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► **To cite this version:**

Julien Gargani. Impact of major hurricanes on electricity energy production. International Journal of Disaster Risk Reduction, 2022, 67, pp.102643. <10.1016/j.ijdr.2021.102643>. <hal-03629036>

HAL Id: hal-03629036

<https://hal.science/hal-03629036v1>

Submitted on 5 Jan 2024

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1 **Impact of major hurricanes on electricity energy production**

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21 **Abstract:**

22 After major hurricanes, electricity production reduced owing to not only
23 electricity infrastructure destruction, but also the economic crisis associated with
24 damage to private and public activities. Here, we describe the electricity production
25 curves for the islands of Saint-Martin, Saint-Barthelemy and Puerto Rico in the
26 Caribbean, where two major hurricanes occurred in 2017. After the major hurricanes,
27 the electricity energy production was characterised by a slow recovery followed by a
28 stable phase during several months, corresponding to approximately 75% of the
29 initial electricity production. A resilience time of several months ($1 \text{ month} < t_s < 5$
30 months) is necessary to attain the new electricity energy production equilibrium E_{is} ,
31 which is lower than the initial electricity energy production E_i . The reduction in
32 electricity energy consumption per capita is of 25%. In Saint-Martin, during the post-
33 hurricane stable phase, the electricity production was only 60% of the initial
34 electricity energy production instead of 75%. The reduction of ~15% in the electricity
35 production of Saint-Martin after Hurricane Irma is attributed to the migration of
36 approximately 8 000 inhabitants (approximately 23%) outside the island. This
37 approach makes it possible to anticipate the production of electricity during several
38 months after a major hurricane in the Caribbean islands and to evaluate population
39 displacement.

40

41 **Keywords:** hurricane; electricity; resilience; Caribbean; risks; migration

42

43 **1. Introduction**

44 Major hurricanes can generate fatalities, damage transport infrastructures [1] and
45 electricity networks [2], destroy dwellings, and devastate natural areas [3]. Several
46 studies have suggested that climatic change could increase hurricane intensity [4].
47 The increase in the destructive power of hurricanes during the coming decades may
48 have an impact on anthropic activities [5]. Urbanisation of the coast has increased the
49 vulnerability to marine submersion in Caribbean islands during the last decades
50 [6,7,8]. Consequently, there is a growing interest to better understand hurricanes
51 consequences in Caribbean islands, to mitigate dramatic effects and to anticipate
52 reorganization of societies.

53 During major hurricanes, the destruction of buildings and infrastructures could
54 be due to wind, heavy rain, landslides, or marine submersion [9]. Winds >250 km/h
55 cause enormous damage, especially in cases where buildings and infrastructures
56 have not been constructed to resist to this risk. Hurricane-proof buildings can reduce
57 damage and increase the resilience [10]. The prevention of risks by adopting specific
58 construction techniques and avoiding the location of sensitive infrastructure in
59 coastal areas, evacuation of population, rescue organisation, and post-crisis
60 management can accelerate the restoration of the initial conditions [1,11]. The ability
61 to return to a new equilibrium after a major devastation is of fundamental interest to
62 societies. The post-crisis period, spanning several months, is considered as a strategic
63 phase to reorganise territories [12] and is defined as short-term adaptation. In this

64 study, the considered duration is of several months after the hurricane occurred.
65 Long-term adaptation is beyond the scope of this study [13,14,15].

66 Resilience (that is, the capacity of the system to return to a new stable state) after
67 a disaster is complex to observe [16]. Short-term resilience after a natural disaster can
68 be monitored using several indicators such as night-time lights [17], health records
69 (number of inhabitants affected by a specific disease), communication statistics
70 (phone calls, SMS, etc.), water consumption [18], and economic statistics (gross
71 domestic product, sales of specific products). Economic statistics are generally
72 monitored on a monthly basis and may not be sufficiently accurate. The observation
73 of night-time lights using tele-detection methods for several months in areas where
74 hurricanes occur provides spatial information about their resilience and allow to
75 correlate spatial information with social arguments [17]. Nevertheless, many social
76 and economic activities taking place in buildings, do not occur during the night (for
77 example, schools) and cannot be detected by this approach. Because many indicators
78 provide limited information, it may be interesting to introduce new indicators and
79 analyse them taking into account other data. For example, monthly or yearly
80 economic and/or demographic statistics (migration or displacement after hurricane)
81 can help interpret the evolution of other indicators with a daily or weekly acquisition
82 period.

