographic factors (such as age, gender, occupation, race, and education level), corporate characteristics (including industry and size), and social networks (for example, geographic organizations and chambers of commerce) [34,38,39].

Institutional and organizational systems comprise entities that directly or indirectly manage physical, social, and economic systems in alignment with public interests. Such organizations, including administrative bodies and public-interest groups, oversee the development and operation of critical artificial environments—like roads, railways, utilities, communication infrastructure, and public housing [33]. The system incorporates urban planning and land-use strategies to regulate the construction of man-made environments [40,41] while also delivering essential public services such as education, healthcare, and welfare. Overall, urban systems are designed to facilitate both residential life and commercial activity through the coordinated interaction of physical, social, economic, institutional, and organizational systems.

2.2 Resilience as stability

The concept assumes a system maintains its state and function during disasters, defining resilience as system stability. Stability includes (1) maintaining operations when exposed to hazards ("robustness") and (2) recovering quickly to pre-disaster levels ("recovery"). Some definitions separate these, using "resistance" for (1) and "resilience" for (2). Despite variations, all focus on system stability, which they break into two main components. This report refers to them as "robustness" and "recovery" [42-45] (see Fig. 2.2-1).

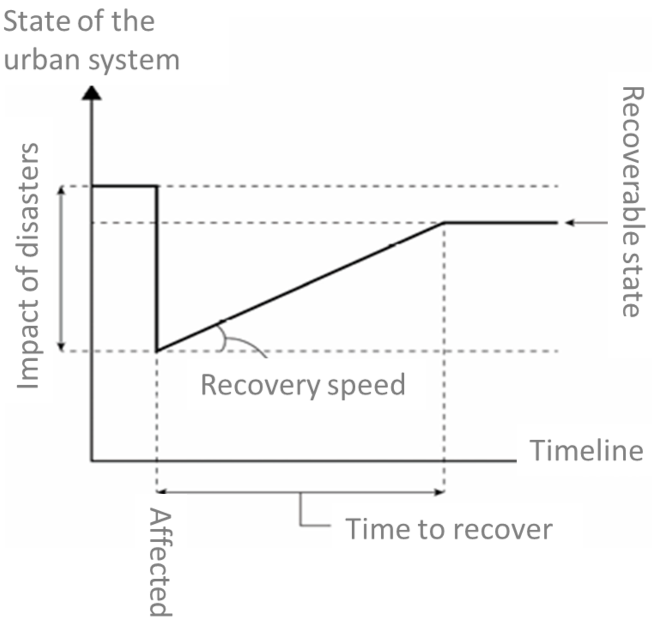


Fig. 2.2-1 The concept of resilience as stability

Bruneau et al. [33] describe (1) as robustness and (2) as rapidity, both contributing to resilience. Alternatively, some define only (2) as resilience, with (1) termed resistance and (2) as resilience [46-49]. Despite varying definitions, both approaches decompose system stability into two key components. This study refers to (1) as "robustness" and (2) as "recovery power."

Fig. 2.2-1 shows resilience as stability, illustrating how a system responds to hazards over time. The vertical axis indicates the system's state, which reflects its ability to function and declines when impacted by hazards, while the horizontal axis represents time. The system's state can be measured by specific indicators; for example, physical systems such as electricity, gas, water, sewerage, and communications use their respective utilization rates to represent system status [33,46].

On the other hand, when targeting social and economic systems, the state of the social and economic systems in the affected areas is expressed by indicators such as the resident population, working population, gross regional product (Gross Regional Product (GRP)), and the number of housing supplies in the affected areas [33-37]. The robustness of an urban system is the property of preserving the system's state and function as much as possible when exposed to hazards. In Fig. 2.2-1, it is measured by the level of the system's state immediately after the disaster relative to its level before the disaster.

To strengthen system robustness:

- Manage building sites with hazard-aware land use [40].
- Reinforce structures against hazards; use elevated or piloted buildings for floods.
- Ensure emergency lifeline redundancy, like backup power supplies [33].
- Establish emergency protocols: evacuation sites, warning systems, plans, and disaster response activities.

Urban system resilience refers to the capacity to promptly restore functions and states impacted by hazards to pre-disaster levels or other acceptable benchmarks. However, urban systems may not always revert to their prior conditions following a disruptive event. Consequently, resilience also encompasses the system’s ability to determine the extent of recovery after a disaster [36]. As depicted in Fig. 2.2-1, resilience is assessed through (1) the level to which the system recovers relative to its pre-disaster state or an acceptable standard, and (2) the duration or rate at which this recovery occurs.

The restoration of state operations and system functionality relies on reestablishing both artificial infrastructure and socio-economic frameworks. To revitalize the socio-economic system, initial efforts must focus on restoring key elements of the built environment—such as electricity, gas, water and sewerage, telecommunications, roads, and railways. Once these critical infrastructures are operational, the socio-economic system can recover through the return of residents and businesses, facilitated by the reconstruction of housing, commercial buildings, and essential equipment.

Urban resilience is influenced by physical, economic, social, and institutional/organizational factors. Physical factors refer to how quickly infrastructure, such as utilities and transport, can recover, which depends on repairability, emergency plans, and organizational capabilities. Economic factors include resident income, savings, employment, company finances, and business continuity plans. Social factors involve community cohesion, communication, problem-solving, support networks, collaboration, attachment, education, and skills. Institutional and organizational factors cover public support, zoning and building regulations, and cooperation among administrative bodies [33-34].

When planning system recovery, it’s important to recognise that components are influenced by the status of other elements, meaning their interactions must be evaluated. Infrastructure systems—such as electricity, gas, water, sewerage, telecommunications, roads, and railways—often rely on each other. For instance, railway and communication networks depend on electrical power, so repairs to the electric grid must happen first. Therefore, assessing the resilience of any one system requires understanding how it connects with others [50]. Research also shows that residents returning to an area is linked to retail stores reopening in the socio-economic network, highlighting the need for recovery plans that account for relationships among all components.

2.3 The concept of resilience as an adaptive restructuring capability

This concept recognizes that a system can have several acceptable states beyond its original condition, enabling flexibility after a disaster. Resilience here refers to a system's capacity to adapt and reorganize into a desirable state following disruption [38,39,41,51].

The capacity to reconstruct a system is influenced by elements such as the economic strength of its components and social capital. These factors closely align with those associated with the concept of "resilience as stability" [23][24][44].

2.4 VIPV

A PV-based system offers a lower risk of battery depletion than a BEV system, as energy donation ends once a car battery is fully discharged. Additionally, PV systems efficiently deliver energy directly to the point of use via solar power.

VIPV may resolve the charging system issues discussed earlier [52,53]. Demonstration vehicles have been developed by Toyota [54], Nissan [55-56], Hyundai [57], Sono Solar [58], and Lightyear [59].

VIPV poses minimal risk to utilities. Unlike stationary PV systems, which can be severely damaged during disasters, mobile VIPV units can be relocated to generate energy and deliver power and supplies to affected areas.

PV modules serve as essential power sources in cars [60]. In our earlier research, we carefully documented and examined the operation of vehicle-integrated PV modules [61].

VIPV systems face distinct challenges, including power losses from curved PV panels [62-65], nonuniform and partial shading [66-70], and technical issues in structure, packaging, and testing that differ significantly from those of Si solar cells and conventional flat installations [71-78]. Performance is also affected by driving conditions, such as parking and MPPT [79-81]. Additionally, there are reliability concerns, such as vibration [82].

These factors influence resilience research related to natural disasters.

2.5 VIPV versus PV charging stations

Most disaster shelters use emergency generators for electricity, but these have drawbacks, including limited fuel supplies; regular maintenance or replacement of batteries and other components, depending on usage; limited output; and ongoing maintenance costs. To address these issues (Fig. 2.5-1), SEVs will be used around evacuation centers. Advantages of SEVs for resilience include:

Note that portable generators are often assumed to be long-lasting assets; however, when used as emergency-only equipment, they require substantial maintenance and periodic replacement of consumables every 3–6 months. This is primarily due to fuel degradation: gasoline oxidizes and loses volatility within 3–6 months, leading to clogged carburetors and non-start conditions during emergencies. In addition, engine oil oxidizes during storage, starter batteries self-discharge, and humid environments accelerate corrosion. As a result, communities must regularly cycle fuel stocks, run the generator under load, and replace consumables to ensure operability. Without this maintenance regime, a significant fraction of standby generators fail to start during real disasters, as repeatedly documented in Japan following typhoons and earthquakes. Therefore, the “3–6 month replacement” refers not to the generator hardware itself, but to the maintenance cycle required to keep the system operational for resilience purposes.

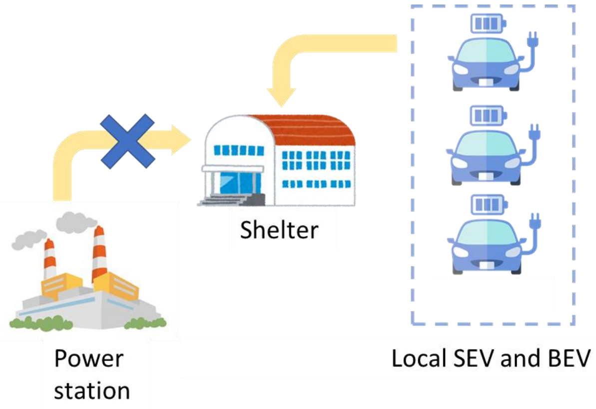


Fig. 2.5-1 The concept of SEV/BEV (a battery-electric vehicle without PV in this report) resiliency

2.5.1 Reduced risk of empty storage batteries

SEVs can produce electricity whenever there's sunlight, unlike emergency generators, which stop working when out of fuel, reducing the likelihood that their battery power will reach zero.

2.5.2 Voluntary provision of electricity can be expected

Because SEVs offer portable, limited power, owners are likely to volunteer to help supply shelters.

2.5.3 Risk diversification over fixed PV

If a stationary PV system is installed in an evacuation centre, severe damage to the centre may render the PV unusable. Using several SEVs around the shelter helps distribute this risk.

2.5.4 Can move to the sun to generate electricity

The output of SEV power generation varies with weather conditions; it is estimated that production on cloudy days is less than half that on sunny days, while output on rainy days typically reaches about one-tenth of that on sunny days. Unlike stationary photovoltaic systems, SEVs can reposition themselves, such as turning or moving several meters from the parking place, to optimize sunlight exposure and enhance electricity generation.

2.5.5 Can also be used as a storage battery

In situations where an evacuation center lacks sufficient storage batteries, the BEV and SEV can be utilized as a temporary power source or deployed to supply electricity to other centers experiencing power shortages.

