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Performance Analysis of a Solar-Powered Multi-Purpose Supply Container

Stephan Peter [1,2,*], Matthias Schirmer [1], Philippe Lathan [3], Georg Stimpfl [3] and Bashar Ibrahim [2,4,5,*]

1 Ernst-Abbe University of Applied Sciences Jena, Carl-Zeiss-Promenade 2, 07745 Jena, Germany; matthias.schirmer@eah-jena.de
2 Department of Mathematics and Computer Science, University of Jena, Ernst-Abbe-Platz 2, 07743 Jena, Germany
3 Nathal Energy®, Brucknerweg 3, A-9500 Villach, Austria; info@nathal.de (P.L.); georg.stimpfl@nathal-energy.com (G.S.)
4 Department of Mathematics & Natural Sciences, Gulf University for Science and Technology, Hawally 32093, Kuwait
5 Centre for Applied Mathematics & Bioinformatics, Gulf University for Science and Technology, Hawally 32093, Kuwait
* Correspondence: stephan.peter@eah-jena.de (S.P.); bashar.ibrahim@uni-jena.de (B.I.)

Abstract: In this article, the performance of a solar-powered multi-purpose supply container used as a service module for first-aid, showering, freezing, refrigeration and water generation purposes in areas of social emergency is analyzed. The average daily energy production of the solar panel is compared to the average daily energy demands of the above-mentioned types of service modules. The comparison refers to five different locations based on the Köppen–Geiger classification of climatic zones with the data for energy demand being taken from another publication. It is shown that in locations up to mid-latitudes, the supply container is not only able to power all types of modules all year round but also to provide up to 15 m^3 of desalinated water per day for drinking, domestic use and irrigation purposes. This proves and quantifies the possibility of combining basic supply with efficient transport and self-sufficiency by using suitably equipped shipping containers. Thus, flexible solutions are provided to some of the most challenging problems humans will face in the future, such as natural disasters, water scarcity, starvation and homelessness.

Keywords: sustainability; renewable energy; self-sufficiency; climate change; primary care; drinkable water; catastrophe response; refugee camps; afforestation

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1. Introduction

Climate change is one of the most serious challenges humans will be confronted with in the future. The predicted increase in greenhouse gas emissions and air temperature is linked to an increase in extreme events such as storms, floods, heatwaves and droughts [1,2]. Developing countries are more severely affected due to their economic and social conditions, which may prevent them from reacting instantly and appropriately to those disasters [3]. Greenpeace expects up to 200 million climate refugees by 2040 resulting from global warming, and water supply plays a significant role in this context. In the 21st century, the global population has increased by approximately 300% and water consumption by 600%. At present, two-thirds of the global population suffer from conditions of temporary water scarcity for at least one month per year [4,5]. In many areas of the world, the water crisis is developing into a food crisis, which is likely to increase and spread further due to increasing environmental pollution, strong population growth and the emerging climate change [4,6,7]. Recently published papers confirm the importance of renewable energy systems and sustainability to deal with these complex scenarios internationally [8–11].

Humanitarian aid aimed at minimizing suffering and saving lives is indispensable in cases of crises caused by humans or the natural environment [12]. The Austrian-German

Think-tank Nathal Energy® has developed a mobile supply container to provide people in disaster zones or refugee camps with electricity and drinking water as fast as possible. Generating water or electricity using containers equipped with solar panels is not an entirely new idea and has been focused on by an increasing number of projects in recent years [13–16]. The supply container provides a uniform framework applicable to different scenarios, some of which are examined in detail in this article. The energy demand of all components of the supply container is completely met by the solar panel attached. Depending on the given conditions, these components can vary and include, for example, batteries, seawater desalination plants, lighting, air conditioning, refrigerators, heating, control units, atmospheric water generators, chemical toilets, etc.

In this study, the use of the supply container as a first-aid module, shower module, freezing, and refrigeration module, as well as a desalinated water generator, is analyzed. Figure 1 provides an overview of potential applications of the supply container.

