Enhancing the environmental sustainability of emergency humanitarian medical cold chains with renewable energy sources

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Abstract

Purpose – Emergency humanitarian medical cold chains (HMCCs) depend heavily on their supporting energy services due to end-to-end temperature requirements in volatile disaster situations. Most energy sources powering emergency HMCCs are fossil-based due to well established processes, regardless of their environmental impact. In response to the recent energy crisis and climate change, a solution to tackle this issue relies on renewable energy sources (RES), whose use has increased to promote climate resilient development. Nevertheless, RESs' capacity to replace conventional energy services in emergency HMCCs remains poorly understood. This study aims to investigate opportunities for, and barriers to, increasing the use of RESs in emergency HMCCs, thereby enhancing their environmental sustainability.

Design/methodology/approach – Based on a review of academic and practice literature, interviews with expert practitioners on emergency HMCCs and sustainable energy, and case study examples, this research aimed to analytically generalise the phenomenon by investigating opportunities for, and barriers to, increasing the use of RESs in emergency HMCCs. The phenomenon is illustrated in a novel framework of typical HMCC, that forms a contextual basis for future research.

Findings – A conceptual framework of typical emergency HMCC shows energy-consuming sections where RES can best be increased. This research is put forth in four propositions to manage the opportunities and barriers of the transition.

Originality/value – This research is, to the best of the author's knowledge, the first attempt to operationalise sustainability by linking energy with HMCCs' logistical activities in complex emergency settings. The cross-findings from literature, example cases and interviews together demonstrate the need to increase the use of RES in HMCCs, and how to do it.

Keywords Cold chain, Humanitarian logistics, Emergency response, Sustainable supply chain, Renewable energy, Humanitarian energy

Paper type Research paper

1. Introduction

The provision of renewable energy sources (RES) is increasing in global supply chains' energy solutions to promote climate resilient development in response to recent energy crisis and climate change risks (IPCC – Intergovernmental Panel on Climate Change, 2022; World Economic Forum, 2022). The current trends in the energy sector towards electrification, increased use of RES and more local energy sourcing is also a pressing issue for humanitarian organisations (HOs) (Frennesson *et al.*, 2021; Thomas *et al.*, 2021). During emergency humanitarian aid operations, humanitarian medical cold chain (HMCC) items are among the most critical supplies delivered (Comes *et al.*, 2018; Dolinskaya *et al.*, 2018). In disaster situations, the reliability of energy services supporting HMCCs is critical because access to energy services becomes more erratic or scarce and the cold chain infrastructure is limited, if it exists at all (Comes *et al.*, 2018; Grafham and Lahn, 2018; Babatunde *et al.*, 2020). To address this, HOs often follow manuals and guidelines to design an efficient HMCC. To date, these continue to favour fossil fuel-centric energy services, despite them being environmentally unsustainable (Grafham and Lahn, 2018), rigid (UNICEF – United Nations Children's Fund, 2022), unreliable (Grafham and Lahn, 2018; UNICEF – United Nations Children's Fund, 2022) and expensive (Dolinskaya *et al.*, 2018; Jusu *et al.*, 2018).

Environmentally sustainable energy services are, so far, scarcely addressed in academic literature despite the importance of using clean energy services in emergency HMCCs to address the risks in relation to sustainability and cold chain infrastructure disturbances (Comes *et al.*, 2018; Dolinskaya *et al.*, 2018; Thomas *et al.*, 2021; The World Economic Forum, 2021; The

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New Humanitarian, 2022). In spite of the recent interest in humanitarian energy (Rosenberg-Jansen, 2022), the limited research on RESs in HMCCs has primarily focused on improving HMCCs' efficiency (Babatunde *et al.*, 2020), particularly on strategic level optimisation (De Boeck *et al.*, 2020), leaving environmental sustainability as a secondary output (Jusu *et al.*, 2018) and lacking the emergency context (McCarney *et al.*, 2013; Lloyd *et al.*, 2015). As energy is the number-one contributor to climate change (UNDP – United Nations Development Programme, 2021), the energy dependence of emergency HMCCs and the large share of fossil fuel to power them is crucial. Moreover, rigid fossil fuel-centric energy services in emergency HMCCs are jeopardising the number of saved lives and the continuity of sustainable health programs in the aftermath of the disasters (OCHA - United Nations Office for the Coordination of Humanitarian Affairs, 2010; UNICEF – United Nations Children's Fund, 2021b).

This paper aims to elucidate where RES can be increased in emergency HMCCs as a means to enhance environmental sustainability, and what the opportunities for and barriers to it are. It focuses on storage activities in- and off-transit in downstream emergency HMCCs, which have been identified energy-wise as the most challenging parts of managing emergency HMCCs during sudden-onset disasters, thereby excluding, for instance, the energy needed to fuel vehicles and upstream HMCC activities. To address the aim of the paper, two research questions (RQs) were formed:

RQ1. What energy sources power emergency HMCCs?

RQ2. What are opportunities for, and barriers to, increasing the use of RESs in emergency HMCCs?

Based on a review of academic and practice literature, interviews from practitioners and case examples, this research aims to analytically generalise the phenomenon. The phenomenon is illustrated in a novel framework of typical emergency HMCC that forms a contextual basis for future research on the topic. Based on the results and findings from academic and applied literature, this research offers four propositions presented at the end. Subsequently, Section 2 of the paper reviews relevant literature, after which Section 3 describes the research design. The results of the analysis are presented in Section 4, and situated within the literature in Section 5, including the propositions. In closing, Section 6 summarises major conclusions, highlights their practical implications and limitations and recommends directions for future research.

2. Frame of reference

2.1 Humanitarian medical cold chains

An emergency aid relief operation is an *ad hoc* response to a disaster caused by a natural phenomenon (e.g. earthquake and hurricane) or a man-made disaster (e.g. terrorist attack) (van Wassenhove, 2006; Mackay *et al.*, 2019). Each operation differs, however, in how the relationship between the disaster's factors and the country profile impacts the supply chain design in three disaster management phases (Mackay *et al.*, 2019): preparation, immediate response and reconstruction (Lee and Zbinden, 2003; Kovács and Spens, 2007). Following a sudden-onset disaster, emergency medical assistance is vital for victims' survival and continues to be critical during reconstruction (Dolinskaya *et al.*, 2018; Mackay *et al.*, 2019). During relief operations, non-perishable medical items, such as field health clinics and protective clothing (Dolinskaya *et al.*, 2018), as well as supplies, such as drugs and vaccines that require storage at cool temperatures, are delivered (van Damme *et al.*, 2002; Syahrir *et al.*, 2015; Dolinskaya *et al.*, 2018).