2.5.6 Comparison to alternative technologies

Although VIPV and SEVs provide technical benefits, their value should be considered alongside alternatives such as portable solar generators, stationary PV-battery systems, and diesel engines. From a resilience standpoint, investments are supported by frequency–impact analysis and least-regret principles. VIPV systems offer low kWh costs during disasters because they combine mobility, energy generation, and storage in a single asset used for transportation. Unlike portable kits or stationary setups, VIPV assets don't require pre-positioning or fuel logistics, and they can autonomously move to areas with higher irradiance, reducing operational costs and single-point failure risks. Thus, VIPV acts as a complementary, least-regret option within a diversified resilience strategy, rather than replacing other emergency power sources. Beyond disaster readiness, VIPV and SEVs provide benefits like lower daily energy costs, reduced long-term expenses, and reliable power during outages. In regions vulnerable to typhoons, earthquakes, or grid disruptions, they improve energy security and can justify their higher initial cost over 10–15 years through their mobility and dependability. While portable solar systems are cost-effective emergency solutions, they depend on storage capacity, deployment conditions, weather, and transportation. VIPV systems overcome these challenges by integrating energy generation, storage, and mobility. In situations with blocked roads or multiple evacuation centers, SEVs' ability to move and supply energy offers a resilience advantage that portable solar cannot provide.

2.6 Energy demand in an emergency

Fragility science, which combines the social sciences, natural sciences, and engineering, includes a vulnerability risk model. The Cutter hazard-of-place model [38] assesses a region's vulnerability by integrating physical and social factors. Physical vulnerability is measured through indicators that estimate the likelihood of different hazards occurring in an area. Social vulnerability, on the other hand, is evaluated based on factors like residents' income, occupation, education level, and race. In this study, it is assumed that local residents are willing to provide electricity. Thus, the model's framework was used to determine the voluntary provision rate.

2.6.1 Facilities

The following facilities are used in evacuation centers during disasters.

(1) Disaster Response Headquarters
(2) Large-scale evacuation centers
(3) Community evacuation centers (community centers)
(4) Nursing homes and nursing homes
(5) Temporary relief and evacuation centers
(6) Mobile phone and smartphone charging port

In addition to the standard functions (1) ~ (4), modes (5) and (6) leverage SEV's mobility and flexibility for temporary relief. While (1) ~ (4) support disaster prevention infrastructure, (5) and (6) offer adaptable, supplemental systems during emergencies. SEVs can also strengthen existing infrastructure, so we will first assess whether SEV can supply emergency power.

Assuming conditions (1) and (2) are met, survivors can be rescued within 72 hours. The SEV system can recharge the needed stationary battery.

For (3) ~ (5), assume there is no stationary storage battery for 72-hour survival. In this scenario, local SEVs transport power to evacuation centers, gradually charging them to meet minimum requirements. The electricity is stored in SEVs at these centers and delivered with supplies to various remote facilities.

The power demands for temporary relief facilities, smartphone charging ports, and air conditioning—meant to support disaster prevention with EVs—were calculated. Disaster prevention bases are expected to have a 24-hour electricity supply, with the evacuation center steering committee managing usage and ensuring continuous access. Additionally, each district will set up one temporary relief facility within a 5 km radius to accommodate disaster victims, along with other key infrastructure.

Each smartphone charging port delivers 20 W, supporting up to 10 devices simultaneously at one location. There is no fixed storage battery; all power comes directly from the SEV when plugged in. For convenience, 25 charging spots are distributed within 5 km, allowing you to walk about 1 km between stations.

The plan was to install 2.2 kW spot coolers in one temporary relief and evacuation center and in five other facilities that need air conditioning. These include places such as evacuation centers and nursing care facilities, where many elderly people are present.

2.6.2 Isolated area

The isolation area covers a 5 km radius, allowing people to reach temporary relief and evacuation centers on foot. Facilities described in (1) are distributed within this zone.

2.6.3 Isolated place

This report examines residential areas in Miyazaki to examine self-consumption during selfish power hoarding, assuming households supply their own electricity.

2.7 The public goods model versus the voluntary contribution model

In many discussions about resilience, the common approach is to quantify the resources required to build resilience by using the allocation of resources to public purposes as a benchmark. This method simplifies the debate by ensuring that the required resources are secured. However, practical issues often arise, such as how to effectively provide public goods, whether to forcibly requisition them, and whether such requisition will proceed smoothly. Additionally, there is a psychological tendency to prioritize securing private resources, especially during disasters.

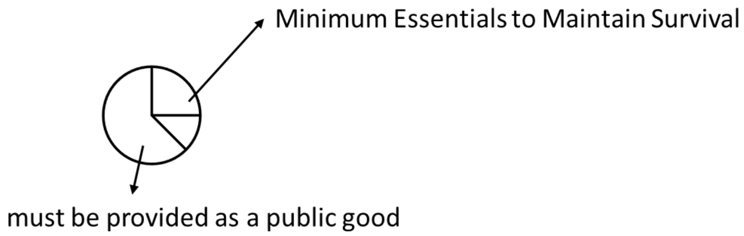


Fig. 2.7-1 Structure of the public welfare model

The concept of public goods can be effectively quantified using a straightforward formula:

(public goods) = (total energy owned by society) - (energy needed for public welfare).

To illustrate (see Fig. 2.7-1), consider a battery electric vehicle (BEV) with a battery capacity of 48 kWh per person. If each person requires 15 kWh over three days, the available energy for public goods is an impressive 33 kWh. This is derived from the total capacity of 48 kWh by subtracting the 15 kWh required for essential needs. Remarkably, this means an astounding 69% of the total energy can be devoted to supporting communal shelters and services. This insight highlights the potential of our collective energy resources to enhance societal well-being.

In the voluntary provision model (see Fig. 2.7-2), individuals are expected to take initiative in supplying resources for public goods, such as shelters. Experience from past disasters, particularly in isolated areas, demonstrates that many community members actively contribute to survival and early recovery through altruistic behavior and mutual assistance. However, it is unrealistic and presumptuous to assume that all individuals will implicitly sacrifice their assets; this attitude mirrors the public goods model discussed earlier.

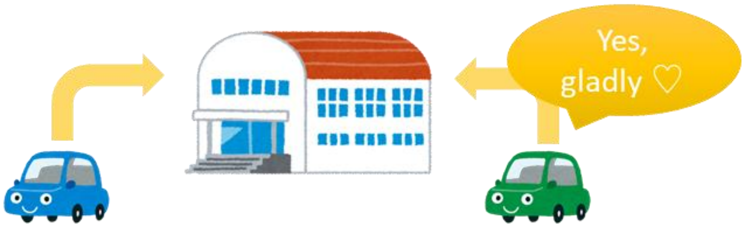


Fig. 2.7-2 Structure of the voluntary contribution model

Some community members will survive by providing resources, while others will have excess supplies. Individual motivations will differ—some are altruistic, while others are purely self-interested. Utilizing a probability model clarifies these dynamics. For instance, if *x*% of solar energy system (SEV) or battery electric vehicle (BEV) owners maintain a state of charge (SoC) of *y*%, then *z*% of these owners will undoubtedly contribute their surplus energy to the shelter. It is critical to recognize that *x*, *y*, and *z* are interrelated. Typically, the greater the surplus energy, the more likely individuals are to offer resources, and the amount of resources donated tends to be substantial.

2.8 100% voluntary or selfish power hoarding

In the previous chapter, we established a fundamental assumption: a specific percentage of surplus energy is provided to the shelter with equal probability, depending on the total energy possessed by all members. However, we must recognize that individuals inherently tend to reserve energy for personal use in the event of a disaster. Consequently, it is essential to develop a model that accounts for this self-reservation behavior. A Monte Carlo simulation that treats self-reserves as a random variable is not just beneficial; it is a more accurate representation of reality (Fig. 2.8-1).

Fig. 2.8-1 Structure of the voluntary contribution model

3 RESILIENCE SCENARIO USING SEV USING A SIMPLE VOLUNTARY MODEL

The possibility of voluntary contributions to the common good is a resilience advantage of VIPV. The likelihood and potential resilience impacts were quantitatively analyzed using the Monte Carlo method, accounting for social as well as technical factors.

PV systems can supply varying amounts of energy depending on their location. In addition, depending on the location, the required types and densities of disaster-prevention equipment and facilities vary. Unlike the simulation of PV energy calculations for vehicles and the charging operation of EVs at PV charging stations, the energy supply at the resilience center must be estimated based on the worst-case scenario; in other words, unanticipated events and sometimes obstacles stemming from selfish human behavior. Resilience scenarios may vary according to the magnitude and type of natural disasters and regional constraints.

For simulations of such unknown and varied cases, a Monte Carlo simulation based on the characteristics of the natural disaster (place, date/time, etc.), and the degree and extent of human activities will be helpful.

A typical scenario may be as follows:

A significant earthquake occurs in a scenario city (“PV City”) (radius 5 km). In the first few hours, the PV City local government transitions schools, community centers, and care centers to evacuation centers equipped with 6 spot coolers (4 hp each) at 6 locations. In addition, the PV City local government calls for temporary first-aid stations and multiple charging stations for mobile devices to help local people access disaster information, alongside conventional disaster infrastructure. There are 25 temporary charging stations accessible within a 1 km walk. Because such facilities require electricity, the PV City local government calls for a voluntary donation of electricity from PV-equipped vehicles; a certain percentage of drivers check the charging status (SoC) of their vehicles (every hour), and if SoC is over 90%, they decide to go to one of the use points and provide electricity until the charge of the battery falls to 50% (vehicle batteries are recharged by PV on vehicles). Other efforts are in place to help keep disaster-prevention equipment and facilities operational. Seven days later, the PV City local government is notified that regional lifelines have been restored.

And, the question is;

“Can the PV City supply enough energy until the external lifeline is restored (with xx% of continuous supply of the required energy)?”

Use cases considered in this report

- Complete grid outage and physical isolation
- SEVs/VIPV used as autonomous generators
- Direct supply to shelters, medical rooms, and communication hubs
- No grid-tie, no synchronization, no multi-generator parallel operation
- Simple plug-and-use interfaces (V2L, standalone inverter, DC supply)

Use cases NOT considered

- Grid-connected V2G operation
- AC synchronization with utility networks

- Parallel operation of multiple inverters on a live grid

This distinction is essential because the technical requirements, cost structures, and operational constraints differ substantially between off-grid emergency supply and grid-integrated V2G systems

Use cases where VIPV/SEVs are highly effective

- Long-duration power outages with partial road access
- Isolated communities awaiting external support
- Scenarios where stationary PV or generators are damaged or inaccessible
- Situations requiring mobile, point-to-point energy delivery

Limitations and scenarios where effectiveness is reduced

- Severe flooding (vehicle submersion)
- Landslides or collapsed structures blocking access
- Direct vehicle damage from earthquakes or debris

These limitations do not negate the value of VIPV/SEVs; rather, they clarify that their contribution is **scenario-dependent**, complementing—not replacing—other resilience measures such as portable solar, stationary PV, and emergency generators.