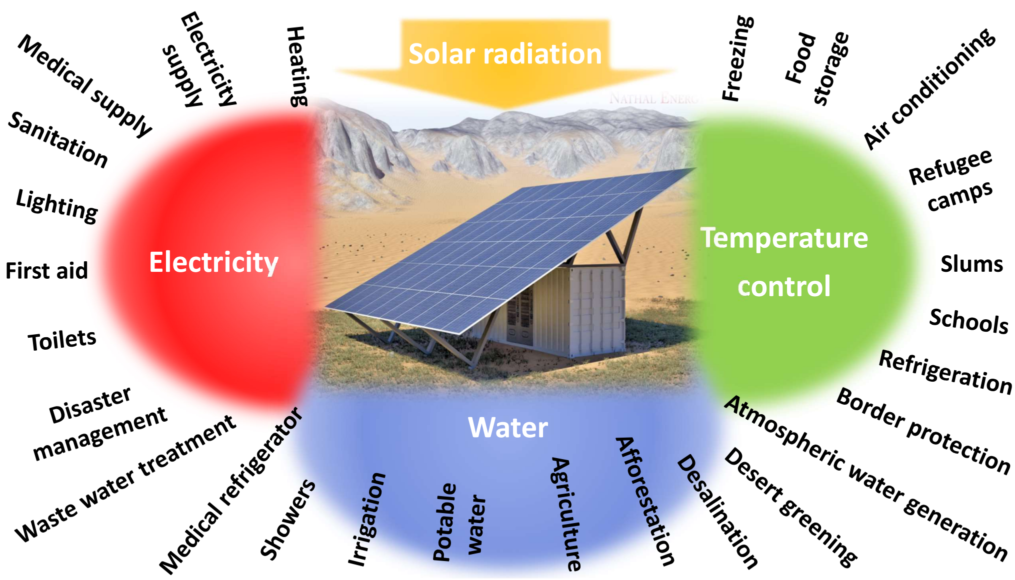

Figure 1. Interface and applications of the supply container. The only input to the containers is solar radiation, which is transformed into electricity by the solar panel. The electricity can be stored in a battery and can be used to provide air conditioning, heating, drinking water, irrigation, sanitary facilities, vacuum for medical purposes, etc. In this article, the performance of the supply container is analyzed when used as a first-aid module, shower module, freezing module and refrigeration module as well as a desalinated water generator.

By enabling a closed transport chain of universal freight container ships, trucks, trains, airplanes or even helicopters, shipping containers have laid the foundation of globalization, with a ratio of over 95% of worldwide trade activity [17]. Thus far, several hundreds of millions of shipping containers have fallen into disuse. According to ISO standards regarding the survival of harsh treatment and rough maritime climates, they are typically made of COR-TEN steel [17]. As they are relatively inexpensive, structurally sound and in abundant supply, they have a great potential of being reused as public toilets, public showering, storage sheds, houses, water generators, etc. [17,18].

Military forces in particular offer the capability for transportation of larger goods such as containers in relatively short periods, which can be exemplified in the earthquake in Haiti in 2010 [19]. Shipping containers are also used in permanent projects, such as air-conditioned accommodation for the U.S. military (Camp Lemonnier, Djibouti) [20]. Therefore, the main literature reference [19] of this article is based on a military background. In [19], the energy demand of four types of modules including first-aid, shower, freezing and refrigeration were calculated in five different locations around the world, of which Figure 2 provides an overview.

Figure 2. Locations considered in this article. The five green and red colored locations were analyzed in [19]. They were chosen to represent the five different climatic regions according to the Köppen–Geiger classification. The green color refers to an all-year-round operation of the supply container with a single panel, while the red color refers to an only seasonal operation.

This article has the following structure. Section 2 the basic configuration of the supply container as well as the calculation of the average daily energy production for each month of the year. In the Section 3, the average daily energy production of the supply container in the above-mentioned five locations is compared to the energy demands of the different types of modules described in [19]. After a brief section about container modules for accommodation the production of drinking water by desalination is discussed. The article is concluded by areas for further research. In the Appendix A, a table with the annual energy production and energy demands of each type of module and each location is presented.

