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# Evaluating the Implementation of the "Build-Back-Better" Concept for Critical Infrastructure Systems: Lessons from Saint-Martin's Island Following Hurricane Irma

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**Abstract:** A limited number of studies in the scientific literature discuss the "Build-Back-Better" (BBB) critical infrastructure (CI) concept. Investigations of its operational aspects and its efficient implementation are even rarer. The term "Better" in BBB is often confusing to practitioners and leads to unclear and non-uniform objectives for guiding accurate decision-making. In an attempt to fill these gaps, this study offers a conceptual analysis of BBB's operational aspects by examining the term "Better". In its methodological approach, this study evaluates the state of Saint-Martin's CI before and after Hurricane Irma and, accordingly, reveals the indicators to assess during reconstruction projects. The proposed methods offer practitioners a guidance tool for planning efficient BBB CI projects or for evaluating ongoing programs through the established BBB evaluation grid. Key findings of the study offer insights and a new conceptual equation of the BBB CI by revealing the holistic and interdisciplinary connotations behind the term "Better" CI: "Build-Back-resilient", "Build-Back-sustainable", and "Build-Back-accessible to all and upgraded CI". The proposed explanations can facilitate the efficient application of BBB for CI by operators, stakeholders, and practitioners and can help them to contextualize the term "Better" with respect to their area and its CI systems.

**Keywords:** "Build-Back-Better" concept; critical infrastructure networks; recovery; sustainability; resilience; disaster risk reduction

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## 1. Introduction

Critical infrastructure (CI) includes the physical and computer service networks/facilities/assets necessary for the proper functioning of a society and its economy [1] CI becomes even more "critical" in times of natural disaster, as its failure can significantly threaten first responder deployment and emergency management services [2]. The importance of CI further extends into the recovery and reconstruction phases of the affected territories. In fact, the recovery phase begins with the restoration of damaged CI networks. Several studies used the re-establishment of CI networks and their return to normal functioning as indicators for measuring the resilience and recovery of societies (e.g., [3–6]).

When considering the disaster risk reduction (DRR) cycle, the recovery phase is often the most time- and resource-consuming phase [7]. Despite its demanding aspect, recovery is the least investigated and most poorly understood phase [8,9], not only in research but also in practice [10].

The recovery phase consists of activities centered around local redevelopment planning to enhance the pace, location, type, density, design, and cost of redevelopment [11,12]. Recovery also presents adequate time for the implementation of disaster mitigation measures and insights to optimize existing DRR legislation and plans. Rubin et al. [8] found that mitigation measures are immediately accepted following a disaster, i.e., during the recovery phase. Hence, the latter is considered as an opportunity for change, evolution, and development [13–15]. Typical recovery schemes focused on the rapid use of disaster relief funds and long-term finance programs to: (i) rebuild the same structures at the same locations, (ii) build protective infrastructure, and (iii) restore the same hazard-prone areas [16,17]. However, these processes often left the affected area as vulnerable as it was (pre-disaster). Therefore, updated recovery plans now consider increasing the resilience rather than restoring the previous state.

According to Arnell et al. [18]: "*In terms of territorial resilience, networks appear to be a structuring element*." In recent years, decision-makers, stakeholders, and CI operators have shown increasing interest in improving the level of CI resilience, especially after disasters (for example, Hurricane Katrina in 2005, 2010 Haiti earthquake, Fukushima NaTech event in 2011, and Hurricane Sandy in 2012) [19,20]. The reason behind this interest is to ensure the sustained functionality of CI in the face of emerging risks [21]. To situate the logic of this paper, a conceptual discussion of the term "resilience" is needed. Holling [22] distinguished local static resilience from the dynamic resilience of a system. In physical sciences [23] and engineering sciences [24], resilience refers to the ability to cope with shocks and returning to normal functioning or initial condition. This definition refers to the static aspect described by Holling [22]. On the other hand, dynamic resilience is linked to the capacity for renewing, reorganizing, and redeveloping what was [25–27], and hence to "Build-Back-Better" (BBB). BBB appeared in the Sendai framework in priority number four as "*Enhancing disaster preparedness for effective response and to "Build-Back-Better" in recovery, rehabilitation and reconstruction*" and in the guiding principles of risk reduction during recovery as "*In the post-disaster recovery, rehabilitation and reconstruction phase, it is critical to prevent the creation of and to reduce disaster risk by "Building-Back-Better" and increasing public education and awareness of disaster risk*" [28].

Despite its relative newness, BBB is a paradigm shift that allows repeated losses in the situation of recurrent natural hazards to be avoided and the vicious cycle of vulnerabilities towards growth and development to be escaped (Figure 1).

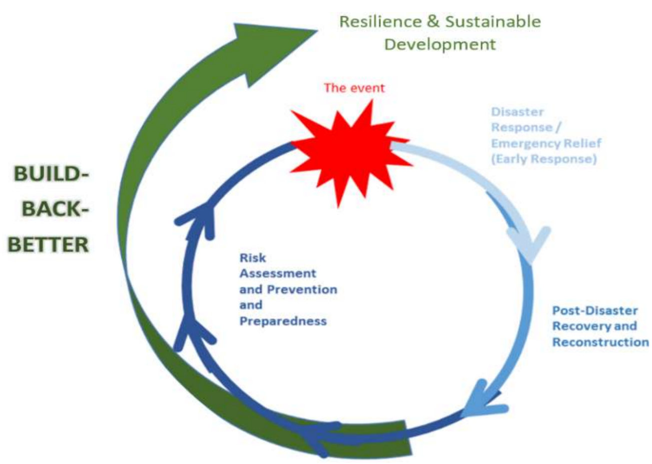


**Figure 1.** Build-Back-Better in the Disaster Risk Reduction cycle, inspired by/adapted from the "adaptation cycle" concept proposed by Gunderson and Holling [25].

Despite the enabling environment offered in times of recovery, the BBB concept remains a desirable goal that is often vague in its application. BBB faces the same difficulties and challenges faced by resilience [29]; therefore, further research on BBB is needed [30]. The existing literature often discusses the theoretical aspect of BBB without tackling its operational angle [31–37]. The absence of a common benchmark to judge the degree of the recovery's success [8] and the BBB's degree of completion adds another layer of complexity. In fact, practical indicators to be used as BBB success metrics are still missing [38]. The application of the BBB concept is further handicapped by the hefty costs of related projects that are needed to finance long-term and uncertain results that may not appear until another disaster occurs. Social (un)acceptance is another limiting factor.

In addition to the above-mentioned elements, the different interpretations of the term "Better" often block BBB at its earliest stages [30]. According to Kennedy et al. [31], the term "Better" can be confusing to practitioners, which is why they favor "Build Back Safer" since, for practitioners, the term "safer" provides a clearer goal. Hallegatte et al. [39] perceive BBB as a means to Build-Back-Stronger (less vulnerable), -Faster (rapid recovery), and -Inclusively (no one left behind).

The concept of Building-Back-Better CI has rarely been tackled in the literature [15,40,41]. The majority of existing papers do not mention BBB CI, but rather focus on the recovery of CI during post-disaster periods, with few ideas for improvement. In addition, very few studies have attempted to discuss the term "Better" for CI networks in a holistic and interdisciplinary approach. Neighboring concepts such as "Build-Back-Smarter" and "Build-Back-Greener" have been proposed [42], while other studies (e.g., [15]) use renewable energy transitions as a measure of BBB.

In light of what was presented, this study aims to provide a better understanding of the BBB concept for CI and its operational aspect, especially in relation to the term "Better". For this purpose, an evaluation of the recovery and reconstruction projects of CI systems in Saint-Martin Island following Hurricane Irma is presented. Saint-Martin was hit at the dawn of 6 September 2017 by Irma, a Category 5 hurricane on the Saffir–Simpson scale, recorded as one of the most severe Atlantic hurricanes, with sustained winds of 185 mph (296 km/h) [43,44]. The hurricane's eye passed directly over Saint-Martin, exposing the island to the highest wind velocities for more than two hours. This was accompanied by a storm surge coupled with high and long incoming waves that caused flooding in the lower coastal areas. Consequently, the electricity, water, telecommunications, and transport networks were considerably damaged due to the combined action of high winds, heavy precipitation, and flooding [45]. Saint-Martin was literally isolated, without electricity, water, or any means of communicating with the outside world. Irma worsened the already fragile CI networks that were already burdened by growing urbanization, pollution, climate change, and aging infrastructure. The CI networks were already old and fragile before Irma. Despite Irma's destructive effect, the post-Irma recovery phase should be considered as a time of major improvement. Accordingly, Saint-Martin and its CI form fertile ground for the integration of BBB. Based on this logic, this paper examines the state of the island's CIs pre- and post-Irma and consequently proposes indicators to assess BBB CI's success. Saint-Martin's BBB CI is evaluated accordingly and additional insights into the BBB–CI relationship are provided.

The paper is organized as follows: Section 2 introduces Saint-Martin, Section 3 presents the adopted methodology, Section 4 illustrates and discusses the obtained results, and Section 5 concludes this paper's findings and proposes perspectives.

## 2. Study Area

The island of Saint-Martin is part of the French overseas territory. It is located in the northeast of the Caribbean Sea (Figure 2) and is divided into two political entities: the southern side of the island is called Sint Maarten and belongs to the Netherlands. The northern section of the island is called Saint-Martin and belongs to France. Marigot is the capital of Saint-Martin, while Phillipsburg forms the capital of Sint Maarten. The island (both northern and southern parts) covers 87 km$^2$, where more than 53 km$^2$ lies on the French side.