3.1 Energy demand in the disaster zone

Energy resilience in the context of disaster response has been frequently discussed by policymakers and is well-documented in Japan. The response plans include designated headquarters for the coordinated disaster response in an area, along with evacuation centers, community halls, and care homes. Each of these facilities uses diesel generators and fixed-tilt PVs as part of the resilience infrastructure (Fig. 3.1-1).

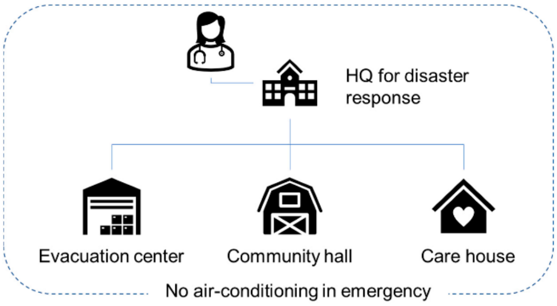


Fig. 3.1-1 Standard resilience facilities with their energy source requirement and estimated energy consumption during disaster response [83]

The standard design of resilience facilities does not include air conditioning, and it is not often included in non-medical evacuation facilities due to the extra cost of diesel generators or portable PV systems. However, there is growing awareness that air conditioning is also crucial, given the rising mortality rate from heatstroke. Typically, the standard disaster response plan does not accommodate charging mobile devices.

Accordingly, the following three temporal facilities and functions would be required in a post-disaster scenario, and each could utilize voluntarily contributed VIPV energy (Fig. 3.1-2).

- Temporary shelter with medical care;
- Mobile device charging station within walking distance; and
- Backup power for air conditioning

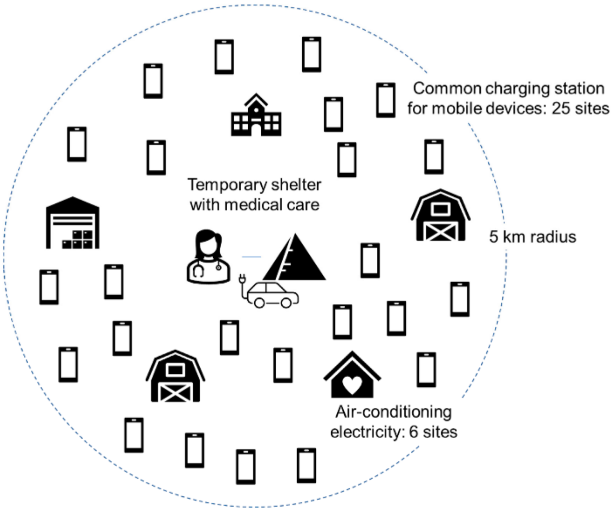


Fig. 3.1-2 Standard resilience facilities with their energy source requirement and estimated energy consumption during disaster response [83]

3.2 Energy donation from VIPV

The results of a community survey are shown in Figure 3. Some respondents said that no one would want to donate the electricity saved in SEVs. Others noted that 5% of the respondents were too pessimistic. The parents of students attending a local junior high school near the University of Miyazaki investigated the percentage of residents who would voluntarily donate (Fig. 3.2-1). Question: Suppose that you have an EV. Would you like to provide electricity to shelters that lack it? A total of 75 participants completed the questionnaire.

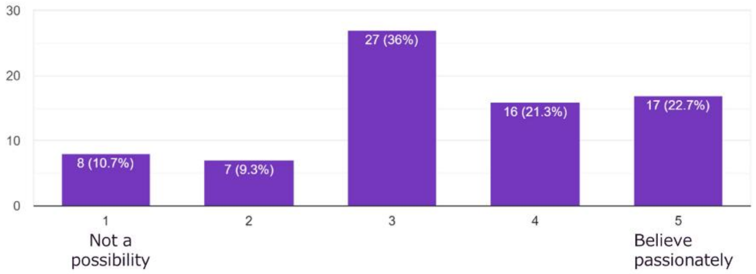


Fig. 3.2-1 Response to community survey regarding willingness to donate energy during disaster relief [83]

More than 40% said that they would be optimistic about donating electricity to public facilities in the event of a disaster. Again, the first assumption is 5% for SoC > 90% SoC. In the case of the Miyazaki community, energy resilience systems based on VIPV and SEV energy supply, along with voluntary mutual support, are a realistic expectation.

3.3 Monte Carlo simulation on the demand-supply balance of the emergency energy

One of the time-series variations in the battery's energy storage status across all resilience facilities is shown in Figure 3.3-1. The time-series trend varied when the dice were thrown; however, this case is representative. The remaining battery charging fluctuated over the 24 h of the cycle; that is, fewer charges occurred at night and more during the day. The peak and bottom values varied with irradiation on that day. A sunny day increases the likelihood of a battery lasting until the following night.

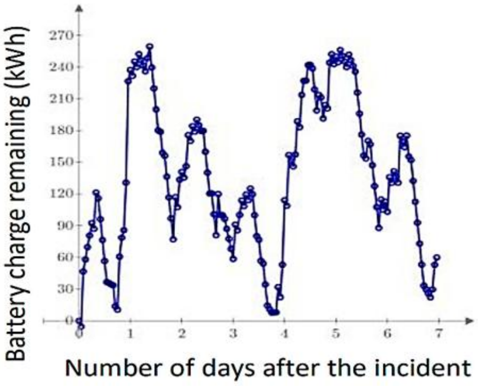


Fig. 3.3-1 Monte Carlo simulation result: A time-series plot of the total battery charge remaining in the facilities supported by SEV [83]

The probability of sustaining the community for 7 days was plotted as a function of the number of SEVs, based on approximately 10,000 trials, in a shaded environment within the residential zone. The logistic curves approximated the probability curves, and the required number of SEVs was approximately 720 in a 5 km radius, which is approximately 1/70 of the population density of Miyazaki City, Japan, where we investigated the feasibility of SEV and VIPV for resilience (Fig 3.3-2).

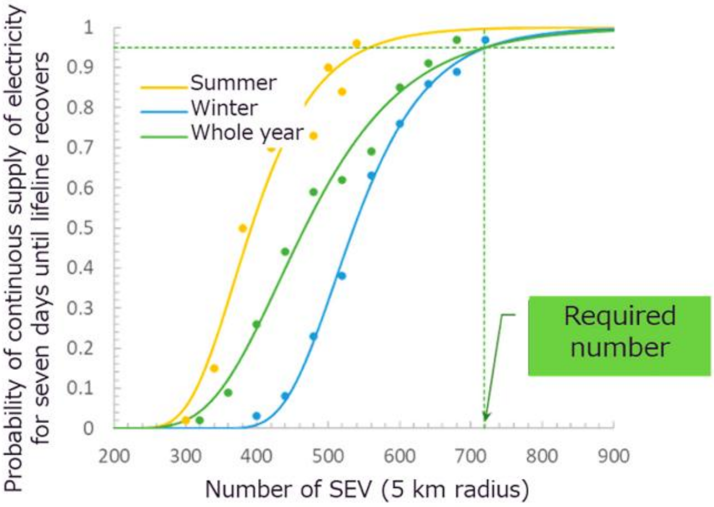
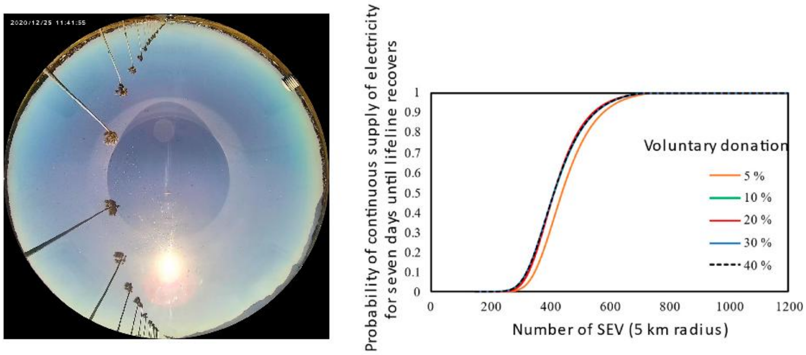


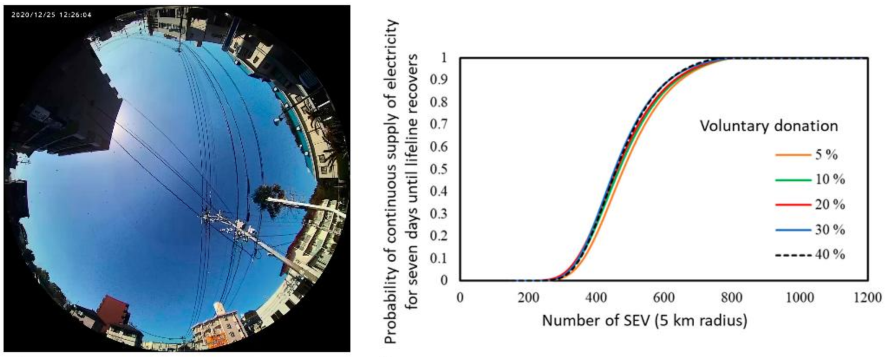
Fig. 3.3-2 Number of SEVs vs. probability of continuous electricity supply for seven days, until the lifeline recovers (residential zone in Miyazaki) [83]

The same types of simulations were attempted in three zones (open, residential, and building) by varying the ratio of voluntary donations (Figs. 3.3-3, 3.3-4, and 3.3-5). The required number of SEVs did not increase when the probability of contribution exceeded 10%; however, it started to decrease at 5%. This was likely because the SEVs' total energy dominated the baseline probability.