2. Materials and Methods

A standard 20-feet shipping container has a weight of 2250 kg and its external dimensions (L $\times$ W $\times$ H) are 6.06 m $\times$ 2.44 m $\times$ 2.59 m. Its internal dimensions are 5.90 m $\times$ 2.35 m $\times$ 2.35 m with an internal volume of 32.61 m^3 [21]. The maximum cargo capacity is 28,230 kg. The supply container is equipped with one or more batteries to save surplus energy and ensure its operation when the energy produced by the solar panel is insufficient. This may be the case at night, immediately after the arrival of the supply container at its destination or in case of technical issues. Furthermore, the supply container is equipped with insulation, which reduces energy demand as well as peak power when a particular inside temperature is to be reached [22]. Even without heating or cooling insulation flattens inside temperature curves of the supply container, and thus, protects the battery performance and life span [22,23].

The effects of solar radiation on containers have been subject to many studies and roof shading was found to exhibit energy savings in cooling demand of up to 20% [24–27]. However, in this article, the effects of roof shading are neglected. Nevertheless, installing the solar panel on top of the container not only protects the container from rain and sun, but also saves additional floor space.

For the calculations, a solar panel module with a peak performance of 320 W, an efficiency of $\eta_{solar} = 18.3\%$, dimensions (L $\times$ W $\times$ H) 1.716 m $\times$ 1.023 m $\times$ 0.035 m and a weight of 19.3 kg is assumed, which results in a module surface of 1.755 m^2 [28]. As shown in Figure 1, 40 modules can be arranged on top of the container in a 8.184 m $\times$ 8.580 m matrix consisting of 5 rows, each of which contains 8 modules. They cover a total area of 70.2 m^2, and during transportation, they are stored inside the container together with all further components. Connecting these 40 modules parallel in two strings yields the following total voltage, current and peak power:

$$U_{tot} = 656\,\mathrm{V} \quad (1)$$
$$I_{tot} = 2 \cdot 9.75\,\mathrm{A} = 19.5\,\mathrm{A} \quad (2)$$
$$P_{peak,tot} = 12{,}792\,\mathrm{W}. \quad (3)$$

The solar panels as energy generators are integrated into an electric circuit, shown in Figure 3.

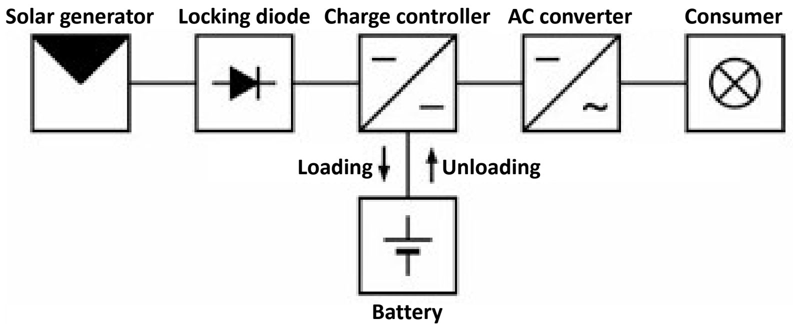

Figure 3. Basic circuit diagram of the supply container. It connects solar panels, batteries and electric consumers via a locking diode, a charge controller and an AC converter. The scheme is adapted from [29].

For each string, we assume an AC converter with an efficiency of $\eta_{ac} = 97.6\%$. The efficiency of the battery must also be taken into account, which could be a lithium-ion battery with a capacity of 11,520 Wh and an efficiency of $\eta_{bat} = 95.3\%$.

Miscellaneous losses for the AC converter of $\nu_{ac} = 1\%$ and the whole photovoltaic system of $\nu_{pv} = 15\%$ were assumed. The average energy produced daily (W_{out}) can be calculated for each month of the year based on the average daily amount of solar radiation W_{in} (unit: $\mathrm{Wh} \cdot \mathrm{day}^{-1} \cdot \mathrm{m}^{-2}$) according to the formula:

$$W_{out} = W_{in} \cdot \eta_{solar} \cdot \eta_{ac} \cdot \eta_{bat} \cdot (1 - \nu_{ac}) \cdot (1 - \nu_{pv}) \cdot 70.2\,\mathrm{m}^2. \quad (4)$$

The results were confirmed using RETScreen software [30]. An optimal inclination of the solar panel was assumed, which approximately corresponds to the latitude of the given location.