83 The domain of energy, and in particular electricity, opens up important questions
84 at the interface of social-environmental relations [19]. The destruction and
85 reconstruction of the electricity network after major disasters have been documented

86 in several studies, making it possible to observe the challenges in rapidly processing
87 a solution to basic needs [17,2]. The destruction of the electricity network reduces the
88 electricity energy production. Numerous deaths occur indirectly after natural
89 disasters due to lengthy power outages and disruption of basic services [20]. Long
90 and recurrent electricity outage favour morbidity increases (related to, for example,
91 hospital dysfunction and reduced opportunities to communicate with doctors or
92 social services) [20]. The collapse of the electricity network considerably reduces
93 social and economic activities. This study focuses on Caribbean islands and
94 particularly on Saint-Martin, Saint-Barthelemy, and Puerto Rico, which were affected
95 by two major hurricanes, Irma and Maria, in 2017 [21,22,23]. No comparison and
96 mathematical description of electricity production after major hurricane in Caribbean
97 islands were conducted before this study to our knowledge. This study also use
98 electricity production as a potential indicator of resilience.

99 The presence of an intermediate, stable electricity energy production occurring a
100 few months after major hurricanes has been observed in at least three cases (in Saint-
101 Martin and Saint-Barthelemy after Hurricane Irma [24,25,54] and also in Puerto Rico
102 after Hurricane Maria [26]) and is found to be intriguing. The origin and meaning of
103 this pattern have never been explained to our knowledge.

104 The aim of this study is to characterise the influence of major hurricanes on
105 electricity energy production from the moment of collapse until a new equilibrium
106 was established and not to describe what occurred before. The evolution of electricity
107 production after a major hurricane is described here to understand the main features

108 of the post-disaster evolution and anticipate the consequences on electricity
109 production. The capacity of territories to restore their activities after a major
110 hurricane have been observed using electricity production and modelling. A
111 quantification of the parameters and processes involved in the restoration is
112 conducted. The potential causes that can explain the delay in restoration of electricity
113 production are discussed.

114

115 **2. Context and Materials**

116 This study focuses on two major hurricanes (Irma and Maria) on three different
117 islands (Saint-Martin, Saint-Barthelemy, and Puerto Rico), where a reduction in
118 electricity production of more than 90% occurred. In the latter case, the infrastructure
119 and social and economic activities were deeply impacted. There was significant
120 damage to the electricity network and destruction of private buildings [17,2]. The
121 selected hurricanes were classified as 5 [22] on the Saffir–Simpson scale [27,28].
122 Hurricane Irma affected Saint-Martin and Saint-Barthelemy on 5 and 6 September
123 2017 [22], whereas Hurricane Maria affected Puerto Rico on 20 September 2017. The
124 winds were associated with marine submersion and heavy rain.

125 There are approximately 35 000 inhabitants in Saint-Martin, 10 000 inhabitants in
126 Saint-Barthelemy [29], and 3.1 million inhabitants in Puerto Rico. Saint-Martin
127 (France) and Sint-Maarten (The Netherlands) are located on the same island. In this
128 study, we focus only on the French side of the island because the electricity

129 production is independent, and data were available only for the French side.
130 Tourism is the main economic activity in Saint-Martin and Saint-Barthelemy. Puerto
131 Rico has a more diversified economic activity.

132 There is a mean daily electricity production of 27.5 MW in Saint-Martin [24] and
133 16.5 MW in Saint-Barthelemy [25]. The electricity production capacity of Saint-Martin
134 is $E_{max} = 56.6$ MW, but only 27.5 MW is produced [24]. In Saint-Martin, the ratio τ
135 between the electricity production capacity E_{max} and the effective electricity
136 production E (i.e., electricity energy really produced) was 0.48 before the hurricane
137 and 0.30 after. The electricity production capacity E_{max} of Saint-Barthelemy is $E_{max} =$
138 34.2 MW, but only 16.5 MW is produced [25]. In Saint-Barthelemy, the ratio τ
139 between the electricity production capacity E_{max} and the effective electricity
140 production E was 0.48 before the hurricane and 0.35 after. The electricity production
141 capacity E_{max} of Puerto Rico is approximately 6 000 MW [26], but only 400 MW were
142 produced before Hurricane Maria. In Puerto Rico, the ratio τ between the electricity
143 production capacity E_{max} and the effective electricity production E was 0.06 before the
144 hurricane and 0.05 after.

145 The data on electricity production are available for Saint-Martin (French side)
146 and Saint-Barthelemy from Electricité De France [24,25,54]. Daily electricity
147 production is presented here, but the precision needed for the modelling can be less
148 precise, especially during stable phases. Hurricane Irma had a significant impact on
149 the electricity production of Saint-Martin and Saint-Barthelemy [24,25,54]. The
150 electricity network was mainly aerial before the hurricane and most of it was

151 destroyed by the wind. The electricity production of Saint-Martin was also impacted
152 by marine submersion because the production unit was located close to the sea [24].
153 However, no major destruction of the production units occurred in Saint-Martin and
154 Saint-Barthelemy.