A tropical savanna climate characterizes the island. Located within the Caribbean hurricane belt, Saint-Martin is characterized by a dry and sunny season, with warm temperatures (25 °C on average) during the January–April period and a wet–hot season (28–30 °C) extending from August to December. The wet season is characterized by heavy rainfall and low atmospheric pressure, which often leads to the occurrence of cyclones and hurricanes, particularly from September until mid-October. Since 1995, Saint-Martin has been exposed to numerous hurricanes, including Donna in 1960 (Category 4), Luis and Marylin in 1995 (Category 4), and Jose and Lenny in 1999 (Category 3). The occurrence of these hurricanes caused multiple destructive disruptions to the island's living conditions, infrastructure, and economic activity. The insular character and the small surface of Saint-Martin multiply the effects of hurricanes, leading to a nationwide extension. Besides the nationwide propagation of hurricanes' damages, the recurrence of these disasters questions the effectiveness of the post-disaster recovery and BBB processes. It has been noticed that political and legal constraints in Saint-Martin greatly reduce the effectiveness of BBB. Nonetheless, slight progress has been observed after the occurrence of the above-mentioned hurricanes, especially in terms of prevention (system of early warning and risk prevention plans) [46].

In terms of sociodemographic characteristics, the island has been experiencing rapid population growth since the early 1980s [47]. The population was estimated at more than 35,000 in 2017 by INSEE (French National Institute of Statistics and Economic Studies), compared to only 8072 in 1982. This created considerable challenges to match population growth with infrastructural development. The rapid population growth also triggered demographic pressure, especially in the coastal areas of Saint-Martin. Accordingly, the greatest concentration of housing, industries, infrastructure, and CI networks (roads, airport, sewage plant, thermal power plant, etc.) is found in the lower coastal areas (Figure 2). Given Saint-Martin's location in Hurricane Alley, the concentration of CI in low coastal lands increases the exposure to cyclonic hazards. Without appropriate preventive measures, the island is becoming increasingly vulnerable.

According to Arnell et al. [18], CI networks in Saint-Martin are considered complex and are compared to underdeveloped reconstruction sites. Despite their state, CI networks are of major importance to the island: (i) they compensate for the absence of raw resources for supplying the networks, absence of freshwater, etc.) and (ii) they provide means and services for the island's tourism-based economy, hence the importance of rebuilding the island's CI to BBB standards.

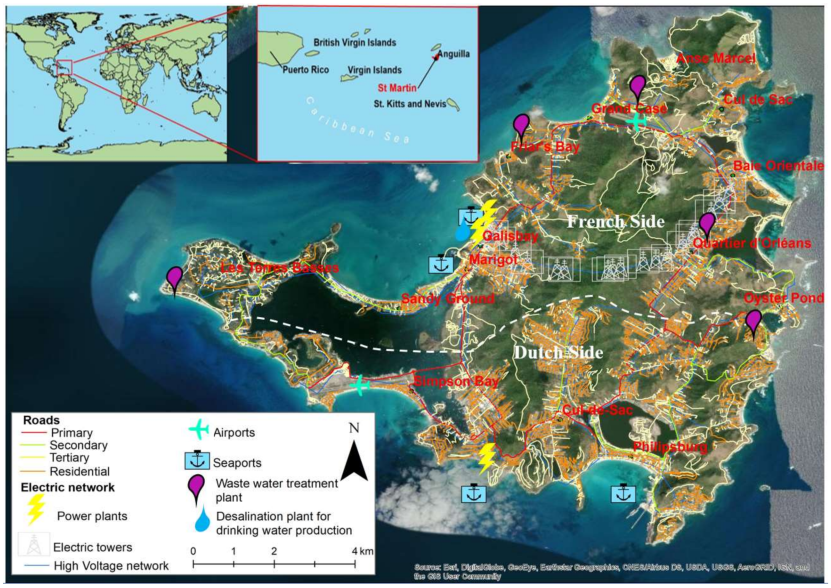


**Figure 2.** Saint-Martin's location and main Critical Infrastructure networks.

## 3. Materials and Methods

The proposed methodology aims to give a better understanding of the BBB concept for CI systems by defining the term "Better". The approach consists of examining the operational aspect of the BBB concept for critical infrastructure systems by analyzing a real-life disaster scenario. Saint-Martin's CI reconstruction projects, in the aftermath of Hurricane Irma, are analyzed following a desk research/document analysis with the help of structured interviews. More precisely, this study conducts a three-step qualitative assessment of CI before, during, and after Irma's occurrence, with a focus on the reconstruction projects' will to solve existing CI problems. Figure 3 summarizes the adopted methodology.

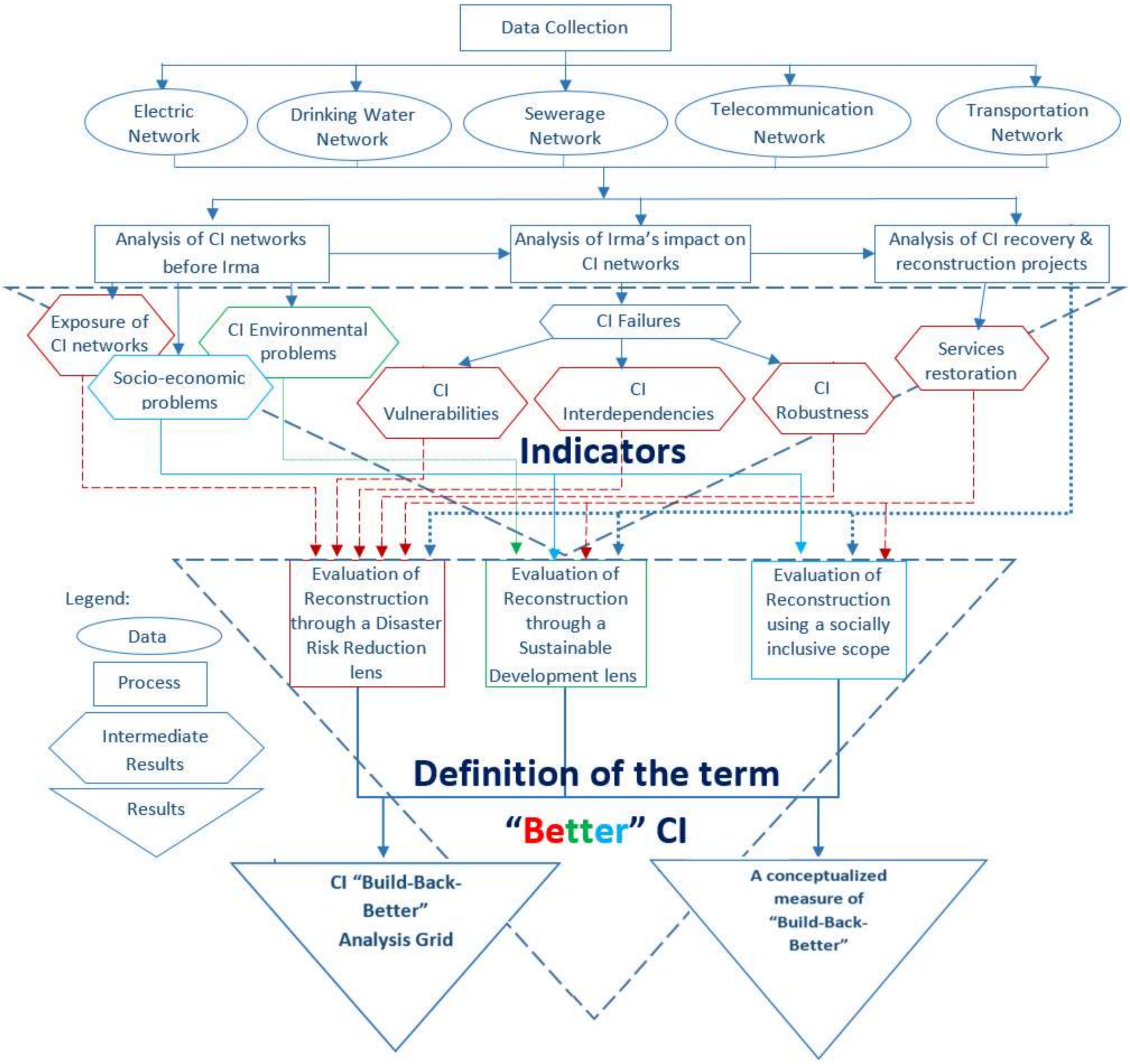


**Figure 3.** Flowchart of adopted methodology to evaluate the Build-Back-Better Critical Infrastructure concept applied to Saint-Martin in the aftermath of Hurricane Irma.

Qualitative and quantitative data were collected from reports, studies, press releases, news feeds, or newsletters from the websites of local authorities and network operators in Saint-Martin and through crowdsourcing/social media. This analysis was supplemented by open-ended interviews that took place on the island and in Paris during the "Retex Irma" conference organized by the French High Committee for Civil Defense (HCFDC), on 13 September 2018, at the French Insurance Federation (Paris). A considerable part of the collected data was from the daily situation reports of the French Directorate General of Civil Security and Crisis Management (Direction Générale de la Sécurité Civile et de la Gestion des Crises—DGSCGC) and the French Interministerial Crisis Management Operational Center (Centre Opérationnel de Gestion Interministérielle des Crises—COGIC) [48]. These reports offered detailed information about the impact of Irma on CI networks, the daily progress of recovery, and the evolution of reconstruction processes.