The five locations considered here (see Figure 2) were chosen from [19]. They represent each of the five different climatic regions A to E of the Köppen–Geiger classification:

- Region A—tropical climate: Port-au-Prince, Haiti (N 18.33°, W 72.20°), Caribbean Sea; located at active fault; high probability of earthquakes (e.g., 2010: 300,000 deaths and 1.8 million homeless), hurricanes, tsunamis and tornadoes; monthly average temperature never below 18 °C with low variation [19],
- Region B—dry climate: Djibouti, Djibouti (N 11.32°, E 43.08°), Horn of Africa; developing area with extreme temperatures [19]; neighboring country of Somalia, violence and conflicts over three decades; droughts; millions of inland refugees,
- Region C—mild climate: Colonia, Uruguay (S 34.28°, W 57.51°), South America;
- Region D—continental climate: Yakutsk, Russia (N 62.2°, E 129.44°), Eastern Siberia; one of the locations with the lowest temperatures in the world in winter [19],
- Region E—polar climate: Puerto Williams, Chile (S 54.56°, W 67.37°); wide variation in daylight over the year [19].

Recycled COR-TEN sea containers used as service modules were subjected to a thermal analysis by [19]. These service modules comprise [19]:

- First aid—designed for first-aid medical assistance; target temperature set at a range of 22 °C to 26 °C (according to UNE-EN ISO 13790 [31] for hospitals); exchange of 100% of the air every hour;
- Shower—important to help maintain a minimum level of hygiene, which is an essential aspect to avoid the spreading of diseases; target temperature is set to be at least 22 °C, and thus, no provision is made for cooling;
- Freezing—target interior temperature is 10 °C, for example, to store food;
- Refrigeration—target interior temperature is −40 °C, for instance, to store drugs and food.

According to [19], the module types were selected based on technical interest and usefulness in cases of emergency. All modules have a door, but only the first-aid module and the shower module are equipped with windows [19]. The energy supplied by each person staying inside the module was calculated based on ISO 7730 [32], which regulates standard data according to a person's activity level.

Regarding insulation, the following assumptions were made by [19]. For the first-aid and shower module, the lateral panels and the roof are sandwich-like walls with an outer steel layer, a polyurethane layer as an insulating material and an inner layer made of galvanized steel. The floor is made of a steel layer, a polyurethane layer, a plywood layer and a final aluminum layer. This results in a roof thickness of 83 mm, a thickness of the outer facade of 63 mm and a thickness of the ground of 69 mm. In contrast, for the refrigeration modules the panels are made of an outer steel layer, a central insulating layer (three layers of polystyrene/polyurethane/polystyrene) and an inner steel layer. This leads to a thickness of the roof and the outer facade of 98 mm each, and the thickness of the ground amounting to 126 mm. The thickness of the insulation of the refrigeration modules is bigger, which leads to a smaller thermal transmittance. For more details on the modules and the computation of the energy demands, the reader is referred to [19].

3. Results

3.1. Analysis of First-Aid, Shower, Refrigeration and Freezing Modules

Following the description in the previous section, we calculated the average daily energy production of the supply container for all locations mentioned in [19]. Figures 4–8 depict the energy production and the demands of the modules.

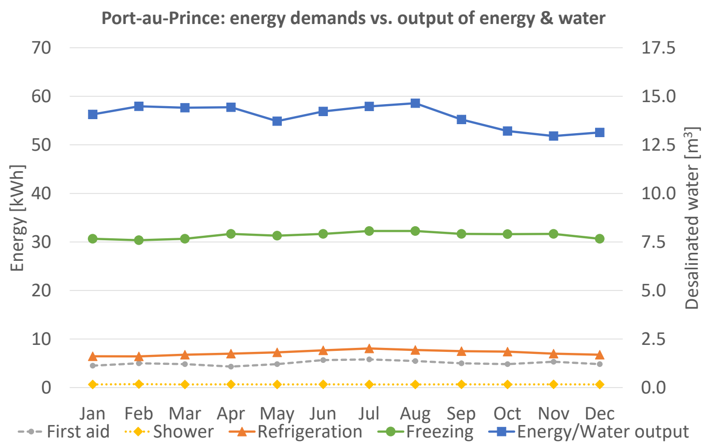

Figure 4. Port-au-Prince, Haiti. Left axis: Average daily demands of the first-aid, shower, refrigerator and freezing modules and average daily energy production of the supply container. The demands of all types of modules can be satisfied easily all year. Right axis: Average daily output of drinking water by desalination of seawater assuming a specific energy of 4 kWh m^{-3}.