Cold chains are temperature-controlled, end-to-end networks of actors, processes and equipment (e.g. refrigerators, cold stores, cold boxes and freezers) needed during transportation and storage activities to keep cold chain items at required temperatures from their manufacture until they reach beneficiaries (Logistics Cluster, 2021). Temperatures required can range from +2°C to +8°C, –15°C to –25°C (Logistics Cluster, 2021) or even –60°C to –90°C (Jusu *et al.*, 2018; WHO - World Health Organization, 2020). Maintaining such temperatures is challenging even in stable environments (Robertson *et al.*, 2017; Logistics Cluster, 2021), but it becomes more exacting in disaster settings when the electricity supply is irregular, access to energy sources is restricted or secure cold chain infrastructure is unavailable (Comes *et al.*, 2018). Any disruption can reduce the HMCC items' effectiveness due to heating or freezing (Logistics Cluster, 2021), thus jeopardising the inventory and increasing the amount of waste (Comes *et al.*, 2018). The information flow between responsible actors, including manufacturers, wholesalers, international HOs, smaller relief organisations, third-party transportation and logistical service providers, governments, donors and beneficiaries, is crucial to ensure an unbroken HMCC (Dolinskaya *et al.*, 2018). Those actors are responsible for cold chain management. They use either active methods, which rely on power grids or a mechanical system powered by generators using petroleum, diesel or kerosene or by solar panels (Logistics Cluster, 2021). Alternatively, they rely on passive methods, in which cold temperatures are maintained by coolants or ice packs placed inside cold boxes or smaller carriers (Logistics Cluster, 2021).

HOs typically procure needed medical items from manufacturers or wholesalers, who ship them to central warehouses for storage in large, cool rooms (PAHO and WHO – Pan American Health Organization and World Health Organization, 2001; Dolinskaya *et al.*, 2018). When a disaster strikes, the needed medical supplies are collected and packed into cold boxes with ice or coolant packs from the central warehouse by the HO or its supplier (PAHO and WHO – Pan American Health Organization and World Health Organization, 2001; Comes *et al.*, 2018; Dolinskaya *et al.*, 2018). In addition, refrigerators, freezers and generators are deployed by air if equipment or stable energy service is unavailable in the disaster area (Comes *et al.*, 2018; Dolinskaya *et al.*, 2018).

Once the entry point into a country is reached, customs formalities are performed by national government agencies who manage emergency consignments' in-country distribution (Kunz and Reiner, 2016; Dolinskaya *et al.*, 2018). However, the nature of the emergency often requires assistance from international and local HOs, as well (van Wassenhove, 2006; Dolinskaya *et al.*, 2018). At the entry point, cold boxes can be exposed to ambient temperatures during unloading and customs procedures (PAHO and WHO – Pan American Health Organization and World Health Organization, 2001).

Those processes can pose a significant bottleneck, and during which items can be left on the tarmac for hours, if not days (Kunz and Reiner, 2016). Typically, cold boxes retain cold for only 48 to 96 h (Logistics Cluster, 2021), and without a stable energy source for back up, the risk of cold chain breaches increases (Comes *et al.*, 2018; Dolinskaya *et al.*, 2018). From the entry point, items are transported to regional or national warehouses in cold boxes or refrigerated trucks if available, after which they are delivered to smaller, impromptu temporary storage units closer to beneficiaries (Comes *et al.*, 2018). In this process, the potentially poor conditions of in-country cold chain infrastructure significantly elevate the risk of cold chain disruptions (Dolinskaya *et al.*, 2018).

The logistical activities, stakeholders and feasible energy sources powering cold chains are interlinked; influencing one another in decision-making and the operationalisation of effective cold chain management (Dolinskaya *et al.*, 2018). The relationships of actors, activities and resources modelled by Håkansson and Snehota (1995, p. 35) imply that each unit depends on the others and that a change in any aspect of those interrelationships effects the overall balance of the whole – cold chain management. A typical emergency HMCC depicting logistical activities powered by energy and managed by actors is summarised in Figure 1.

2.2 Environmental sustainability of humanitarian medical cold chains

To efficiently balance the management of cold chains, several performance measures influence decision-making in each phase of disaster management (Mackay *et al.*, 2019) to find an optimal cold chain design (De Boeck *et al.*, 2020). Such are, for instance, cost-effectiveness (Haavisto and Kovács, 2014, 2019), response time, number of items supplied or delivery flexibility (Beamon and Balcik, 2008). However, environmental sustainability remains rare among factors evaluated in the short- or long-term objectives of emergency HMCCs (Dolinskaya *et al.*, 2018; Haavisto and Kovács, 2019; Bag *et al.*, 2020). Whether environmental sustainability should even be considered in emergency HMCCs remains debatable, as the primary focus is operational efficiency to save lives (van Damme *et al.*, 2002; Haavisto and Kovács, 2019). For instance, Privett and Gonsalvez (2014) identified 10 key challenges in health supply chains but factored out environmental sustainability. The environmental sustainability is, nevertheless, significant for HMCCs; it is both the responsibility of HOs to reduce carbon emissions from their operations and to help to rebuild the affected area sustainably (Gibert, 2008; Haavisto and Kovács, 2019; Sarkis, 2021). In addition, environmentally sustainable HMCCs can address the constraints those delicate chains need to tackle, thus promoting resilience (UNICEF – United Nations Children's Fund, 2021b).

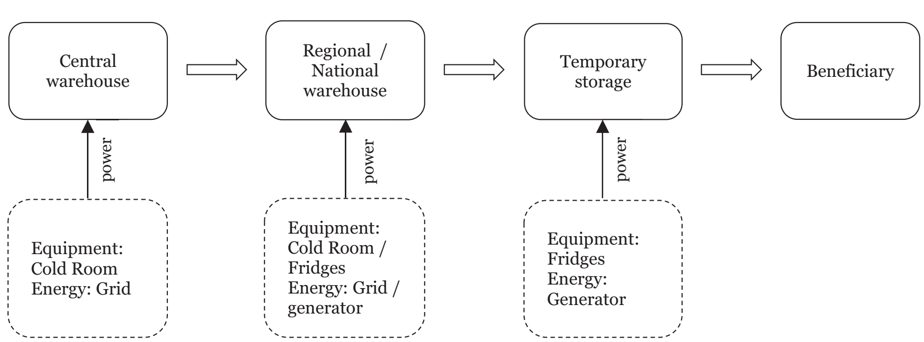
The do-no-harm principle requires collective responsibility and effective collaboration should be pursued by humanitarian actors (Khaled, 2021). For this purpose, Bag *et al.* (2020) have proposed a holistic framework capturing how enablers and their interrelationships for green humanitarian supply chain management are weighed at different levels to achieve sustainable, resilient humanitarian supply chains. Green practices and using scarce resources effectively in preparation for, and response to, disasters can considerably enhance environmental sustainability (Gibert, 2008; Bag *et al.*, 2020). The current transition towards low-carbon economies promotes increasing energy efficiency and using RESs, as strongly advocated and legislated in commerce (European Commission, 2021). Decarbonising HMCCs in emergencies using cleaner energy solutions is, however, still in its infancy (Zarei *et al.*, 2019), although it benefits the global environment, as well as societies and economies in the long-term (Halldórsson and Kovács, 2010; Bag *et al.*, 2020; Sarkis, 2021; UNICEF – United Nations Children's Fund, 2021b).

