Inequality growth and recovery monitoring after disaster using indicators based on energy production: Case study on Hurricane Irma at the Caribbean in 2017

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A R T I C L E I N F O

A B S T R A C T

Recovery and inequality growth after a disaster are often difficult to estimate. In this study, specific indicators were developed to analyze recovery and inequality growth. Here we show that after a major disaster the difference in recovery between two territories causes inequality growth. Energy production is relevant for describing variations in social and economic activities. This indicator was applied to a case study of a natural disaster, that is Hurricane Irma in 2017. The hurricane caused fatalities and destruction in the Caribbean islands of Saint Martin and Saint Barthelemy, which are two French overseas territories. Energy production after Hurricane Irma exhibited a significant decrease due to the destruction of the electricity network as well as per- turbations in economic and social activities. The energy production restoration rate was faster in Saint Barthelemy than in Saint Martin. The energy production 18 months after Hurricane Irma was identical to that before Hurricane Irma in Saint Barthelemy, whereas this was not the case in Saint Martin. During recovery, an increase in the gap between energy production in Saint Bar- thelemy and Saint Martin was observed. This gap represents an inequality growth between Saint Barthelemy and Saint Martin. The indicators emphasized that the wealthier territories recover faster than the less wealthy and that natural disasters favors inequality growth. Inequality growth is expected to occur with natural disaster development. The number of inhabitants must be considered during indicator construction to avoid any bias.

1. Introduction

Disasters caused by extreme events may increase with climate change. The intensity of extreme events is expected to increase with climate change and cause risk growth [1]. Coastal areas are particularly affected by natural risk, and Caribbean islands are vulnerable to hurricanes [2–4]. During hurricanes, strong winds, marine inundation, heavy rain and landslides could occur. In the case of a disaster, (i) infrastructure and buildings are physically damaged, (ii) social and economic activities are disturbed, and (iii) fatalities and injuries occur [4,5]. However, the quantification and monitoring of some of these evolutions may be difficult after a disaster and differences in recovery not fully understood. Indicators necessary for a holistic comprehension and useful for decision are often not available because existing indicators are too specific and not able to give a global description. Risk management focuses on reducing the potential negative effects of disasters by anticipating these effects and proposing solutions promoting rapid recovery and better

reconstruction, but also by adopting strategies evolving during recovery using high frequency (*i.e.* minutes or hours or days) indicators.

This study focus on the capacity to a territory to return to a steady state after a disaster (i.e. recovery), more than to the ability to absorb changes (i.e. resilience [6]). To consider the collective dimension of post-disaster recovery, this study analyzed a territorial rather than an individual scale. The ability to return to comparable social and economic pre-crisis activities could be different from a territory to another, in relation to pre-existing different vulnerability and capacity. The role of natural disasters in increasing inequality between territories is also investigated. Inequality can be considered, as recovery, at an individual or at a collective (*i.e.* territory) scale. Energy consumption in a territory/country is proportional to GDP per capita in many cases [30]. Disaster causes difficulties to perform social and economic activities, and affects individual wealth [10], especially for low incomes [11], but comparison of the impact of the same disaster on different territories have been less studied. The potential increased gap in social and economic activities after a disaster between territories could characterize territorial inequality growth, but has never been described to our knowledge and this study propose to do it. In the present case, inequality between territories is considered as the differences in energy production per inhabitants between two territories and will be quantified.

Natural disasters cause damage to infrastructure, including electricity plants and networks, which can have serious effects on health [12,13] and economic and social activities [14]. The reduction or interruption of electricity influences the availability of other networks (water, communication, sewerage, etc.) [15]. Furthermore, a decrease in economic and social activities cause a reduction in energy demand [14,16,17]. The insular context has specific constraints on the energy system, such as supplementary cost in production (fuel transport) and consumption (water desalination) [18]. A long-term monitoring of specifics indicators or a socio-economical trajectory description before disaster give a useful basis for comparison and understanding.

Many social and economic activities are directly or indirectly associated with energy consumption [16,17]. The influence of energy on society has increased since the 19th century and has deeply transformed and constrained the social as well as economic activities at present [19]. Human-nature interactions are conditioned by techniques and, in particular, energy production [20]. Consequently, analysis of recovery of social and economic activities is difficult without considering the evolution of energy production or consumption. Thus, this study considered energy production as a key indicator for analyzing recovery.

Monitoring energy consumption allows the analysis of the evolution of social and economic activities. Electricity consumption depends on (i) the hour of the day, (ii) the day of the week, and (iii) the season [21]. Energy consumption changes when people are at work or at home, during social events or when temperature changes [21,22]. Previous studies have emphasized the relationship between wealth and energy consumption [8]. Although the effect of the COVID-19 pandemic on electricity generation has been accurately analyzed recently [23–25], the evolution of energy production after other kinds of disasters has been less explored [13], especially on islands [18]. The effect of hurricanes on energy production and consumption is often combined with other social and economic effects and has been rarely studied: this study propose to improve our knowledge about these evolutions.

This study investigates a case where a natural disaster caused significant and very similar damages to nearby territories with
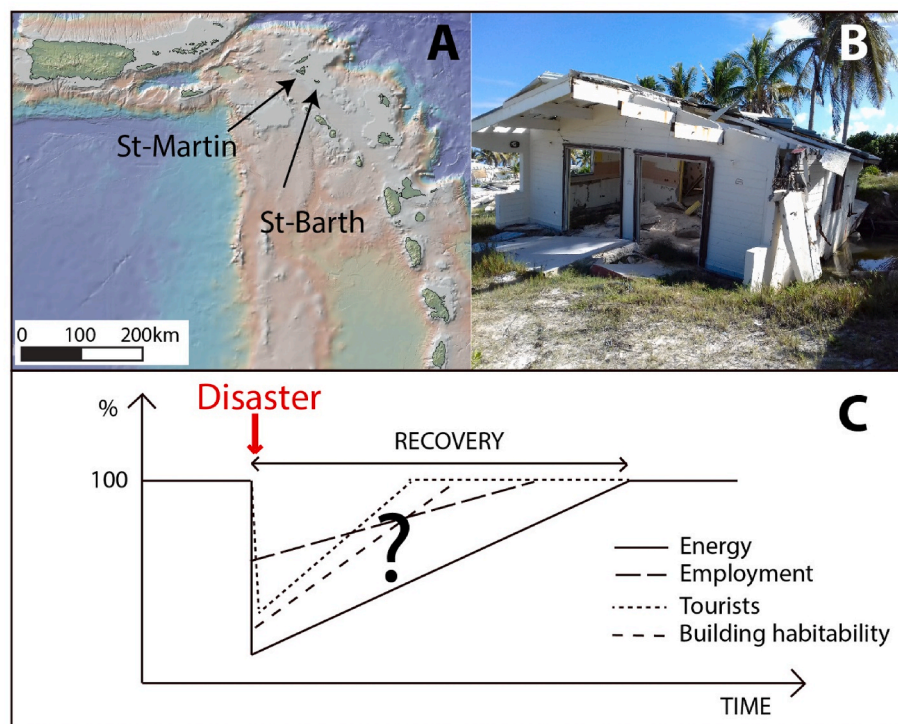

Fig. 1. Recovery after a natural disaster, a case study, (A) in Saint Martin and Saint Barthelemy, Caribbean, (B) after Hurricane Irma, September 5–6, 2017, Oriental Bay, Saint Martin, and (C) recovery of social and economic activities.

different initial wealth. Specifically, in this study, the disaster corresponds to Hurricane Irma which occurred in 2017 and was classified as five on the Saffir-Simpson scale (Fig. 1). Hurricane Irma caused damage, trauma, and death that affected the economic, social, health, and environmental scenarios in the Caribbean [26]. The area considered in this study is composed of two islands, Saint Martin and Saint Barthelemy, which are two French overseas territories. Various activities have been affected by Hurricane Irma [5]. Comparison of two different islands allowed the distinction of trends related to the influence of socio-economic trajectory from hurricanes consequences. When focusing on specific territories, the context must be accurately described to permit the understanding of what is due to a specific natural disaster and specific vulnerability on one hand, and what has other causes on the other hand. For example, old dwellings and infrastructures could have preexisting, but hidden, weaknesses and disaster highlights this vulnerability.

The possibility that environmental disasters increase inequality between individuals has been suggested by several studies [27], but remains unverified at the scale of a territory. Is electricity production a good indicator to analyze recovery and inequality growth for territories? Electricity consumption was monitored during the last 13 years, which was used to analyze the temporal variations and correlated those with natural or anthropogenic events. Standardized electricity generation is used as an indicator to characterize recovery of two Caribbean islands after Hurricane Irma and to compare recovery between these territories. The indicator estimates will be compared with economic data to evaluate the efficiency of this indicator. These indicators based on electricity generation will be used to analyze demographic variation, including migration, for these territories and to characterize inequality growth.

2. Vulnerability, resilience and recovery after natural disasters

During the last decade, vulnerability and resilience have been used to describe and improve risk management. Vulnerability refers to the inability to withstand the effects of a hostile environment. The concept of vulnerability is often used to characterize the inability of a system to resist the effects of social or environmental changes [28,29]. Natural disasters destabilize social organization, result in psychological trauma, destroy wealth, and cause fatalities, thus, highlighting the vulnerability of the social system to natural disasters [30]. Various types of vulnerabilities exist, such as structural, physical, human, institutional, functional, social or environmental vulnerability, and they could be very specific, such as vulnerability to hurricanes or marine inundation. They are defined in relation to a calibrated event, over a given period or at a given time. There are thus, many typologies, among which we find essentially (i) structural vulnerability for physical infrastructures (buildings, physical networks, engineering structures, etc), (ii) physical vulnerability for physical persons (physical damage), (iii) human vulnerability for populations (social or psychosocial approaches), (iv) institutional vulnerability for governance, (v) environmental vulnerability fot the various components of the natural environment (vegetation, water ressources, etc.), and (vi) functional vulnerability for the various functions and activities (economic in particular).

Vulnerability to natural disasters reveals the multidimensionality of natural disasters and their numerous and complex relationships with social and environmental scenarios [31]. Vulnerability is multidimensional, and the totality of relationships in a social or environmental scenario could be affected *a priori* by a change [31]. In this case, vulnerability deserves a systemic approach [32]. The operational implementation of systemic vulnerability break down the issues generated by major components (human, material and environmental). This system approach introduces the idea that the concept of vulnerability and its measurement cannot be reduced to simply the summation of the types of vulnerability (i.e. structural vulnerability, physical vulnerability, human or social vulnerability, institutional vulnerability, environmental vulnerability, functional vulnerability).

Numerous studies have focused on vulnerability and proposed quantification through specific indicators [33]. Thus, comparisons could be made and coordinated mitigation achieved. Nevertheless, quantification of vulnerability from a natural disaster is difficult because of the multidimensional aspects that must be considered and are not well described by a financial cost [3,5]. Furthermore, vulnerability and/or economic indicators cannot be interpreted without considering the historical context [34], and the quantification of vulnerability remains challenging.