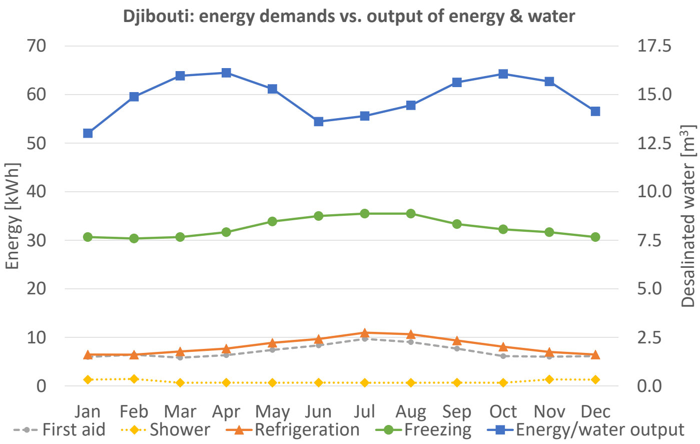

Figure 5. Djibouti. Left axis: Average daily demands of the first-aid, shower, refrigerator and freezing modules and average daily energy output of the supply container. Right axis: Average daily drinkable water output of the supply container by desalination of seawater assuming a specific energy of 4 kWh m^{-3}.

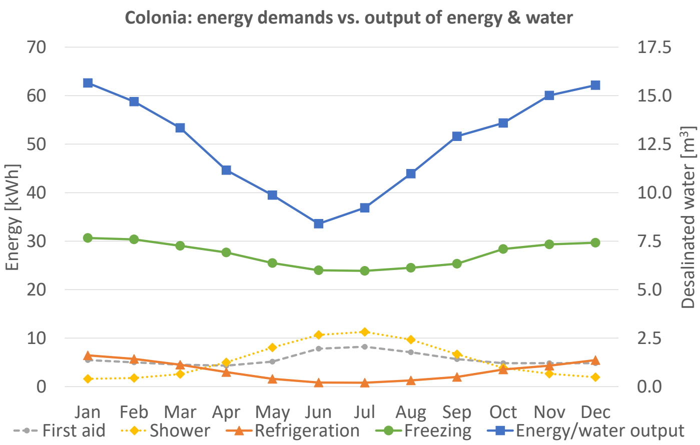

Figure 6. Colonia, Uruguay. Left axis: Average daily demands of the first-aid, shower, refrigerator and freezing modules and average daily energy output of the supply container. Right axis: Average daily output of drinking water by desalination of seawater assuming a specific energy of 4 kWh m^{-3}.

The requirements of the first-aid module are met all year round in Port-au-Prince, Djibouti and Colonia. For each of these three locations, the demands of the first-aid module are lower than 25% of the monthly energy production. Due to the demands for heating, the first-aid module demands are not met in Yakutsk (Nov to Feb) and in Puerto Williams (June and July). They temporarily exceed the energy production by up to 370% for Yakutsk and 160% for Puerto Williams, respectively. Since the demands of the shower module are limited to heating, they are similar to those of the first-aid module in Yakutsk and Puerto Williams. The demands of the refrigeration module are comparatively low. They are met throughout the year in all five locations reaching 20% of the energy production (in Djibouti in July) at most. The demands of the freezing module are satisfied all-year-round for all locations except for Puerto Williams, where it exceeds the energy production from May to July by 200% at most. For each of the other four locations the demands for freezing are constantly below two-thirds of the energy production. It should be noted that the annual sum of the energy produced exceeds the annual demands of all types of modules in all locations, even though this does not hold true for every single month. Surplus energy can be used to produce water for drinking, sanitation or irrigation, as described in Section 3.3.