2.3 Energy services in humanitarian medical cold chains

HMCCs depend heavily on their supporting energy services, of which access is often limited in disaster settings (Grafham and Lahn, 2018). As a concept, energy service can be ambiguous (Halldórsson and Kovács, 2010; Fell, 2017), and the peer-reviewed work and understanding on humanitarian energy is divergent and shallow to date (Thomas *et al.*, 2021; Rosenberg-Jansen, 2022). Following Fell's (2017) taxonomy on energy services, the term refers to functions performed (e.g. refrigeration) that use energy (e.g. diesel-generator) to achieve an end state such as storage. On that note, Centobelli *et al.* (2017) proposed a framework for green initiatives to enhance the environmental sustainability of logistics services by achieving a green aim (e.g. using RESs) by first adopting a green practice (e.g. supplying alternative energy sources) with supporting technological tools (e.g. emissions control systems).

To date, fossil fuels dominate in global energy systems (World Economic Forum, 2022), including in humanitarian energy services (Sandwell *et al.*, 2021; Rosenberg-Jansen, 2022).

Figure 1 Simplified emergency HMCC



However, fossil fuel-based energy is prone to price fluctuations, and the resources are limited (Halldórsson and Svanberg, 2013; Salzenstein and Pedersen, 2021; World Economic Forum, 2022). Currently, without a reliable grid network, the dominant solutions in emergency HMCCs involve the intense use of fossil fuel-based generators (Sandwell *et al.*, 2021; Thomas *et al.*, 2021) even if they are costly and expose the environment to degradation (OCHA – United Nations Office for the Coordination of Humanitarian Affairs, 2010; Haavisto and Kovács, 2019). However, emergency HMCCs' high dependence on fossil fuel generators threatens their resilience, as the dependency on a constant diesel supply is expensive and not always feasibly available (Syahrir *et al.*, 2015; Sandwell *et al.*, 2021).

2.4 Renewable energy sources in humanitarian medical cold chains

RES include wind, marine, solar, hydro, geothermal or bioenergy resources (UN – United Nations, 2022). In emergency HMCCs, the most prevalent RES is solar power (Adair-Rohani *et al.*, 2013; Comes *et al.*, 2018), as many sudden-onset disasters occur in countries with sunny environments (OCHA - United Nations Office for the Coordination of Humanitarian Affairs, 2017) and photovoltaic technology has been developed since the 1980s (McCarney *et al.*, 2013). Alternative solutions include using wind energy in remote locations to create electricity via wind turbines (Panwar *et al.*, 2011; WFP - World Food Programme, 2017) or using hydro-powered energy solutions (ESCOM – Electricity Supply Corporation of Malawi Limited [ESCOM], 2015). Nevertheless, to match a country's contexts and needs, one solution independently is often not secure enough; thus, several solutions are needed in parallel (Olatomiwa, 2016; Olatomiwa *et al.*, 2018; UNICEF – United Nations Children's Fund, 2021b).

With solar energy, more people have safe access to health services, especially in rural areas (UNICEF – United Nations Children's Fund, 2021b). Also, the benefits of solar energy include more power generated than refrigerators and freezers need for functioning, and the surplus power can be used for other purposes, including charging laptops and phones or powering fans and lighting – all of which are crucial during emergency situations (GAVI – The Vaccine Alliance, 2020). Harvesting excess energy can remarkably enhance off-grid health clinics' long-term operations and capabilities (GAVI – The Vaccine Alliance, 2020; Thomas *et al.*, 2021). However, often the lack of funding limits the technical expertise needed to implement sustainable energy solutions and train humanitarian logisticians and local staff to use them properly (McCarney *et al.*, 2013; Dolinskaya *et al.*, 2018). In response to disruptions emergency HMCCs face when using conventional energy services, the provision of RES used in HMCCs has started to gain the needed attention in practice (MSF – Médecins Sans Frontières, 2020; UNICEF – United Nations Children's Fund, 2021b). Table 1 collects examples of logistical challenges HMCCs have faced and responded to with RES.

3. Research design

Following an abductive research process proposed by Kovács and Spens (2005) in logistics research, academic and practitioner literature was reviewed to develop a conceptual framework for understanding actors, activities and energy sources used in emergency HMCCs. Aiming for analytic generalisation, qualitative, in-depth data via semi-structured interviews and selected case examples from practice was collected and reviewed to validate the framework and to better understand the interplay of environmental sustainability between the links of energy sources and logistical activities (Yin, 2013). Since the focus of this research is extremely narrow, in-depth empirical data connected to the literature and case examples in the real world leads to a stronger understanding and interpretation of the phenomenon, which can be further replicated and tested (Yin, 2013).

3.1 Sampling and data collection

The empirical evidence was primarily collected through key informant sampling and, later, snowball sampling (Patton, 2015; Saunders *et al.*, 2016) with practitioners, managers and specialists in the humanitarian sector. Interviewees were also asked to suggest other individuals with special expertise in the research niche. The informants were contacted and selected based on their unique and special knowledge and experience in cold chain management, supply chain management or sustainable energy use in humanitarian contexts. In total, ten semi-structured interviews were conducted, each lasting between 30 and 60 min, with representatives of different international and national HOs. Due to anonymity-related requirements, neither the names of the organisations nor of the informants are disclosed. The empirical data was collected between October 2019 and June 2021. Three of the interviewees were working in academia at the time of the interviews. However, their professional experience included prior practical work on the topic.

Semi-structured interviews were chosen due to the narrow research topic and limited academic literature on the given focus, as well as to flexibly collect reliable data. Interviews followed an interview guide that left room for open-ended questions and applied an abductive strategy, which allows researchers to investigate the phenomenon under investigation according to predetermined themes. Simultaneously, this allowed informants to elaborate on their experiences and knowledge concerning cold chain management in emergency settings and its sustainability, thereby allowing new potential interactions to emerge (Kovács and Spens, 2005; Saunders *et al.*, 2016). The interview guide was based on the frame of reference on HMCCs in emergency settings regarding actors, activities and energy sources and developed by interlinking theory of supply chain sustainability with knowledge of energy sources and logistical activities. The four interviews conducted in 2021 were more structured as themes had emerged from prior collected data and allowed targeted data collection by focusing on themes. Also, the preliminary framework of typical emergency HMCC was shown to and discussed with the four interviewees. During the interviews, extensive notes were taken. The interviews were recorded and transcribed verbatim. In addition to the semi-structured interviews, secondary data from guides and handbooks for cold chain management published by leading HOs in the field was used for the purpose of this research. The details of the data collection appear in Table 2.