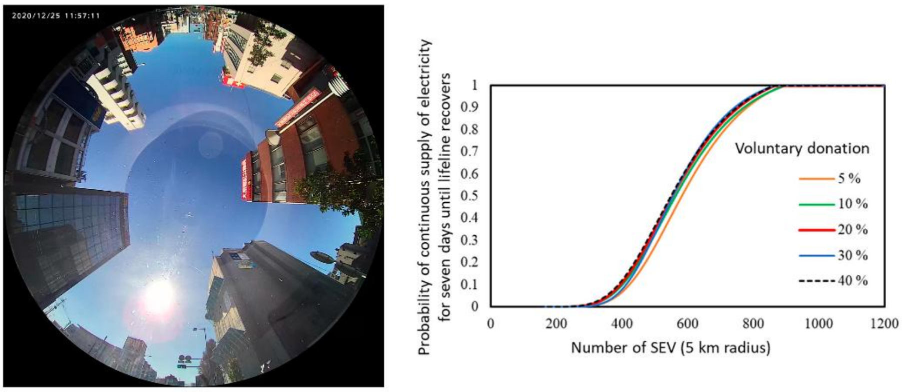
(a) (b)

Fig. 3.3-3 Probability of sustaining resilience energy for a week in open zone: (a) fisheye image; (b) probability curves [83]



(a) (b)

Fig. 3.3-4 Probability of sustaining resilience energy for a week in residential zone: (a) fisheye image; (b) probability curves [83]



(a) (b)

Fig. 3.3-5 Probability of sustaining resilience energy for a week in building zone: (a) fisheye image; (b) probability curves [83]

A unique advantage of SEV-based resilience is that energy can be collected through voluntary contributions. A density of approximately 13 SEVs per km^2 (1 000 SEVs in a 5 km radius) is sufficient to support temporary resilience facilities (one temporary shelter with medical care, six spot air conditioners for care homes and community halls, and twenty-five charging stations for mobile devices).

4 RESILIENCE SCENARIO USING BEV USING A SIMPLE VOLUNTARY MODEL

We will directly compare the resilience effects of BEVs and SEVs, assuming that 5% of BEV owners with automotive solar cells will actively supply surplus energy when their batteries are nearly fully charged. This approach will not impose any obligations on BEV owners who are unable to recharge their vehicles.

Not all vehicles will be fully charged at the time of the disaster. Moreover, sunny weather is expected to persist after the disaster, though solar radiation availability may be limited. Depending on their location, some vehicles are likely to remain in the shade. Therefore, we will calculate the remaining charge for each car in the affected area and assess shading conditions at the time of the disaster using a robust probabilistic model. Each vehicle's initial charge will be assigned a random value, and we will determine whether the vehicle owner contributes excess energy as a random variable according to the established probabilities. The results are clearly illustrated in Fig. 4-1. Psychological barriers to donating from BEVs without a full charge were not considered.

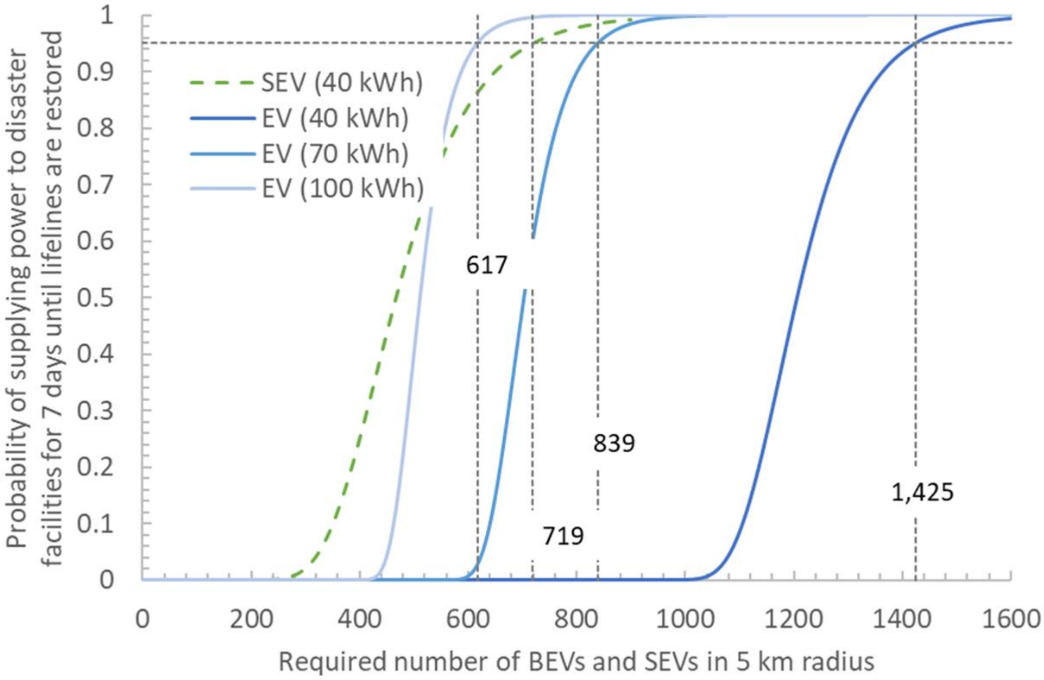


Fig. 4-1 Determine the necessary number of vehicles and electric vehicles equipped with solar cells, all within a 5 km radius, and ensure they all use batteries of the same capacity.

Installing VIPV ensures that power remains available even when unattended, effectively halving the number of battery-equipped vehicles in disaster-stricken areas. This solution is crucial for enhancing energy availability and resilience during crises.

5 RESILIENCE SCENARIO USING VIPV WITH SELFISH POWER HOARDING

We must adopt a more realistic model for reserving self-consumption and delivering surplus energy to shelters during disasters. Given that self-retention is permitted, it is unnecessary to impose rigid restrictions, such as mandating an offering when the state of charge (SoC) exceeds 90%. Even if the surplus is slightly larger, as long as the self-reserve is secured, we will run the Monte Carlo simulation assuming the surplus will be available.

Drivers of SEVs with at least 60% or 70% battery capacity will supply power to the facility until their vehicle's battery drops to 20% or 30%, based on the chosen provision rate. When traveling to the facility, energy is drawn from the car battery, and drivers return home with the remaining charge (Fig. 5-1).

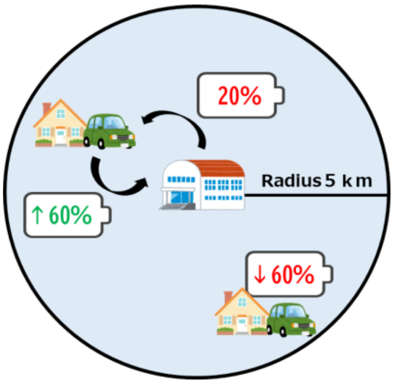


Fig. 5-1 Overall view of the selfish power-hoarding model

The voluntary provision rate is based on Cutter's hazard-of-place model, utilizing the number of vehicles owned per household in the region as the variable x. The provision rate adjusts in phases according to the residual charge level.

Table. 5-1 Spontaneous provision rate by remaining charge

Remaining charge	Voluntary Provision Rate
More than 60% and less than 70%	$\frac{2}{5}x \times 100\ \%$
More than 70% and less than 80%	$\frac{4}{5}x \times 100\ \%$
More than 80% Less than 90%	$\frac{6}{5}x \times 100\ \%$
More than 90% and less than 100%	$\frac{8}{5}x \times 100\ \%$

Given that research is only possible if there is spare power seven days after a disaster, a Monte Carlo simulation was used to calculate the surplus car power after this period. The analysis assumed 1 000 affected individuals.

SEV's value is assessed by comparing it with EVs:

- SEV remaining charge = disaster charge – power usage + projected generation
- EV charge level = disaster charge – power usage

Both formulas help simulate surplus power during a disaster.

Table 5-2 divides disaster power consumption into air conditioning, lighting, kettle, mobile charging, and hot water supply, with set utilization rates and required power for each. The electricity used per person varied randomly, as illustrated below.

Table 5-2 Daily electricity usage and utilization rate

Devices	Electricity (kWh)	Utilization rate (%)
Air conditioning (winter)	**2040**	**30**
Air conditioning (summer)	**1680**	**30**
Lighting	**240**	**90**
Pot	**100**	**60**
Mobile Charging	**10**	**90**
Hot water supply	**300**	**30**

How many SEVs are needed to continue supplying power to evacuation centres for seven days after the disaster occurs, using Monte Carlo simulations?

- Selection of time/vehicle for donation

The selection of cars shall be once a day and shall be randomly selected from 24 hours, with each hour separated.

- Check the charging level of the target car

If it does not exceed the default value (60% or 70% of the remaining charge), it is not eligible.

- Selected according to the voluntary provision rate

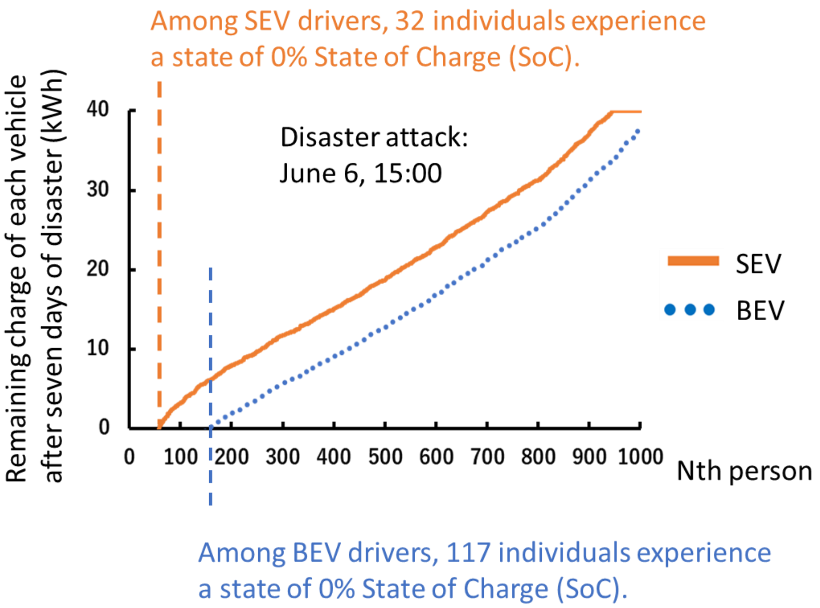
For each car, the voluntary provision rate is determined according to the remaining charge. After that, perform a probability calculation and select the target car.

- The target car provides power to the evacuation centre

Since isolated areas are assumed to have a radius of 5 km, the power required for 5 km of driving is subtracted and provided until the remaining charge reaches the specified level (20% or 30% of the remaining charge level), and the power required for returning home is deducted. When providing electricity, if the power at the evacuation centre is at its maximum, electricity shall not be provided.

These will be carried out for 7 days for each car, and it will be assessed whether it is possible to continue supplying power to the evacuation centre. If the power of the evacuation centre shows 0 even once for 7 days, it is considered a failure to provide electricity, and if it can continue to show a value greater than 0, it is considered successful.

