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Perspective

When Cities Go Nuclear: Exploring the Applications of Nuclear Batteries Toward Energy Transformation

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Abstract: Global society faces the pressing question of how to eliminate reliance on fossil fuels while meeting increasing energy demand. In comparison to solar and wind energy, nuclear power has been largely ignored in urban studies research. However, nuclear energy has recently regained attention through the emergence of Small Modular Reactors (SMRs), and as the stakes of decarbonization become increasingly essential. To evaluate situations in which SMRs bring value to urban energy mixes, this paper focuses on Nuclear Batteries (NBs), a specific class of SMRs, that can fit in standard shipping containers. First, we outline an evaluation framework for the use and application of NBs; second, we present use cases for NBs in real-world situations, from disaster relief to grid reinforcement; and third, we discuss the social challenges around this technology.

Keywords: nuclear energy; energy transition; urban design

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1. Introduction

By 2050, global energy consumption could increase by up to 50% [1]. Energy demand will be driven by global population growth, increasing access to electricity, rising incomes, and urbanization [1]. This demand will be spatially unevenly distributed, with accelerating urbanization happening in the global south, and the industrial hinterland feeding their appetites for food, water, fuel, data, and other resources. Manufacturing, materials processing, transportation, and buildings are already responsible for over 80% of global carbon emissions [2].

Fossil fuels continue to dominate the energy market, producing more than 80% of global energy [3]. The projected growth in energy demand over the next 30 years will occur in regions heavily reliant on CO_2-emitting energy sources [1] The International Energy Agency [4] has set the imperative of transitioning to net-zero carbon emissions by 2050 to avert the worst effects of climate change.

Renewable energy sources are the fastest-growing segment of the energy sector [1]. The global installed capacity of renewable energy reached 2537 GW at the end of 2019, with hydropower leading the way (1190 GW globally), followed by wind energy (623 GW), and solar (586 GW) [5]. Explaining the simultaneous growth in demand for fossil fuels and growth in renewable energy adoption is a daunting cost differential; the overhead of capital required to begin renewable energy projects has been cited extensively as a barrier to renewable energy adoption, though the cost of clean energy relative to traditional energy has diminished substantially in recent years. Now, the overestimation of risk by financial institutions, the lack of legal and regulatory frameworks, and limitations on existing infrastructure and skills hinder the deployment of clean energy [6]. These obstacles apply particularly to nuclear energy [7].

Global energy market issues were intensified by the Russian invasion of Ukraine, as Russia is a top oil and gas exporter, and faced international sanctions, disrupting supply chains and threatening an energy crisis [8]. To achieve the deep decarbonization required to address these issues on a planetary scale, it is necessary to integrate low-carbon energy solutions into every sector of the economy while addressing the unprecedented need for speed and scaling, while balancing security, affordability, and sustainability [9].

The most recent research about creating carbon-neutral cities focuses on the potential roles of solar and wind energy in [10,11]. Some governments have been funding solar and wind farms [12,13] and financially penalizing emissions while giving tax rebates or loans to building owners to convert their current energy systems to be less carbon-intensive [14,15].

Nuclear reactors are operating in 32 countries and regenerate about 10% of the world's electricity, and fast-urbanizing countries such as India, the United Arab Emirates, and Pakistan have been pushing ahead with the construction of nuclear plants. In percentage, 9 of the top 10 countries generating electricity via nuclear reactors are in Europe, from France (62.6%) to Bulgaria (32.6%). Therefore, some of the most energy-intensive megacities or large metropolitan areas already depend, to varying degrees, on conventional nuclear power generated by large reactors distant sometimes hundreds of kilometers away—the list includes Rio de Janeiro, New York, London, Paris, Moscow, Delhi, Tokyo and Beijing.

Still, nuclear energy has been largely ignored as a source of clean energy in urban studies [16]. In the past few decades, partially due to the nuclear accidents of Chernobyl (1986) and Fukushima Daiichi (2011), several countries have shut down or paused their nuclear energy programs [17,18], and some scholars studying the energy transition have even welcomed the rollback of investment in nuclear.