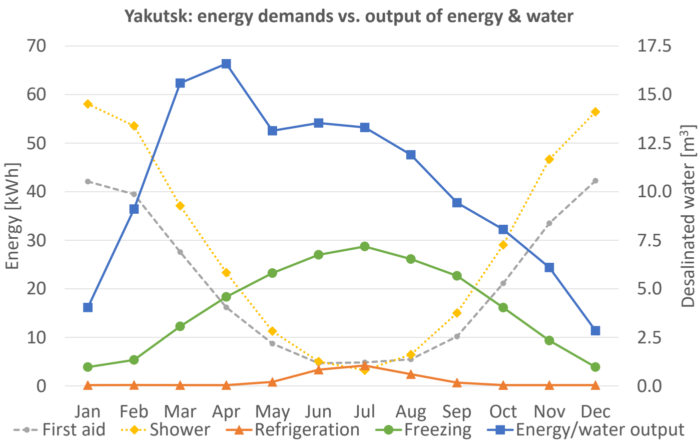

Figure 7. Yakutsk, Russia. Left axis: Average daily demands of the first-aid, shower, refrigerator and freezing modules and average daily energy output of the supply container. Right axis: Average daily output of drinking water by desalination of brackish water (because of the big distance to the ocean) assuming a specific energy of 4 kWh m^{-3}.

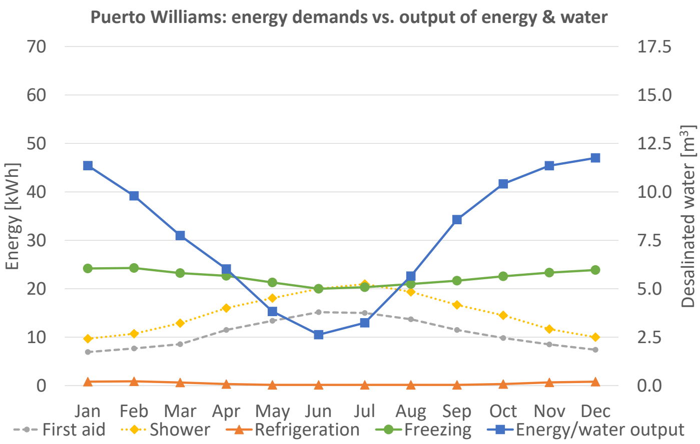

Figure 8. Puerto Williams, Chile. Left axis: Average daily demands of the first-aid, shower, refrigerator and freezing modules and average daily energy output of the supply container. Right axis: Average daily output of drinking water by desalination of sea water assuming a specific energy of 4 kWh m^{-3}.

Table 1 summarizes the results of the comparison of energy production and demands and relates them to the WorldRiskReport 2021, which assesses a country's risk of being struck by natural hazards such as floods, sea-level rise, storms, droughts and earthquakes [3]. The WorldRiskReport is published annually by "Bündnis Entwicklung Hilft" in cooperation with Ruhr University Bochum—Institute for International Law of Peace and Armed Conflict (IFHV). Interestingly, those of the five countries with the highest world risk indices (Djibouti, Haiti, Uruguay) exhibit the best performance of the supply container in powering the four types of modules. This is a promising result regarding the effectiveness of the supply container as a measure for disaster relief. The locations of Yakutsk and Puerto Williams, however, demonstrate the supply container's limitations rather than providing all-year-round solutions. By using other energy sources, such as wind energy, the temporary lack of energy could be compensated for. Better energy storage systems could also solve the problem of a temporary lack of energy, since the annual energy consumption for all module types is below the annual energy production of the supply container in each location, as the table in the Appendix A shows.

Table 1. The upper part of the table describes the performance of the supply container with regard to the first-aid, shower, refrigeration and freezing modules. The colors green (yes) and red (no) mark whether the supply container satisfies the energy demands of a module all year round. The lower part of the table shows the world risk indices (WRI) of the five countries considered and their rank in an ordered list of 181 countries [3]. A country's WRI is the product of its exposure to natural hazards and its vulnerability [3].