The results are examined using the number of vehicles equipped with PV as an explanatory variable, the remaining charge of the car 7 days after the disaster as the objective variable, and the number of vehicles needed to remain above 0 even after 7 days. For example, in the case below, 32 SEVs were fine, while BEVs require 117 units (Fig. 5-2).


Among SEV drivers, 32 individuals experience a state of 0% State of Charge (SoC).

Disaster attack: June 6, 15:00

Among BEV drivers, 117 individuals experience a state of 0% State of Charge (SoC).

Fig. 5-2 The remaining charge of the car after 7 days (disaster occurred: 15 o'clock on June 6)

Likewise, it can be expressed as a probability maintained for 7 days, as in the previous chapter.

The 70-20% drawn by the solid green line means that if the battery's surplus power exceeds 70%, there is a 1% chance it will supply power until the remaining power reaches 20%. The blue colour is set to provide power to evacuation centres until the remaining charge is 20% from cars with 60% or more charge. The probability gradually increases from around 100 units, and when it reaches 450 or more, the power supply to the evacuation centre becomes stable. Based on this value, we sought a future approach by considering cases in which the power supply is reduced from 20% to 30% (orange graph) and in which the scope of supply is increased from 60% or more to 70% or more (green graph). The graph from 60% or more to 30% has the same general shape as the blue graph, and it seems that the number of requests has increased. In addition, the graph from 70% or more to 20% has a gentle slope and is closer to a straight line. Both graphs showed that if there were more than 550 SEVs, the evacuation centre's capacity could be sustained for 7 days.

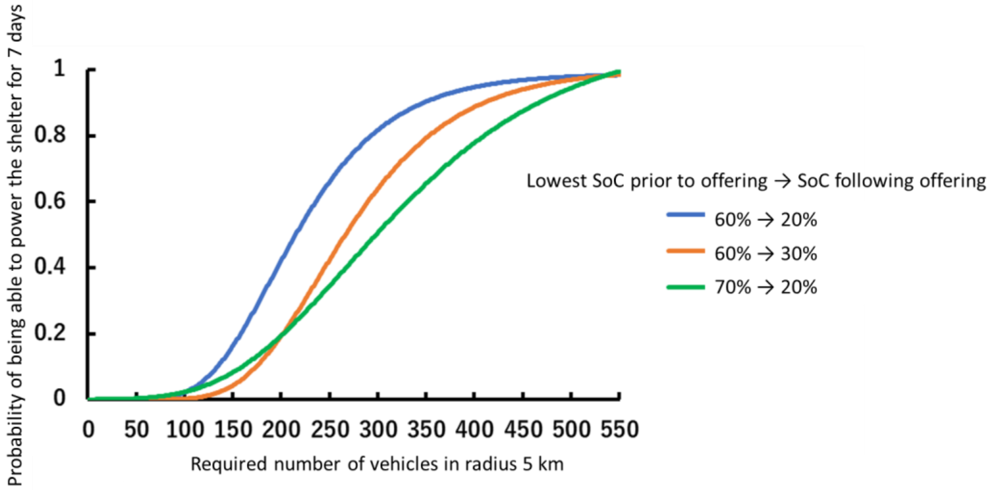


Fig. 5-3 Probability of sustaining resilience energy for a week, examined by the cases of threshold of the charging rate

In this way, if the probability of providing electricity to the disaster base decreases due to selfish judgment in addition to self-consumption, the opportunity to provide it to public goods decreases, so even if the number of EVs increases compared to Figure 4-1, the probability that the required power at the disaster base can be maintained until the lifeline is restored does not increase easily. As a result of numerical experiments varying various parameters, the effective approach is to "catch from where you can catch it". In other words, it is not 60%-30%, but 20%. This is more effective than "attracting motivated people" by changing 70%-20% to 60%-20%.

Incentive design is important for policies based on public goods. In particular, in the design of a system such as "let's take what we can take," as in this scheme, it is important to provide sufficient rewards to donors.

From the simulation results, it was found that more than 450 SEVs are required in the area to continue supplying power to the evacuation centre for 7 days if it is isolated in a radius of 5 km due to a disaster, but in order to know how much is 450 units within a 5 km radius, Table 3.2 shows the indicators of Miyazaki Prefecture and Miyazaki City, which are the target areas of this time. In Miyazaki Prefecture, the penetration rate will be 6%, and this will be possible if 1 in 16 SEVs are present in the area. If it is limited to Miyazaki City, the penetration rate will be 1%, so it is enough to have 1 SEV for every 100 vehicles. Although SEV is not yet widespread, it is thought to be sufficient for disaster resilience if it becomes widespread in the future.

Table 3.2 Number of households and passenger cars in Miyazaki Prefecture and Miyazaki City

	Miyazaki Prefecture	Miyazaki City
Passenger car (unit)	685,051	247,791
Number of households (households)	474,819	188,647
Area (km2)	7,735	643
Passenger cars within 5 km	6,956	30,267

Looking at the comparison between the case of reducing the power supply and the narrowing of the range of recipients, as the number of units increased, the probability of stability was shown when the power provided was reduced, so when there were many SEVs in isolated areas, it was easier to gather power if the number of people was increased even if the number of people provided per person was reduced. However, if there are few SEVs in isolated areas, it is more likely that the power supply will continue if it can take as much as it can from the person providing the electricity.

In addition, this survey is a case in which the SEV that stores and transports the collected electricity between the scattered temporary relief facilities operates without a hitch. Even if the total amount of electricity at scattered relief facilities is supplied by SEV drivers in isolated areas who voluntarily provide electricity, if the SEVs that carry electricity are not operational, the number of relief facilities experiencing power shortages will increase. Therefore, in order to respond effectively, it is necessary to cooperate with the government's traffic maintenance and those who transport supplies, and I believe that it is important to clarify response measures and the chain of command in the event of a disaster

6 GUIDELINES CONSIDERING REGIONAL VIPV ENERGY GENERATION

The Monte Carlo simulation described thus far is a powerful tool for evaluating resilience, as it can depict not only photovoltaic (PV) power generation output but also social behaviour, disasters, and the community's condition at that time. This model is highly transparent and utilizes probability-based numerical methods. However, the calculations can be complex and challenging to grasp. It may be more intuitive to multiply the amount of power generated by a proportional coefficient. This chapter explores this approach.

Indoor test results are used to evaluate the basic performance of photovoltaic (PV) modules, but they do not serve to certify the modules themselves. Instead, these tests assess the performance of specific indoor-tested VIPVs. The VIPV product's rating may be indirectly affected by its performance within a specific zone.

Multiple factors complicate the assessment of solar irradiance and its impact on VIPV performance.

- The orientation angle of the VIPV changes frequently during driving.
- The VIPV has a higher probability of shading.
- Shading objects, such as street trees and signals, are small and highly influenced by partial shading loss.
- Curved surface.
- The impacts above interact and depend on the module's local coordinates.
- Rapid solar irradiance fluctuations, generally occurring in milliseconds, result from dynamic partial shading.
- Rapid fluctuations of the solar spectrum.
- Temperature variation between parking and driving.

The annual energy yield is calculated using the following formula:

The annual energy yield is calculated as follows: (VIPV Energy).

= (Performance test result by IEC 60904-1-3) × (Shading factor) × (Partial shading factor) × (Shape factor) × (Temperature factor) × (Spectrum factor).

IEC 60904-1-3 is currently under discussion in an IEC TC82 project and has not yet been finalized for publication. Various IEC standards provide the fundamental procedures for performance measurement and rating.

Solar irradiance on VIPV is influenced by the surrounding shading environment, which can be categorized into three zones: lightly shaded (suburban area, SVF 0.9), medium shaded (residential area, SVF 0.7), and deep shaded (valleys between skyscrapers or hills, SVF 0.5) [78]. The shading factors discussed in the IEC TC82 PT600 project team are presented in Table 6-1 to 6-4 [78]. Reflection from shading objects was included in the calculation of these factors.

Table 6-1. Values of shading factors [78].

Climate zone	Zone category (IEC 61853–4 [85])		
	Lightly shaded	Medium shaded	Deep shaded
High elevation	0.92	0.68	0.45
Subtropical arid	0.93	0.69	0.45
Subtropical coastal	0.92	0.71	0.49
Temperate coastal	0.90	0.67	0.46
Temperate continental	0.91	0.66	0.43
Tropical humid	0.93	0.74	0.54

Table 6-2. Values of the partial/dynamic shading factors [78].

Climate zone	Zone category (IEC 61853–4 [85])		
	Lightly shaded	Medium shaded	Deep shaded
All climate zones	0.99	0.97	0.98

Table 6-3. Values of shading factors (Roof or rear window, single-peaked, and no self-shading by other parts of the car body) [78].

Climate zone	Zone category (IEC 61853–4 [85])		
	Lightly shaded	Medium shaded	Deep shaded
High elevation	0.95	0.96	0.96
Subtropical arid	0.95	0.95	0.96
Subtropical coastal	0.96	0.96	0.96
Temperate coastal	0.97	0.97	0.97
Temperate continental	0.96	0.96	0.96
Tropical humid	0.96	0.96	0.96

Table 6-4. Values of shading factors (engine hood, self-shaded by front window) [78].

Climate zone	Zone category (IEC 61853–4 [85])		
	Lightly shaded	Medium shaded	Deep shaded
High elevation	**0.94**	**0.96**	0.96
Subtropical arid	**0.93**	**0.96**	0.96
Subtropical coastal	**0.95**	**0.97**	0.97
Temperate coastal	**0.97**	**0.97**	0.95
Temperate continental	**0.94**	**0.96**	0.97
Tropical humid	**0.96**	**0.97**	0.97

Note that the shape factor varies by climate zones and shading environments. Generally, the shading factor is higher in sunny areas and open environments (fewer shading objects).

When calculating power generation during a disaster, it is imperative to acknowledge the unpredictability of disaster timing. Photovoltaic (PV) power generation relies heavily on solar radiation, which can differ significantly from recorded data. Furthermore, solar radiation experiences notable regional and seasonal variations.

Focusing on Miyazaki City, a region with relatively stable solar radiation, it is crucial to recognize that these levels can fluctuate by tens of percent from year to year. Seasonal changes are also critical and must not be ignored. Relying on annual data or seasonal averages to calculate probabilities results in vastly different outcomes. Using annual data for power generation estimates results in significant overestimation.

Moreover, solar radiation data must be viewed through the lens of "the amount of solar radiation required to maintain a lifeline with a probability of more than 95% of the time," rather than merely considering average survival probabilities in resilience design. Therefore, we must specifically evaluate solar radiation levels during the week when solar exposure is at its worst, rather than indiscriminately applying annual solar radiation data, as shown in Tables 6-1 to 6-4.