However, nuclear energy has recently regained attention as the stakes of increasing carbon-free energy capacity become increasingly dire [19]. Partially responsible for the new wave of interest in nuclear energy technologies is the growing popularity of Small Modular Reactors (SMRs), which package nuclear reactors in smaller and simpler devices, thereby potentially lowering costs and increasing application flexibility [20,21].

This paper explores applications for this new wave of nuclear power systems by presenting use cases for one type of SMR, called Nuclear Batteries (NBs), which can autonomously generate between 1 and 20 MW of carbon-free heat, electricity, or both. We present a framework for the evaluation of use cases for NB deployment, focusing on social and environmental concerns, and on factors that make NB technology uniquely suited for some applications, specifically for large construction sites, informal settlements, grid resilience, emergency refuges, industrial power, and remote communities—cases which are often disconnected from the regular energy grid, or require substantial investments to be connected to the grid, or need large amounts of energy for short periods.

2. Nuclear Battery Technology

The renewed interest in SMR technology [22,23], has also boosted attention toward the class of systems known as Nuclear Batteries, but the phenomenon of a small nuclear reactor is not an unprecedented idea: SMRs (including small NBs) emerged in the early days of nuclear power [19]. The US Army experimented with terrestrial NBs in the 1960s, but the early devices were abandoned due to the high cost of development compared to the reliability of diesel generators.

Advances in nuclear technology, manufacturing methods, and supply lines as well as forthcoming opportunities for urban integration have made the adoption of SMRs, including NBs, more viable in recent years [20]. While nuclear energy has historically relied on the field construction of Gigawatt-scale reactors that can take decades and billions of dollars to complete, NBs represent a relatively low-cost alternative that can deliver nuclear energy through a modular and distributed infrastructure at a Megawatt scale. Some NBs can fit into a 6-m intermodal shipping container (ISO), be factory manufactured and fueled, and transported to use sites via existing shipping routes, becoming operational within days or weeks of arrival [24]. These devices operate semi-autonomously for five to ten years before fuel resupply is necessary, after which they can be switched out for fresh devices and returned to the fueling facility for refurbishment [21].

NBs consist of a micro-reactor and turbine housed inside steel containment vessels that can fit within shipping containers. They meet all three requirements for nuclear reactor safety without operator intervention: (1) Rapid shutdown of the fission chain at the onset of anomalous conditions, (2) adequate cooling of the nuclear fuel during shutdown, (3) no uncontrolled release of nuclear material into the biosphere), and are refueled at centralized factory locations, eliminating the need for nuclear waste handling, long-term storage, or disposal at their operating sites. The spent nuclear fuel can be recycled or securely stored underground [25]. In this paper, we assume that each NB can produce 15 MW of heat and 5 MW of electricity consistently with refueling intervals of about 5–10 years.

Currently, there are no commercial nuclear batteries in operation. The leading designs, power, site and timeline of implementation, are MARVEL: 20 kWe, INL site, 2024; BWXT: 5 MWe, INL site, 2025; eVinci (Westinghouse): 5 MWe, INL site, 2026; and Hermes (Kairos): 35 MWt, Oak Ridge, 2026.

3. Nuclear Battery Evaluation Framework Methodology

We propose an evaluation framework to identify and evaluate characteristics of suitable use cases for NB technology. First, we describe the framework approach. Second, we explain how to apply the framework to energy systems. Lastly, we describe how this framework is situated within the energy literature.

3.1. Framework Background and Considerations

We began with a landscape analysis of needs for power sources in the tens of megawatts range for use cases that rely heavily on diesel generator configurations. Conceptual, qualitative, and quantitative factors are considered in the framework that evaluates the feasibility of a given NB use case, following a multi-criteria decision-making (MCDM) approach [26].

While the environmental impacts of renewable energy technologies are less harsh and far-reaching than fossil fuels, even clean energy technologies may negatively impact the environment and biodiversity [27]. To better understand the site-specific suitability of NBs compared to a different type of carbon-free electricity, the evaluation framework suggests taking into account local environmental effects [28,29]. We do not take into account the full life-cycle impacts of renewable energy technologies, as the framework is intended to serve as an aid in use case selection rather than perform a full environmental impact analysis of different options. Nevertheless, we acknowledge that this is a critical point to be taken into consideration in engineering and policy studies. The suitability of NBs for use in urban environments is considered through the "Site Attributes" factor.