155 The data from the U.S. Energy Information Administration were used to study
156 the influence of Hurricane Maria on electricity production in Puerto Rico [26].
157 Hurricane Irma also influenced the electricity production of Puerto Rico over a few
158 days, but with a moderate impact in comparison with that of Hurricane Maria. In
159 Puerto Rico, the daily electricity production [30] is superimposed with the
160 normalised monthly peak of electricity production to observe it over a longer period
161 of time. Some of the electricity production units were out of order in Puerto Rico
162 after Hurricane Maria [17]. The electricity production considered here takes into
163 account only that generated by electricity companies. Individual production of
164 electricity by small electricity generators or individual solar panels was not taken
165 into account.

166

167 **3. Quantified description**

168 *3.1. Characteristic of electricity energy production after major hurricane*

169 The pattern of the curves of electricity energy production can be characterised by
170 a few parameters such as:

- 171 • Resilience time t_r

-
- 172 • Electricity resilience ratio $ER_R = E_i / E_{is}$
 - 173 • Electricity production restoration rate E_{is} / t_r ,
 - 174 • Offset resilience of the electricity production $E_i - E_{is}$

175

176 These parameters allow us to characterise the restoration of stable electricity
177 energy production. Here, the resilience time t_r is not the time necessary to restore the
178 initial state, but the time necessary to reach a new intermediate equilibrium. In this
179 study, resilience time was reached when the electricity production became stable at
180 E_{is} . The resilience time t_r of Saint-Barthelemy was smaller than that of Saint-Martin.
181 The resilience time t_r of Saint-Martin was smaller than that of Puerto Rico (Table 1).

182 The intermediate equilibrium of electricity production has been characterised by
183 several indicators. In Saint-Martin, the electricity resilience ratio was $ER_R = E_{is} / E_i =$
184 0.62 (Table 1). The higher the ER_R ratio is, the more the system has restored the initial
185 electricity capacity. In Saint-Barthelemy, $E_{is} = 12$ MW and $E_i = 16.5$ MW. The
186 electricity resilience ratio was $ER_R = E_{is} / E_i = 0.73$. In Puerto Rico, $E_{is} = 300$ MW and E_i
187 $= 400$ MW. The electricity resilience ratio was $ER_R = E_{is} / E_i = 0.75$. The resilience ratio
188 ER_R of Puerto Rico and Saint-Barthelemy was higher than that of Saint-Martin (Table
189 1).

190 The electricity production restoration rate is estimated using the ratio between
191 the intermediate electricity production (E_{is}) and resilience time (t_r). This rate
192 represents the velocity of the system to reach a new equilibrium. Puerto Rico and
193 Saint-Barthelemy have a higher rate of restoration of electricity energy production

194 than Saint-Martin (Table 1). The electricity production restoration rate is not strictly
 195 proportional to the electricity power capacity (i.e., the initial electricity production E_i)
 196 of the territory, as shown by the comparison between Saint-Barthelemy and Saint-
 197 Martin (Table 1). Saint-Martin has a lower electricity production restoration rate,
 198 whereas the electricity power capacity of Saint-Martin is higher than that of Saint-
 199 Barthelemy.

200

201 **Table 1.** Main characteristics of electricity production resilience after a major
 202 hurricane.

Caribbean Island	Resilience Time t_r (month)	Initial Electricity Production E_i (MW)	Intermediate Stable Electricity Production E_{is} (MW)	Electricity Resilience Ratio E_i/E_{is}	Electricity Production Restoration Rate E_{is}/t_r (MW/month)	Offset Resilience of Electricity Production $E_i - E_{is}$ (MW)
Saint-Barth.	1	16.5	12	0.73	12	4.5
Saint-Martin	2	27.5	17	0.62	8.5	10.5
Puerto Rico	5	400	300	0.75	60	100

203

204 However, the offset of the electricity energy production from the initial state $E_i - E_{is}$
 205 was higher for Puerto Rico and Saint-Martin than for Saint-Barthelemy (Table 1). This
 206 parameter is related to the initial electricity power capacity (i.e., initial electricity
 207 energy production, E_i). In the three cases studied, the resilience time, t_r , is
 208 proportional to the system size (initial power capacity) but is not correlated to the
 209 electricity resilience ratio E_i / E_{is} . However, not all the parameters investigated are
 210 proportional to the system size. For example, the electricity resilience ratio is not
 211 related to the system size. The electricity resilience ratio is higher in Saint-Barthelemy

212 and Puerto Rico than in Saint-Martin, whereas the initial electricity energy
213 production E_i is higher in Saint-Martin than in Saint-Barthelemy.