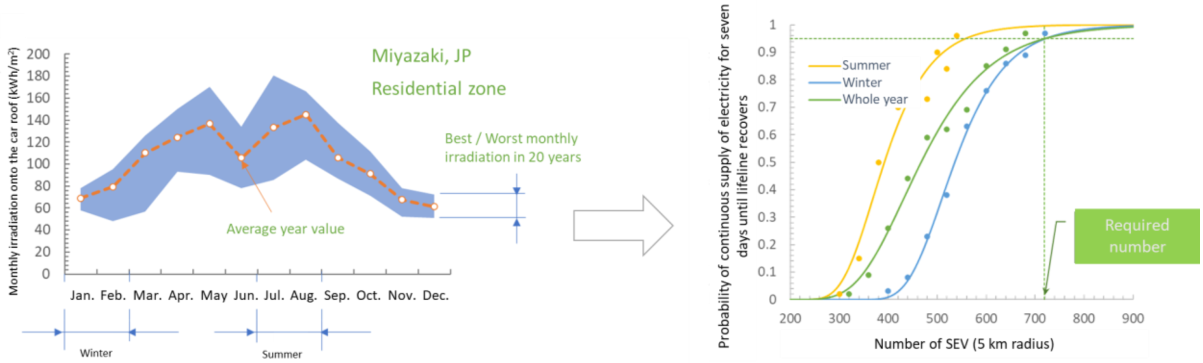


Fig. 6-1 Effect of seasonal variation of solar radiation on stochastic calculations by Monte Carlo simulation.

Q1. Should we provide an approximate estimate of vehicle numbers for typical cities worldwide?

- Yes, that might be necessary.

Q2. Is it appropriate to use a standard VIPV solar irradiance database (PT100 table) for a basic calculation?

- Likely not for a simple interpretation. Apply the solar irradiance and energy demand from the worst week instead.

7 COMMERCIAL VIPV SYSTEM FOR EMERGENCY POWER SUPPLY IN MIYAZAKI, JAPAN BY IM EFFICIENCY

Section 7 presents a realistic architecture comprising a small number of larger VIPV/SEV units with well-defined power interfaces. This reflects the intended use case of this study: direct supply to isolated shelters, not integration into a functioning distribution network.

In such off-grid conditions, the technical requirements are significantly simpler than those for grid-synchronized operation. Only a basic inverter-based AC output or DC supply is needed, and no frequency synchronization, phase matching, or protection coordination with the utility grid is required.

The case study in Section 7 reflects this hazard-dependent framing. It assumes that some vehicles remain operable after the disaster and can be deployed to shelters once minimal road access is restored. This aligns with real-world disaster logistics, where mobility is often restored before electricity, allowing SEVs to function as early-stage, flexible power sources rather than as universally resilient infrastructure.

7.1 Context and Motivation

The 2011 Great East Japan Earthquake revealed the severe vulnerability of centralized power infrastructure, leaving approximately 1.9 million fixed telephone lines and 29,000 mobile base stations inoperative across the Tohoku and Kanto regions. Power outages persisted for days and weeks in affected areas, incapacitating evacuation centers, hospitals, water treatment facilities, and communication infrastructure during critical moments.

Recent policy initiatives by Japanese national and local governments emphasize the need for distributed, resilient energy systems capable of maintaining essential functions during grid failures. However, conventional emergency power solutions largely rely on diesel generators, which have significant limitations:

- Require continuous fuel resupply via road networks, often damaged during disasters
- Limited to 24-72 hours of operation with stored fuel
- Produce noise, air pollution, and CO_2 emissions
- Fuel distribution disruptions can last for weeks, as seen in 2011
- Depend on trained operators, maintenance, and safe fuel storage

To address these challenges, IM Efficiency, a Dutch renewable energy startup, created SolaronTop—an innovative system that transforms standard trucks and trailers into mobile solar power units by installing high-efficiency PV modules on trailer surfaces. SolaronTop is a VIPV system designed to enhance emergency power capabilities (Fig. 7-1).

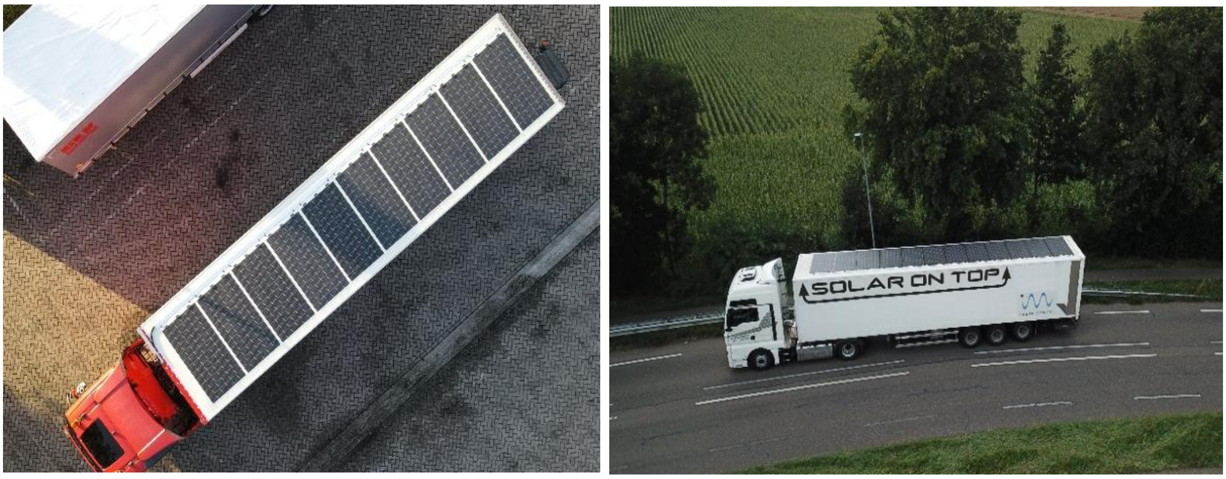


Fig. 7-1 Aerial view of SolaronTop showing comprehensive PV coverage on the truck-trailer roof surface

- PV modules: High-efficiency monocrystalline silicon modules designed for horizontal and vertical mounting on truck and trailer roofs and sides.
- Advanced Energy Management System: Control boards, MPPT (Maximum Power Point)
- Tracking), and DC-DC converters optimized for independent top and side string management.
- Energy Storage: Lithium-ion battery system sized for daily energy cycling; capacity varies with configuration.
- Power Distribution Interface: Standardized AC (100V/200V Japanese standard) and DC (12V, 24V, 48V) outputs with safety protection.
- Monitoring and Telematic System: Real-time data on energy generation, storage, and consumption via cellular connectivity.

7.2 Energy Generation Performance in Miyazaki

IM Efficiency conducted an analysis of the potential contribution of the solar panels over a 12-month period from January 2024 to December 2024, assessing real-world energy generation from SolaronTop systems under Japanese climate conditions, as shown in Fig. 7-2.

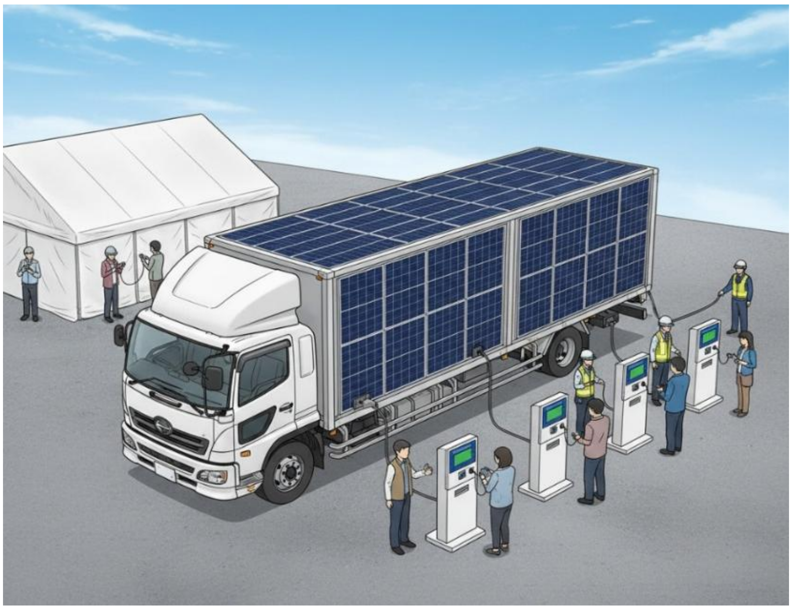


Fig. 7-2 SolaronTop mobile power unit for emergency power needs at disaster evacuation center. (Made using AI © Copyright IM Efficiency)

- Key findings from the data indicate that the combined top and sides configuration produced 13,967 kWh annually, averaging 38.3 kWh daily throughout the year. Peak generation occurred in the summer months (July-August), with over 45 kWh per day, while winter output ranged between 30 and 33 kWh per day. Top panels contributed 47.8% (6,674 kWh/year) while side panels contributed 52.2% (7,293 kWh/year), demonstrating the value of multi-orientation PV integration (Figures 7-3 and 7-4).