The selection of factors included in the evaluation framework, shown in Table 1, was based on the wide range of factors present in the energy transition literature, including socio-technical system considerations [30], ability to escape from carbon lock-in in existing energy infrastructure [31], environmental policy [32], global political economy considerations [33], as well as on the system architecture of established energy evaluation frameworks such as the World Economic Forum's Energy Transition Index [34] and energy selection models for the United Nations Sustainable Development Goals (SDGs) [28]. Literature comparing different energy sources to each other for evaluation on multiple criteria was further reviewed to establish consistent definitions for each factor taken into account [29]. The twelve factors listed in the framework do not follow any hierarchy, rather they are factors that need to be satisfactorily addressed when assessing the feasibility of implementing nuclear batteries and may serve as guidelines in the decision-making process.

Table 1. Evaluation Factors and Units.

Factor	**Unit**	**Definition**
Installation Urgency	Days/Weeks/Months	Installation urgency defines the time sensitivity of the deployment, specifying the time frame in which an NB would need to arrive at the site.
Deployment Length	Weeks/Month/Years/Permanent	Deployment length refers to the amount of time that the NB would need to be operational at the site to provide a steady stream of energy.
Grid Connection	Yes/No	Grid connection states whether the NB would be connected to an existing local network, or if it would be a standalone source of power.
Site Attributes	User Input	Site attributes refer to a set of characteristics associated with the proposed location for the NB, such as whether it is space-constrained, remote, waterborne, faces extreme temperatures regularly, or challenges transporting the NB to the site.
MW/Site	Megawatt	MW/site estimates the energy demand (heat and/or electricity) of the use case based on a literature review of similar cases.
Global Site Count	10, 100, 1000, 1000+	Global site count is the estimated number of sites where the outlined use case for NBs could be applicable under scaled conditions.
Energy Market	(MW/Site multiplied by Global Site Count)	Energy market metric estimates how many global MW of power NBs could fill under the proposed use cases at scale.
People Served	100, 1000, 10,000, 100,000, 1,000,000, 1,000,000+	People served estimates the number of people NBs could provide heat and/or electricity to, based on population and industry data relevant to use case locations from public sources and scientific literature. Defined as 100+, 1000+, etc.
Social Barriers	User Input	Social barriers include security concerns, social opposition, and justice and equity concerns
Ecological Concerns	User Input	Ecological concerns center around possible disruption to land, water, or wildlife, and biodiversity.
Financial Constraints	User Input	Financial constraints look into funding for deployment, scalability economics, financial competitiveness of alternatives, and financial benefits to the community.
Most Competitive Alternatives	Diesel/Wind/Solar/Other	Most competitive alternatives are the status quo in terms of the current dominant energy technology for a given use case, based on a literature review.

3.2. Framework Architecture

Twelve factors were taken into account in the framework:

The framework's conceptual architecture, depicted in Figure 1, categorizes relevant factors, which can be combined and analyzed to generate a feasibility score. The framework's effectiveness was assessed through the evaluation of various use cases. Initially, three members of the research team proposed 10–12 use cases each, along with relevant information such as the use case context, real-world example, MW/site, people served per site, number of global sites anticipated, and the global energy market. Use cases that required MW output closest to the output of 1–3 NBs were given priority, as were cases that served a larger population and had the potential for scaling across many sites. The use cases were then reviewed by the group to identify any similarities and eliminate cases with insufficient information or those that were deemed too experimental.

A shortlist of cases was systematically evaluated using the standardized framework. Priority was given to cases where NBs would replace polluting energy sources such as diesel generators. Population data from academic literature and official records were used to determine the scale of people served. Social and environmental concerns were gathered from relevant academic literature and local government websites. Logistics considerations such as installation urgency and deployment duration were also taken into account, including the feasibility of nuclear battery refueling and delivery in the event of a natural disaster. The evaluation process aimed to identify the most viable energy alternative for each use case.