Table 1 Case examples of HMCC challenges

Organisation	Year	Country	Challenges	Response	Source
UNICEF	2022	Nepal	Challenging terrain and poor road access Unreliable electricity due to extreme weather conditions	Installing solar-powered vaccine refrigerator	UNICEF – United Nations Children's Fund (2022)
COVAX	2022	World	Rapid, country-tailored end-to-end cold chain solutions Logistical challenges due to global transport disruptions Funding to install extensive cold chain capacities to store millions of COVID-19 vaccines in a limited time frame, including electric power stabilisation, backup power supply	Creating and implementing data and information dashboards Cross-organisational cooperation Future investing in health-care services, including end-to-end cold chain infrastructure	COVAX (2022)
UNICEF	2021	Malawi	Power outages Excess dependency on back up power from diesel generators Growing need for energy to growing population Water insecurity within hydro-powered energy solutions National electric grid extension to remote areas is slow and expensive Inadequate financial sustainability and supply chain models to support operations and maintenance in energy demands	Decentralised renewable energy solutions, namely solar energy solutions Long-term and sustainable cooperation with private and public energy partnerships	UNICEF – United Nations Children's Fund (2021b)
World Bank	2020	Yemen	Long-lasting power outages Lack of transport options Fuel shortages	Solar systems installed in health facilities in rural areas	World Bank (2020)
MSF	2020	Democratic Republic of Congo	Scattered population Rough terrain Difficulty of transporting fuel Costly fuel transportation	Powering hospitals on solar energy, and installing solar power storage units	MSF – Médecins Sans Frontières (2020)

Table 2. Data collection

Interviews		
Respondent	Position	Date
1	Manager of supply chain with experience in the field	21.10.2019
2	Supply manager with experience in the field	29.10.2019
3	Heading a logistical unit with experience in the field	29.10.2019
4	Head of Mission and General Manager	3.6.2021
5	Technical support to medical cold chains with experience in the field	29.10.2019
6	Supplies' officer with focus on cold chain and health with experience in the field	8.11.2019
7	Officer working in the area of cold chain with experience in the field	20.11.2019
8	Cold Chain Specialist with experience in the field	14.6.2021
9	Expert in sustainable energy in humanitarian operations	7.6.2021
10	Expert in sustainable energy in humanitarian operations	14.6.2021
Written documents		
Code	Name of the document	Publisher
A	Cold chain equipment technology guide	GAVI – The Vaccine Alliance (2020)
B	Global Shelter Cluster Meeting 2019 ECoP Session on Energy	Global Shelter Cluster (2019)
C	Immunization in Practice – A practical guide for health staff	WHO (2015)
D	Introducing solar-powered vaccine refrigerators and freezer systems. A guide for managers in national immunization programmes	WHO and UNICEF – World Health Organization and United Nations Children's Fund (2015)
E	Vaccine management Handbook	WHO (2022)
F	Solar direct-drive vaccine refrigerators and freezers: evidence brief	WHO and UNICEF – World Health Organization and United Nations Children's Fund (2017)

3.2 Data analysis

Following the Gioia method for structuring data (Gioia and Chittipeddi, 1991; Corley and Gioia, 2004; Gioia *et al.*, 2013), the content was colour-coded into 18 codes (Spiggle, 1994) that referred to actors, activities or energy sources. Informant-centric terms (first-order concepts) were then categorised under researcher-centric concepts (second-order themes) using the 18 code colour scheme from the literature. Four aggregated dimensions, namely, resources, awareness, infrastructure and prerequisites were identified. This allowed some conclusions to be drawn regarding the link between energy services and logistical activities to operationalise enhanced sustainability according to energy source, and to investigate opportunities for, and barriers to, increasing the proportional use of RESs versus fossil fuels. Table 3 shows the data structure used during the analysis.

3.3 Research quality

To ensure high research quality and to avoid selective interpretations, triangulation was conducted by selecting a range of informants and complementing the empirical data with the analysis of written documents (Halldórsson and Aastrup, 2003). Because the interview guide was grounded on a literature review and because the interviews helped to analyse the interplay of environmental sustainability between energy and logistical activity in emergency HMCCs, the qualitative data's trustworthiness was evaluated according to four criteria, suggested by Halldórsson and Aastrup (2003): credibility, transferability, dependability and confirmability. Credibility means accepting that reality is constructed and interpreted by individuals (Halldórsson and Aastrup, 2003). Therefore, the researcher's findings were discussed, and informants were asked probing questions to ensure correct understanding of the context.

The second criterion; transferability or the general application of the findings, requires data richness (Halldórsson and Aastrup, 2003), which was ensured by conducting multiple interviews to construct a conceptual diagram of emergency HMCCs' typical actors, activities and energy sources (Figure 2) and to identify opportunities for, and barriers to, enhancing sustainability due to the increased use of RESs. Although the number of informants threatened to limit the findings' generalisability, similarities in processes of emergency HMCC management in the three mentioned phases can be pinpointed because, though each emergency scenario is unique, the HMCC management tends to follow certain guidelines and processes (van Wassenhove, 2006; Mackay *et al.*, 2019). Moreover, this research aimed for analytic generalisation, which is founded on in-depth knowledge creation rather than numeric one (Yin, 2013). The third criterion; dependability, was ensured by keeping detailed records of the research process and methodological decisions (Halldórsson and Aastrup, 2003). Finally, to avoid biased interpretations, the conformability was ensured by comparing the findings to those in the literature (Halldórsson and Aastrup, 2003).

4. Results

The interviewees acknowledged that, although emergency HMCC items are highly valuable given their costliness and efficacy, their proportion among all relief items is small. Nevertheless, urgency and pressure during emergencies complicate the management of cold chain items that are vulnerable to temperature, which, in turn, puts pressure on the supporting energy services. Meanwhile, the complexity of actors, activities and energy sources only increases the more uncertain and volatile the disaster is, and HOs' importance on delivering medical items is crucial as "often there's no private sector that's functioning. And we are the only source of these high-quality products" (6). Building on the evidence from the interviews, Figure 2 expands the typical emergency HMCC vertically by detailing energy services; and horizontally by presenting energy consuming sections where RES can be most feasibly increased. It was clarified with the interviewees, that here, *energy-consuming section* refers to cold chain structures and strategies in relation to energy services, not technical aspects in relation to energy consumption. It encompasses the type of energy consumed at certain supply chain nodes, the equipment's requirements, energy and power sources for keeping the chain cool and decisions made based on the criteria. Subsequently, Section 4.1 presents the findings on which energy services are powering emergency HMCCs, focusing on energy sources. Secondly, Section 4.2 presents the findings on increasing the use of RESs, highlighted in orange in Figure 2 in the energy-consuming sections. The final section introduces what the opportunities are for, and the barriers are to, increasing the use of RESs in the energy-consuming sections.

4.1 Energy services in humanitarian medical cold chains

Energy services link the energy source(s) to logistical activities in emergency HMCC. Following the frame of reference, the interviewees confirmed factors influencing the choice of energy service, which were defined by stability, security and reliability. As one interviewee stated, "the main focus is the reliability of a cold chain. You can't have a cold chain breach, because then it's just a waste of so many of the efforts" (2). Thus, the interviewees agreed that the most viable energy source to power a certain logistical activity in an emergency HMCC depends heavily on the energy service's evaluated risk, availability and affordability. For example, the interviewees described that in central warehouses, cold chain items are stored in cold rooms or large fridges and the ice packs in freezers, and the needed energy is generated from the national grid. Logisticians or technical supporters at headquarters typically manage active cold chains at central warehouses. Once a disaster strikes, HOs often partner with third-party logistics service providers for transport from central warehouses to the field. This is critical for cold chain management because items are packed in cold boxes with ice packs, which should last 24 to 48 h until reaching the first entry point and/or the national or regional warehouse. The first entry point is, however, where the risk of cold chain breaches increases because cold boxes may be left for an extended period of time on tarmacs or in nearby storage at airports without additional energy source, waiting for customs clearance:

> This is where the different capacities will start to show themselves. In some settings, you have at the port of entry the adequate facilities for cold chain, but [. . .] often times, there is no capacity for storing those temperature-regulated products while the customs clearance process is taking place (6).