All of Saint-Martin's CIs were studied: electricity, potable and sewage water, telecommunications, and transportation (roads, airports, and seaports) networks. The analysis was carried out at the level of each CI and included four main steps: (1) analysis of CI state before Irma, (2) analysis of CI damage from Irma, (3) analysis of the CI recovery, and (4) examination of the BBB aspect in the proposed reconstruction projects.

Step (1) Analysis of CI state pre-Irma: Building an inventory and examining all the already observed CI-related issues.

Step (2) Analysis of CI damage from Irma: Uncovering the underlying CI problems that were revealed by Irma.

Step (3) Analysis of the CI recovery: Investigates the early recovery of CI (service restoration) and uncovers more CI-related problems.

The logic behind steps (1–3) is to offer a better understanding of the term "Better" in CI and to propose a conceptual measure of the BBB CI concept by revealing related indicators.

Step (4) Evaluation of the BBB aspect in the proposed reconstruction projects: Exploring, according to proposed BBB CI indicators, the improvements that can be offered by the proposed reconstruction projects and whether these respond to the revealed underlying problems from steps (1–3). This analytical work is summarized in a BBB CI evaluation grid to highlight the main findings of the study.

## 4. Results and Discussion

This section presents the obtained results in two parts. Part 1 reveals the state of each CI network in Saint-Martin before and after Irma and part 2 uncovers the results of the BBB evaluation and highlights the main findings of this study.

### *4.1. Assessment of CI Pre- and Post-Irma*

The quality of the reconstruction projects and the efficient implementation of the BBB concept depend on knowing beforehand what worked and what did not [28].

This section sheds light on each CI network's specific problems revealed before Irma, during Irma, and finally during the early recovery phase.

#### 4.1.1. Electric Network

Before Irma, electricity production in Saint-Martin was mainly (99%) provided by two thermal plants operating on diesel-powered engines [49]. The production generated by photovoltaic systems, with solar panels on roofs connected to the electricity network, was marginal, not exceeding 1.8 MW (1% of electricity production). Diesel is imported by sea. In addition to increasing production costs and the ecological footprint of the island's inhabitants, the use of diesel led to the complete dependence of the electricity system on heavy fuel oil supplies. Accordingly, the electric network became dependent on the transport networks (road and seaports). The two thermal power stations are located on the same site in Calisbay, Marigot, in the coastal areas. Both power plants are operated by EDF (Electricité de France). However, one is owned by EDF while the other is owned by ContourGlobal/Energie Saint-Martin. The EDF plant, put into service in 1976, provides a total power of 42.5 MW from four 4.1-MW generators (operationalized between 1992 and 1995), and three 8.7-MW generators (operationalized in 2016). This power station supplies an electricity network of 127 km of medium voltage lines and 196 km of low voltage lines and serves around 17,800 customers. The second plant, equipped with three 4.7-MW generators (operationalized in 2003), provides a total power of 14.1 MW [50]. Both thermal plants had an excess production capacity, inducing additional production costs. The controllable production capacity in Saint-Martin reaches 56.6 MW, almost twice the peak consumption, which amounted to nearly 31 MW in 2017. This oversizing, also called reserve margin, is not uncommon in island electrical systems as it is useful given that technical problems may take longer to be resolved (import of a spare part, etc.). However, the electrical network suffered shortcomings and failures long before Irma, with outages of up to 473 min per year. In terms of power distribution, the network is divided into high-, medium-, and low-voltage transmission lines, mostly overhead/above-ground. It is also noteworthy to mention the abusive use of low-voltage transmission lines and electric poles on which are entangled television and telephone cables.

The impact of Irma on electricity production can be considered moderate. The two thermal power plants did not suffer irreparable damages but were temporarily flooded. This led to an immediate total blackout that lasted for several days on almost half of the island [48]. This blackout revealed the weakness and the vulnerability of the electrical network as a result of its location in the flood-prone coastal areas. In addition, this blackout pointed out another vulnerability in terms of the production based on a single non-renewable energy source (diesel). The absence of solar energy, absence of wind energy due to topographic factors, absence of hydraulic energy due to a deficit in water resources, and the absence of geothermal energy due to the geological characteristics of the island are the main reasons for diesel dependence. Moreover, another element of vulnerability was revealed: the disconnection of Saint-Martin's Northern French and Southern Netherland sectors. Surprisingly, in an isolated territory like Saint-Martin, the electrical network is not connected to an external backup system (from another neighboring island) that could compensate for a breakdown. This isolation of the electrical network aggravates the mono-productive nature of the network and therefore reduces its redundancy. A significant proportion of the photovoltaic panels was destroyed by wind. While the production system suffered little damage, the distribution network was significantly damaged. Almost all of the overhead power grids were totally or partially destroyed. Moreover, 26 out of 233 substations and transformers were destroyed [49]. However, the underground network remained operational.

In the aftermath of Irma, hundreds of experts (in the island and from abroad) were mobilized to restore the electrical network [51]. The vital and priority sites (hospital, desalination plant, airport, etc.) were quickly replenished with electricity (from 8 September 2017), and on 15 October 2017, power was restored throughout the network [48]. Service resumption in five weeks is considered a record time compared with Puerto Rico, where more than half of the population remained without electricity three months after the occurrence of Hurricane Maria [52]. Although power generation was restored some three weeks after the hurricane, distribution required additional time. Before the complete restoration of the service, an emergency power supply was provided by one hundred generators transported urgently from France [48], which again uncovers the lack of redundancy. The restart of the production units was delayed due to an interdependence with the water network. Demineralized water was indispensable to cool the generators.

The electrical network reconstruction phase did not officially start until August 2018 with the official signing of the contracts. The strategy was based on undergrounding 100% of the network, which presents an opportunity to ensure resilience in the face of hurricanes [48] and protect the network from floods, landslides, and seismic risks. In addition, undergrounding offers a guarantee of safety and continuous service for users. Network reconstruction and undergrounding operations were financially supported by EDF and state funds of up to EUR 14.7 million [53]. Undergrounding raises the question of the necessary coordination with the operators of other networks, specifically those of telecommunications. Due to the plurality of operators in Saint-Martin, the community can play an important coordination role. EDF announced later in 2019 a new strategy, indicating that the high voltage network will remain mostly overhead because its mechanical dimensioning allows it to withstand hurricanes and must be repaired very quickly. Medium- and low-voltage substations were also reconstructed identically to the pre-Irma situation. This reconstruction also offers an avenue for adjusting production capacity for demand and user consumption in Saint-Martin. In fact, the controllable production capacity in Saint-Martin is twice the peak of consumption (overcapacity). In addition, following Irma, there has been a considerable drop in activity and therefore in the level of consumption. In this situation of reduced consumption, the risk of load shedding and blackout is also accentuated. However, the evolution of consumption in Saint-Martin is challenged by many uncertainties (tourism, exodus, reconstruction activity, roof insulation, installation of solar water heaters, development of electric vehicles, etc.). EDF also stresses that reconstruction represents an opportunity to operationalize the island's energy transition to control energy demands by a 33% gain in energy savings by 2023. This transition is expected to take place through help programs that enable individuals to re-equip their houses with high-performance equipment [54]. EDF also wants to gradually transition the country's energy matrix from a fossil-fuel-based system to a least-cost energy matrix, with an increased contribution from clean renewable alternatives from 1% to 22% by 2023 [54].

4.1.2. Potable Water Network

Saint-Martin is a dry island, without watercourses or fresh water sources. The underground water resource of the island remains, to this day, poorly understood and barely exploited. Potable water production is completely carried out by a single desalination plant. The latter, put into service in Galisbay in 2006, is a reverse osmosis filtration plant that treats sea water and produces 5000 $m^3$/day [55]. This plant is considered to be aging and consumes significant energy (4.5 kW/$m^3$). The potable water distribution network, serving around 45,000 people (15,000 subscribers), is divided into pumping stations, 141 km of pipelines, and 55 km of connections (20,000 connections). Six storage facilities/reservoirs exist in Saint-Martin, with a total capacity of 16,000 $m^3$, equivalent to only three days of production [56]. According to Chambre territoriale des comptes de Saint-Martin [57], the performance of the potable water network was only 63.5% in 2016, resulting in a chronic shortage of potable water. The relatively poor service was considered expensive [57] and led to more than 20% of unpaid bills. Before the occurrence of Irma, the potable water service had multiple operators: Veolia was the service provider for the water production part, while EEASM (l'Etablissement des Eaux et de l'Assainissement de Saint-Martin) and GEG (Générale des Eaux Guadeloupe) were responsible for all public services related to water after its production (water distribution, reservoirs and network renovation and maintenance, etc.) [58].