	Port-au-Pr. Haiti	**Djibouti Djibouti**	**Colonia Uruguay**	**Yakutsk Russia**	**Puerto Will. Chile**
First aid	yes	yes	yes	no	no
Shower	yes	yes	yes	no	no
Refrigeration	yes	yes	yes	yes	yes
Freezing	yes	yes	yes	yes	no
WRI	14.54	14.48	12.53	3.53	11.32
WRI rank	21/181	17/181	27/181	137/181	33/181

3.2. Supply Containers Used as Modules for Accommodation

Simulations performed for the Italian city Perugia (43°7′ N, 12°23′ E) show that using end-of-life shipping containers allows for the construction of nearly zero energy buildings (nZEB), which guarantees comfortable living conditions [33]. In [33], the authors included thermal aspects, lighting and heating water concluding that containers can definitely be used as temporary accommodation or post-disaster homes, but also for the improvement of living conditions in poor and densely populated urban areas. The following breakdown of annual energy consumption of a 20-feet container used for living in Perugia was determined [33]:

- 45.44 kWh spent on lighting;
- 228.83 kWh spent on hot water;
- About 370 kWh to 400 kWh spent on heating;
- 110 kWh to 120 kWh spent on cooling.

This results in a total annual energy consumption for a 20-feet container used by one person of between 759 kWh and 798 kWh, depending on the insulation [33], and represents 5 to 6% of the annual energy production of the supply container in Perugia. Thus, official incentives for support schemes such as EU Directives, such as Zero Energy Buildings, can be implemented easily by using supply containers.

3.3. Desalination of Water by Reverse Osmosis (RO)

For modern desalination plants based on reverse osmosis, the specific energy demand is approximately 3 kWh m^{-3} [34]. For Duba, Saudi Arabia, for example, a specific energy demand of 3.01 kWh m^{-3} was calculated for a RO desalination system producing an annual average of 1000 m^3 permeate per day [34]. The Carlsbad reverse osmosis system in San Diego, California is one of the world's most modern seawater desalination plants whose specific energy consumption is less than 3.3 kWh m^{-3} including backwashing, cleaning, elimination of cleaning dilutions and return of the surplus concentrate to the sea [34].

Since for smaller plants, such values are realistic too and as the ratio of the essential ions of sea water is nearly identical in all oceans, we can assume 4 kWh m^{-3} as a good estimate for the energy demand of the desalination of sea water in different locations [34–38]. The amounts of drinking water produced by the supply container per day are represented by the blue lines in Figures 4–8. The values are shown on the vertical axes on the right-hand side of the graphs and are summarized in Table 2.

Table 2. Daily water production (a) by desalination (mean, standard deviation and 15-liter rations for drinking and domestic hygiene needed per person each day according to minimum standards in humanitarian response [39]) and (b) by collecting rain water using the (inclined) solar panel of an area of 70.2 m^2.

	Port-au-Prince	Djibouti	Colonia	Yakutsk	Puerto Williams
mean of daily desalinated water (m^3)	14.0	14.9	12.5	10.3	7.7
standard deviation (m^3)	0.6	1.0	2.4	4.3	3.2
number of 15-liter rations	933	993	833	686	513
range of daily rain water (liters)	36–132	15–124	123–251	11–76	60–98

With increasing absolute values of the latitude of a location, the mean of desalinated water per day increases and the standard deviation decreases, as expected. The maximum mean value of desalinated water is nearly 15,000 liters for Djibouti, which corresponds to 1000 15-liter rations for drinking and domestic hygiene needed per person each day according to minimum standards [39]. The amount of rain water that can be collected by using the inclined solar panel of an area of 70.2 m^2 is comparatively much smaller for all locations examined.

As mentioned above, desalinated water can not only be used as drinking water but also for other purposes, such as the irrigation of plants. In terms of energy efficiency, it is important to adjust the desalination process to the purpose the water is used for, since some plants allow for more salt or pollution contained in the desalinated water than others [14,40].

Drip irrigation is a very efficient irrigation method. Studies of solar-powered drip irrigation and pumping conducted in Sudano-Sahel, India and Bangladesh give an indication of its impacts [41–43]. It has been found that solar-powered drip irrigation and pumping significantly increase both household income and nutrient intake, particularly during the dry season [41]. Moreover, it is cost-effective compared to alternative technologies [41]. As a comparatively cheap and clean technology, which can be automated and sensor-controlled, solar-powered drip irrigation helps governments and farmers to cope with the imminent energy crisis [42,43]. In this context, it is already used in practice to revegetate land and to produce crops [13].