Vulnerability depends on public awareness and community preparedness [35] and often on wealth. Informed decision-making on disaster risk reduction should be based on knowledge of vulnerability and exposure, and relevant options for actions on preventive disaster measures [36]. Evaluating vulnerability could help communities to target for increasing resilience [37]. Fast recovery of economic activities after disaster are not necessary associated with a reduction of vulnerability. Nevertheless, when a Build Back Better recovery occurred, vulnerability is expected to decrease contemporaneously (Sendai Framework). However, it seems prudent to reduce disaster risk in the short term as a precursor to adapting to climate change and its impacts in the longer term [38].

Many different definitions of resilience have been proposed in different fields ranging from physics to psychology. It has been defined as a process of adaptation in the face of adversity, crisis, or stress [39] or to the ability of a system to absorb changes [8]. Resilience is also multidimensional and could develop after shock and disruption that modify significantly a preexisting state [6,40]. Anticipating and promoting resilience development suppose a level of acceptance of risk, because resilience improvement is promoted only when society consider impossible or not appropriate to suppress the risk [41,42].

De Terte and Ian [43] defined resilience as having the ability to cope with a crisis or to rapidly return to the pre-crisis stage. The time of return to normalcy is a temporal reference that varies according to the territory, depending on its own characteristics (specific disaster, vulnerability to a specific risk) [41]. When this concept is used to describe post-disaster evolution, it can be gauged on an individual, community, or physical level, for example, when the effects on infrastructure [42]. Economic resilience can be strengthened by implementing policies aimed at mitigating the risks and effects of severe crises. The benefits of economic policies could be balanced against their costs in terms of reduced expected growth. However, difficulties to quantify all the activities and uncertainties could cause difficulties to perform an accurate cost-benefits analysis.

Resilience has been criticized because this concept is often ambiguous and involves responding instead of promoting prevention. It could also promote injustice by favorably describing the scenario leading to a disruptive change that could have a political, social, or

economic origin [44]. For example, circumstances that cannot be changed are not easily defined objectively and that, consequently, should be accepted. Policies of resilience can put the responsibility of disaster response on individuals rather than publicly coordinated efforts, and promoting resilience draws attention away from governmental responsibility and self-responsibility [42].

Vulnerability, resilience as well as recovery indicators can be considered scientific concepts, as well as government tools. The choice of a specific indicator by a government is not necessary neutral. Economic resilience anticipation can be ambiguous because transformation of society and adaptation of individuals after a disaster or crisis could be oriented without democratic procedure [44]. Creative destruction by economic crisis has been considered a fundamental criterion for economic dynamics in the past [45]. Nevertheless, changes are not necessarily positive after a crisis or disaster. Herein, we considered the capacity to return fast to a steady-state after the disaster (i.e. recovery). Recovery is a trajectory that returns to equilibrium after the severe perturbation of a territory. Perturbation could be caused by environmental, economic, social, or health changes. The trajectory of recovery corresponds to a temporal evolution of the state of every element that returns or does not return to its initial state before any perturbation (Fig. 1C).

When considered for a territory, a different recovery could cause different mean income during several months or years and cause inequality. Individual inequality could be estimated using income differences statistics, and more precisely by comparing income percentile: for example, analyzing the variation of wealth of the 1%, 5%, 10% or 50% of the wealthier or poorer inhabitants, as well as the Gini coefficient [7]. When considered at the collective scale, gross domestic product per capita (i.e. GDP per capita), could be used to estimate wealth and, consequently, differences of wealth between territories. However, GDP has been criticized as not fully representative of welfare, because not including all the social activities and including negative economic activities [9]. In many territories and countries, energy use is proportional to GDP per capita [30] and consequently to wealth. In this study, variations in energy production/consumption between territories is considered as a relative variation of wealth for these territories. When accumulated during several months or years, variation of energy consumption between two territories with comparable technologies is expected to be related with variations in economic activities and consequently with variations in mean income.

3. Context and method

3.1. Context

Saint Martin and Saint Barthelemy are two French Caribbean islands with 35 000 and 10 000 inhabitants, respectively [46]. Their population has increased significantly during the last decades (Fig. 2), after which the French government implemented the tax exemption law in 1986 to develop tourism and economic activities [47,48]. In 2014, the gross domestic product per-capita (GDP per-capita) of Saint Martin and Saint Barthelemy were 16 600 euros/inhabitant and 40 000 euros/inhabitant, respectively [49,50].

The island of Saint Martin is divided between the French side, called Saint Martin, and the Dutch side, called Sint-Maarten, both with approximately the same number of inhabitants. By convention, Saint-Martin will be used only to designate the French part. The area of Saint Martin size 53 km^2, while that of Saint Barthelemy is 24 km^2 [45]. In 2007, Saint Martin and Saint Barthelemy changed their status from municipalities administratively attached to Guadeloupe to two relative autonomous French overseas regions. Saint Barthelemy is outside the territory of the European Union since 2012, whereas Saint Martin is not. The two islands have the same tax exemption laws, favoring investments. The number of tourists arriving at the airports of Saint Martin/Sint-Maarten was 1.5–2.5 million [50] for approximately 73 000 inhabitants in the entire island in 2016–2017. More precisely, the number of tourists arriving annually
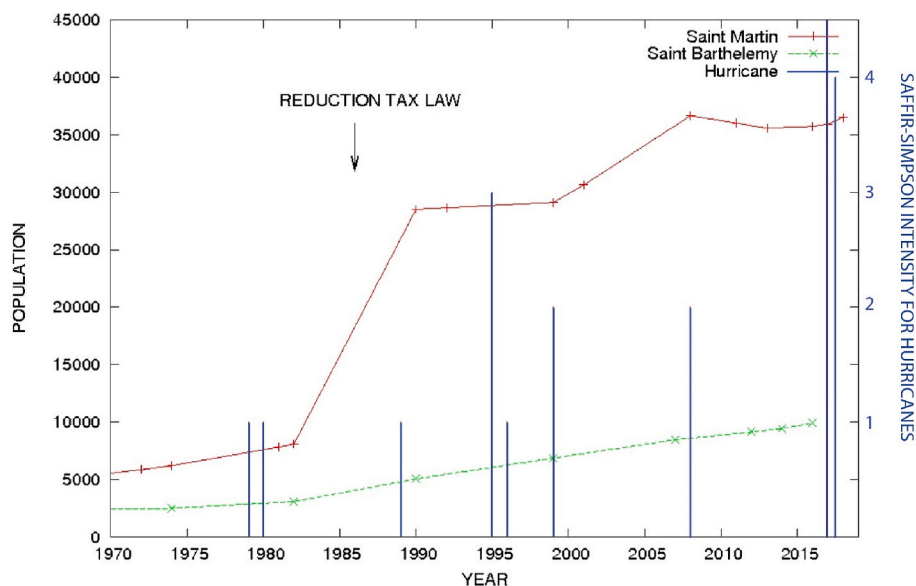

Fig. 2. Number of inhabitants in Saint Martin and Saint Barthelemy [49,50]. Hurricanes are indicated by vertical lines and their lengths are based on the Saffir-Simpson scale.

via air are 0.1×10^6 in Saint-Martin and 2×10^6 in Sint Maartens each year before Hurricane Irma [45,49–51]. The number of arrivals at the Saint Barthelemy airport was estimated to be approximately 240 000 in 2017 [49,52]. Tourism represents the main economic activity of these islands [3,53], with tourists from North America and Europe. In 2017, there were 0.74 buildings per capita in Saint Barthelemy, whereas there were only 0.34 buildings per capita in Saint Martin [3]: in these islands, buildings are hotels, guest houses, shops, restaurant and resident homes, whereas there are only few industry, offices and administrative buildings. Differences are due to the higher number of collective habitat in Saint Martin than in Saint Barthelemy.

There are no industries (<4% of employment) in the two islands, and the main economic activities are related to tourism (shop, restaurant, hotel, etc.). During the last decades, tourism increased in Saint Martin and Saint Barthelemy. Development of similar economic activities was observed for both the islands (Table 1).

Many tourists come from the United States and Canada. There are around 100 000 arrivals per year in Saint Martin airport and a few thousands in the harbor. A significant part of tourist arrivals in Saint Martin came from Sint Maarten airport and harbor [51]. Arrivals in Sint Maarten are 500 000 per year at the airport and >1 500 000 at the harbor. In Saint Barthelemy, there are around 75 000 tourists arrivals per year at the airport [52]. Tourism decreased in 2007–2008 during the subprime mortgage crisis.

The two studied territories have many similarities: (i) both are islands in the Caribbean, (ii) their economies are dominated by the tourism industry, (iii) both are French overseas territories, and (iv) their areas and number of inhabitants are small (<50 000 inhabitants; <100 km^2). However, they differ by their generated income, that is, their different per capita GDPs. Although GDP cannot accurately describe all social and economic activities [19], it suggests that the average income in Saint Barthelemy is higher than that in Saint Martin. Field work conducted in December 2019 and satellite image analysis revealed that the income is distributed more homogeneously in Saint Barthelemy than in Saint Martin, where low income is overrepresented in several neighborhoods (Sandy Ground, Quartier d'Orléans) and high income in others (Terre Basse, Oriental Bay) [53].

Electricity in the two studied territories is mainly supplied by the Electricité de France (EDF). Electricity is generated by two power plants, one located in Saint Barthelemy and the other in Saint Martin. Fuel oil is used to produce electricity in both islands, and the production of renewable energy is negligible (2% in 2019); geothermal energy is not available locally, even if these islands are old volcanic edifices, aeolian energy is not developed, and use of solar energy is slowly increasing. Geothermal resources on the islands of Saba, Saint Eustatius and Saint Kitts, and electricity interconnection feasibility with Saint Martin are being studied by the Saint Martin administration. In Saint Barthelemy, the production capacity reaches 34.2 MW [54]. In Saint Martin, the power plant can produce 56.6 MW, whereas the peak of daily electricity generation is 27.5 MW [55]. Individual electricity generators are present in the better-off neighborhoods and used in the case of a blackout, but their total electricity generation capacity is unknown.

In September 2017, Hurricane Irma occurred and has a significant impact on Saint Martin and Saint Barthelemy, but also on Barbuda, Anguilla, Virgin islands, Cuba, Haiti, Puerto Rico, Bahamas and United States. Maximum sustained wind has been measured at 285 km/h and minimum atmospheric pressure at 914 hPa [56]. Eleven fatalities occurred in Saint Martin and Saint Barthelemy. Destruction or damage of 60–70% of the houses was estimated [26]. In the detail, destruction and highly damaged dwellings represent 19.7% of buildings in Saint Martin but only 2.5% in Saint Barthelemy [57]. Saint Martin and Saint Barthelemy islands are near (<25 km) and this difference is not due to different climatic conditions during Hurricane Irma. Much of the network infrastructure was damaged. In this specific case, the electricity plant was damaged and the network was destroyed. The majority of the population in these islands was without water, electricity or phone during several weeks/months [15]. During the weeks following the disaster, French State committed 3000 people (military, medical staff, emergency staff) and material (two million bottles of water, 350 tons of food, etc.) to help the population at a total cost of 163 million euros [58]. Around 7000 inhabitants move outside of Saint Martin during several months [14,58].