Table 3 Data structure

1st order concepts (example of a quote)	2nd order themes	Aggregated dimensions	Conclusions
"I would say that the mains powered refrigerators would definitely be the most viable, mainly due to the increased costs linked to the solar powered refrigerators. . . . You have to pay for the solar panels and installation is quite more complicated" (7)	Financial	**Resources**	The temperatures required for cold chains pose challenges because a steady power supply is difficult to ensure during emergencies (Dolinskaya *et al.*, 2018). Technical knowledge to maintain the cold chain equipment is a critical task (Dolinskaya *et al.*, 2018) that requires both financial and human resources from HOs and local governments (Comes *et al.*, 2018)
"If you look at the whole, as they [renewables] are being used as a long-term solution for a community resilience in a way, if it's not cared with local capacity building, then people can't maintain the systems" (9)	Knowledge		
"Implementing a system, a technology that is not really fitting the context, although it can do the job with some maintenance and training, but it can be a big challenge, and it sometimes, it's not possible" (8)	Technology		
"So there's whole hosts of the complex issues depending upon the. . . the capacity of the country, the existing capacity the country before the crisis, the ability of the staff from the different international organisations, or NGOs, to even know that they should be managing it in the first place, but then also have the funds, or the, or the, the infrastructure to manage it well" (6)	Capacity		
"So, you may end using like passive cold chain because you actually have maintenance problem or staff problem, that there is not technician available to repair the fridge" (5)	Actors		
"So, these generators, of course, are running at least once per day from 30 minutes up to a couple of hours sometimes. And, of course, it's sucking a lot of fuel, you know, it's consuming a lot of fuel. . . . So, and this will be a standard in every African mission, . . . You will always have a big generator. The bigger your house, the bigger your generator the bigger the fuel consumption. You will always have drums of diesel there" (4)	Energy sources		
"From all angles, going solar makes sense for humanitarians. Not only for the cold chain, you expand the - you benefit your cold chain but there are a lot of more benefits coming from going solar" (4)	Sustainability	**Awareness**	External and internal incentives increase the sustainable mindset among organisations (Seuring and Müller, 2008); however, sustainability is not at the core of HMCCs (Haavisto and Kovács, 2019). Because cold chains cannot risk breaches, RESs are not necessarily regarded as the first choice for increasing sustainability in emergency settings (Oloruntoba and Gray, 2006)
"They are so relying on diesel and the structures that procure and manage diesel, that they really, really would struggle to change" (10)	Trade-off		
"And I would hope that it becomes more of a standard practice for agencies, but then the problem is that it's not always contributing to the local development, there's still this siloed 'we bring in and deliver stuff' -mindset" (9)	Collaboration		
"In general, still the community's perspective is 'we need to go in, we need to save lives', which is understandable . . ., but I don't think that we as a humanitarian community have accepted that . . . we are also leaving a huge environmental impact" (5)	Attitude		

(***continued***)

Table 3

1st order concepts (example of a quote)	2nd order themes	Aggregated dimensions	Conclusions
"I don't think we're putting special force or priorities in making emergencies more sustainable, it's more how the organisation is working on it, and then that will have an impact on that" (1)	Prioritisation		
"There's always a contingency plan in place, there's always back up fridges because if one breaks down, you have to be able to change it over quickly" (1)	Reliability	**Infrastructure**	Because humanitarian operations occur in volatile environments (Kovács and Spens, 2007), the reliability of every logistical activity has to be applicable to the rapid-response phase (Dolinskaya *et al.*, 2018)
"If it's an emergency, you don't have time to think. You do, that it works. You clean up afterwards, but you just ship... It's a matter of the first few days of the response" (2)	Speed		
"There is no one system that is applicable for every context, so it's quite challenging that for every context - depending on climate, on war, on the volatility of the politics, then different systems are needed. And that is quite challenging, because you have the impression that every time again you have to rethink everything what you already have been designing" (8)	Stability		
"For us, the number one priority is to deliver the equipment fast to the country, install them and run the operation" (3)	Practicality		
"There's quite some procedures to follow if something happens" (1)	Guidelines	**Prerequisites**	Because emergency HMCCs consist of different activities and actors, the robustness of cold chains is ensured by guidelines to be followed (Dolinskaya *et al.*, 2018), for the relationships between actors, activities and energy sources are strongly linked in processes and influence the supply chain's design (Håkansson and Snehota, 1995)
"To me, it's almost just a shift from standard operating practices if the management says, ok, we're going green and we're going to make this a priority, I think it could happen, the technology is there, for sure" (9)	Process		
"If something is green itself, we will use, whatever it is on hand. But it needs to be already pre-thought. You don't think about green in emergency" (2)	Planning		

Source: Adapted from Gioia *et al.* (2013)

From the entry point, the items are delivered to national or regional warehouses. Those facilities include cold rooms or fridges and freezers; however, weak capacity in some settings may mean that adequate facilities for cold chains are unavailable. Occasionally, those facilities are powered by grids; however, they are not necessarily environmentally sustainable, because "even compared to a mains-operated refrigerator, that electricity still comes in a lot of these contexts from coal-fired power plant as well" (7).

Due to the irregularity or absence of grid power, a disaster's circumstances often require the use of diesel generators. Such generators are typically deployed along with other HMCC equipment and items, and they are needed both in the national/regional warehouses and further in rural health facilities. Beneficiaries receive the items either directly at health facilities or the items are relayed onward using smaller carriers to reach the most remote locations. In the field, the energy supply becomes more unstable; thus, "there's always a contingency plan in place" (1). This means back-up energy sources and equipment, which usually rely on diesel generators due to a lack of secure grid power:

> I think, very few, are [powered] by the public electricity system in the city where they are. But normally, this is not very reliable, this power supply from the country. So, most of the time, it's like a fuel generator (5).

4.2 Increasing the use of renewable energy sources

All interviewees stated that, as more RESs are offered in markets, the humanitarian community has begun to investigate their operations' environmental sustainability regarding energy. "It's not uncommon to see something that's solar-powered, but it's not like systematic where you see it everywhere" (6). In emergency HMCCs, energy-consuming sections were identified by the interviewees as the best places where fossil fuel energy sources could be replaced by RESs, namely, diesel generators with solar panels or mini-grids. The interviewees perceived RESs as desirable energy sources for enhancing sustainability, but the dimensions of resources, awareness, infrastructure and prerequisites are, in principle, defining the choice of energy sources for emergency HMCCs:

> Our main goal is to save lives, and we cannot make solutions, we cannot think sustainable or green values if it means that our operation will slow down or become more difficult, resulting in people dying. That is not an option (3).