Irma heavily damaged the potable water network, resulting in total service disruption. Both the production plant and distribution network were completely out of service [59]. The desalination plant was severely affected, with collapsed roofs and walls and flooded electrical controls [60]. The head of the desalination plant's sea inlet pipe was blocked. Damage to supply pipelines (1.7 km of pipes was destroyed or seriously damaged) and boreholes was significant, leading to underground leaks and risks of contamination and sanitary problems due to overflowing of septic tanks [48]. This total cut-off of potable water revealed the vulnerability of the network in terms of exclusive production from a single desalination plant located on the coast and therefore highly exposed to hurricane hazards and high sea levels/waves. Almost all reservoirs were destroyed; only 10,000 $m^3$ of water remained in stock [61]. This volume is equivalent to only two days of standard supply. The occurrence of Irma pinpointed the low redundancy of the potable water network in Saint-Martin and the need to design more water towers.

To put the Saint-Martin potable water network back into operation, immediate interventions by local and external teams were necessary. Restoring the potable water network first required the reestablishment of the production capacity as quickly as possible, followed by a sectoral approach (sector-by-sector recovery strategy) for repairing the distribution network [48]. The unavailability of pumping equipment and the insufficient number of local experts hampered the rapid restoration of this service. The island lacked emergency water production units. Three weeks after Irma, emergency water production units (600 $m^3$/day) transported by plane arrived at Saint-Martin [61]. The potable water production did not resume until 22 September, and with a capacity that did not exceed 30% of the production before Irma [59]. On November 2nd, more than a month and a half after Irma, water production was completely recovered [48] and with a considerable improvement in the production capacity, which is now 9000 $m^3$/day, almost twice the capacity before Irma. As for the distribution network, it became fully operational 14 months after the occurrence of Irma, and 100% of the access to the service had been restored by November 2018 [48]. The restoration of the potable water network in Saint-Martin was slow and laborious due to several factors, such as the quality of buildings and urban development, the lack of manpower, violence to agents and theft of equipment, and, most importantly, the dependence of the water network on the electrical and transport networks.

As a reconstruction plan, Veolia considered structural improvements to protect the desalination plant and decrease its vulnerability. This plan has not been implemented since Veolia did not renew its contract as a service provider in Saint-Martin in early 2019 because of the significant percentage of unpaid bills. SAUR (Société d'aménagement urbain et rural) then took the lead and is now 100% responsible for the potable water service: production and distribution, network maintenance, invoicing, etc. [62]. The potable water network has now a single operator, which is considered an improvement since cooperation is now guaranteed and operations can be facilitated and carried out more quickly. While production has improved considerably, the distribution network performance dropped from 63.5% before Irma to 56.7% in the early recovery period, which means that almost one in two water liters produced did not reach the consumer and were therefore unbilled. SAUR's reconstruction plan aimed to reduce leaks by renovating the network and improving water system management hardware and software in order to reach a percentage of 79.6 for network performance in 2028 [63]. This improvement will notably go through the operational control center located in Martinique or through the deployment of active listening technologies in order to detect and locate leaks in the networks. In addition, SAUR promises a comprehensive diagnosis and significant technical improvements in the desalination plant. The objective is to halve the energy consumption of the reverse osmosis process (currently 4.5 kW/$m^3$ with a cost of EUR 800,000 per year). SAUR also intends to improve performance in terms of customer relations by managing unpaid debts, which today amount to 20% [63]. SAUR's objective is to reduce unpaid bills to 5% by 2028, by putting in place payment methods that are suitable for families with financial difficulties. They also aim to facilitate payment processes by allowing payments via local relay shops [64]. Projects to improve emergency reserves and response through the construction of another desalination plant and the optimization of water tank storage through two retention basins of 140,000 $m^3$ in areas far from the coast are under discussion. However, these require considerable funds.

#### 4.1.3. Sewerage Network

The sewerage network in Saint-Martin is made up of a 68-km-long pipeline network, 29 sewer discharge stations, and six wastewater collection basins of various sizes for six wastewater treatment plants (WWTPs) that treat 960,000 $m^3$ and serve 10,000 users. Saint-Martin also houses 4000 non-collective sanitation facilities (NCF) that account for 40% of the network. Long before Irma, the sewerage network and its related services were considered poor, dilapidated, aging, and undersized. In some neighborhoods, wastewater treatment is minimal or even non-existent (around 33%). In response to this situation, discharges are directly dumped into the natural environment. Extreme weather and sea salt wear out the already fragile equipment and shorten its lifespan. In addition, the rapid development of the territory and the high influx of tourists exert considerable pressure periods during which wastewater is left sometimes untreated. Only a small part of the generated sludge is used for the production of compost. Similar to the potable water network, the sewerage network had multiple operators before Irma complicated operations; these were Veolia, EEASM, and GEG. Furthermore, the majority of WWTPs and sewer discharge stations are located on the coastline, close to the sea, and are therefore highly exposed to hurricane hazards and high sea levels/waves. For example, the WWTP at Pointe des *Canonniers*, having the highest treatment capacity, is located just 53 m from the sea.

Irma caused extensive damage to the already fragile sewerage network in Saint-Martin [58]. Four out of six WWTPS were completely damaged, while the remaining two were totally destroyed. Flooding further damaged or destroyed the discharge stations [48]. Saint-Martin's sewerage network also showed direct failures due to the disruption of the electrical network. The sewer networks were blocked, and septic tanks overflowed, causing contamination and health problems. According to Latreille [58], apart from health risks, the damages led to discharges being directly routed into the sea.

The restoration of Saint-Martin's sewerage network was delayed due to the unavailability of experts, spare parts, and equipment on the island. Collectively, these factors reflected a poor level of resourcefulness [48]. Restoration was also delayed due to the dependence on the road and telecommunication networks. The staff encountered challenges to reach their workplace and to cooperate with each other from different spots [48]. Two of the damaged WWTPs were left out of service due to missing electronic boards. It was only until 2 November 2017, almost two months after Irma, that a single WWTP was restored. Two other WWTPs followed and became operational on 1 September 2018. Almost a year after Irma, three out of six treatment plants were still not functioning. In the same manner, only one of the 29 discharge stations was functional since it was completely replaced [48]. The restoration of the sewerage network service in Saint-Martin has proven to be a gradual and fairly time-consuming process.

In terms of sewerage network reconstruction projects, the general idea is to rebuild better while respecting the environment. EEASM announced its commitment to take into account the risks encountered during Irma, such as high sea levels/waves, debris impacts, and power supply interruptions, while putting into place preventive measures. The latter would consist of protective structures, improvement of infrastructure robustness, and permanent assessment/audit of the networks' functioning [65]. No relocation of heavily damaged WWTPs has been planned. Completely destroyed WWTPs will be replaced by new stations at the exact same locations. As in the case of the potable water network, SAUR has replaced Veolia and is committed to improving the performance of the existing WWTPs by implementing a centralized and optimized management control. SAUR also aims to build a new biological WWTP that takes into consideration post-Irma constraints [63]. The new station alone, with its considerable capacity, will be able to treat nearly 50% of the pollution generated by Saint-Martin's population. SAUR focuses on improving the efficiency and rapidity of return to normal performance after a disaster since, according to them, it is impossible to mitigate the impacts of hurricanes. Particular attention will also be given to the quality of discharges reaching the sea.

#### 4.1.4. Telecommunications Network

Saint-Martin's IT or telecom infrastructures are divided into four networks: (1) undersea network, (2) cable network (TV and internet), (3) mobile network (18 stations), and (4) Digital Subscriber Line (DSL) network. The complexity of the telecommunications network comes from its management by several operators/service providers: Orange (national level), Digicel and Dauphin Telecom (local companies), UTS, TDF, and COS (Canal plus Overseas) [66]. However, multi-party management offers service redundancy, which can be considered as a strong point. Prior to Irma, the distribution system consisted of above-ground and buried transmission lines that were in the form of traditional copper (13,300 telephone lines) and coaxial cables. Transmission capacities on the landline copper network are limited and become weaker with distance from the subscriber's home. In addition, the signals, carried over a shared coaxial cable television and Internet, are regenerated regularly using broadband amplifiers to compensate for the weak performance of cables. The coverage of the territory at high speed and very high speed is also not equally distributed between all neighborhoods [66]. It is important to point out that landline, Internet, and mobile networks are highly dependent on electricity.

Telecommunications networks in Saint-Martin sustained significant damage during Irma, primarily due to strong winds (additional damage was caused by exposure to wind-driven moisture and rainfall) [18]. Hurricane Irma damaged installations, mobile high points, subscribers' connection nodes, above-ground and undersea cables, relays, pylons, and antennas and destroyed nearly half of Saint-Martin's overhead wired telecommunications networks (around 90 km of networks hosted on air carriers) [48]. Moreover, telecommunications were completely cut off on the island due to major damage to the power plants, revealing the interdependency of telecommunications networks to the electrical network [67]. The island was completely disconnected, devoid of any kind of communication just seconds after the hurricane [18]. There was a total blackout of radio, television, landline, mobile, and Internet services for more than 72 h. The only possible communication forms were ensured by approaching the neighboring British island of Anguilla, 13 km north of Saint-Martin [48]. This obviously had important consequences for first aid and crisis management operations. Irma's occurrence revealed that Saint-Martin's telecommunications networks were not robust.