4. Discussion

The results for three of the five locations considered here have shown that up to mid-latitudes the supply container can operate all year round as a first-aid, shower, refrigeration, freezing or accommodation module. Depending on the type of module and the amount of solar radiation, surplus energy is produced, which can be used for other purposes, such as water generation. It has been shown that by desalination up to 15 m^3 of drinking water per day can be produced, which can also be used for irrigation purposes in afforestation or agriculture. Thus, it is proved that shipping containers converted into supply containers combine the provision of basic supplies with fast transportation even if the infrastructure is insufficient. This makes them highly suitable for rapid emergency relief in cases of natural disasters, resource allocation conflicts, climate change, etc., which are likely to increase in the future. Such events are particularly dangerous for countries with high world risk indices. Most of these countries are exposed to high levels of solar radiation, which guarantees a high performance of the supply container.

This study shows various fruitful directions for future research. More locations can be analyzed to achieve more detailed results in terms of climatic conditions. Air conditioning produces condensation water as a by-product, and many studies suggest studying the combination of air conditioning and water generation [5,44,45]. Furthermore, intelligent and autonomous control of the supply container, incorporating, for example, weather data and consumer behavior, is a promising field. This can be achieved by incorporating simulations of complex models, which are based on artificial neural networks [46,47] or partial differential Equations [48–51]. The stochastic spatial effects can also be considered using rule- and agent-based modeling [52–56]. Another direction for future research is the focus on other sources of water, such as atmospheric water generation, pumping ground and underground water or greywater recycling. The energy production could be optimized, for example, by using solar tracking PV modules [57]. For regions with comparatively low solar radiation such as Yakutsk and Puerto Williams, other sources of energy could be explored, which could be wind or geothermal energy or bioreactors. Another solution for such regions would be better energy storage systems, since the total annual energy production is above the annual energy consumption for all module types at each location considered here Table A1. Detailed calculations of the costs and the payback periods, which were omitted in this article mainly because of their high fluctuations, should be analyzed in a further study. Finally, it is planned to run pilot projects to prove the concept and gain practical experience.

The supply container was developed by Nathal Energy® [58] by using the Nathal method®, which is an approach to systematically access the full range of human potential in terms of creativity and intuition. Thus, it is an example of how practical solutions can be developed in relatively short times by using an intuitive method. Therefore, Nathal Energy® aims at linking an education program to the sale of licenses for the production of the supply container to an education program. Preferably, governments of developing countries would buy such licenses, since most of them exhibit a high world risk index and a high degree of solar radiation. It was found that for the population of such countries, the supply container could be a very effective measure to ensure their basic supply in terms of water, electricity and shelter. Finally, the production of supply containers could provide them with new economic impulses.

5. Patents

Autarkic supply container for independent supply of water, cold, heat and power, patented by Dr. Philippe Lathan and Georg Stimpfl, Issued 15 May 2018, number WO2018127731.

Author Contributions: S.P. and B.I. supervised the project and conceived the study. S.P. performed the implementation and computations. All authors analyzed the results and did the final conclusions. S.P. and B.I. wrote the paper with critical input from M.S., P.L. and G.S. All authors have read and agreed to the published version of the manuscript.

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

Appendix A

Table A1. Total annual energy consumption (in kWh) from [19] for each module type at each location compared to the annual energy production of the supply container for each location. The green background color shows that the annual energy consumption of all module types is below the annual energy production at each location.

Energy Demands	Port-au-Pr. *Haiti*	Djibouti *Djibouti*	Colonia *Uruguay*	Yakutsk *Russia*	Puerto Will. *Chile*
first-aid heat	123	171	1412	7422	3850
first-aid cold	3093	2146	545	140	7
Shower	43	60	1841	10,200	5407
Refrigeration	2591	2989	1194	341	98
Freezing	11,400	11,800	11,800	985	8068
Energy production	20,385	21,743	18,279	15,041	11,221

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