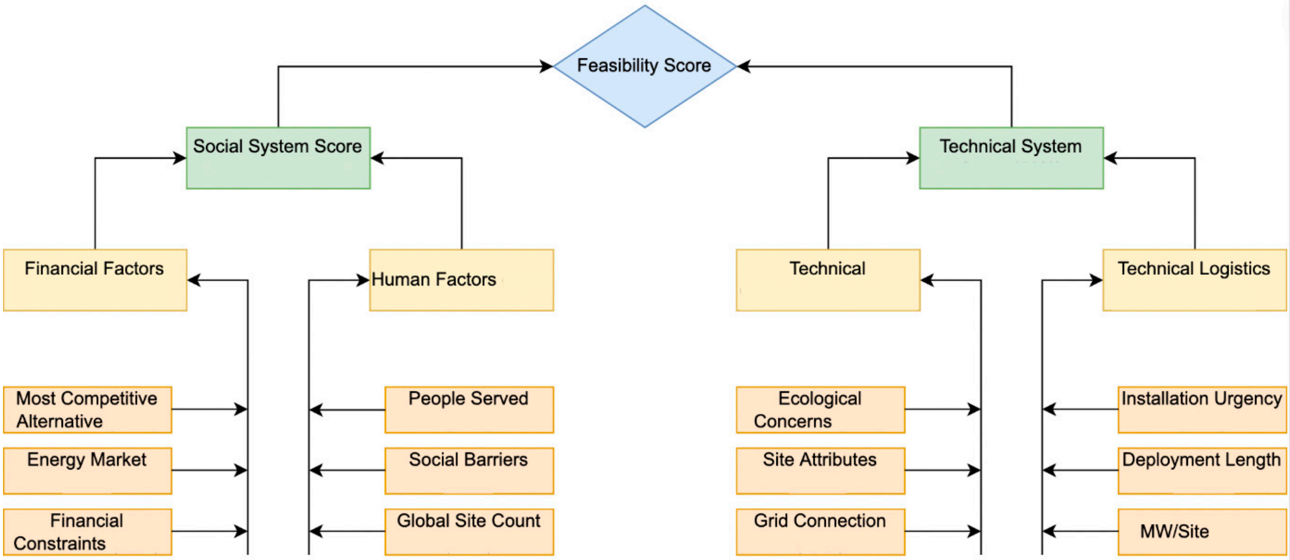

Figure 1. Evaluation Framework.

4. Use Cases

The following use cases focused on but not limited to the urban context, illustrate the breadth and depth of the potential impact of NBs. Each use case is technically feasible within the bounds of today's technology. The designs in this paper make the most of the technical qualities of these devices as clean, long-lasting, and energy-dense, as well as their formal characteristics as portable, replaceable, and small. The use cases locate NB-produced heat and electricity across sites that represent a spectrum of scales and contexts, but primarily center around urban or settlement-focused situations that are permanently or temporarily disconnected from the grid, or cases where temporary events would stress the grid. We also include use cases outside urban environments to provide insight into the applicability of this technology to different environments.

4.1. Construction

The construction industry takes up ~10% of the US GDP yet consumes only 1% of the electricity supply [35]. Out of 11 billion dollars spent on gas annually [36], USD 8 billion is spent on fuel to power mobile vehicles, while the other USD 3 billion is spent on static on-site equipment: concrete mixing stations, welding facilities, lighting, crane operations, and employee facilities. On average, 25% of the on-site energy is supplied through connections to the local grid, which burdens the domestic energy supply. The other 75% of the local energy supply is from portable diesel generators. The total energy consumption for various tools ranges from 7 kW for a single welding station or similar human-scale equipment to 244 kW for a large crane [37] and other heavy machinery, amounting to 10,400 kWh per year of operation.

Diesel generators are commonly exchanged between different construction sites, circulating in a closed market. In Canada, there are over 620,000 operable portable generators. Most of these construction diesel generators range from 1 to 225 kW [38]. The power costs of nuclear batteries can be on par with traditional diesel generators if installation costs and deployment length are optimized [36]. While the energy consumption rates per generator and relative size of typical diesel generators are comparable to nuclear batteries, the cost efficiency of the latter improves with longer deployment length and consumption scale. Despite challenges posed by the shorter deployment of most construction sites, NBs could become competitive on large construction sites, pooling equipment sources, as well as maintaining a resilient fleet of exchange of nuclear batteries between construction sites at various stages of development.