All the operators' teams were mobilized on Saint-Martin to restore the telecommunications networks as quickly as possible with the aim of reconnecting the island. Technicians and equipment were brought from abroad. The urgent need was to cover the territory in terms of service coverage and reconnect all subscribers. The restoration of telecommunications networks began with the restoration of the mobile network and lasted eight to 12 weeks, depending on the operator [48]. Mobile coverage maps were established by ANFR (Agence Nationale des FRéquences) on a periodic basis in the aftermath of Irma. These maps, along with the calendar for restoring mobile network stations, showed an unequal spatial distribution of recovery over time. Mobile services were first restored in the capital and in relatively wealthy neighborhoods. The mobile network was first restored given its low dependency on the electric network [67]. In fact, this interdependence was also revealed during the recovery period. Even when connectivity was restored, access to some telecommunication networks was impossible due to weak electrical supplies. Further dependence on electricity was observed in the case of Internet and landline networks. Telecommunication boxes are directly supplied with energy by the subscriber's electrical network via metal segments. The Internet connection also depends directly on the landline network. The restoration of both networks was delayed because operators did not have a quick breakdown of the damage; as a result, restoration activities did not begin until 11 September [48]. Regarding radio and television channels, the recovery was achieved in five days following the restoration of the main transmitter at Pic Paradis. Restoring the mobile network was considered relatively slow, and landline and Internet network restoration was extremely slow as a result of improvement plans for optimization through the introduction of a fiber optic system.

Irma's occurrence revealed that the reconstruction of the telecommunications networks was a necessity for making them less vulnerable and more robust to weather events such as Irma. Reconstruction was also envisaged to improve the quality of service and achieve "digital growth". The reconstruction strategy focused on developing resilient communications infrastructures with built-in redundancy to ensure that communications remain uninterrupted throughout the island. Irma's consequences accelerated plans that were already decided but never implemented. According to Orange, reconstruction projects will mainly focus on replacing conventional copper with optical fiber (more resilient because it is independent of telephone networks and cables), transitioning to underground [65] and more secure networks. Further steps include the installation of technical measures that can limit damages, reinforcing towers' structures, systematizing underground supply of housing, securing international connections with redundancies of undersea cables, and optimizing the architecture of terrestrial networks. These projects are long and costly and require governmental funds along with a coordination between operators and local authorities. For the operator Dauphin Telecom, reconstruction is an opportunity to build infrastructure differently—for example, creating shared mobile sites between operators and building underground networks even if underground civil engineering is more expensive than overhead. One of the other objectives is to put an end to degraded Internet access and ensure maximum coverage of the territory at high and very high speeds. Accordingly, several subscriber connection nodes will be established (for example, new subscriber connection node in *La Savane*, to increase Asymmetric Digital Subscriber Line (ADSL) coverage in the Grand Case district). Among the luxury services, the provision of very high-speed connections appears to be an essential element in welcoming tourists. Therefore, the reconstruction of these networks should tackle the question of their resilience in the face of climatic hazards. As part of reconstruction plans, local operators have also decided to work on improving the redundancy of their equipment and to install generators where necessary [53].

4.1.5. Transportation Network

Transportation networks in Saint-Martin are divided into: (1) road network, (2) seaports, and (3) airports. The road network is characterized by a scarcity of traffic lanes and consists of:

- A single main road (RN7) of nearly 16 km, circling the island by the coast to avoid inland hills;
- 17 km of secondary roads, and tertiary and residential roads.

The RN7 exhibits an average of 20,000 vehicles/day and is considered to be saturated. Traffic jams are very common throughout the day, with the only coastal road regularly congested by tourists and residents. A considerable under-sizing is observed for the road network that was designed in the 1980s, when the territory of Saint-Martin was six times less populated than it is today [56]. Furthermore, the single-line typology of Saint-Martin's road network reveals a lack of redundancy and increases its vulnerability. A single main road means that, in some places, and in the event of a road block, no secondary roads or detours exist. Secondary, tertiary, and residential roads are also narrow, mainly due to topographic factors, and are not always sufficiently signposted. Traffic jams are accentuated particularly during rain events. Urban storm water runoff and the resulting flash floods are a persistent problem in some places, aside from development activities and increased coverage of areas with impervious surfaces. Inadequate drainage affects private property and the sustainability of small businesses. On the other hand, the climate is harsh for the asphalt and the local bridges and roadways, and most roads are frequently under repair. The main maritime communications routes on the island are the ports of Galisbay and Marigot on the French side [65] and the Pointe-Blanche port complex of Phillipsburg on the Dutch side. Saint-Martin is dependent on "Sint Maarten", which houses the main seaport, Philipsburg Harbor. This harbor is a significant port for cargo operations and cruise tourism in the Caribbean, with an annual average of 1.8 million cruise-ship visitors. The port establishment of Saint-Martin (30,000 $m^2$ of land, 200 m of quay with 6.5 m of draft corresponding to the reception of ships of 120 to 130 m maximum) transits 300,000 T of goods (equivalent only to 25% of the island's traffic) [57]. The port of Marigot receives passengers (300,000 passengers per year) through the Marigot ferry terminal from neighboring islands at around fifteen trips per day via low-capacity cruise ships. It is important to note that the freight sector, which also depends on the Dutch part, is vital for the functioning of the infrastructure networks and for the economy of the island. Not only does it generate income, but it also provides the majority of food and products needed by Saint-Martin's inhabitants via seaway importation. The well-managed operation contributes significantly to the health and wellbeing of the island's people. Saint-Martin has also many large and small private marinas for yachting; most of these marinas were built 50 years ago and are considered dilapidated. The airport of the French part of Saint-Martin is Grand-Case Espérance Airport (SFG). The airport has an average of 8000 commercial flights, 4000 flights, and 160,000 passengers per year and is only connected by direct flight to Saint Barthélemy, Guadeloupe, and Martinique [65]. In fact, its runway is too short to accommodate large-capacity planes and can only accommodate light transport planes and helicopters. The runway requires an extension of around fifty meters. Saint-Martin is therefore dependent on Sint Maarten's Princess Juliana International Airport

(SXM), considered an important hub for regional travel, with a large network of connecting flights across the Caribbean and approximately 1.8 million in annual passenger traffic. The insular character of Saint-Martin makes all of the transport infrastructures, and specifically the seaport and airport, strategic elements in business-as-usual situations and especially during relief interventions. The insular character of Saint-Martin also makes all CI networks dependent on transportation infrastructures. The road network, in turn, depends partially on the electrical network for lighting and road traffic signs. The port also depends on the electrical network and the road network for its operation. As for the airport, it depends on the electricity network, drinking network, sewerage network, Internet and landline networks, and on the road network.

Damage to the roads due to Irma's occurrence was relatively minimal and consisted of road blockages (more than 76% of roads) by boat debris, trees swept by winds, blown roofs, etc., and some pothole formation damage to road surfaces [68]. Irma revealed that Saint-Martin's roads were the most robust among all critical infrastructures on the island. Road signs were also torn off, and the remaining ones were not functional due to electricity outage. Moreover, 85% of street lighting was severely damaged, and 53% of the 1589 lights installed along public roads disappeared after 6 September 2017 and 32% were heavily damaged [48]. Gasoline was also unavailable.

All of the above-mentioned factors made it impossible for the first responders to reach the most affected areas and hospitals. Further, experts' access to damaged sites for CI service restoration was also impossible. The port of Marigot was severely damaged. Galisbay Port was not destroyed but other related facilities were damaged due to wind and wave damage or debris-induced blockages [69]. The port was still operational the day after Irma and guaranteed the only maritime connection of the island with the exterior [70]. All marina facilities were severely affected; some were completely destroyed, while others were heavily damaged and put out of service [48]. Almost the entire naval fleet was destroyed by winds and waves. Limited damage was observed at Grand-Case Espérance Airport (SFG), which remained operational and was able to deliver material and other aids, as the first aerial reconnection of the island with the outside.

Directly after Irma, there was a mobilization to restore the transportation services in Saint-Martin to quickly reconnect the island with the outside world [18]. The beginning of Saint-Martin's recovery started through the restoration of transportation networks. It was necessary to restore roads, seaports, and airports to transport the materials and human resources necessary for the restoration of all CI networks. The civil security military units, supported by local firefighters and pre-positioned soldiers, including gendarmes, began road-clearing operations, thus allowing the rapid restoration of roads [69]. However, for two weeks, the lighting poles on the roads were not functional. The port was opened first for military purposes only after the emergency clearing of land routes, nautical accesses, installations, and docks and verification of their condition. Following this phase, the port gradually opened for the transportation of goods [48]. As a result of a major power cut, the port was equipped with two generators, which increased its redundancy level. The activity of Marigot port resumed on September 10th 2017. However, due to the state of its infrastructure after Irma, its activity was subject to several constraints. As for the marinas, only two became partially functional and only after a long time following Irma. The other marinas were still out of service. Air links from Saint-Martin resumed through SFG Airport, almost a week after Irma. These were focused first on humanitarian aid and evacuation and then on commercial flights. Passenger flights were resumed in December 2017.