Resources. As the interviewees clarified, solar power is viewed as the most feasible alternative to diesel generators. Wind and biofuels were also mentioned by some interviewees but not characterised as realistic solutions in emergency settings. However, "in an emergency, you don't have time to set your solar panels. You just go with fuel" (2). Overall, cold chains were seen to be the last emergency supply chain structures to switch to solar power due to specific technical requirements, urgency and established processes of using diesel generators in emergency settings. The interviewees preferred using RESs, first, in stable humanitarian operations, and only later gradually increasing their use in emergency settings, as training people and maintaining and repairing equipment requires more financial resources and knowledge.

Awareness. Tapping into solar energy in emergency cold chain management remains in its infancy and is not systematic, according to the interviewees. Despite the push to replace polluting absorption-model fridges with solar-powered fridges to decrease their negative impact on the environment and beneficiaries' livelihood and health, the interviewees nevertheless considered sustainability to lack priority during emergencies. "There's none. You are efficient and that's it. If it's an emergency setting, you don't have time to think" (2). Even so, the interviewees reported sustainable energy to have significant long-term benefits for the local area and the planet, even though, in emergency settings, "you will not be green. You're efficient" (2).

Infrastructure. In rapid-response operations, HMCC activities need to meet robust criteria to be efficient. The interviewees emphasised that, typically, detailed guidelines and protocols are to be followed to minimise the risk of losing inventory, and a back-up plan is always established. "Sometimes they are carrying these things up to the mountains on donkeys" (6). Using electricity from the grid and diesel generators to power cold chains is an entrenched process that comes with constraints. Interviewees emphasised irregular power cuts, and constant diesel supply, which cannot necessarily be bought or delivered nearby, and might be of poor quality. All of those possibilities increase expenses and pollution. By contrast, solar power was considered by the interviewees to possess great potential for emergency HMCCs, because many humanitarian emergency operations occur in sunny environments, and the running costs are low. However, interviewees viewed switching to solar power to require more capital investment, to create a need for special expertise and to require training local staff in maintenance. Solar energy was seldom considered to be as resilient as diesel. Therefore, the most viable energy service is often:

> [. . .] a combination of national grid, solar and generators. Aiming, of course, also to use the generators as few as possible, but we of course would need to cover the peak loads [. . .], and purely as a back-up if the system fails. So, the hybrid is fully something where we work on (8).

Prerequisites. Emergency HMCCs are often managed by following a strict procedure entailing several prerequisites depending on disaster type, infrastructure, location, access to stable electricity, local resources, available funding and technical knowledge. Existing guides mostly opt for standardised diesel generators, which are easily accessible and are maintained and repaired the world over; however, the dependency on fuel sources hinders resilient cold chain management. All the interviewees highlighted that solar energy's practicality and functionality should thus be pre-evaluated carefully, with attention to the planning phases in disaster responses:

> There is no one system that is applicable for every context, so it's quite challenging that for every context – depending on climate, on war, on the volatility of the politics, then different systems are needed (8).

For example, although solar power could be a reliable energy source in many countries where disasters occur, it cannot be used in countries lacking constant solar radiation.

4.3 Opportunities for, and barriers to, increasing the use of renewable energy sources in emergency humanitarian medical cold chains

Among all RESs, all the interviewees considered solar energy offering the longest-term environmental sustainability, and they confirmed that it has been used in various pilot projects in relatively stable humanitarian settings. Establishing the use of RESs in emergency HMCCs, however, requires collaboration with the private sector, research on best practices and innovation. To that end, because HOs rely purely on funding, "it needs to be pushed from the donors and sponsors. Because they demand cost-effectiveness from us" (3). RESs were also viewed by the interviewees as contributing to the development of local markets in the aftermath of disasters. "You know, like, luckily, when a crisis ends, you know, they should be able to use those to help rebuild back their health system. Strengthen their health system" (6). Once the emergency has subsided, the donated equipment can promote local market's reconstruction, even though:

> [. . .] renewable energies may not be perceived as priority. But I think, if it's not a priority, it's a responsibility. [. . .] If you're not applying renewable energy sources, you may end up with a lot of wastage with a lot of struggles, so you will not be able to maintain the long-term process because it's very costly. So, yeah, even if it's at first difficult to see, I think, in the mid- to long-term, you have a big impact (5).

If RESs were used in emergency HMCCs in the immediate response phase, then countries can disseminate lessons learned to the rest of the area:

> What we will also start seeing, most probably, is where there will be a move away from individual equipment solarisation, but more towards a facility-level solarisation. Like, when we talk about the use of, let's call it mini-grids, where it's a small village that is entirely solar-powered. And then you would use a normal mains-powered refrigerator to cool from that mains grid. Or the whole health facility is powered by solar panels. And then you get additional benefits of being able to cover other health-related activities, or other economic activities inside the mini-grid area that can be covered as well. Not just cold chain-related (7).

Journal of Humanitarian Logistics and Supply Chain Management
Volume 13 · Number 2 · 2023 · 157–172

However, most interviewees highlighted that solar-powered equipment cost more than fossil fuel generators, and organisations would also need financial resources and knowledge to train people, and to maintain and repair it:

> If I'm going to tell my country officers to buy this inflatable cold chain unit [powered with solar energy] right now, I'm going to advise them to purchase the generator version. Not because I don't think the solar version is great, but I know that we are so strapped for financial resources, and it's significantly cheaper. So, it's, you know, finances and prioritisation among different organisations (6).

Moreover, "things like solar panels often get stolen. In some of the resource-constraint countries. Because it's a valuable commodity" (7). At times, space for implementing a solar solution in larger warehouses or hospitals is unavailable, which has promoted the choice of traditional diesel generators instead. All interviewees also mentioned the barrier of people's resistance because not everybody is keen to try new things and decisions are impossible if information is not available about whether an alternative solution will work in extreme settings. The transition thus needs to start both from inside HOs and with pressure from stakeholders. Today, the change is still happening slowly:

> There has been a lot of talk about solarisation and how important it is to solarise these generators that provide that power. What I would say is that the transition is incredibly, incredibly slow (10).

Table 4 summarises the opportunities and barriers identified. The interviewees declared that environmental sustainability between energy sources and logistical activities can be enhanced if it does not complicate emergency HMCC management. Thus, to increase the use of RESs while remaining pragmatic, the interviewees considered a hybrid model, including both fossil fuels and RESs used to support one another, to be the most feasible option before fossil fuels can be fully subsidised with RESs in emergency HMCCs.