Before the disaster, public services (hospital, police, school, administration) were less developed than in French metropole. The total cost of insured damage is estimated at 1176 million euros for the French part of Saint Martin [56]. In Saint Barthelemy, the insured damage were of 823 million euros for only 10 000 inhabitants [57,58]. Insurance compensation was for 50% for homes, 45% for business premises, 4% for cars, 1% for boats in Saint Martin. In Saint Barthelemy, insurance was for 61% for homes, 36% for business premises, 3% for cars, >1% for boats [57]. Real cost of damages are higher because 60% of people are not insured in Saint Martin and 40% in Saint Barthelemy [57].

3.2. Method

Yearly and monthly electricity production data in Saint Martin and Saint Barthelemy were used in this study. Electricity consumption is almost equal to electricity production. Using electricity production is equivalent to analyze electricity consumption.

3.2.1. Yearly electricity production

Annual electricity generation was available from 2006 to 2020 for Saint Martin [50,51,59] and from 2007 to 2020 for Saint

Table 1
Employment statistics in Saint Martin and Saint Barthelemy.

	Unemployment (%)	Accommodation services (%)	Building Construction	Public services and NGO (%)	Trade, business	Industry (%)
St Mart.[a]	33.1	14	11	29	36	4
St Barth.[b]	4.2	20	19	10	41	4

[a] in 2020 [51].
[b] in 2020 [52].

Barthelemy [49,52]. For comparison, yearly electricity generation data from 2007 to 2020 was utilized, when the annual electricity generation was available for both the islands. Annual electricity generation (E_Y) was used to analyze long-term (i.e., decanal) evolution. The annual electricity generation was standardized using the initial value of our dataset, *i.e.* the value recorded in the 2007 (E_{y2007}). Specifically, standardized annual electricity generation was obtained by dividing electricity generation E_Y by the value of annual electricity generation recorded in 2007. Standardized annual electricity generation (i.e., $E_{SY} = E_Y/E_{Y2007}$ – eq. 1) evolution over time was compared for the two islands. The ratio between the standardized annual electricity generation of Saint Martin E_{SY-SM} (SY-SM = Standard Yearly for Saint Martin) and standardized annual electricity generation of Saint Barthelemy E_{SY-SB} was used to analyze the relative evolution of electricity generation $I_Y = E_{SY-SB}/E_{SY-SM}$ (eq. 2).

This represented a case study to evaluate the efficiency of an indicator based on electricity generation to monitor the evolution of social and economic activities in the two different territories. In the general case, the indicator $I_Y = [E_{Y\text{-}Territory\ 1}(t)/E_{Y\text{-}Standard\ Year\text{-}Territory\ 1}]/[E_{Y\text{-}Territory\ 2}(t)/E_{Y\text{-}Standard\ Year\text{-}Territory\ 2}]$ (eq. 3) measures the variation in electricity generation between the two territories. In this study, $E_{Y\text{-}Standard\ Year\text{-}Territory\ 2} = E_{Y\text{-}2007\text{-}SM} = 180.6$ GWh for Saint Martin and $E_{Y\text{-}Standard\ Year\text{-}Territory\ 1} = E_{Y\text{-}2007\text{-}SB} = 92.3$ GWh for Saint Barthelemy. When this indicator is > 1, it implies that social and economic activities that consume electricity have increased more in Saint Barthelemy (i.e., Territory 1) than in Saint Martin (i.e., Territory 2) and that the gap is further increasing between both islands.

To determine the effect of demographic variation on electricity generation, a specific indicator was constructed $I_{Y\text{-}Demo} = [E_{Y\text{-}Territory\ 1}/E_{Y\text{-}Standard\text{-}Territory\ 1}/inhabitant]/[E_{Y\text{-}Territory\ 2}/E_{Y\text{-}Standard\text{-}Territory\ 2}/inhabitant]$ (eq. 4) and compared to I_Y. In the case of significant demographic variation, $I_{Y\text{-}Demo}$ could be more appropriate than I_Y to measure the intensity of variation in electricity generation between the two different territories. The number of inhabitants in Saint Martin and Saint Barthelemy has been collected by the French National Institute of Statistics (INSEE) since 1954 [46,51,52]. Demographic evolution was required to interpret trends in electricity consumption E_Y over several years due to the significant variation in the number of inhabitants. These indicators were constructed to explore the discrepancies between Saint Barthelemy and Saint Martin.

3.2.2. Monthly electricity production

Monthly electricity generation data in Saint Martin and Saint Barthelemy are available from January 2013 to May 2019 [49,50,54, 55,60]. This study focused on the impact of Hurricane Irma that occurred in September 2017, and data on monthly electricity generation were presented and used from December 2016 to May 2019, over 29 months, including the cyclonic season. To compare monthly electricity generation evolution between Saint Martin and Saint Barthelemy, a standardized value was obtained by dividing the monthly electricity generation (E_M) by the initial value. More precisely, the initial value corresponds in this specific case to the maximum monthly electricity generation ($E_{M\text{-}max}$) that is December 2016 for Saint Martin and March 2017 for Saint Barthelemy. The ratio between the standardized monthly electricity generation of Saint Barthelemy E_{SM-SB} (SM-SB = standard monthly for Saint Barthelemy) and standardized monthly electricity generation of Saint Martin E_{SM-SM} (SM-SM = standard monthly for Saint Martin) was used to compare electricity generation in Saint Martin and Saint Barthelemy, on a monthly basis. From a theoretical perspective, the indicator $I_M = [E_{M\text{-}Territory\ 1}/E_{M\text{-}Max\text{-}Territory\ 1}]/[E_{M\text{-}Territory\ 2}/E_{M\text{-}Max\text{-}Territory\ 2}]$ (eq. 5) represented the variation in electricity generation between the two different territories and permit to observe changes with a shorter time step than I_Y.

To avoid any bias in the interpretation of monthly electricity generation due to different numbers of inhabitants in Territory 1 (in this study, Saint Barthelemy) and Territory 2 (in this study, Saint Martin), a comparison between monthly electricity generation per
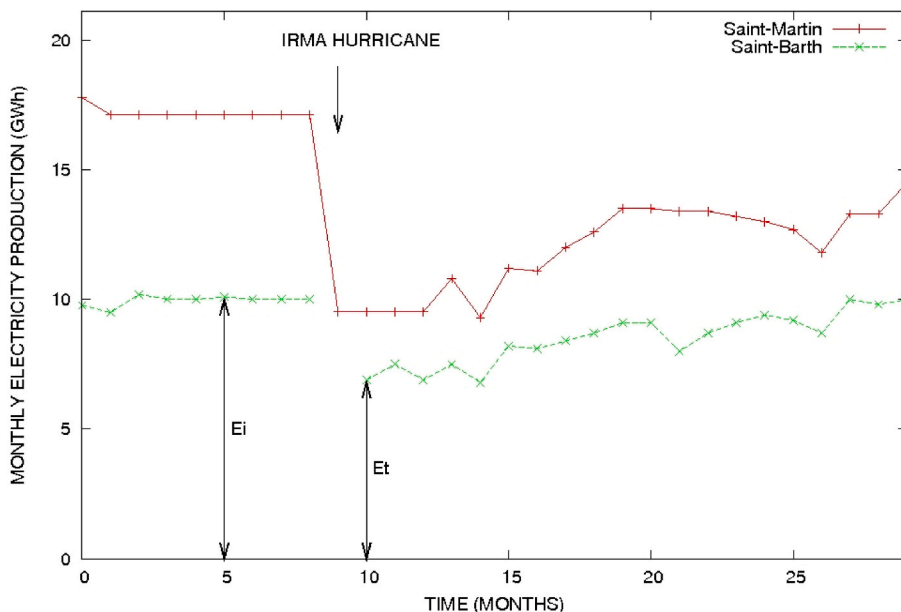

Fig. 3. Monthly electricity production in Saint Martin E_{M-SM} and Saint Barthelemy E_{M-SB}. Data from Refs. [49,50,54,55].

inhabitant for the two territories was also conducted. The comparison of monthly electricity generation per capita of Territory 1 ($E_{M\text{-}Territory\ 1}$/inhabitant) with that of Territory 2 ($E_{M\text{-}Territory\ 2}$/inhabitant) more accurately measured the intensity of the variation between the two different territories when a different number of inhabitants existed. It could also be useful when the consumption of electricity per capita differed significantly, as potentially after disaster and migration. The trend and absolute value of monthly electricity generation per inhabitant for Saint Martin $E_{M\text{-}SM}$/inhabitant and for Saint Barthelemy $E_{M\text{-}SB}$/inhabitant were analyzed. The use of the ratio of monthly electricity generation $E_M(t)$, such as $E_M(t)/E_{M\text{-}max}$ and $E_M(t)/E_{M\text{-}Max}$/inhabitant, instead of monthly electricity generation allowed us to more accurately compare the trends of the two different territories.

In a first time, estimation of E_M/inhabitant was calculated considering that the number of inhabitants was constant for a period of 29 months at 35 000 for Saint Martin and 10 000 for Saint Barthelemy. There is only one official demographic estimates of the variation in the number of inhabitants between January 2017 and May 2019: in January 2018, there were 34 099 instead of 35 746 in 2016. A potential decrease of the population from 35 000 to 28 000 has been also simulated for Saint-Martin: during several months, there are some indices that suggest a decrease of the number of inhabitants just after Hurricane Irma [14,58].

The long-term velocity of electricity restoration after disaster (V_{LR}) is defined by $V_{LR} = (E_{M\text{-}t}/E_{M\text{-}max} - E_{M\text{-}min}/E_{M\text{-}max})/\Delta t$ (eq. 6), where $E_{M\text{-}max}$ is the maximum value of monthly electricity generation (in GWh), $E_{M\text{-}min}$ is the minimum value of monthly electricity generation after disaster (GWh), $E_{M\text{-}t}$ is the monthly electricity generation (GWh) at time t (year), and $\Delta t = t\text{-}t_0$ is the duration to restore monthly electricity generation, where t_0 is the time when a disaster occurs.

4. Results

4.1. Monthly electricity production and impact of hurricane on infrastructures

Monthly electricity production in Saint Martin $E_{M\text{-}SM}$ was between 25% and 40% higher than in Saint Barthelemy $E_{M\text{-}SB}$ (Fig. 3). The gap decreased from 40% to 25–30% corresponding to a decrease in energy production between Saint Martin and Saint Barthelemy of 10–15% after Hurricane Irma. In both cases, E_M showed the same trend: an initial constant value, then an abrupt decrease to a low value followed by a slow increase.

More precisely, after an abrupt decrease to a low value, that remained stable for 3–4 months, followed by a slow increase of the monthly electricity production. The monthly electricity production $E_{M\text{-}SB}$ was 10 GWh in Saint Barthelemy during the first eight months of 2017. This initial value $E_{I\text{-}SB} = 10$ GWh was used as a reference for Saint Barthelemy. Then, $E_{M\text{-}SB}$ decreased to 7 GWh in one month, representing a decrease of 30% in September 2017. During the next 19 months, a slow increase in $E_{M\text{-}SB}$ occurred from 7 to 10 GWh. Finally, a complete restoration of monthly electricity production $E_{M\text{-}SB}$, identical to the values observed at the beginning of 2017, occurred in March 2019.