Besides the on-site construction equipment, mobile vehicles directly involved in on-site activities can be efficiently powered with nuclear energy, provided they rely on electric charging. Because construction vehicles do not typically leave the boundaries of the construction site, special fueling services are arranged for individual construction objects. Such fueling stations require a regular supply of diesel in tanks, which poses separate logistical and environmental concerns. EV recharging facilities can be additionally powered by nuclear batteries which can further increase the utilization factor of nuclear energy on-site. Considering the average for all types of heavy machinery equipment, it is estimated that the TCO (Total cost of ownership) for electric-powered machinery will be on par with the diesel alternatives around 2025 [39], which makes a strong case for nuclear electricity generators as charging stations.

The construction use case responds mainly to the following factors within our framework: deployment length (ranging in months, large construction sites consume a substantial amount of energy during a relatively short period), grid connection (it does not need to be connected to the surrounding grid), site attributes (especially for large construction sites distant from consolidated urban areas), MW/Site (NB can supply the required high energy usage for a relatively short period without stressing the grid), energy market (NB can be moved to other construction sites easily), and ecological concerns (often large construction sites rely on diesel, especially for the machinery, to avoid stressing the local grid).

4.2. Informal Settlements

Informal urban settlements, also derogatorily referred to as "slums", persist as cities in the Global South grow rapidly. In total, 23.9% of the world's population lives in informal settlements [40] and 759 million people did not have access to electricity in 2019. Thus, any solution needs to consider two of the factors in our framework: global site count, in the order of thousands, and people served, in the order of millions.

Due to the political and regulatory hurdles complicating the delivery of electricity grid to informal settlements, energy access is most successfully facilitated by a wide range of medium-scale local stakeholders, from resident groups, and cartels [41] to community groups and NGOs [42], while top-down options to connect to the expanded grid prove generally unaffordable, challenging to organize, and face the challenges of damaged or stolen equipment or inequitable access and demand [43].

Even in cases in which solar-based microgrids are a viable option, investors may lack the motivation to install them due to the uncertain prospect of getting access to the central grid at any time, as well as dealing with complex maintenance, security, and vandalism [42]. Here, we have other factors in our framework: site attributes, which might hinder traditional energy-supply solutions, grid connection and, while a permanent solution is not achieved, deployment length. The possibility to install nuclear batteries temporarily (3–10 years [44]) and relocate them later makes it possible to use them as a temporary "infill" solution for electricity-deprived areas while the national grid takes time to adapt to the rising demand, not burdened by high operating and equipment security costs and the prospect of potentially unused infrastructure. Moreover, Nuclear Batteries are better adapted to handle variable energy loads and energy storage issues. A security fence might be necessary depending on the site's location.

With a population estimate of 200,000 to 700,000 and an area of two square kilometers [43], Kibera is one of Africa's largest informal settlements. Despite relative proximity to downtown Nairobi's electricity grid, the upfront costs associated with connecting to the grid are unaffordable for the majority of residents. Alternative informal electricity suppliers provide undercover connections that are unstable, unsafe, and lead to major power disruptions in the main grid. Thus, charcoal and kerosene [40,43] are the main sources of fuel in Kibera, which are purchased and delivered in a decentralized manner—thus NBs should be assessed with competitive alternatives, which currently raise ecological and public health concerns.

Following the Nairobi Metro 2030 vision, the city is expected to expand its electricity infrastructure and energy grid [40]. With the influx of industry and population to the metropolitan area, the existing grid, already strained, faces increasing pressure. The Kenya Power and Lighting Company, a major actor in Nairobi's infrastructure space since 2007 [43], has been piloting subsidized connectivity programs and capping consumption per household at 40 kWh/month [45]. Community wishes and concerns about energy technologies [46] must be taken into account when applying the evaluation framework, as these use cases need community buy-in and enthusiasm to be realized.

4.3. Grid Resilience

The current intermittency issues with grid integration may hinder the large-scale adoption of renewable energy technologies [47]. Grid firming is a practice that addresses this by balancing the electric grid with other forms of stable energy to fill in the gaps [48], a practice relevant to both large-scale and microgrids.