5. Discussion

The provision of RES is increasing in global supply chains' energy solutions to promote climate-resilient development (IPCC – Intergovernmental Panel on Climate Change, 2022; World Economic Forum, 2022). However, RESs' applicably to emergency HMCCs remain loosely understood (Comes *et al.*, 2018; Thomas *et al.*, 2021; Rosenberg-Jansen, 2022). High-valued HMCC items are among the most critical supplies delivered in emergency humanitarian operations (Comes *et al.*, 2018; Dolinskaya *et al.*, 2018). To keep the chain cold and safe, constant energy supply is required (Mackay *et al.*, 2019), which, to date, is mostly ensured with fossil-centric energy services, such as diesel or kerosene generators (Grafham and Lahn, 2018; Thomas *et al.*, 2021). Emergency settings, however, pose a volatile environment for securing energy access (Comes *et al.*, 2018). Energy services are hampered by a range of disturbances, including scarce grid connections, irregular power supply and shortage of fuel to power cold chain equipment (Comes *et al.*, 2018; Grafham and Lahn, 2018; Babatunde *et al.*, 2020). In spite of established processes, fossil fuel-centric energy services, thus, come with many flaws. They prolong dependency on fossil fuels, are costly, unreliable and have an evident negative environmental impact on the whole community and region during the immediate response and reconstruction (Dolinskaya *et al.*, 2018; Grafham and Lahn, 2018; Jusu *et al.*, 2018; UNICEF – United Nations Children's Fund, 2022).

The results of this paper highlight which energy sources power emergency HMCCs (*RQ1*), which is illustrated in a conceptual framework of a typical emergency HMCC (Figure 2). Aiming for analytical generalisation, the results from *RQ1* together with a literature review and practice case examples explored the energy-consuming sections most feasible for increasing the use of RES in emergency HMCCs (Figure 2), which helped to answer *RQ2* what are opportunities for, and barriers to, increasing the use of RESs in emergency HMCCs. Both *RQs* and respective results are discussed next, concluded in propositions at the end of each section.

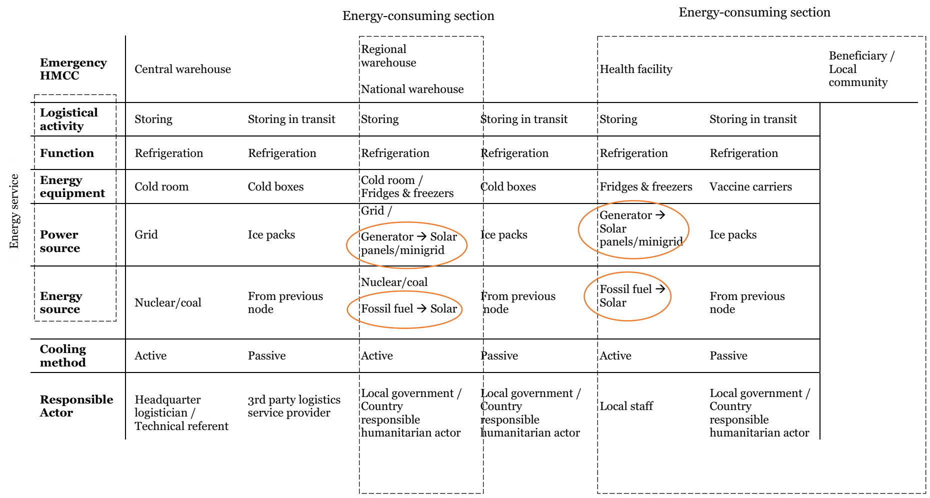
5.1 Environmentally sustainable emergency humanitarian medical cold chains

The responsibility for enhancing the environmental sustainability of emergency HMCCs lies in HOs' decisions when running their operations, to which energy offers one solution. A shift in the mindset of HOs is gradually emerging: the search for both reliable and sustainable energy solutions to run HMCCs. Both academia and practitioners agree the number one rule with emergency HMCCs is to ensure no cold chain breach occurs. With that in mind, the technical knowledge to maintain the cold chain equipment is a critical task (Dolinskaya *et al.*, 2018) that requires both financial and human resources from HOs and local governments. Currently, the majority of emergency HMCCs are relying on fossil-centric energy services (Sandwell *et al.*, 2021), which is the established and known way of operating. Alternative approaches in

Table 4 Opportunities for, and barriers to, increasing the use of RESs

Opportunities	Barriers
Short- and long-term environmental sustainability	Mindset and lack of knowledge
Long-term economic benefits	Environmental criteria not part of performance measurements
Increased environmental awareness	Lack of resources
Environmental friendliness	Lack of proof of practicality and reliability
More efficient and resilient emergency HMCCs	Lack of local capacities and competences
Local market development	Lack of funding mechanisms
Entry point to local communities' sustainable reconstruction	Lack of pressure from stakeholders
Responsibility	Lack of technological knowledge
	Lack of private sector involvement
	Volatility of disaster settings

Figure 2 Typical emergency HMCC with respective energy services, cooling methods and actors



managing cold chains include RES solutions (Robertson *et al.*, 2017; Comes *et al.*, 2018), but before their use will be increased, RESs' capacity to ensure constant energy reliability needs to be understood and guaranteed, leaving environmental sustainability as a secondary output (Jusu *et al.*, 2018). Growing the portfolio of using RESs in emergency HMCCs would thus require HOs to strengthen their technological knowledge, and ensure the knowledge is shared and implemented in processes by considering countries' varying capacities. More resources for training logisticians and local staff would be needed, however, which reflects the need to have funding mechanisms earmarked specifically for sustainable operations (Comes *et al.*, 2018). Given emergency HMCCs' importance, the change would likely start first in stable operations, but overall, it requires a change in mindsets and building awareness. To increase the use of RESs and enhance HMCCs' environmental sustainability would need to be prioritised by HOs in all disaster management phases (Mackay *et al.*, 2019), to which logistical activities' reliability must be ensured. Thus, the cold chain infrastructure has to meet the criteria of being reliable in emergency situations, as well as stable, yet practical. Given the challenging infrastructure requirements, prerequisites define how the emergency HMCC is created. Often, there are guides or manuals to follow, which still opt for fossil-centric generators over renewable energy in emergency situations (Grafham and Lahn, 2018). Should the use of RESs increase, it would need to start from the donors, governments and higher-level management to advocate using more RESs and include that in planning phases, as underscored by Oloruntoba and Gray (2006), Seuring and Müller (2008) and Patil *et al.* (2021). Based on this, the following proposition is suggested:

P1. To ensure the reliability and applicability of RES in emergency HMCCs, HOs must adopt a holistic view of RES to include resources, awareness, infrastructure and prerequisites.

Increasing the use of RESs is still in its infancy and not systematic, even in stable settings. The trade-off between sustainability and current processes that are known to work in emergency situations is hindering the change towards new standardisation (Oloruntoba and Gray, 2006). Overall, the interviewees supported what Haavisto and Kovács (2019) noted, that HOs' perspective still today is, to firstly be efficient, and secondly, to be sustainable, especially in emergency operations. However, clean energy sources used in emergency HMCCs benefit other aspects of the operations, for instance, charging laptops, phones and lighting health facilities (UNICEF – United Nations Children's Fund, 2021a). Creating awareness, engaging and sharing knowledge with local actors on using RESs-powered equipment also reduces later dependency on HOs' support with rebuilding the area:

P2. A comprehensive use of RES in emergency HMCCs, including not only equipment but facilities, can increase the environmental sustainability of the operation in total.