In Saint Martin, the monthly electricity production $E_{M\text{-}SM}$ was constant at approximately 17 GWh during the beginning of 2017 and decreased to 9.5 GWh in September 2017 (Fig. 3). This decrease represents 45% of the initial value of monthly electricity generation. The initial value $E_{I\text{-}SM} = 17$ GWh was considered as a reference value for $E_{M\text{-}SM}$ in this study. The $E_{M\text{-}SM}$ increased from September 2017 (month 9) to May 2019 (month 29), where it reached a value of 14.5 GWh. In May 2019, $E_{M\text{-}SM}$ was always lower than the $E_{I\text{-}SM}$ value
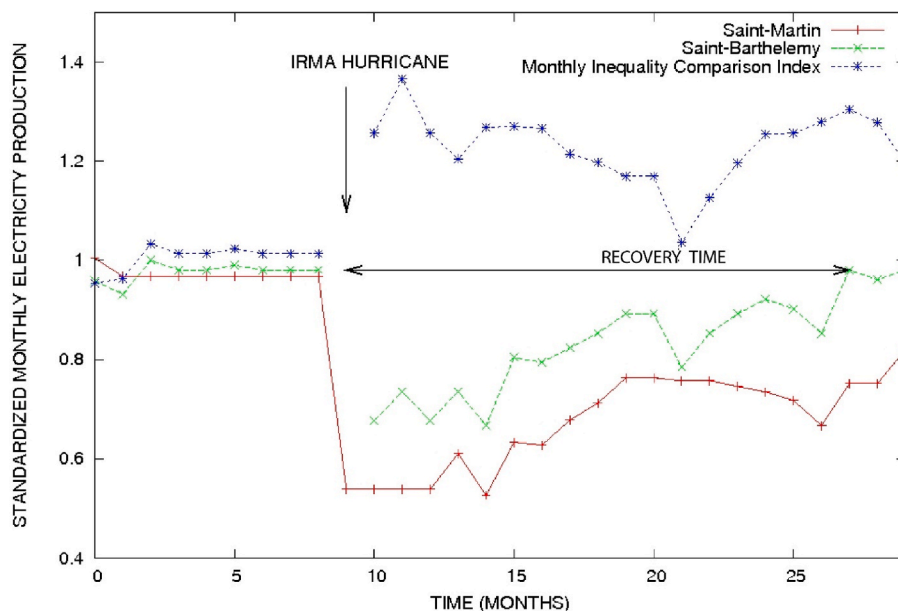

Fig. 4. Standardized monthly electricity production in Saint Martin $E_{SM\text{-}SM}$ and Saint Barthelemy $E_{SM\text{-}SB}$. Monthly electricity production from January 2017 to May 2019. A post-disaster relative inequality growth indicator was established from standard monthly electricity production $E_{SM\text{-}SB}/E_{SM\text{-}SM}$ as defined in equation 5 (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observed during the first eight months of 2017 and this was intriguing, comparing to Saint Barthelemy.

The power plant was stopped in Saint Martin after marine inundation affected the production unit. In Saint Martin, Hurricane Irma damaged between 40% [4] and 90% [58] of buildings. Tourism related infrastructure near the sea was particularly damaged by marine inundation [4,61]. During 3–4 months, monthly electricity generation E_M was low in Saint Martin and Saint Barthelemy. The apparent difficulty in restarting over several months was not solely due to delays in electricity network restoration, as the electricity network was almost completely restored after one month [62].

Standardized monthly electricity production $E_{SM} = E_M/E_I$ permits an easier comparison of Saint Barthelemy and Saint Martin in terms of electricity generation and recovery over 29 months (Fig. 4). A slow increase in monthly electricity generation started after 3–5 months in both cases due to the gradual restoration of social and economic activities. For example, the activity of industrial harbors was characterized by an increase in concrete import during this period [49,50]. The electricity network was improved after the hurricane, even though a part of the electricity network was buried. In Saint Barthelemy, the monthly electricity generation was restored to the initial pre-disaster values after 18 months (Figs. 3 and 4). This implied that restoration of economic and social activities at conditions equivalent to those that existed before Hurricane Irma were reached after $t_{long\ resilience} = 1.5$ year in Saint Barthelemy. Moreover, the long-term velocity of electricity restoration after disaster for Saint Barthelemy, $V_{LR-SB} = 0.2$ yr^{-1}, considering that $E_t/E_{max} = 1$, $E_{min}/E_{max} = 0.7$, $\Delta t = t_{long\ resilience} = 1.5$ year and equation 6 (Table 2).

In the case of Saint Martin, the restoration of standardized monthly electricity generation (E_{SM-SM}) had not been completed 20 months after the disaster (Fig. 4). The mean long-term electricity restoration velocity at Saint Martin was $V_{LR-SM} = 0.15$ yr^{-1}, 20 months after Hurricane Irma, considering that $E_{SM-t}/E_{SM-max} = 0.8$, $E_{SM-min}/ES_{M-max} = 0.55$ (Table 2), $\Delta t = 20$ months = 1.67 year and equation 6 (Fig. 4).

The long recovery time $t_{long\ recovery}$ required to restore the monthly electricity generation in Saint Martin as it was before Hurricane Irma was estimated by calculating $t_{long\ recovery} = (E_{M-max}/E_{M-max} - E_{M-min}/E_{M-max})/V_{LR-SM} = 3$ years (September 2020). The long recovery velocity in Saint Martin was lower than that in Saint Barthelemy and, consequently, the recovery time higher (Table 2).

Recovery time, which is the time required to restore conditions to those before the disaster had occurred, was 1.5 year in Saint Barthelemy and 3 years in Saint Martin. A comparison of electricity generation in Saint Barthelemy and Saint Martin showed that when E_{SM} was less impacted during 3–5 months just after a disaster, recovery occurred faster. In the present case, the smaller value of E_{SM} in Saint Barthelemy was 15–20% higher than that in Saint Martin (Fig. 4). This different impact on these two territories caused the same disaster is due to a different resistance of dwellings to similar winds: 19.7% of buildings were distructed or highly damager in Saint Martin, instead of 2.5% in Saint Barthelemy.

The electricity network was gradually restored in approximately one month, but electricity generation remained low [14,62]. Thus, electricity network infrastructure was not responsible for the delays in electricity generation, and had other causes. The recovery velocity was slightly higher in Saint Barthelemy than in Saint Martin due to the higher financial capacity of inhabitants in Saint Barthelemy, where reconstruction of damaged buildings was conducted using insurance funding as well as their own financial stock. Building reconstruction favored the restart of economic activities. The higher income of Saint Barthelemy inhabitants is documented by higher GDP per capita, but also by the energy consumption per capita. GDP and energy consumption per capita are often correlated [8,22,63].

The different recovery velocity suggests that social and economic activities recovery did not evolve at the same rate in Saint Barthelemy and Saint Martin. After Hurricane Irma, the ratio I_M (eq.5) increased (Fig. 4, blue line) and was always >1 until May 2019. This is in agreement with the fact that economic activities restarted faster in Saint Barthelemy than in Saint Martin. Field analysis and interviews with stakeholders confirmed that reconstruction was more advanced in Saint Barthelemy than in Saint Martin in December 2019. Moreover, tourism activities restarted more slowly in Saint Martin. Tourist flux also showed that the economy of Saint Barthelemy was at the same level as before Hurricane Irma in December 2019 [49].

4.2. Influence of social and economic activities on annual electricity production

Yearly electricity production in Saint Martin E_{Y-SM} was between 30% and 50% higher than that of E_{Y-SB} in Saint Barthelemy (Fig. 5). The gap between the annual electricity generation of Saint Martin and Saint Barthelemy decreased and was minimal at approximately 30% in 2018. From 2007 to 2016, a slow increase in the annual electricity generation occurred in Saint Barthelemy; E_{Y-SB} increased from 90.6 GWh to 117.3 GWh (Table 3). This represents an increase of +29.5% in nine years at a mean annual increase rate of approximately +3.3%. Then, a decrease of 14% in the annual electricity generation from 117.3 GWh in 2016 to 100.7 GWh in 2018 was caused by Hurricane Irma. This represents a mean annual decrease rate of −8.3% in the annual electricity generation in Saint Barthelemy. In 2019, energy production increased in Saint Barthelemy and was higher than that in 2016 before Hurricane Irma.

Table 2
Main features of monthly electricity production.

	GDP/inhab (€/inhabitant)[a]	E_i (GWh)[b]	$t_{long\ recovery}$ (year)[c]	E_{SM-MIN}/E_{SM-MAX} (no unit)[d]	$E_{SM-MAX} - E_{SM-MIN}$ (GWh)[e]
St Mart.	16 600	17	3 (estimated)	0.55	0.45
St Barth.	40 000	10	1,5	0.7	0.3

[a] Gross Domestic Product per inhabitants.
[b] Initial monthly electricity production.
[c] Recovery time.
[d] Monthly electricity ratio between maximum and minimum values.
[e] Monthly electricity production difference between minimum and maximum values.
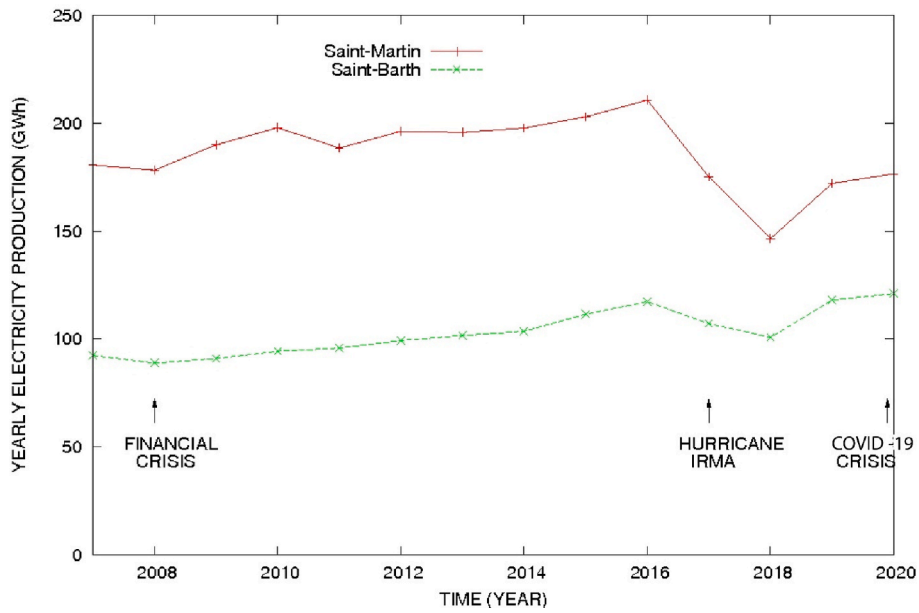
Fig. 5. Yearly electricity production in Saint Martin $E_{Y\text{-}SM}$ and Saint Barthelemy $E_{Y\text{-}SB}$ between 2007 and 2020. Data from Refs. [46,47,53–55].