Although the road network presented several weaknesses long before Irma, the reconstruction of the roads was not a priority. This may have been due to the robustness that the road network structures displayed in the face of Irma. On the other hand, it was necessary to rebuild but also rethink the road lighting. A reconstruction project was already prepared before Irma under a development aid contract. This project consisted of putting all public lighting back into service within two to three years while offering an opportunity for improvement for saving energy. This step was envisaged through the usage of LED bulbs [18] that require 70% less energy and are aesthetically better. LED bulbs also guarantee an optimum mechanical resistance to future climatic events (replacement of aluminum by concrete or galvanized steel, transition of all power supplies to underground). Regarding the commercial port of Galisbay, even if its damage was limited and despite its activity being enhanced after the disaster (the main port located in the Dutch side was out of service), Irma revealed the limits of this port and the fact that it was undersized. In fact, the materials needed for reconstructing the island are expected to place the port under pressure. Thus, the port authorities have reaffirmed their interest in the extension of the port [70]. Irma legitimizes this project, which was already envisaged. It allows trade to be deployed to neighboring islands, to rebalance traffic between the northern and the southern parts of the island and to give Saint-Martin independence in terms of maritime traffic. The port of Galisbay could also become the base port for medium- and high-end cruise lines, which could benefit tourism. The reconstruction strategy also emphasizes the restoration of the marinas to full operation and ensuring their future resilience by the installation of solid concrete docks and other construction methods. An example is the construction of a dike to protect the Marigot marina. Irma also revealed the limited capacity of Grand-Case SFG Airport (the A400M humanitarian planes were unable to land on its runway) and this was the main reason behind a project to expand the airport and its runway. This project was planned in 2012 but was forced into action by Irma. This project will allow the airport to accommodate large aircrafts and thus capture part of the aviation activity of Sint Maarten's Princess Juliana International Airport (SXM) or that of neighboring airports. The reconstruction strategy focuses also on repairing the damaged facilities of the airport to higher standards and ensuring resilience to future disasters [65].

### *4.2. Evaluation of the BBB Aspect of Reconstruction Projects*

Based on the reveled infrastructure shortcomings in Saint-Martin, BBB CI indicators are presented below.

Some weaknesses were observed before the occurrence of Irma; these mainly led to the following indicators: a BBB CI's success can be measured by its improvement with respect to (i) the networks' exposure to the cyclonic hazard (due to the constrained size and configuration of the territory, and the rapid population growth on coastal areas), (ii) socioeconomic (sub-indicators: aging infrastructure, inaccessibility, high prices, poor services, etc.) and (iii) environmental (sub-indicators: use of non-renewable energy, pollution, etc.) issues. Access to some CI services seemed to be a privilege that was not afforded to everyone, and even the quality of services differed from one neighborhood to another. To overcome this inequality, the island's inhabitants turned to two solutions: "resourcefulness" or "illegality". Resourcefulness means that residents resorted to alternative means, such as individual generators to become independent of the grid. Other inhabitants were illegal consumers who diverted the network to access services without paying. The problem with these practices is that they can be a danger for inhabitants, a source of loss for operators, and sometimes cause service degradation. Furthermore, some of the pre-Irma CI networks were very polluting. Wastewater was discharged directly into the sea [58], electricity was supplied by generators running on diesel, the desalination plant consumed a considerable amount of energy, etc.

The occurrence of Irma served to reveal some other dysfunctions, leading to more BBB CI indicators. Irma offered an actual worst-case scenario, with on-site observations and validated facts both during CI's response and the recovery phase. Analysis of CI damage from Irma revealed the following BBB CI indicators: a BBB CI's success can be measured by its improvement with respect to (i) underlying vulnerabilities, (ii) robustness, and (iii) interdependencies translated by networks' failures. Robustness is an important dimension of a CI network as it denotes its ability to cope with damage caused by a disastrous event without losing its functionality [71–76]. The hurricane's occurrence clearly demonstrated that the island's CI were, in their majority, not made to withstand and cope with such a disaster.

The analytical work of the post-Irma period uncovers the following BBB CI indicators: a BBB CI's success can be measured by its improvement with respect to (i) CI interdependencies in times of recovery, (ii) their resourcefulness/recovery speed, and (iii) socioeconomic inequalities. Recovery patterns revealed discrepancies in terms of restoration time and location as dictated by socioeconomic inequalities. Recovery speed is another important dimension of CI networks. It implies the technical and organizational ability to restore a network's service in the shortest possible time and its return to full operational mode [71,72,76,77]. Recovery speed can be explained by resourcefulness, which is "*the availability of various types of human, financial, and infrastructural resources during planning, absorption, and recovery stages*" [78]. A common lack of resourcefulness for all CI networks in Saint-Martin was revealed in the aftermath of Irma during the period of early recovery: there was a lack of human resources (experts, technicians, etc.) and equipment on the island. Moreover, a lack of redundancy/high dependency on other CI services was also observed. All these problems related to CI networks caused the slow recovery of the systems and consequently of the entire island.

The conducted assessment of CI before, during, and after Irma revealed that BBB CI indicators can be divided into:

(1) Resilience aspects (indicators responding to exposure to hurricane hazards, vulnerabilities, lack of redundancy, lack of robustness, slow recovery speeds, and high interdependency levels);
(2) Environmental and sustainable indicators;
(3) Socioeconomic development indicators.

The proposed indicators should be supplemented by national, sub-national, and CI-network level indicators to cover the CI issues relative to each context.

Evaluating the implementation of BBB involves an examination of the term "Better", which connotes an improvement relative to a prior state [31](before and during Irma). Accordingly, an efficient BBB CI program should respond to all the above-mentioned indicators. Rebuilding Saint-Martin's CI presents an opportunity to offer the inhabitants "Better" services that improve their overall quality of life, enhance local economies, enforce social cohesion on the island, and improve environmental conditions. It is necessary to adapt each damaged CI not only for restoration of its pre-disaster state but to make these CI more resilient and to meet socioeconomic and environmental needs. Within the reconstruction framework, and for an efficient BBB CI, a holistic and interdisciplinary approach is necessary. To support this statement, the following equation (Equation (1)) of the BBB CI concept was derived:

$$\text{Build-Back-Better Critical Infrastructure} = \text{Function}\ [(\text{Build-Back-more resilient}) \times (\text{Build-Back-more sustainable}) \times (\text{Build-Back-upgraded CI and accessible to all})] \quad (1)$$

Equation (1) Conceptualized measure of BBB for CI.

A BBB evaluation grid (Figure 4), summarizing all the conducted analytical work above and the resulting indicators, was therefore established. The uncovered characteristics of CI networks are summarized in the evaluation grid below. The BBB CI evaluation grid also highlights the proposed CI reconstruction projects and hence the application of the BBB concept in comparison with the previously discussed CI indicators to examine the term "Better". Measures for responding to the DRR-related indicators for decreasing the degree of exposure (relocation/resettlement), of vulnerability (re-evaluating building code, etc.), and of interdependence and for increasing the degree of robustness and redundancy are equally shown in red in the analysis grid (Figure 4). In response to the sustainable development indicators, measures taken to respect the environment with more environment-friendly CI are shown in green. In terms of customer satisfaction indicators, proposed measures offering an improvement in service quality are highlighted in blue. These aim to provide modernization measures, upgrade public facilities, and promote social equity, local economies, and livelihoods.

(**a**)

| INDICATORS | Potable Water Network | Electric Network |
|---|---|---|
| **Exposure** | Desalination plant highly exposed to flooding from high sea levels and waves | Power plants highly exposed to flooding from high sea levels and waves |
| **Vulnerability** | -Collapsed roofs and walls and flooded electrical controls of the desalination plant<br>-Mono-productive character: production of water exclusive to a single desalination plant that is aging<br>-Damage to supply pipelines and boreholes<br>-Lack of equipment<br>-Lack of manpower and experts/ low level of resourcefulness | -Overhead transmission lines<br>-Abusive use of low-voltage transmission lines and electric poles on which are entangled television and telephone cables.<br>-Production exclusivity: A single source of non-renewable energy<br>-Double insularity of Saint-Martin (not interconnected with the Sint-Maarten network or any other neighboring island) |
| **Redundancy** | -Very low level due to the insufficient storage capacities<br>-Lack of emergency water production units | Lack of backup generators for emergency supply |
| **Robustness** | Very low level, out of service | Very low level, out of service |
| **Recovery speed** | Slow | Moderately fast |
| **Interdependence** | -High interdependence to electrical and transportation networks<br>-Geographic interdependence with the sewage network | -Interdependence with the transport network (road and port) for diesel transport<br>-Interdependence with the potable water network for cooling |
| **Environmental issues** | -Energy consuming desalination plant | - Non-renewable thermal resources: 99% dependent on imported heavy fuel oil and only 1% generated from photovoltaic panels |
| **Socio-economic issues/Underdevelopment issues** | -Network performance of 63.5% resulting in a chronic shortage of potable water<br>-Expensive service<br>-20% of unpaid bills | -Increasing costs due to diesel importation<br>-An excess production capacity inducing additional production costs<br>-Illegal consumers |
| **Reconstruction/Build back better=Disaster Risk Reduction + Sustainable Development+ Customer Satisfaction Optimization** | -Improvement of production capacity (almost twice the capacity of before IRMA)<br>-Project to optimize efficiency (reduction of leaks, renovation & modernization)<br>-The potable water network has now a single operator, which is considered an improvement since cooperation is now guaranteed and operations can be facilitated and carried out more quickly<br>-Construction project of two retention basins of 140,000 m3 in areas far from the coast<br>-The objective is to halve of the energy consumption of the reverse osmosis process<br>· Reconstruction project of another desalination plant<br>-Reducing unpaid bills to 5% in 2028, by putting in place mechanisms helping families encountering financial difficulties and by facilitating means of payment, in particular via local relay shops. | -Adjustment of production capacity to demand and user consumption<br>-Shift from overhead lines to underground cables ensuring a continuous service, and inhabitants' safety.<br>-Energy transition of the island offering an energy demand management program aiming at a 33% gain in energy savings by 2023 via help programs to enable individuals to re-equip their houses with high-performance equipment.<br>-Objective to increase the rate of renewable energy on the island from 1% to 22% by 2023 (develop clean energies e.g. photovoltaic, biogas production, use of bioethanol, interconnection project with neighboring islands with geothermal potential) |