5.2 Opportunities for, and barriers to, environmentally sustainable emergency humanitarian medical cold chains

RESs, especially solar energy, present a more resilient power supply, while the dependency on constant fuel-sourcing diminishes. But, despite the general consensus that RESs are being cleaner, less polluting and environmentally more sustainable, the primary opportunities identified in this research emphasised the two other dimensions of sustainability: cost-effectiveness and possible social improvement (Elkington, 1998). This follows the perception that environmental sustainability is not prioritised in emergency operations (Haavisto and Kovács, 2019) but overridden by the effectiveness and reliability of known practices in cold chain management. Increasing the use of RESs thus has to derive from economic and social needs, and from a goal to benefit the environment. Value creation in the humanitarian context often excludes the broader dimension of sustainability, which stresses the need to include environmental criteria in performance measurements.

Nevertheless, the evidence from the interviews and academic dialogue supports the idea that health can act as an entry point to long-term sustainability, as clean energy planning and strategies implemented in response phases benefit local reconstruction efforts (Gibert, 2008; Eng-Larsson and Vega, 2011; Haavisto and Kovács, 2019). Instead of having to use a donated diesel generator and continue with an uncertain and costly fuel supply, locally-sourced solar energy could be used to power health facilities and even a larger proportion of communities. In turn, it would strengthen longer-term economic and social aspects because less continuous humanitarian aid would be needed, and the community would be able to rebuild itself to be more resilient. The available renewable energy could additionally provide energy for several activities within the community, including cooking and lighting, and thereby address issues such as famine or children's access to education (UNICEF – United Nations Children's Fund, 2021a). Supporting this, HOs' localisation strategies should be aligned with increasing the use of RESs in emergency HMCCs, which according to Frennesson *et al.* (2021), is still in its infancy:

P3. Redesigning emergency HMCCs with more RESs helps in rebuilding the affected community in a climate-resilient manner, benefitting other mandates as well.

The lack of resources and technical knowledge are among the biggest barriers in energy-consuming sections to increase the use of RESs in emergency HMCCs. Thereby, emergency HMCCs are likely not the first supply chain structures to adopt fully implemented strategies with renewable energy. Moreover, streams of funding are not necessarily earmarked for enhancing emergency operations' sustainability, unless clear benefits are evident (Oloruntoba and Gray, 2006). As the interviewees clarified, because cold chains need to be reliable before being made environmentally sustainable, HOs should have access to more data from the field so that emerging proof of RESs' stability can be better understood and validated in emergency settings.

The responsibility of HOs is to guarantee access to clean energy services before, during, and after the emergency; a goal towards which RESs in emergency HMCCs contribute to (OCHA – United Nations Office for the Coordination of Humanitarian Affairs, 2010; McCarney *et al*., 2013; Robertson *et al*., 2017; Thomas *et al.*, 2021). The interviews and case example from practice shed light on what the current literature suggests: RESs offer one feasible alternative to be used in nodes, where access to secure electricity is not guaranteed. As Figure 2 depicts, emergency HMCCs are, to date, dependent on fossil fuel-centric energy services, but in the energy-consuming sections of first entry points and rural health facilities, the use of RESs can best be increased. Currently, solar energy is seen as the most feasible alternative, replacing diesel or kerosine generators in those sections, because most operations occur in sunny locations, its cost-effectiveness pays off in the long-term and equipment is more resilient and energy-effective than legacy equipment. But dimensions of resources, awareness, infrastructure and prerequisites define the level and depth of that change in emergency HMCCs:

P4. In emergency HMCC, a hybrid model combining fossil fuel and RES is most advantageous to ensure energy security while continuously aiming to increase the provision of RES used.

6. Conclusion

This study investigated opportunities for, and barriers to, increasing the use of RESs in emergency HMCCs to enhance environmental sustainability, which is not prioritised when responding to emergencies. The provision of RES is increasing in global supply chains' energy solutions, yet fossil fuel-centric energy services are still today the dominant power source in emergency HMCCs. In fact, the importance of energy is often excluded in response operations' planning, even though energy is essential for ensuring secure cold chain management, thus saving lives. Emergency HMCCs offer a novel perspective on how energy is, *de facto*, intertwined into humanitarian operations, and how through health, more long-term, local and environmentally sustainable energy solutions can be achieved through RESs.

By decoupling the energy services of typical emergency HMCCs, Figure 2 was developed to frame how the use of RES can be increased in energy-consuming sections, namely, with solar energy. Despite the high capital investment required, emergency HMCCs with RESs result in more resilient and sustainable cold chain management, strengthening local, affordable and climate-resilient capacity building in the aftermath of the disaster. Although RESs offer many opportunities, various barriers hinder the scaling up using RESs in emergency HMCCs. The general mindset of transitioning from established practices to new ones is hesitation, influenced by a lack of available resources, competences, knowledge and private sector involvement. The lack of pressure from stakeholders – and funding mechanisms advocating the use of RESs especially – delay the transition. Solar energy is regarded as unreliable and requiring more work to maintain in emergency settings, which more practical work in the field could serve to change. Nevertheless, RESs play a critical role in emergency HMCCs operations while transitioning from fossil-centric energy solutions to using cleaner energy services, which benefits not only the immediate operation but also climate-resilient reconstruction.

This study focused on the energy services in downstream emergency HMCCs, but the environmental sustainability could also be perceived from the actors' perspectives or in a specific supply chain node, such as rural health facility. Regarding practical implications, this paper provides a new perspective on linking energy sources and logistical activities to enhance environmental sustainability in emergency HMCCs. By mapping emergency HMCCs and their respective energy services, this study identified the energy-consuming sections in which RESs can replace conventional energy sources and key opportunities and barriers during the transition, which can be followed up by both practitioners and academia.

This research aimed to analytically generalise the phenomenon in-depth by linking literature, qualitative research data and practical case examples, resulting in a conceptual framework, which comes with limitation by being a general overview but forms a base for further replication and testing in practice. For instance, the term *energy service* is limited to cold chain structures and strategies, which excluded the technical perspective. Also, the term could have been interpreted differently, which would have altered the niche of this research. In addition, this research concentrated on energy sources considering the concept of energy service, which excluded, for example, the energy needed to fuel vehicles, equipment's material and sourcing strategies. Moreover, the empirical data was derived from 10 expert interviews, all conducted from the perspective of HOs, which excluded other relevant stakeholders (e.g. donors and local communities). The research also focused only on downstream cold chain management in emergency settings, excluding, e.g. vaccination campaigns and slow-onset disasters.

Energy's role in enhancing environmental sustainability in emergency HMCCs calls for further research by validating the conceptual framework quantitatively, for example, calculating emissions generated by using different energy sources, both fossil and renewable. The barriers and opportunities identified could be examined in greater depth through the lens of, for example, funding structures for humanitarian operations, end-to-end HMCC design or HOs' localisation strategies with respect to sustainable energy sourcing. Another avenue for future research is cross-sectoral environmental evaluation, which can be performed in the different phases of disaster management. Therefore, the humanitarian sector has an opportunity to become an early adopter and leader in using clean energy sources in non-traditional supply chains, which is everyone's responsibility, and the direction we all need to take to reduce health-care disparities worldwide.

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