The increasing frequency and intensity of natural disasters place additional stress on energy systems, affecting both energy demand and system resilience [49]. These consequences could be economically and socially costly for areas with high population densities such as cities [50]. The annual impact of weather-related blackouts in the United States has been estimated to be between USD 20 billion and USD 55 billion annually [51], although a single recent incident, the Texas cold snap, and resulting blackout, was estimated to cost USD 15–27 billion in direct economic costs alone [52]. Reliable sources of energy can power critical infrastructure in emergencies through a variety of strategies, one of which could be small modular reactors or even NBs.

Using nuclear batteries to support grid-firming is considerate of large-scale power outages, but NBs could also be used to provide power for neighborhoods that are affected by weather-related blackouts. When not used for emergency power, the NBs would need to be used for other applications to ensure a good lifecycle utilization of these assets. This use case responds to factors such as grid connection, MW/site (or variation in energy demand), and financial constraints (increasing energy generation at this scale requires work that might take several years with large spatial footprints).

The site considered for this application is an existing power generation facility, so social concerns about proximity to the nuclear battery are lower. Ecological concerns are minimal, as the NBs will be sited in an area already being used for energy generation. Further, nuclear batteries are expected to be cost-competitive with industrial diesel generators, when used with a high-capacity factor, and have the added benefit of not contributing to greenhouse gas emissions or poor air quality.

During the Texas 2021 cold snap, 26,000 MW of electricity load was wiped off the grid [52], with millions of people losing power and over 240 dying as a direct or indirect result [53,54]. This incident presented an unusually dire energy situation as the overall problem was not downed power lines or other issues common in storms, but rather that every power generation source contributing to the energy mix on Texas' grid was underperforming in the cold due to poor winterization [55]. Like other energy sources that Texas was reliant upon—primarily natural gas, but also including coal and wind—nuclear also underperformed during the storm, but this was partially due to one of four nuclear reactors going offline due to a feedwater pump issue. Nuclear batteries do not rely on water as a coolant or working fluid in their operation [55].

4.4. Emergency Refuge

As natural disasters increase in frequency and intensity due to climate change, there is an increased risk of population displacement [56]. In total, 916,000 people were displaced by disasters in the US alone in 2019. Sports stadiums, conference centers, and other large buildings have been used to provide shelter to populations immediately impacted by these events. These structures are often located in downtown areas, and emergency shelters need to be easily accessible [57]. Stadiums and convention centers will also typically have large parking lots, which could be good sites for nuclear battery installation—and respond directly to the factor's installation urgency (it must happen in matters of hours, of days) and deployment length (NBs are needed during the critical phase, before the grid is rebuilt).

In the wake of natural disasters, the power source for a shelter facility needs to be robust as it faces environmental security challenges, including but not limited to emergencies such as ongoing earthquake aftershocks, flooding, fires, deep snow, extreme heat, or other dangerous weather conditions. The power demands vary, but sports stadiums on game days may use up to 10 MW. Convention centers use a lower amount of power per day but are continuously used. The Pennsylvania Convention Center in Philadelphia reported using roughly 24,000,000 kWh of electricity over the course of 2019, which would equate to roughly 2.7 MWh of continuous operation.

Stadiums, conference centers, and similar facilities tend to be in commercial districts surrounded by large parking lots or in open spaces outside the city, so the social concerns may not be as severe as if within dense residential areas. Ecological concerns are minimal since nuclear batteries are emission-free with a container-size footprint and are equipped with radiation shielding. It is possible that for both general and environmental security reasons, such as protection from debris dislodged by strong winds, flooding, and more, these nuclear batteries could be embedded below grade.

Financial constraints associated with this use case could be mitigated by federal, state, or private funding. For instance, in the United States, the Disaster Relief Fund (DRF) is a congressional budget overseen by the Federal Emergency Management Agency (FEMA), but it is not designed for resilience, only response [58]. FEMA also has grants for disaster preparedness but seems more driven toward research than toward infrastructure installation [56].