**Figure 4.** *Cont.*

(**b**)

| | | Sewerage Network |
|---|---|---|
| INDICATORS | **Exposure** | All wastewater treatment plants (WWTPs) highly exposed to flooding from high sea levels and waves |
| | **Vulnerability** | -WWTP without protective measures despite their exposure<br>-WWTP considered dilapidated, aging and undersized.<br>-All WWTP have been severely damaged by IRMA |
| | **Redundancy** | Very low level: unavailability of experts, spare parts and equipment on the island, reflecting a low level of resourcefulness. |
| | **Robustness** | Very low level, out of service |
| | **Recovery speed** | Very Slow, extremely long process |
| | **Interdependence** | High interdependence to electricity, telecommunication and road networks |
| | **Environmental issues** | - Undersized WWTP: Existing sewerage facilities capacities do not allow the treatment of all collected water in some peak periods<br>-In some neighborhoods, wastewater treatment is minimal or even non-existent, in which discharges are made directly into the natural environment.<br>-Small population of the island and the scattered sewerage systems do not allow the production of biogas in a profitable and reliable manner. |
| | **Socio-economic issues/Underdevelopment issues** | -In some neighborhoods, wastewater treatment is minimal or even non-existent, in which discharges are made directly into the natural environment. |
| **Reconstruction/Build back better=Disaster Risk Reduction + Sustainable development+ Customer Satisfaction Optimization** | | -Rebuilding better using environmentally sustainable designs:<br>-Integration of risks and hazards such as high sea levels/waves, the projection of debris and power supply interruptions as well as the integration of preventive measures such as the protection of works, improvement of infrastructure and permanent audit of network operation .<br>improving the efficiency and rapidity of return to normal performance after a disaster<br>-Centralized management of the 6 stations planned by SAUR<br>-Reconstruction of a new treatment station in Friar's Bay (possibility of doubling its capacity in the future)<br>-Identical repair of the *Canonniers* station<br>-WWTPs will be replaced by new stations at exactly same locations<br>-Construction of a biological treatment plant in Quartier *d'Orléans* which takes into account post-IRMA constraints<br>-Particular attention will be paid to the quality of discharges at sea. |

**Figure 4.** *Cont.*

(**c**)

| | | **Internet Network** | **Landline Network** | **Mobile Network** |
|---|---|---|---|---|
| **INDICATORS** | **Exposure** | Equipment highly exposed to heavy winds (above-ground) | | |
| | **Vulnerability** | -Above-ground<br>-Copper cables | -Above-ground<br>-Copper cables | -Damaged equipment during Irma' s occurrence |
| | **Redundancy** | -Multiple operators providing same service (higher service redundancy)<br>-Technicians and equipment have been brought from abroad. | Very low level<br>Technicians and equipment have been brought from abroad. | -Multiple operators providing same service (higher service redundancy)<br>-Technicians and equipment have been brought from abroad. |
| | **Robustness** | Very low level, out of service | Very low level, out of service | Very low level, out of service |
| | **Recovery speed** | Considerably slow | Considerably slow | Relatively slow |
| | **Interdependence** | High interference to electricity<br>Dependence to transport networks for the supply of equipment and emergency | Interdependence to electricity and transport networks | Low level dependence to electricity |
| | **Environmental** | Non available | Non available | Non available |
| | **Socio-economic issues/Underdevelopment issues** | -Degraded signal quality: Signals carried over a shared coaxial cable television and Internet, are regenerated regularly using broadband amplifiers limiting the attenuation of the cable.<br>-The coverage of the territory at high speed and very high speed is not distributed equitably between all neighborhoods.<br>-Inequality observed during service restoration (In the capital and wealthier neighborhoods first) | -Transmission capacities on the copper network are limited and exhibit an increasing degradation with the distance from the subscriber's home to his connection node<br>-Inequality observed during service restoration (In the capital and wealthier neighborhoods first) | -Poor coverage quality in peak periods<br>-The coverage of the territory at high speed and very high speed is not distributed equitably between all neighborhoods.<br>Inequality observed during service restoration (In the capital and wealthier neighborhoods first) |
| | **Reconstruction/Build back better=Disaster Risk Reduction+ Sustainable development+ Customer Satisfaction Optimization** | -Transitioning to underground and more secure networks<br>-Implementing technical measures that can limit damages<br>-Switching to optical fiber (more resilient)<br>-To put an end to degraded Internet access and ensure the maximum internet coverage of the territory at high and very high speed.<br>through the implementation of several connection nodes<br>-Improve the quality of service and achieve a digital development<br>-Developing resilient communications infrastructures with redundancy built in to ensure communications<br>-Reinforcing towers' structure against hurricane | -Transitioning to underground and more secure networks<br>-Implementing technical measures that can limit damages<br>-Optimization of the terrestrial network architecture<br>-Switching to optical fiber (more resilient)<br>-Improve the quality of service and achieve a digital development<br>-Several subscriber connection nodes will be implemented<br>-Improving the redundancy of equipment and to install generators where necessary to ensure the networks' redundancy<br>-Reinforcing towers' structure against hurricane | -Transitioning to underground and more secure networks<br>-Implementing technical measures that can limit damages<br>-Systematization of underground housing adduction<br>-Securing international connections with redundancy of submarine cables<br>-Improve the quality of service and achieve a digital development<br>-Developing resilient communications infrastructures with redundancy built in to ensure communications remain uninterrupted to the subscriber for all inhabitants of Saint-Martin.<br>-Reinforcing towers' structure against hurricane<br>-Optimizing the architecture of terrestrial networks.<br>-Creating shared mobile sites between operators |

**Figure 4.** *Cont.*

(**d**)

| INDICATORS | *Galisbay* Commercial Port | *Marigot* Port | *Grand-Case Espérance* | Roads Network |
|---|---|---|---|---|
| **Exposure** | Highly exposed to flooding from high sea levels and waves | | | |
| **Vulnerability** | Limited structural damage | Heavily damaged | Limited structural damage | -Minimal structural damage - climate is harsh for the asphalt, and the local bridges and roadways -Vulnerability of roads signs and lightings |
| **Redundancy** | Low level, dependence to electricity | Low level, to electricity | Low level, to electricity | Low level: single-line typology |
| **Robustness** | Remained partially operational | Very low level, out of service | Remained partially operational | 24% of roads remained operational |
| **Recovery speed** | Fast | Slow process | Fast | Very Fast |
| **Interdependence** | Totally dependent to Phillipsburg port for freight services | Totally dependent to Phillipsburg port | Dependent to Sint-Maarten Princess Juliana International Airport (SXM) | Dependence on electricity for lighting |
| **Environmental issues** | Non available | Non available | Non available | Energy consuming lighting |
| **Socio-economic issues/Underdevelopment issues** | Undersized: transits only to 25% of the island's traffic | Undersized: hosts only low-capacity cruise ships | Limited capacity due to small runway only connected by direct flight to three destinations | -Undersized main roads and therefore saturated with numerous traffic jams -Secondary, tertiary and residential roads are also narrow -Not always well signposted -Urban storm water runoff and resulting flash flooding |
| **Reconstruction/Build back better=Disaster Risk Reduction+ Sustainable development+ Customer Satisfaction Optimization** | -Platform extension/expansion and development project which would allow trade to be deployed to neighboring islands, and to rebalance traffic between the northern and the southern parts of the island and Saint-Martin to gain independency in terms of maritime traffic. -Equipped with two new generators -Enhanced activity -Project to also become the base port for medium and high-end cruise lines, which could thus initiate actions in favor of tourism development. | -Reconstruction projects, involving the installation of solid concrete docks -Discussions about the construction of a dike ensuring their future resilience to protect the Marigot marina. | -Expand of the airport and its runway to capture part of the aviation activity that arises today either at Sint-Maarten Princess Juliana International Airport (SXM) or at the airports of neighboring islands. -Repairing the damaged facilities of the airport to higher standards that ensure resilience to future disasters. | -Saving energy, in particular by using LED bulbs that require 70% less energy -Improving the general aesthetic design of all these luminaires -Guaranteeing an optimum mechanical resistance to future climatic events (replacement of aluminum by concrete or galvanized steel, transition of all power supplies to underground). |

**Figure 4.** (**a**) Build-Back-Better Critical Infrastructure (CI) evaluation grid, applied for Saint-Martin's CI in the aftermath of Irma; (**b**) Build-Back-Better Critical Infrastructure (CI) evaluation grid, applied for Saint-Martin's CI in the aftermath of Irma; (**c**) Build-Back-Better Critical Infrastructure (CI) evaluation grid, applied for Saint-Martin's CI in the aftermath of Irma; (**d**) Build-Back-Better Critical Infrastructure (CI) evaluation grid, applied for Saint-Martin's CI in the aftermath of Irma.