Table 3
Annual electricity production in Saint Martin and Saint Barthelemy from 2007 to 2020.

	2007	2008	2009	2010	2011	2012	2013	2014	2915	2016	2017	2018	2019	2020
St Mart[a]	181	178	190	198	188	196	196	198	203	211	175	146	172	177
St Bart[b]	92	89	91	94	96	99	102	104	111	117	107	101	118	121

[a] in GWh ±0.5 GWh [51,55].
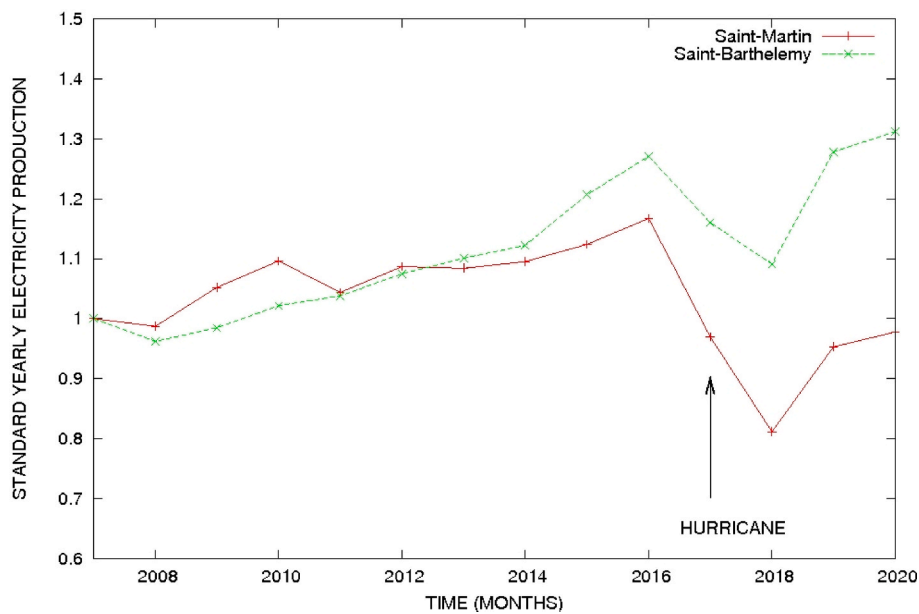[b] in GWh ± 0.5 GWh [52,54}.

Fig. 6. Standardized evolution of annual electricity production of Saint Martin $E_{SY\text{-}SM}$ and Saint Barthelemy $E_{SY\text{-}SB}$. The annual electricity production was divided by electricity generated by each island in 2007 E_{y2007} ($E_{Y\text{-}2007\text{-}SM} = 180.6$ GWh for Saint Martin and $E_{Y\text{-}2007\text{-}SB} = 92.3$ GWh for Saint Barthelemy) as defined in equation 1.

In Saint Martin, $E_{Y\text{-}SM}$ increased from 180.6 GWh in 2007 to 210.8 GWh in 2016. This is a +16.7% increase in nine years, equivalent to an annual increase rate of +1.9%, which was lower than that in Saint Barthelemy. The growth in $E_{SY\text{-}SB}$ was higher after 2012 (from 2013 to 2016) than that in $E_{SY\text{-}SM}$ (Fig. 6), when autonomy increased in Saint Barthelemy, and also contemporaneously with tourist arrivals increase. An increase in electricity generation of 10–20% occurred from 2014 to 2016 in both territories, corresponding to the period of higher number of tourists in the last 20 years. After 2016, $E_{Y\text{-}SM}$ decreased by 30.5% from 210.8 GWh to 146.5 GWh, representing an annual rate decrease of −15.25% caused by Hurricane Irma. In 2019, energy production increased in Saint Martin but remained lower than that in 2016 and this observation is coherent with monthly electricity production.

The decrease of annual electricity generation in 2017 and 2018 was caused by Hurricane Irma in agreement with monthly electricity production. During the first eight months of 2017, before Hurricane Irma, electricity generation was high, and the annual values represented an average value between the amount of electricity generated before and after the hurricane. Consequently, annual electricity generation was lower in 2018 than in 2017. This is in agreement with the number of tourist decrease and unemployment increase that suggest economic activity decrease. In 2019, E_Y increased in both islands contemporaneously with employment and merchandize import increase as well as export. The number of employees for reconstruction increases was favored by economic activity [51,].

Whereas there is a difference of energy production of around 100 GWh between Saint Martin and Saint Barthelemy in 2016, there is 50 GWh of difference in 2018–2020. This evolution must be carefully interpreted. This not means that social and economic activities of Saint Martin and Saint Barthelemy are converging as suggested by standardized data.

In Saint Barthelemy, the standard annual electricity generation $E_{SY\text{-}SB} = E_{Y\text{-}SB}/E_{Y\text{-}2007\text{-}SB}$ increased steadily from 2008 to 2016, and decreased in 2017 and 2018 (Fig. 6). In Saint Martin, $E_{SY\text{-}SM}$ increased slowly compared to that in Saint Barthelemy and decreased more intensely in 2017 and 2018 (Fig. 6). Standard annual electricity generation was 8% lower in Saint Martin in 2017, 27% in 2018, and 40% in 2019 after Hurricane Irma. The standardized annual electricity generation E_{SY} shows that the gap between Saint Barthelemy and Saint Martin was significantly increasing, especially after Hurricane Irma during the recovery phase (Fig. 6) in agreement with results suggested by monthly electricity production and with economic trends: the number of employee reduced significantly and during a longer time in Saint-Martin than in Saint Barthelemy, the number of tourists increased more rapidly in Saint Barthelemy than in Saint Martin after the disaster [51,]. In December 2019, tourist arrivals were identical than before the disaster in Saint Barthelemy, whereas it was not the case in Saint Martin.

The ratio between standard annual electricity generation in Saint Barthelemy and Saint Martin $E_{SY\text{-}SB}/E_{SY\text{-}SM}$ had been increasing since 2010 (Fig. 7, green line) and had accelerated since 2017. This indicator revealed that since 2010, social and economic activities in which energy consumption is necessary have evolved and increased more in Saint Barthelemy than in Saint Martin. Thus, this indicator emphasized that differences (i.e., inequality) in social and economic activities that consume electricity was increasing between the two islands. Field observations conducted in December 2019 indicated that recovery was better in Saint Barthelemy than in Saint Martin, from a qualitative perspective. This is in agreement with the higher unemployment rate in Saint Martin than in Saint Barthelemy [49, 50], as well as the higher reduction in tourists in Saint Martin than in Saint Barthelemy [49,50]. As indicator I_Y represents an increasing
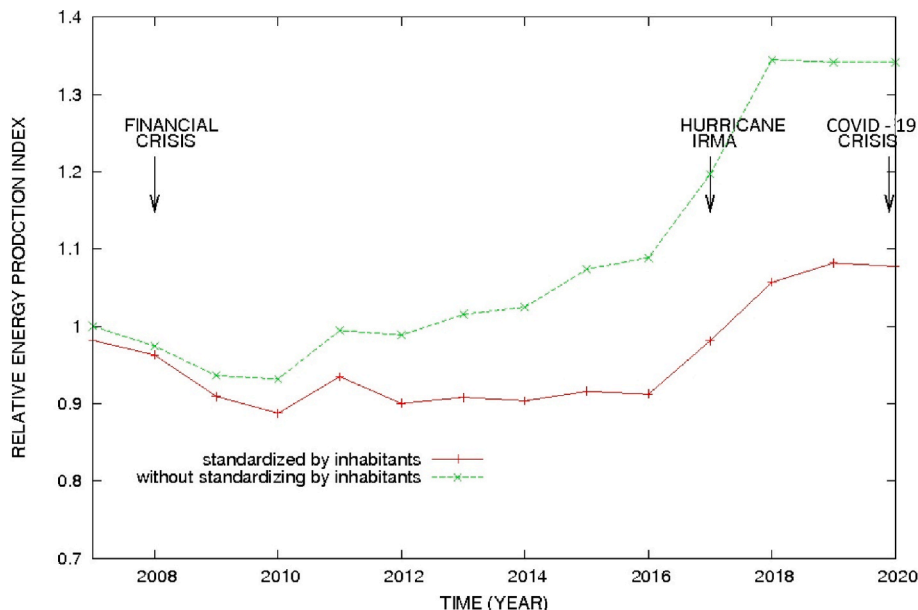

Fig. 7. Evolution of inequality with time. In green and red, the indicator I_Y is constructed with the ratio between the standard annual electricity production of Saint Barthelemy and Saint Martin, i.e. $I_Y = E_{SY\text{-}SB}/E_{SY\text{-}SM}$ (eq. 3). In red, the indicator $I_{Y\text{-}Demo}$ is constructed using the ratio between the standardized electricity per inhabitants for Saint Barthelemy and for Saint Martin, (eq. 4, i.e. $[E_{Y\text{-}SB}/E_{Y\text{-}SB\text{-}2007}/\text{inhabitant}]/[E_{Y\text{-}SM}/E_{Y\text{-}SB\text{-}2007}/\text{inhabitant}]$). Number of inhabitants from IEDOM (2021) [51,]: in January 2018, there was officially 34 099 inhabitants. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

difference in energy production between the two territories after a disaster, suggesting an increase in inequality between the two territories after Hurricane Irma, the indicator I_Y can be considered reliable for detecting and characterizing the inequalities in other cases.

4.3. Impact of demographic growth

On a relatively long duration (13 years), the influence of population growth cannot be neglected. A specific analysis is necessary to highlight the role of demographic evolution on electricity production especially when significant migration after disaster are suspectedn. To avoid any bias in indicator construction, another indicator was established considering the population evolution $I_{Y\text{-}Demo}$ (equation 4) and it was compared with I_Y. There are at least two hypothesis to interpret the increase in social and economic activities after 2012, when autonomy increased in Saint Barthelemy. It could be due: (i) to the better adaptation of new rules to the local context that permitted economic growth, (ii) to an increase of population in Saint Barthelemy attracted by potential new tax exemption. During 2007–2016, population growth in Saint Barthelemy was higher (17%, from 8450 to 9912) than that in Saint Martin (<0.1%, from 35 714 to 35 746) and especially after 2012. The comparison between I_Y and $I_{Y\text{-}DEMO}$ shows that a significant part of the higher growth in annual electricity generation observed in Saint Barthelemy is explained by demographic growth (Fig. 7).

$I_{Y\text{-}DEMO}$ indicator (Fig. 7, in red) incorporated the population evolution of each territory and exhibited the same trends as the previous indicator (in green), but also a difference. The comparison between these indicators I_Y and $I_{Y\text{-}DEMO}$ permits to discriminate the influence of demographic growth. Population growth of approximately 15–20% in Saint Barthelemy caused an increase in electricity generation from 2007 to 2016 (Fig. 7). In comparison, the number of inhabitants in Saint Martin was almost constant during this period and might have decreased after Hurricane Irma. During the last decade, population growth had significantly increased in Saint Barthelemy and favored the development of social and economic activities. Consequently, electricity generation was also developed in Saint Barthelemy because of the population growth and not only by wealth growth or new electronic/electric devices. The different growth in energy consumption between Saint Barthelemy and Saint Martin was favored by a higher population growth in Saint Barthelemy.