In the wake of Hurricane Katrina's impact on the United States Gulf Coast in, 2005, the New Orleans Superdome became a refuge of last resort. During the hurricane, the Superdome was running on its backup generator within one day of the storm making landfall, over the course of 5 days, 27–31 August 2005. While thousands of people were saved by taking refuge inside it, conditions were awful—there was no running water, not enough light, and no air conditioning—partially because of energy limitations as the facility was operating on its backup generator. This generator also had to be refueled with oil during the emergency, which was especially challenging to access due to floodwaters. In this instance, nuclear batteries which can be deployed in days, possibly less than a day if the system is delivered fully functional and pre-assembled on a barge or container, would have been able to provide more energy without refueling, thereby improving the conditions and stability of an emergency substantially.

4.5. Industrial Power

Roughly a quarter of global greenhouse gas emissions are induced by the industrial sector [59], which is primarily powered by coal and natural gas. The interdependence between power-hungry industrial facilities and the fossil fuel industry represents a serious challenge to overcome for the desired energy transition [60]. It also complicates the logistics of factory constructions that have to be situated closer to large-scale, expensive power plants or initiate the long-term construction of new energy grids and power sources. This geographic co-dependence is further aggravated in remote or sparsely populated areas with few prominent industries, such as aluminum production and hydropower in Iceland [61]—while aluminum can be produced with carbon-free electricity, the scalability of the process is limited by geographical constraints. As heavy industries are tied to major power sources and not to major nodes of supply or transportation, the additional logistical expenses further aggravate their carbon impact.

In steel making, a key part of the process is to use a coal-fired blast furnace to strip oxygen from iron ore, creating a product called pig iron that is then turned into steel in an electric arc furnace. The blast furnace stage can be replaced by an electrolysis process, similar to the process used to make aluminum. There are early attempts to decarbonize steel production with other renewable energy sources that face challenges of scale and deployment. [62] Nucor's Sedalia micro-mill, the world's first wind-powered steel factory, consumes 55 MW of power and has required the establishment of a USD 250 million wind farm in Kansas that transfers electricity to Nucor's mill in Missouri [63]. The costs of coordinating and co-locating two infrastructure projects, the uncertainty of wind power output, and the construction schedule can be alleviated with only six 10-MW nuclear batteries capable of powering a similar-scale plant for several years, within several days from deployment. The constant high-volume demand for energy characteristic of heavy industrial plants can take full advantage of energy-intensive and compact nuclear and thus tackle the initial high installation costs.

In addition to decarbonizing conventional carbon-heavy industries, nuclear batteries can effectively power novel "green heavy industries". One of the prospective applications is the joint installation of nuclear batteries with hydrogen facilities. Like nuclear batteries, hydrogen power plants are actively investigated as novel energy sources for heavy industries [64]. However, the operation of a hydrogen plant itself necessitates a significant energy input which brings installation challenges similar to those of conventional plants, but progress is being made—in Denmark, a green hydrogen testing plant is being powered by a 3 MW wind turbine [65]. The compactness and speed of installation of nuclear batteries can allow the deployment of such hydrogen production facilities far beyond the regions with abundant renewable energy supplies.

Nuclear batteries' introduction to the heavy industry sector may be particularly promising due to lower pressure from social and environmental concerns. The air quality and other health impacts of heavy industrial facilities, and their high land and infrastructure footprint significantly outnumber the technical challenges associated with nuclear microreactors and may be reduced with the introduction of compact, reliable, carbon-free energy sources like nuclear batteries.

4.6. Remote Communities

Remote communities often face barriers to electricity access. In 2020, ~800 million people remained without access to electricity [66], with roughly 84% residing in rural areas [67]. Remote communities typically have microgrid power systems ranging from 200 kW to 5 megawatts (MW). "Last-mile electrification" is an exceedingly complex challenge for electricity providers to overcome, spanning regulatory, policy, and technological aspects. Remote and rural communities worldwide often rely on diesel generators or other polluting sources to generate electricity and heat [68]. A business-as-usual approach is unlikely to improve electrification rates significantly.

Electricity access has traditionally been pursued through grid expansion programs [69], which may not account for unique factors and limitations present in rural or remote communities [67]. Alternate technological frameworks such as mini- or micro-grids, solar home systems, or diesel generators may better fit into the needs of a remote community. However, communities primarily powered by diesel generators are susceptible to supply chain disruptions for their primary power source, as well as fuel price volatility [70]. Additionally, there is an urgent need to reduce carbon emissions in grids that rely on coal, oil, and natural gas. This need, coupled with the rapidly decreasing costs of renewable and carbon-free electricity, the necessity of high reliability in remote locations, and the difficulty of expanding centralized grid infrastructure to remote locations favor a distributed generation approach [71].