The established BBB evaluation grid revealed that the reconstruction of the majority of the CI networks in Saint-Martin responded to all indicators by trying to resolve existing weaknesses and therefore encompassed the objectives of CI "Build-Back-Better", by "Building-Back-more resilient", "Building-Back-more sustainable", and "Building-Back-upgraded CI and accessible to all". For instance, transitioning to underground networks, for electric and telecommunication networks, was considered an improvement on many levels: (1) robustness to the digital networks that became protected from major climatic events, (2) safety to inhabitants, with no risk of falling cables or of incidents during work in public spaces, (3) aesthetic improvement of the urban setting with the disappearance of overhead networks, (4) reducing the number of poles on sidewalks and along roads makes it possible to widen the circulation spaces (for pedestrians, vehicles), and (5) optimization of the quality of the service, leading to better local economies and livelihoods. In addition, Irma's occurrence offered an opportunity to start the already planned projects for improving public services (transition to optical fibers). Moreover, reconstruction measures, especially in the electrical, potable water, and sewerage networks, showed that it is possible to combine proactive prevention with service optimization and sustainable development. The BBB CI evaluation grid confirmed that the occurrence of Irma on Saint-Martin offered an opportunity to rebuild better CI networks.

On the other hand, some impediments hampered the application and implementation of the BBB CI concept. Some indicators were not taken into consideration during reconstruction projects, as listed below.

- Uncertainties related to demographic dynamics: following Irma, there were uncertainties about where people would live, whether they would stay on the island [79], and what their post-disaster demands from these infrastructure components would be. For instance, the peak demand on the electricity system dropped to 20 MW after Irma, in comparison to 30 MW before Irma [49]. Additional concerns focused on the possibility of future investments that would attract more tourists and inhabitants. Therefore, knowledge of demographic dynamics and projection models are necessary for an optimal BBB CI that responds to "Building-Back-upgraded CI and accessible to all". Also important was the consideration of informal settlements and illegal consumers, along with their dynamic and uncertain evolution as a consequence of Irma.
- Lack of anticipation: anticipation through measures such as contingent reconstruction plans, CI lifecycle cost analyses, pre-approved contracts, and financial arrangements is crucial to ensure a faster BBB that reduces disaster impacts by accelerating reconstruction. The lack of anticipation induces time constraints that result in a "building-back like before" strategy and thus implying simple restoration instead of robust reconstruction. Anticipation can help to avoid compromises/trade-offs and questions such as "is it better to leave people without public services the time to build more robust CI in the face of disasters that might not occur in the near future, or is it worth it to cause an environmental risk to build more resilient WWTP?" In fact, the relocation of highly exposed and heavily damaged WWTPs in Saint-Martin was not possible because of the environmental risk of contamination amid a lack of anticipated reconstruction projects. All WWTPs were reconstructed at the same locations. On the other hand, telecommunication networks' BBB was considered efficient because plans and projects were already prepared long before Irma.
- Uncertainties related to climate change: while Irma's risks and other past hurricanes have been taken into consideration in the BBB of Saint-Martin's CI, future climate change was more complicated to capture and to integrate into the BBB. Studies on climate change, particularly analyses by the IPCC [80], predict changes in the level and temperature of the oceans, but also in the intensity and frequency of climatic events. Given the exposure of Saint-Martin, these changes will have direct consequences for the impact of natural disasters and may threaten the success of "Build-Back-more resilient". With the increasing frequency of extreme weather events, a Category 5 hurricane such as Irma with a 50-year return period today may have only a 20-year return period in the course of the lifetime of an infrastructure investment. Such uncertainty must be accounted for in the reconstruction of CI networks.
- Limited spaces of Saint-Martin's Island: the geography and topography of Saint-Martin's Island often make it difficult to implement conventional BBB measures such as reducing exposure and proposing relocations of CI facilities that are exposed to high sea levels/waves. Furthermore, limited transportation networks constituted a problem for the BBB, particularly during the transitioning of overhead to underground networks.

- Organization and coordination problems: regarding the coordination of CI reconstruction works, the networks undergoing reconstruction in Saint-Martin are numerous (electricity, potable water and sewerage, telecoms, lighting, etc.) and managed by multiple operators and service providers with different priorities. This creates an additional layer of complexity that necessitates coordination, cooperation, and organization among all operators for the effective implementation of the BBB concept [81]. Blockages were noted in the reconstruction management in Saint-Martin. Besides constraints linked to the economic activity, tourist influx periods do not allow large-scale work and this hinders efficient CI BBB. For instance, roadworks (underground, lightings, etc.) were numerous and often repeated, thus paralyzing traffic, especially in the capital, Marigot, where alternative routes are rare. Besides the cooperation between operators, the BBB did not involve joint infrastructure projects with Sint Maarten to rebalance relations between the French and Dutch parts and to strengthen bilateral cooperation. This cooperation would have solved the problem of double insularity, without creating a dependency, and would therefore serve the three objectives of "Build-Back-Better" CI in Saint-Martin.
- Lack of a "systemic reconstruction approach": cooperation among all CI operators is crucial in order to build systemic resilience. Because of interdependencies and subsequent cascading failures, a systemic approach is needed when tackling CI resilience and BBB, within the objective of "Build-Back-more resilient", instead of a silo-based CI-by-CI reconstruction process. Strong coordination and cooperation among all CI operators can facilitate the BBB CI process by adopting a systemic reconstruction approach, starting with a prioritization of CI network reconstruction based on interdependency. Instead of this, the reconstruction of each infrastructure alone was observed in Saint-Martin.
- Lack of a "multi-hazard approach": in addition to hurricanes, Saint-Martin is prone to floods, landslides, and seismic risks, which makes it necessary to adopt a "multi-hazard approach" when planning for BBB projects. This was only applicable for the electric network reconstruction projects and not for other networks. Accordingly, a "multi-hazard approach" was not observed in the "Build-Back-more resilient" projects of Saint-Martin.
- Funding and legislation problems: sustainable reconstruction has sometimes been difficult to guarantee due to legislative and financial issues. For instance, the environment-efficient reconstruction of housing (thermal insulation, efficient air conditioning, solar water heaters, LED lighting, etc.) proposed by EDF to reduce energy demand was at first difficult to implement due to the evolving legislative context for the financing of these actions.

## 5. Conclusions

"Build-Back-Better" is an emerging concept, widely debated, particularly regarding the term "Better". BBB CI, as a decision-making criterion, is gradually gaining acceptance but remains vague in its application. The term "Better" in BBB is often confusing to practitioners, leading to ambiguous, often non-uniform objectives for guiding accurate decision-making. Consequently, BBB is blocked at its earliest stages. While the different interpretations of the term "Better" have been debated in theoretical discussions, particularly for the general aspect of reconstruction (Build-Back-Stronger, -Faster, and -Inclusively), an interpretation of this term for CI is still missing. In an attempt to fill these gaps, this study investigated the application of the BBB CI concept by providing indicators derived from an evaluation of the ongoing CI rebuilding efforts in Saint-Martin's Island following Hurricane Irma.

To analyze the operational aspect of BBB, it was necessary to examine the term "Better". For this purpose, Saint-Martin's CI states before and after Irma were investigated to unveil BBB CI indicators and accordingly evaluate the ongoing BBB programs.

Key findings of this study provided BBB CI indicators and offered further insights and a new conceptual equation of the BBB CI concept. The proposed explanations would facilitate the efficient application of BBB for CI by operators, stakeholders, and practitioners. The obtained results pinpointed the necessity of a holistic and interdisciplinary approach to BBB CI, as a guiding principle to "Build-Back-resilient", "BB-sustainable", and "BB-accessible to all and upgraded CI". Nonetheless, the proposed approach requires collaboration and cooperation among all actors to develop and implement sustainable strategies that address economic, environmental, risk, and social dimensions.

BBB CI should be an opportunity to increase the infrastructures' resilience and to promote equality in service access. Analysis showed that BBB CI offers the possibility to pursue societal objectives (socioeconomic and environmental sustainability, a better quality of life, social equity, social cohesion, etc.) synergistically with disaster recovery and risk reduction. On the other hand, although the proposed BBB CI can be standardized and benchmarked, it should be adaptive and contextualized. The term "Better" is actually context-specific, unique to locations, infrastructure criticality, and driven by the economy and dynamics of each community. The term "Better" is also relative to the problems that the system or society was experiencing before the disaster, during the response, and during early recovery from the disaster. Therefore, the proposed indicators should be supplemented by national, sub-national, and CI-network-level indicators to cover the CI issues relative to each context. The evaluation of ongoing BBB CI projects in the case of Saint-Martin showed that Irma was not only an indicator of previous weaknesses and dysfunctions of CI; the hurricane also highlighted the need to deeply rethink and consolidate these CI networks.

Based on some observed impediments, the following recommendations are given: proactive and anticipatory efforts are needed for the efficient application of BBB CI. Without anticipation, CI recovery will only be focused on speed of service restoration (social, political, and media pressure) and therefore BBB would become a trade-off. A political, legislative, and governance framework also needs to be leveraged and implemented; nonetheless, these recommendations, as perspectives, are further incentives for future research.

Some angles worth developing are the elaboration of a quantitative methodology to assess the proposed indicators and evaluate the BBB concept for CI according to the presented equation, and the integration of uncertainties related to unique situations, including pandemics such as COVID-19 (changes in staff availability, changes in CI demands, etc.).

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