4.4. Impact of migration

In 2017–2019, energy consumption was more impacted in Saint Martin than in Saint Barthelemy by Hurricane Irma and caused an increasing gap as it was previously analyzed using monthly electricity production. During the first 4 months after Hurricane Irma in 2017, the difference of the monthly electricity production (Fig. 3) between Saint Martin and Saint Barthelemy should be explained, at least in pat, by the migration of 7000 inhabitants from Saint Martin. The decrease in standard annual electricity generation was higher in Saint Martin than in Saint Barthelemy in 2017 and 2018 after Hurricane Irma. In this study, the change in the number of inhabitants was found to be responsible for a significant part of electricity consumption and production. The number of inhabitants in a territory
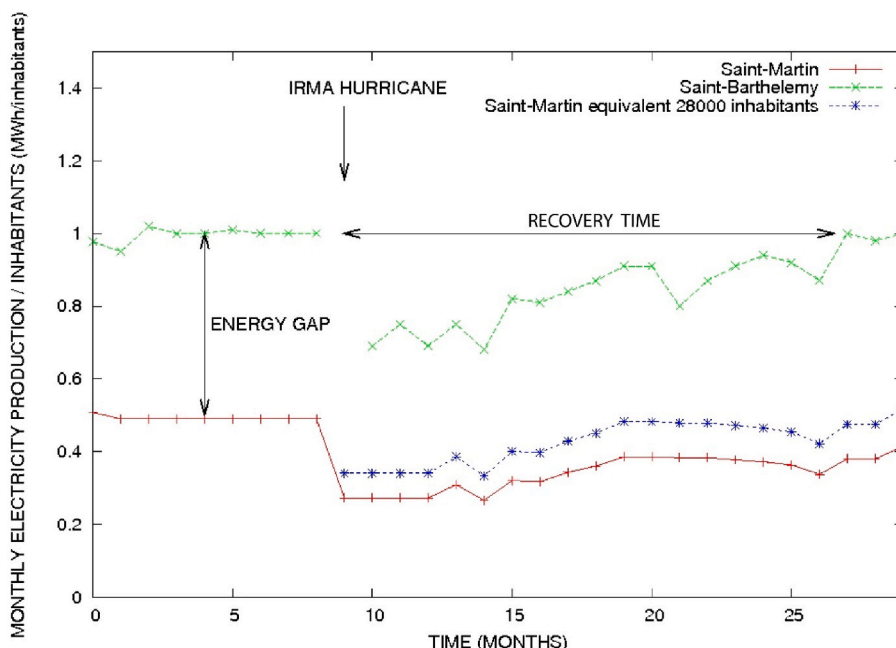

Fig. 8. Monthly electricity production/inhabitant in Saint Martin $E_{M\text{-}SM}$/inhabitant and Saint Barthelemy $E_{M\text{-}SB}$/inhabitant. The number of inhabitants is considered constant between 2017 and 2019 in Saint Martin (35 000 inhabitants, red curve) and Saint Barthelemy (10 000 inhabitants). To discuss the potential decrease of Saint-Martin's population after Hurricane Irma, the case where there were 28 000 inhabitants is represented in blue. After 4 months (January 2018), official statistic indicates that there were more than 34 000 inhabitants in Saint Martin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

influences the number of social and economic activities. The increase in the number of inhabitants caused growth in the social and economic activities and consequently in electricity production. On the contrary, the decrease of the number of inhabitants should cause a decrease in social and economic activities, and consequently in electricity production.

From 2016 to 2019 after Hurricane Irma, I_Y, growth was approximately 25%, whereas I_{Y-Demo} increased by approximately 20%. Although the long-term (2007–2020) population growth in Saint Barthelemy was not related to the effects of the disaster, the population evolution in Saint Martin was more complex and evolved in 2017 in relation to Hurricane Irma. The variation in the number of inhabitants after a disaster, due to death or migration, must be considered in the analysis of energy consumption after major hurricane. At least part of electricity production difference between Saint Martin and Saint Barthelemy was due to the displacement of 7000 inhabitants of Saint Martin from the island after Hurricane Irma. The indicator based on the number of inhabitants could be less accurate after 2017 because, after than inhabitants left Saint Martin, there was some uncertainty on the timing of their come back. Nevertheless, migration has reduced the recovery of electricity generation in Saint Martin.

The monthly energy production E_M also depends on the number of inhabitants. It was higher in Saint Martin than in Saint Barthelemy (Fig. 3). To avoid misinterpretation when comparing monthly electricity generation in Saint Martin and Saint Barthelemy, Fig. 8 shows the monthly electricity generation per inhabitant. Monthly electricity generation per inhabitant was twice that in Saint Barthelemy than in Saint Martin (i.e., 1 MWh/inhabitant vs 0.5 MWh/inhabitant) before Hurricane Irma. The hurricane caused a decrease in the monthly electricity generation per inhabitant $E_M/inhabitant$, which was higher in Saint Barthelemy (0.3 MWh/inhabitant), than in Saint Martin (0.2 MWh/inhabitant). Nevertheless, these higher "absolute" impact on energy consumption must be interpreted carefully in term of vulnerability because those represent a decrease in the monthly electricity generation/inhabitant of 30% (from 1 to 0.7 MWH/inhabitant) in Saint Barthelemy and that of 40% (from 0.5 to 0.3 MWh/inhabitant) in Saint Martin (Table 4). Social and economic activities that consume electricity were proportionally more impacted in Saint Martin than in Saint Barthelemy. The energy gap ΔE between Saint Martin and Saint Barthelemy was 0.5 before Hurricane Irma (Fig. 8) and increased up to 0.6. This represents an increase of 20% in the energy gap.

After Hurricane Irma, the population of Saint Martin decreased significantly (i.e., 7000 inhabitants migrated from the island to Guadeloupe, France Metropolitan, or North America) during at least 4 months [57,58] and was confirmed during field interview. This influenced the electricity consumption in Saint Martin and explained part of the discrepancy in the monthly electricity generation E_M observed between Saint Martin and Saint Barthelemy just after the occurrence of the hurricane (3–5 months).

Electricity generation in Saint Martin and Saint Barthelemy was mainly due to consumption by electrical devices in luxurious residences (air conditioners, swimming-pool pumps, etc.), airport services, and building construction, but not by industry. Industry play a reduced role in these territories.

5. Discussion

5.1. Cause of post-crisis recovery differences

The different recovery after Hurricane Irma is responsible of the energy production difference and of the inequality growth between these two territories. The inequality growth between these two territories after Hurricane Irma was due to (i) more dwellings destructed or very damaged in Saint Martin (19.7%) than in Saint Barthelemy (2.5%) [56] (Table 5), due to sturdier and more expensive construction in Saint Barthelemy, (ii) more people insured in Saint Barthelemy (60%) than in Saint-Martin (40%) [57], (iii) higher income and financial resources in Saint Barthelemy than in Saint Martin allowing to start reconstruction before at the individual scale, (iv) post-hurricane investment in dwelling's construction/reconstruction in Saint Martin was not considered as a secure investment, (v) tourism industry's fast recovery in Saint Barthelemy promoted a speedier overall economic recovery, (vi) the migration of people outside the island of Saint-Martin.

During the post-disaster period, recovery and inequality growth were widely constant according to the $E_{M-Territory\ 1}/E_{M-Territory\ 2}$ ratio, thereby indicating that the scenario of Saint Barthelemy was consistently better than that of Saint Martin (Fig. 4). Some variations could be due to seasonal activities related to tourism, which depended on the weather.

The monthly electricity generation per inhabitant before Hurricane Irma $E_{M-i}/inhabitant$ in Saint Barthelemy (1 GWh/inhab) was twice that in Saint Martin (0.5 GWh/inhab; Fig. 8). In both cases, tourism is the main economic activity. Differences in electricity generation per inhabitant were not explained by the different economical activities but by different intensities of consumption. The GDP per capita in Saint Barthelemy was more than twice that in Saint Martin (Table 2). The average income in Saint Barthelemy was higher than that in Saint Martin.

Table 4
Main characteristics of electricity generation per inhabitant in Saint Martin and Saint Barthelemy.

Island	Number of inhabitants	E_{M-i}/inhab (GWh/inhab)[a]	E_{M-min}/inhab (GWh/inhab)[b]	$[E_{M-min}$/inhab] $/[E_{M-i}$/inhab][c]	$[E_{M-i}$/inhab]-$[E_{M-min}$/inhab] (GWh/inhab)[d]
St Mart.	35 000	0.5	0.3	0.6	0.2
St Barth	10 000	1	0.7	0.7	0.3

[a] Initial monthly energy production per inhabitants.
[b] Minimum monthly energy production per inhabitants.
[c] Ratio between Minimum and initial monthly energy production.
[d] Spread between initial and minimum energy production per inhabitants.

Table 5

Main characteristics of Saint Martin and Saint Barthelemy Islands before and after disaster.

	N. of building in marine inundation risk areas[a]	Number of building per inhabitants per surface in marine inundation risk areas[a]	% of insured people[b]	% of very damaged or destructed building after Irma[c]	Total reimbursement per inhabitants after Irma (keuros/ inhabitants)[d]
St Mart.	3262	0.018	40	19.7	33
St Barth.	1064	0.071	60	2.5	82

[a] in 2017 [61].
[b] [57].
[c] [57].
[d] [57,58].

Inequality variation at the individual scale was beyond the scope of this study. Previous studies have suggested that inequalities increase after a disaster at the individual scale [27,43,64] or at the neighborhood scale [53], but not at the scale of an island. This suggests that inequality growth during the recovery phase after a natural disaster is observed at various scales (individuals, neighborhoods, and islands). The interdependence and causal relations between one scale and the others may be determined, but have not been investigated in the detail herein.

5.2. Policies, planning and crisis management

These territories differ from at least two aspects concerning risk management: (i) Saint Martin has a prevention plan since 2011 whereas Saint Barthelemy has not, (ii) local administration in Saint Barthelemy is considered as more efficient to promote urban construction rules respect than in Saint Martin [61].

Nevertheless, Saint Martin prevention plan was implemented late, after that many buildings were constructed and has moderately influenced vulnerability evolution (Table 6). Furthermore, pre-existing construction rules in coastal areas in Saint Martin, before the prevention plan implementation, were not respected and many building were constructed in marine inundation risk areas [61]. No prevention plan was implemented in Saint Barthelemy. The number of construction in marine inundation risk areas per inhabitants in Saint Barthelemy is similar or slightly higher than in Saint Martin [61]. Saint Barthelemy restricted low-income arrivals. Since 2012, Saint Barthelemy is outside EU territory.