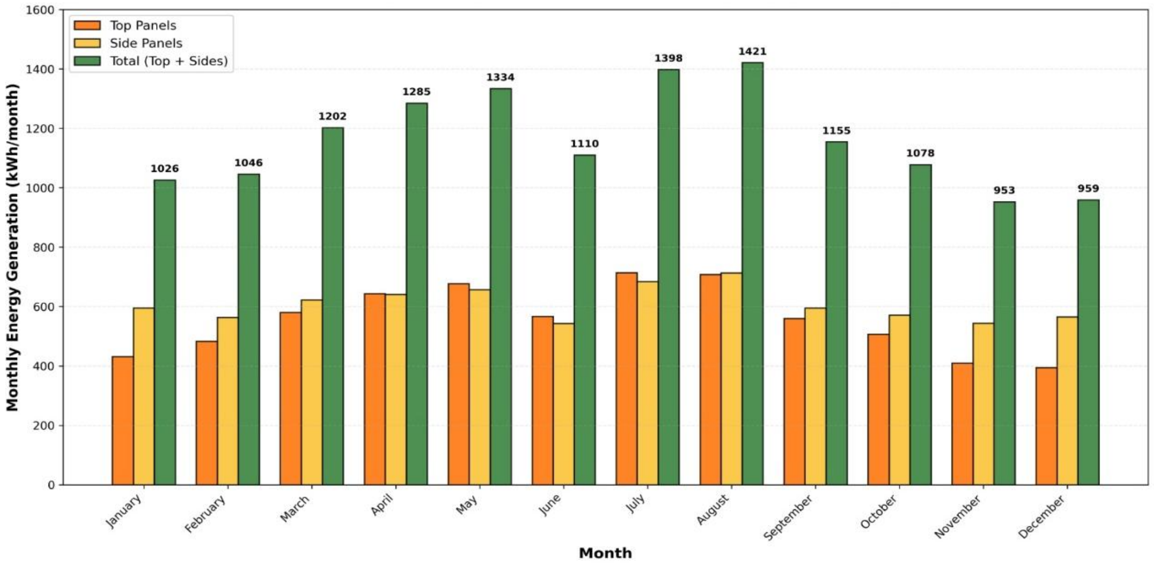


Fig. 7-3 SolaronTop monthly energy production from top and side panels in Miyazaki, Japan (2024)

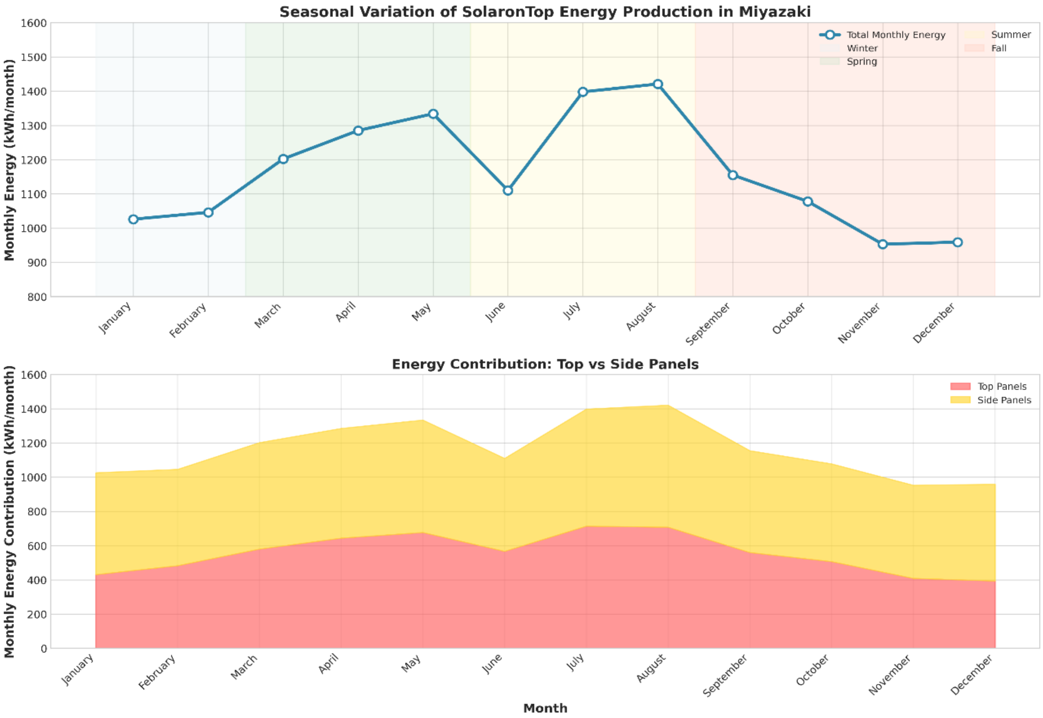


Fig. 7-4 SolaronTop Seasonal variation analysis showing total energy production trends and relative contributions of top versus side panels throughout the year

- Vertically-mounted side panels showed remarkably consistent daily averages (18-23 kWh/day) across seasons, providing stable baseload generation
- Even during the lowest-generation month (December), the system produced 959 kWh/month or 31 kWh/day, sufficient for critical emergency loads

The simulated data demonstrate that SolaronTop can provide reliable daily energy yields of 30-45 kWh/day even under worst-case (winter, cloudy) conditions. This performance envelope supports a wide range of emergency applications beyond telecommunications infrastructure.

The graphs in Fig. 7-5 summarize the SolaronTop system's performance over a year in Miyazaki. The top-left boxplot shows that typical daily energy generation is highest in summer (around 34 kWh/day) and lowest in winter (around 43 kWh/day), with spring and fall in between. The top-right bar plot breaks this down by month and by top versus side panels, revealing that side panels deliver a very stable 18–23 kWh/day while roof panels vary more strongly with season. The bottom-left curves show how energy accumulates hour by hour on representative days, with summer and spring reaching the highest daily totals fastest, and winter and fall saturating earlier and at lower levels. The bottom-right bar plot combines top and side output to give total average daily energy per month (about 31–46 kWh/day) and highlights the overall annual average of 38.3 kWh/day, indicating that even in the worst winter months, the system still supplies over 30 kWh/day for emergency loads.

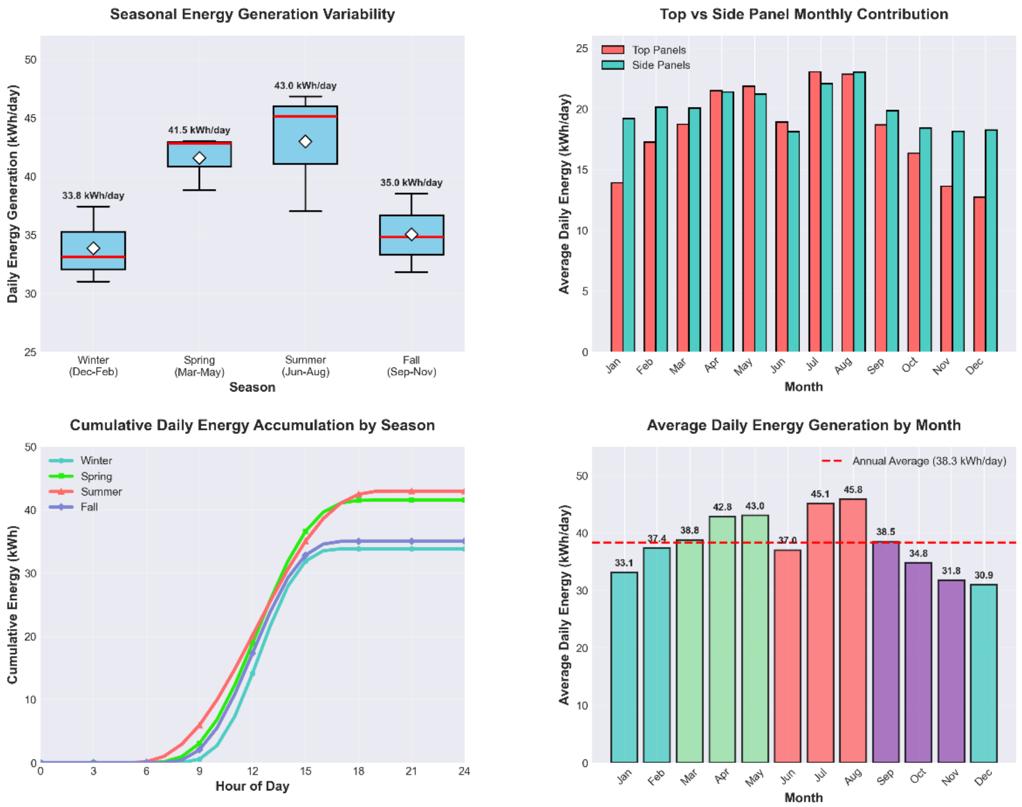


Fig. 7-5 SolaronTop performance analysis: (1) seasonal generation variability with box plots; (2) monthly top vs side panel contribution comparison; (3) cumulative daily energy accumulation profiles by season; (4) average daily energy production per month

7.3 Study on Emergency Power Allocation

Japan's disaster response frameworks identify multiple critical electricity needs at evacuation centres and emergency facilities. Table 7-1 and Fig. 7-5 summarizes typical daily energy requirements for key emergency applications.

Table 7-1. Emergency energy requirements [89-95]

Application	**Daily Energy (kWh/day)**	**Description**
Mobile phone charging (2000 devices)	13-14	Assuming 6.5 Wh per full smartphone charge (5,000 mAh × 3.8V / 1000 / efficiency)[89] required critical for public communication

4G/5G mobile base station (reduced capacity)	25-35	Temporary setup serving 1-2 km radius. Based on 5G base station consumption of 3.5-4 kW full load, reduced capacity operation[90][91]
LED lighting (evacuation center)	8-12	High-efficiency LED (5-12W per fixture) for 500-1000 m² facility operating 12-16 hours/day[92]
Medical equipment (refrigeration)	8-12	Vaccine/medication refrigeration (0.8 kWh/24hr per unit)[93], oxygen concentrators, diagnostics etc.
Water pumping and purification	10-15	Portable RO purification system (60-120W continuous operation)[94] serving 500-1000 people
Emergency communications hub	5-10	Satellite terminals (5-20W), radio repeaters (10-50W), Wi-Fi access points[95]

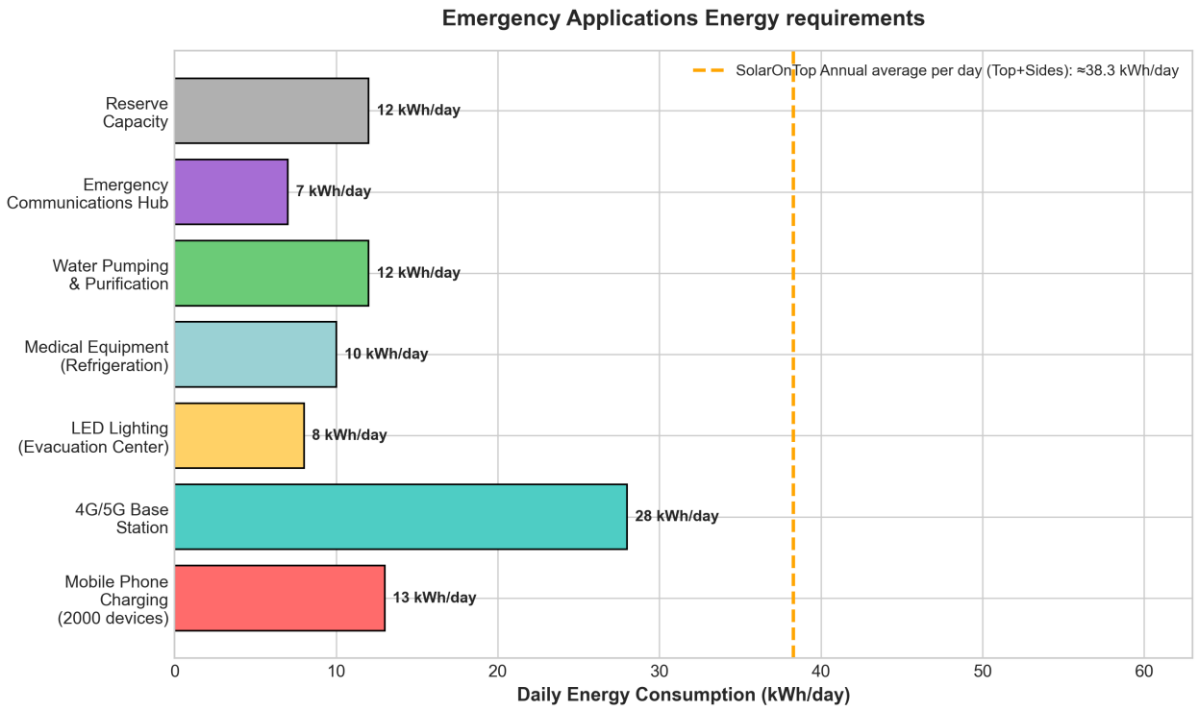


Fig. 7-5 Emergency applications power budget

A single SolaronTop truck (top+sides configuration) can generate **40-45kWh/day** (typical spring/fall performance). With two trucks, all the basic emergency power needs can be easily met.