Rural communities in Canada, home to over 6.5 million people [72] are not situated close enough to each other or other large towns to warrant a connected electrical grid. In Canada, 70% of remote communities rely on diesel generators to produce electricity, 13% on hydro, and 17% use a combination of other fossil fuels [73]. In Nunavut, which forms much of the Canadian Arctic Archipelago, there are ~26 remote communities, representing a total population of around 20,000 people [72]. All of Nunavut's off-grid communities run on diesel power, requiring about 55,000,000 L of diesel per year for an electrical capacity of about 78 MW in total [74]. Nunavut consumes the least total energy of any of Canada's provinces, and its per capita energy demands are also the smallest [74], but it is routinely exposed to the risks of fuel transport: over the last five years, Nunavut has experienced at least 549 fuel spills, averaging a spill almost every three days [75].

Replacing diesel with NBs in Nunavut's fuel infrastructure could deliver major benefits at a minor conversion cost: the existing trucks and vessels that transport Nunavut's 55 million liters of fuel each year could be retrofitted to carry shipping-container-sized NBs, and bulk fuel facilities, or "tank farms", could be converted to NB storage or exchange centers. Almost every town in Nunavut could be sustained with only a 5 MW NB; the only exception is the territory's capital Iqaluit, which could be served by a set of NBs adding up to 20 MW [76]. This change would minimize the risk of fuel spills and diminish the overall stress on Nunavut's endangered Arctic ecoregion by replacing a months-long season of intensive fuel transport every year with NB exchange operations every 5 to 10 years. A reduced number of diesel generators may need to be retained as a contingency plan in the unlikely event of NB failure.

5. Conclusions

Nuclear Batteries offer a potential solution to the limitations posed by the politics of energy investment and regulation on traditional nuclear power plants, enabling more efficient and manageable modes of construction, distribution, and management. However, significant regulatory uncertainty remains about several aspects of NBs and their deployment. The scarcity of operational data presents a significant barrier to regulatory assessments in the area, especially given the vast number of environments in which NBs can function, including urban environments, where special licensing considerations may be needed, and remote areas, where NBs will largely be operating autonomously. Another key consideration is shipment, including whether to ship NBs with fuel or transport them separately, which requires insight into transportation limitations and requirements, as well as the implementation of processes around delivery, audit, and storage. Answering these questions is critical to suitably addressing considerations around refueling, a key aspect of NBs' unique value proposition as an energy source.

Considerations also remain for the upfront costs of NB fabrication and deployment, and pathways to reduce cost through factory fabrication to allow the technology to scale, which further merits exploration of business models for commercialization in domestic and international markets [77].

Lastly, ensuring the security of NB energy sources and any necessary safeguards for the technology is crucial. While physical safety is an essential component of NB design (including a robust fuel-reactor package, the possibility of remote monitoring, and the lack of possibility of runaway reactions), cybersecurity measures and attention to physical damage to the NB containers must be implemented [77].

The use cases presented in this paper demonstrate the persuasive ability of NBs not only to wedge themselves into existing energy uses but also to drive strategies for multimodal environmentally sustainable infrastructure in the urban sphere. The use cases discussed here were selected based on a twelve-factor framework we propose as a guideline to assess situations in which the implementation of nuclear batteries presents clear advantages over currently used alternatives. Unlike traditional nuclear power plants, which demand the configuration of cumbersome policies and financial structures around their needs, NBs embody a new paradigm of energy adaptability, potentially not only lightening the political burden of clean energy integration but also creating new opportunities for the emergence of unconventional hybrid development between infrastructure and industry. We illustrate their relevance to climate change mitigation and adaptation, in the form of designs for their use in humanitarian relief and remote settlements. Finally, we reveal the advantages of NBs over those technologies in terms of energy density and relative ecological unobtrusiveness, being an alternative to outdated systems whose drawbacks have historically prevented nuclear energy from making its full potential contribution to global decarbonization.

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