After Hurricane Irma, several action were conducted to favor island's recovery. First, French state, NGO and several companies organize emergency help. Second, French state and EU funded also the reconstruction of infrastructures: for example, electrical network has been progressively buried. Private companies invest for reconstruction of internet, cell and water network. Concerning water network it was partly funded by French state. Three, insurance distributed progressively money to insured people. It corresponds to 1176 million euros for the French part of Saint Martin and 823 million euros for Saint Barthelemy [57,58]. This help was proportionally higher in Saint Barthelemy (82.3×10^3 euros/inhabitants) than in Saint Martin (33.4×10^3 euros/inhabitants). Four, inhabitants used their own money to reconstruct. Due to higher income and lower destruction in Saint Barthelemy than in Saint Martin, recovery was faster in Saint Barthelemy than in Saint Martin at the individual/family scale. Five, economic activities growth after Irma were promoted, in a first time, by activities in relation with reconstruction and then by tourism slow increases. Progressive economic growth favored new investment for reconstruction. This may explain part of the different recovery: post-crisis reconstruction favor tourism increases; this later causes income growth, and then higher investment in the reconstruction are available. Six, part of recovery was due to informal initiative. In low-income neighborhood of Saint Martin, solidarity by family and/or community occurred by sharing goods (food, home) and cooperating (home reconstruction). This process has been described by people during the field investigation, but was not quantified in this study.

5.3. Demographic evolution

A comparison of relative differences indicators I_Y and $I_{Y\text{-}Demo}$ based on standardized energy showed that population variation played a role in electricity consumption indicators and cannot be neglected during interpretation. Considering the evolution of the number of inhabitants in the indicators allowed us to confirm that part of the long-term economic growth in Saint Barthelemy in comparison to Saint Martin was influenced by the increase in the number of inhabitants and not only by the presence of a different economic organization. Any uncertainty in population variation could cause an uncertainty in the interpretation of the indicators. The population growth impact on GDP vary with the level of a country's development, the source or nature of the population growth, or other factors that lead to nonuniform impacts [65].

From 2007 to 2016, population increase in Saint Barthelemy whereas it was stable in Saint Martin (Fig. 1). If it is not considered,

Table 6

Planning and policies in Saint Martin and Saint Barthelemy Islands.

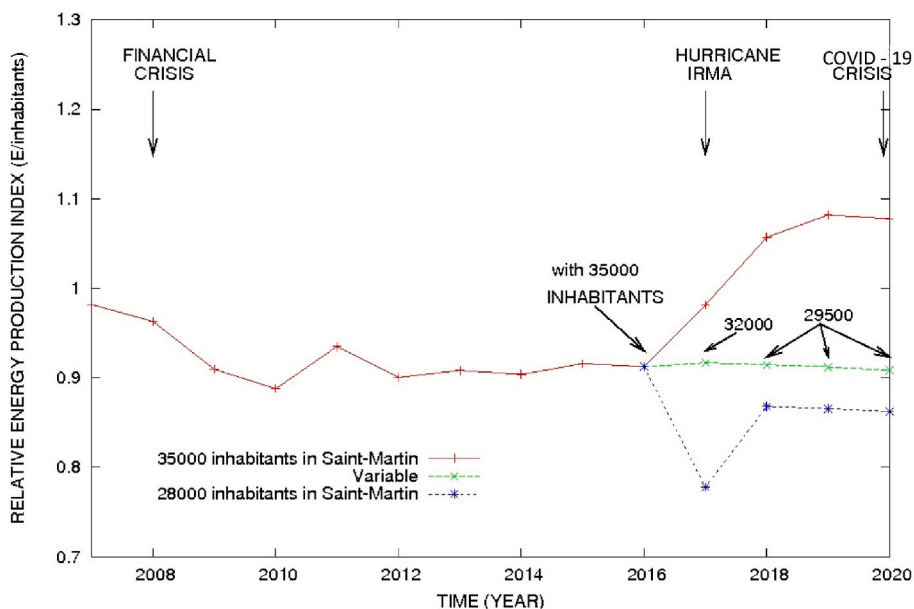| Island	Prevention plan	European Union territory	Autonomous law (2007)	Taxation law (Pons law)	Coastal protection law (1986)
St Martin	Yes (2011)	Yes	Yes	Yes	Yes
St Barth	No	No (since 2012)	Yes	Yes	Yes

Fig. 9. Relative inequality evolution between Saint-Martin and Saint-Barthelemy. After 2016, the potential effect of the number of inhabitant variation in Saint Martin is presented in three different cases. In red, the number of inhabitants is around 35 000 (official data) and this curve is similar to the red curve in Fig. 8. In blue, the mean number of inhabitants is considered constant at 28 000 from 2017 to 2020. In green, the number of inhabitants decreases from 35 000 in 2016–29 500 in 2020 and the indicator $I_{Y\text{-}Demo}$ is almost constant after the hurricane. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interpretation of the relative evolution of electricity production I_Y growth from 2007 to 2016 could be wrong. When taking into account the number of inhabitants, the relative evolution of electricity production $I_{Y\text{-}Demo}$ between Saint Martin and Saint Barthelemy is almost stable from 2007 to 2016. From 2007 to 2016, demographic evolution play the main role on annual electricity production (Fig. 5).

After September 2017, migration of around 7000 inhabitants (20%) outside Saint Martin and less than 1000 inhabitants (<10%) outside Saint Barthelemy has been suggested [57]. Demographic studies conducted after hurricane Irma in Saint Martin suggest that the number of inhabitants returned to 34 100 in January 2018 [51]. Considering than the number of inhabitants returned to almost the same value several months after Hurricane Irma, this study shows that electricity production per inhabitant in Saint Martin has decreased more than in Saint-Barthelemy (Fig. 7, red line). It suggest that the indicator growth in 2016–2019 is not only due to the Saint Martin's population decrease. However, difficulties to estimate the number of people present on the island after the hurricane is real. It have been suggested that in September 2018, alwost 20% of the population of Saint Martin was not returned back using school statistics [57]. Nevertheless, the decrease of the number of students is contemporaneous with new workers arrivals for reconstruction.

The potential effect of population decrease is discussed using Fig. 9. Considering the purely theoretical case where Saint Martin population decreases and remains stable at 28 000 inhabitants from 2017 to 2020, conduct to a relative increase of electricity production per inhabitants in Saint Martin in comparison to Saint Barthelemy and, consequently, an increase of $I_{Y\text{-}DEMO}$ (Fig. 9, blue line). This scenario seems not realistic because in contradiction with field observations and with economic indicators, such as unemployment or number of tourist arrivals, that suggest a better recovery in Saint Barthelemy [51,]. Relative inequality growth between Saint Martin and Saint Barthelemy, advantaging Saint Barthelemy, if the mean number of inhabitants is higher than 32 000 in Saint Martin in 2017 as well as more than 29 500 in 2018, 2019 and 2020 (Fig. 9, green line). Considering than during 8 months in 2017 the population was of 35 000 and during 4 months of 28 000, the mean number of inhabitants in Saint Martin is slightly higher than 32 000 in 2017. In 2018, the number of inhabitants was estimated by the French statistical institute to be higher than 29 500 in Saint Martin [51] causing $I_{Y\text{-}DEMO}$ increases and is $I_{Y\text{-}DEMO} > 1$ (Fig. 9, red line). It suggests an inequality growth between these two territories and a better improvement in social and economic conditions for Saint Barthelemy than for Saint Martin.Despite the uncertainty regarding the number of inhabitants leaving Saint Martin and their return timing, this study suggests that social and economic activities have been more impacted and for longer time in Saint Martin than in Saint Barthelemy. Population displacements outside the territory after the disaster caused part of this situation.

5.4. Vulnerability and inequality

The direct or indirect effects of hurricane on health [12], stress [26,66], migration or displacement [67], and unemployment [49, 50] have been described in previous studies. An heterogeneous distribution of the impact of disasters on inhabitants has been suggested in Saint Martin after Hurricane Irma [14] and in New Orleans after Hurricane Katrina [68]. Demonstration and riots that occurred in December 2019 in Saint Martin against the risk prevention plan, may have been caused also by the slower recovery and specific difficulties for low-incomes. This study demonstrated the occurrence of heterogeneous impacts at the scale of an island, not

only at the individual scale.

Comparison of the curves of indicators I_Y and $I_{Y\text{-}Demo}$ (Fig. 7) revealed the similar trends, and showed that the amplitude of variations might differ. The evolution of indicators was broadly similar, but after 13 years, the evolution varied by more than 20%. Both indicators suggested that inequality growth was concentrated during the post-disaster period (2017–2019).

The results of this study can be considered as a starting point for the interpretation of processes that lead to inequality growth at the scale of a territory after a disaster. Physical destruction caused by natural disasters has an impact on material goods. Income or wealth can be gained and accumulated via various modalities (buildings, money, stock options, cars, etc.), and material goods such as buildings or home appliances are only one modality to accumulate wealth. The destruction of wealth has not been homogeneously distributed because (i) a difference exists in the vulnerability of buildings between high-income and low-income groups [69], and (ii) high income groups could accumulate more wealth using financial stock.

Considering that the income of Saint Barthelemy was initially higher, the monitoring of $I_{Y\text{-}DEMO}$ emphasized the effect of a natural disaster on the inequality growth and reflected on the role of pre-existing inequalities on recovery. Moreover, a higher financial stock after a natural disaster could enable a faster and more efficient restart by restoring damaged equipment and buying new goods. The processes that play a role at the individual scale might produce an effect at the territorial scale. The precise relationship that causes socio-economic evolution in territories remains debatable [10,69–71].

Saint Martin was economically more vulnerable to hurricane than Saint Barthelemy, as suggested by the fact that more buildings were highly damaged in Saint Martin and that the reduction of standardized monthly electricity generation caused by hurricanes was higher in Saint Martin ($E_{SM\text{-}min\text{-}SM} < E_{SM\text{-}min\text{-}SB}$, Fig. 4) and recovery faster in Saint Barthelemy ($V_{LR\text{-}SB} > V_{LR\text{-}SM}$). The higher vulnerability of Saint Martin might have been favored by the higher vulnerability of the inhabitants in that territory [11,45]. Nevertheless, the difference in income is not the only factor that explains the variation in vulnerability between the two territories [5, 45]. Organizational weakness in Saint Martin has been highlighted by previous studies and it plays an evident role in its vulnerability [5,26].

5.5. Disaster repetition and inequality growth

The analysis of a recent disaster in this study revealed that a single event can cause a difference in energy consumption, representing an inequality growth of more than 15% between the two territories (Fig. 9, from 0.9 to more than 1.05). Consequently, the repetition of natural disasters in the same area could lead to an accumulation of inequalities. This could represent a significant difference in electricity generation between the two territories after several disasters. For example, if an Irma-type-disaster occurred twice in the same territories, the inequality growth should be more than 30%. During Hurricane Luis (1995), damages and death occurred in these territories. In this later case, it have been described that some building were not renovated for decades suggesting difficulties in the recovery. Some of these building are still abandoned as the Hotel *La Belle Creole*. There are also some testimony that many Haitian in a slum in the neighborhood of Concordia were expulsed [72] causing a population decrease. Even if not identical, hurricanes have almost similar consequences on theses territories. The repetition of similar causes and consequences causes growing differences in social and economic activities of these two territories. This study suggests that disaster repetition on these territories is expected to cause inequality growth between these territory (Fig. 10).