7.4 Comparison with conventional solution

The six evaluation criteria shown in Fig. 7-6 were determined by analyzing Japanese disaster response priorities and aligning them with international standards for emergency power system evaluation [96-98]. Each metric uses a 0-10 scoring scale, where higher values indicate superior performance in emergency power provision, following resilience assessment frameworks established in the IEEE and NFPA literature [99-100].

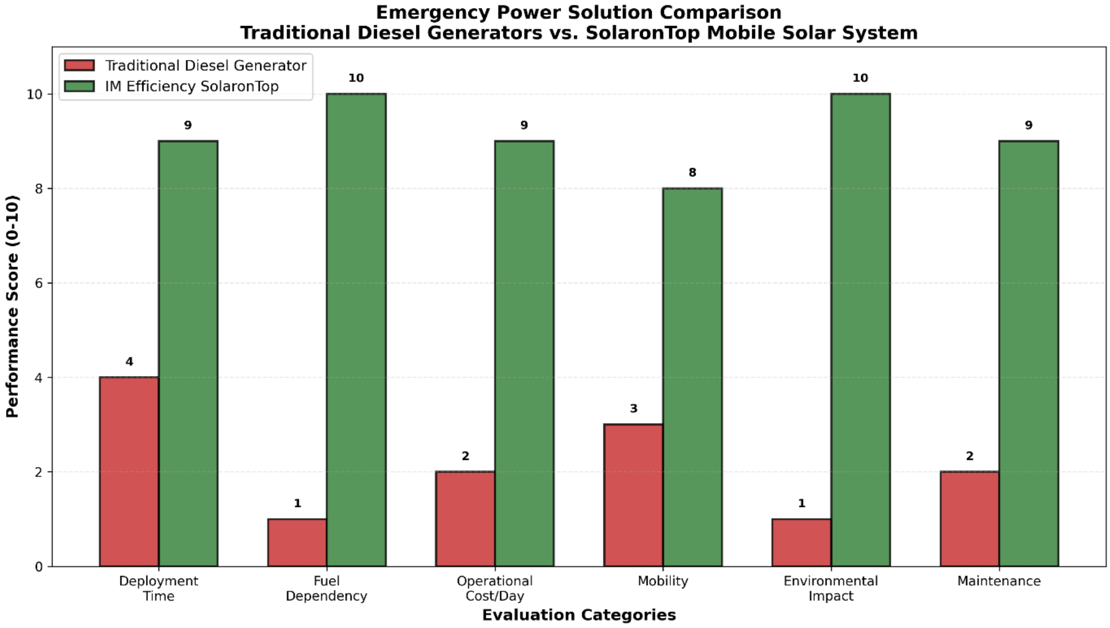


Fig. 7-6 Performance comparison across key evaluation criteria for emergency power solutions

Deployment Time: Diesel generators score 4 based on a typical 2-4 hour deployment cycle, including transport, setup, (re)fueling, and testing, per NFPA installation acceptance procedures [101]. SolaronTop scores 9, reflecting a 30-60 minute deployment (drive to site, park, connect power distribution) with no logistics for fuel supply required, meeting emergency response time criteria established by FEMA for critical facility power restoration [97].

Fuel Dependency: Diesel systems score 1 due to 100% dependence on external fuel supply chains, which are vulnerable to logistics disruptions, as demonstrated during the 2011 Great East Japan Earthquake, when fuel distribution remained compromised for 2-3 weeks[85-86]. This represents a critical vulnerability in power system resilience frameworks [99-100]. SolaronTop scores 10 with zero fuel requirement and indefinite operational autonomy, using a universally available solar resource, eliminating the supply chain fragility identified in IEEE resilience assessment standards [102].

Operational Cost per Day: Diesel generators score 2 based on €50-100/day (9000 – 18000 JPY/day) fuel costs at 4 L/hour consumption over 12-16 hour operation plus maintenance requirements per NFPA Chapter 7[101,103]. SolaronTop scores 9 with near-zero marginal operating cost after the initial capital investment (except for periodic PV cleaning), representing significant lifecycle cost advantages documented in FEMA benefit-cost analysis methodologies for alternative power systems [97, 104].

Mobility: Diesel generators score 3, requiring dedicated transport to disaster sites and fixed positioning once deployed, limiting operational flexibility during multi-site emergency response scenarios[96]. SolaronTop scores 8 as a fully mobile platform capable of repositioning between multiple evacuation centers within the same deployment, leveraging existing truck chassis for road mobility and meeting distributed emergency power system requirements [87-88].

Environmental Impact: Diesel systems score 1 due to local air pollution (NO_x, particulates, CO), noise (65-85 dBA typical generator operation [103]), and CO_2 emissions (2.7 kg/L; 65-80 kg CO_2/day typical operation). SolaronTop scores 10 for zero operational emissions, silent operation (<40 dBA), and direct alignment with Japan's 2050 carbon-neutrality commitment and renewable energy integration targets [87].

Maintenance Requirements: Diesel generators score 2, requiring regular oil changes, filter replacements, skilled technician interventions, and fuel maintenance as specified in NFPA maintenance schedules and Joint Commission standards [101-103]. SolaronTop scores 9 with minimal maintenance needs limited to periodic PV surface cleaning and standard vehicle maintenance, reducing long-term operational complexity and skilled labor dependencies during extended emergency deployments.

These metrics collectively demonstrate SolaronTop's operational superiority for Japanese disaster response applications, with particularly strong advantages in fuel independence, environmental performance, and operational cost factors critical for extended emergency operations when conventional fuel logistics are compromised. The evaluation framework aligns with established power system resilience assessment methodologies that emphasize pre-event estimation and post-event evaluation capabilities [99-100, 102], disaster response performance criteria from FEMA and NFPA standards [97, 101, 103], and IEEE frameworks for evaluating distributed energy resource resilience under extreme events [96, 105].

8 CONCLUSION

Vehicle-Integrated Photovoltaics (VIPV) and Solar Electric Vehicles (SEVs) represent a critical advancement in developing disaster-resilient energy systems. This report's quantitative modeling, social science-based probability analysis, and real-world case studies conclusively demonstrate that mobile PV systems provide significant advantages over both Battery Electric Vehicles (BEVs) and static photovoltaic installations.

8.1 Core Advantages of VIPV and SEV for Disaster Resilience

- Across all scenarios, VIPV systems consistently outperform conventional BEVs and fixed PV in several critical aspects:
- They reduce the risk of complete battery depletion by continuing to generate energy even when unattended.
- They operate independently of damaged grid infrastructure, eliminating the vulnerability of centralized PV systems.
- They offer mobility, allowing vehicles to relocate to areas with higher irradiance and to physically transport energy and supplies.
- They serve a dual purpose as both transportation assets and distributed energy resources.
- They are compatible with voluntary energy-sharing models, significantly boosting resilience when community members contribute surplus energy.

8.2 Insights from Monte Carlo Modelling

- The Monte Carlo simulations—incorporating shading environments, social behavior, and disaster timing—demonstrate that:
- A simple voluntary contribution model shows that approximately 1,000 SEVs within a 5 km radius (about 13 SEVs per km²) are sufficient to sustain essential temporary facilities such as medical shelters, spot coolers, and mobile device charging stations.
- Even when self-reinforcement behavior is included, a selfish power-hoarding model reveals that just 450+ SEVs within a 5 km radius can maintain evacuation center power for seven days. Policy implication: Incentive design is crucial. Systems based on a "take what you can" approach must offer meaningful rewards to ensure ongoing donor participation.
- Operational insight: When SEV density is low, maximizing contribution per vehicle is most effective; when density is high, distributing smaller contributions across more vehicles enhances stability.

For a detailed mathematical model for the Monte Carlo simulation, see [106].

8.3 Integration of Real-World Evidence: IM Efficiency Case Study

Section 7.5 confirms the validity of the modeling results. The SolaronTop VIPV system demonstrates that VIPV is not only theoretically feasible but also practically mature. Key findings from the case study include reliable daily energy generation of 30–45 kWh, even in winter, sufficient to power essential loads such as telecommunications, lighting, refrigeration, and water purification. It clearly shows operational advantages over diesel generators.

- near-zero operating costs
- no fuel dependency
- rapid deployment
- minimal maintenance
- zero local emissions

It also highlights how fleet integration can enable logistics operations to provide emergency power without relying on dedicated equipment. These results support the use of VIPV systems as mobile micro-power sources that can assist evacuation centers and critical infrastructure during extended outages.

8.4 Synthesis: What This Means for Future Disaster Preparedness

The modelling and case-study evidence conclusively demonstrate that:

- VIPV and SEV fleets can establish a decentralized, self-healing energy network capable of functioning during disasters.
- Even modest penetration rates, such as 1% in urban areas, deliver significant resilience benefits.
- Mobile PV systems not only complement but often outperform traditional emergency power solutions, particularly when fuel supply chains are disrupted.
- Social behavior plays a crucial role—voluntary contribution models can succeed but require well-designed incentives.
- Commercial VIPV systems already meet the technical standards necessary for real-world deployment, effectively bridging the gap between theory and practice.

8.5 Final Remark

VIPV is now a proven, practical, scalable, and socially compatible resilience technology. By integrating mobility, distributed generation, and community-driven energy sharing, VIPV systems establish a strong foundation for future disaster-resilient cities. The deployment of commercial solutions such as SolaronTop confirms that the transition from research to implementation is underway, firmly establishing VIPV as a key element of next-generation emergency energy strategies.

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