At least 17 hurricanes have occurred during the last century in these territories [47]. The 50% difference in electricity generation per capita between Saint Martin and Saint Barthelemy, as well as the GDP per capita difference, could be partly due to past disasters. Other economic processes or political decisions have played a role in this difference, but the above-mentioned cause cannot be neglected. Disasters must be better considered in the analysis of inequality growth and the mitigation of natural hazards improved. Mitigation of natural hazards by efficient prevention plan, especially in Saint Martin, is necessary to protect population against natural risk [61], but also to protect population from inequality growth [73]. This study emphasized that the heterogeneous effects of natural
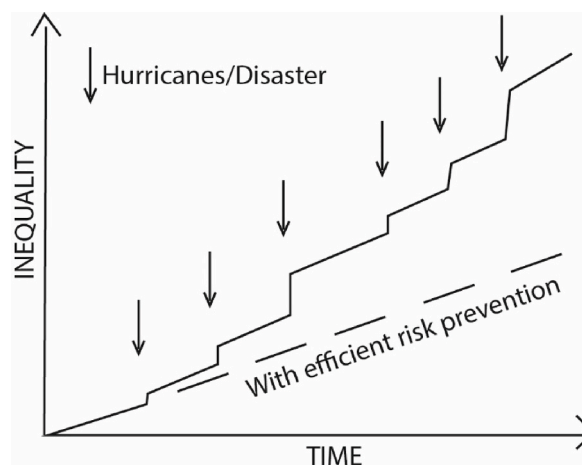
Fig. 10. Inequality growth with time between two different territories when natural disasters occur and potential effect of risk prevention.

disasters on territories impacted by the same event should be better anticipated in the future.

5.6. Subprime mortgage crisis and Covid-19 pandemic crisis

The Irma disaster is not the only event whose impact can be observed with indicators based on electricity generation. The inequality growth between these two territories between 2007 and 2016 was mainly due to a population growth in Saint Barthelemy corresponding to a stagnation in Saint Martin as discussed above. However, during 2008–2010, a decrease in the indicators I_Y and $I_{Y\text{-}Demo}$ was observed (Fig. 7) in relation to the subprime mortgage crisis that started in the USA. North American tourists are numerous in the Caribbean, especially on these islands (60%). Income related to North American (USA, Canada) tourists could be significant in the economic activities of Saint Martin and Saint Barthelemy [53,74–76].

Reduction of tourist flux [59,75] and electricity generation in these two islands occurred in 2008. Reduction of energy consumption in developed countries during financial crises has been described in previous studies [77]. The impact of this crisis was higher in Saint Barthelemy than in Saint Martin, as suggested by the decrease of 5–10% in I_Y and $I_{Y\text{-}Demo}$ from 2007 to 2010 (Fig. 7). The financial income of inhabitants in these two islands might have been impacted differently due to different pre-existing income. Annual electricity generation increased more in Saint Martin than in Saint Barthelemy in 2009 and 2010, as shown in Figs. 5 and 6. This increase was also observed in indicators I_Y and $I_{Y\text{-}Demo}$, where a variation of 5% occurred. Contrary to the impact of Hurricane Irma, infrastructures were not directly impacted by the financial crisis. The difference between Saint Martin and Saint Barthelemy between 2007 and 2011 could be due to a different economic strategy (mass vs. luxurious tourism), but could not be confirmed in this study.

Due to health restriction during Covid-19 crisis, touristic flux decreased significantly from 2019 to 2020 in Saint Martin (passenger arrivals: 73.3% by boat, −50% by planes) [53] and Saint Barthelemy (passenger arrivals: 56.4% by boat, −35% by plane) [], whereas electricity production increased (Fig. 3). During confinement and displacement restrictions in relation with Covid-19 conditions, inhabitants were constrained to stay home more than usual. This behavior conducted to an increased use of home devices. Electricity consumption by inhabitants increased, whereas reduction in electricity consumption by industry was limited, due to the reduced industry development in these territories. The Covid-19 pandemic influenced electricity consumption and generation, as observed in other areas [23–25]. It could have stopped recovery from Hurricane Irma in Saint Martin where electricity production was always below the value of 2016 (Figs. 4 and 5). In Saint Barthelemy electricity production in 2020 was higher than in 2016.

5.7. Comparison with other areas and economic diversification

Electricity production after hurricanes Irma and Maria in 2017 was also recorded in Puerto Rico [13]. The recovery time observed in monthly electricity production in Puerto Rico was 12 months [14] in comparison to 18 months in Saint Barthelemy. Considering that Puerto Rico has a lower GDP than Saint Barthelemy, it can be concluded that the recovery time was not proportional to the GDP in every case. Cuba is evidently less vulnerable to hurricanes than other areas with higher GDP [48,68]. Nevertheless, financial support could favor (i) better infrastructure and building construction and (ii) increased funding for reconstruction [78].

Puerto Rico is a bigger island than Saint Martin and Saint Barthelemy, and other factors play a role in the restoration of Puerto Rico as it has a more diversified economy [77–79]. When economic activities depend on a unique sector that is highly affected by hurricane destruction, economic activity slowly evolves and restoration takes longer [79,80]. Tourism related infrastructures (hotels, guest-houses, and restaurants) may require longer to be restored than other public infrastructures (airports and harbors), networks (electricity and telecom), industry, and agriculture when numerous failures occur, and market dynamics are low. Recovery is not only due to the delay in electrical network restoration. Restoration of social and economic activities also depends on other parameters, such as availability of restored buildings, funding, security, public relations with tourism agencies, communication about the recovery of the territory, public and private investment [80,81].

5.8. Efficiency of the indicators and their limitations

Previous studies show that electricity production depends and permits to analyze: (i) day/night cycles, (ii) week/week-end cycles, (iii) season cycles and temperature changes, (iv) social events [21,22]. This study shows that electricity production was influenced by: (i) Hurricane Irma crisis, (ii) recovery post-crisis, (iii) demographic evolutions, (iv) tourist flux and tourism activity, (v) subprime mortgage crisis, (vi) covid-19 crisis, and permits to analyze (vi) social and economic activities, (vii) relative inequality development between two different territories after a natural disaster.

This case study shown that energy production is useful for monitoring and understanding the intensity of social and economic activities. The ability to use electricity generation to characterize social, environmental, and economic events was suggested by the present case study. As previously described, the decrease in energy (electricity) production in Saint Martin and Saint Barthelemy is contemporaneous with social and economic activities decrease in these islands after Hurricane Irma. The trend obtained with the indicators after Hurricane Irma is consistent with the simultaneous growth in unemployment in Saint Martin (+18,5%) and Saint Barthelemy [49,50], as well as with the decrease in arrivals at the airports (−25.9% in Saint Martin) [49,50], which characterized the decrease in economic activity in 2018. The slow increase in electricity generation after the collapse in September 2017 is consistent with a slow increase in tourist arrivals and an increase in import of concrete from September 2017 to 2019 [49,50]. After this critical period, tourist arrivals in Saint Barthelemy in December 2019 were similar to those in December 2016 [39], which suggested that economic activities had been restored in accordance with monthly electricity production (Fig. 8). In contrast, tourist arrivals in Saint Martin in December 2019 remained lower than before hurricane and electricity production also remained lower than before September 2017. Wealthier territories could spend more to rebuild touristic infrastructures faster and cause income growth faster and, consequently, inequality growth.

Monthly electricity production per inhabitant $E_M/inhabitant$ permits the characterization of the time to return to the initial state

more accurately than other indicators. For example, seasonal tourist arrivals is not relevant to describe all the social and economic activities such as building construction, school and non-profit activities.

The return to the initial state does not imply that each activity is identical to that before the disaster, but that the total energy consumption would be unchanged. When the E_M/*inhabitant* became identical to that before disaster, it implied that the activities consuming electricity continued to consume an equivalent quantity of electricity as before, but not necessarily each activity had not been restored to its state before the disaster. Energy production is a *proxy* for various activities. The identity of indicators based on energy is a consequence of the consumption of electricity of the various activities and not of the similar state of each activity.

During the recent decades, technological transformations such as numerical communication and platforms (Airbnb, etc.), and the increased utilization of air conditioners, electric cars, smartphones, and light-emitting diode (LED) home appliances have altered the electricity consumption trend. The difference in electricity consumption per inhabitant between the two territories is well established (Fig. 8) and could be explained by the higher utilization of electrical devices in high-income territories. Nevertheless, from 2007 to 2020, a transformation that could increase the pre-existing differences at the same rate as the technological progress was difficult to establish. Our analysis was conducted during 2007–2020 and the potential increase of renewable energies or strategies to mitigate energy consumption in the context of global warming were not considered, but could play a role on electricity generation in the future [62,82]. The effects of energy production on the environment influence political decisions in many countries. In the future, strategies that favor sustainability and use of renewable energy will modify future energy production to mitigate CO_2 production [63].

This study was based on the energy (electricity) production recorded by the main electricity company in these islands. The individual generation of electricity was not considered. Individual generators of electricity are often used in these islands to avoid outage, and this production could be significant just after hurricane, when blackout occurs.

5.9. Recommendation

Comparison between these two territories concerning the effectiveness of recovery suggests several recommendations, some of which have been previously proposed [61,83]: (i) efficient prevention plan to promote vulnerability reduction and promote inequality mitigation, especially those related to natural disaster consequences, (ii) sturdier and adapted construction with specific funding to promote para-cyclonic constructions, (iii) favoring insured dwellings and cars, with specific funding for low incomes, (iv) qualified construction companies and construction staff to avoid unsuitable reconstruction, (v) construction material/tools availability and emergency stock to avoid delay during recovery, (vi) resilient/sturdier infrastructures including buried electricity network and if necessary public investment, (vii) efficient public services including technical staff for prevention/mitigation/reconstruction, (viii) a diversified economy not based only on tourism, (ix) re-migration strategies after that 20% of inhabitants leave, (x) promoting economic investment confidence for rebuilding, including communication strategy after crisis, (xi) promoting build back better strategies and renewable energy development, (xii) reducing inequality.

6. Conclusion

Investigating the energy production in terms of electricity generation in the two territories impacted by a natural disaster (Hurricane Irma) led to the following conclusions:

(1) Energy (electricity) production can be used to monitor social and economic activities.
(2) Disaster causes a significant decrease (from 30 to 45%) in monthly electricity generation from 17 GWh to 9.5 GWh in Saint-Martin and from 10 GWh to 7 GWh in Saint-Bathelemy.
(3) Energy (electricity) production restoration rates differ across territories, even if these territories have been impacted by the same event.
(4) The energy restoration rate after a disaster is almost constant for a territory, and complete recovery could be anticipated.
(5) During post-disaster recovery, an increase in the gap between electricity generation per inhabitant occurs between territories.
(6) Inequality growth occurs between territories during the recovery phase.
(7) Disaster repetition could cause inequality increase (and prevention plan are necessary also to avoid inequality growth and not only to reduce risk)
(8) The financial crisis that occurred in 2007–2008 caused a decrease in electricity generation in Saint Martin and Saint Barthelemy, and this effect was more intense in Saint Barthelemy than in Saint Martin.
(9) Population variation plays an evident role in electricity generation and must be considered in the analysis.
(10) Preventions plans must be used to avoid vulnerability and inequality increase that are expected to growth with future natural disaster repetition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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