214 The intermediate equilibrium of the electricity production is significantly lower
215 than that before the major hurricane occurrence in the three Caribbean islands
216 studied. This reduction ranges between 25% and 38%. The decrease in electricity
217 production (i.e., the offset resilience of electricity production $E_i - E_{is}$) is proportional to
218 the initial electricity production E_i (Table 1).

219

220 *3.2 Theoretical description*

221 First, a theoretical model was developed. The model intends to estimate the
222 electricity production at various times based on several parameters.

223 The model assumes a competition between the accumulation and consumption
224 of electricity energy. More precisely, the rate of the electricity energy production V^a
225 (in MWh/h) is counterbalanced by the rate of electricity energy consumption V^{ob} (in
226 MWh/h). The electricity system is considered at equilibrium (i.e., the ratio V^a / V^{ob} is
227 constant) until the collapse generated by the hurricane generates an abrupt decrease
228 in the electricity energy production. Starting from a low value, the electricity energy
229 production is constrained by the rate of electricity energy production. The rate of the
230 electricity energy production V^a changed after the hurricane occurrence and reached
231 a new value, lower than the previous one.

232 The electricity production curve shows a stable plateau after several months. This
233 specific pattern must be reproduced as well as the trajectory of the electricity

234 production from the main blackout until the stable plateau. These patterns can be
235 described by a mathematical function.

236 The electricity production can be described by :

$$237 \quad E = [\varpi + a \times \ln(V/V_0) + b \times \ln(V_0 \times \theta/L)] \times E_{max}, \quad (1)$$

238 where E_{max} is the maximum electricity power capacity of the system (in MW), V^a is the
239 rate of the electricity energy production, V_0^b is the rate of the electricity energy
240 consumption, and ϖ is the ratio between the effective electricity energy production
241 and the maximum electricity energy production capacity of the system $E_{effective} / E_{max}$. L
242 is the characteristic electricity power (in MWh) of the system. The smaller the value
243 of L is, the better the resilience of the electricity production. Parameters a and b are
244 constants with $0 > a > b$. The amplitude of the combined parameter $a + b$ influences
245 the loss of energy from the initial stable condition until the new equilibrium, after
246 which the electricity production collapses. t represents time, and θ is a characteristic
247 time and a state variable (a state variable can be used to describe the state of a
248 dynamical system; see for example in [31]) of the system defined by :

$$249 \quad \Delta\theta / dt = 1 - V \times \theta / L \quad (2)$$

250 First, at the equilibrium $\Delta\theta / dt = 0$, and thus $1 - V \times \theta / L = 0$

$$251 \quad \Leftrightarrow V = L / \theta$$

252 Including it in Equation (1), the electricity production at the equilibrium becomes

$$253 \quad E_{effective} = [\varpi + a \times \ln(V/V_0) + b \times \ln(V_0/V)] \times E_{max}$$

$$254 \quad \Leftrightarrow E_{effective}/E_{max} = \varpi + (a-b) \times \ln(V/V_0)$$

$$255 \quad \Leftrightarrow E_{effective}/E_{max} - \varpi = 0 = (a-b) \times \ln(V/V_0), \text{ by definition of } \varpi$$

256 $\Leftrightarrow \ln (V/V_0) = 0$

257 $\Leftrightarrow V = V_0$

258 $\Leftrightarrow V^a = V_0^a = (V_0^b)^{a/b},$

259 (3)

260 Consequently, at equilibrium, the competition between the rate of electricity
 261 production V^a and the rate of electricity energy consumption V_0^b is described by a
 262 power law (Equation 3). Post-cyclonic-electricity-energy production is a non-linear
 263 process that can be described by equation 1 and 2.

264 Second, when the hurricane occurs and the electricity system collapses, there is a
 265 discrepancy between the electricity energy production and electricity energy
 266 consumption. The condition necessary to restore the electricity system is that the rate
 267 of the electricity production V^a be greater than the rate of electricity energy
 268 consumption V_0^b . According to Equation (1), the following can be written:

269
$$E/E_{max} - \varpi = a \times \ln(V/V_0) + b \times \ln(V_0 \times \theta / L) \quad (4)$$

270 During the collapse, the electricity energy is not at equilibrium. There is a
 271 relaxation of the system. After the collapse, during the restoration of the electricity
 272 energy production, an intermediate phase of equilibrium is observed (for example, in
 273 Figure 2). During this phase, the ratio between the electricity production and the
 274 maximum capacity of the electricity energy production E / E_{max} is constant and equal
 275 to ϖ .

276 Consequently, from Equation (4) we obtain during the restoration of the
 277 electricity energy production:

278 $a \times \ln(V/V_0) + b \times \ln(V_0 \times \theta/L) = 0.$

279 We can deduce that $\exp[a \times \ln(V/V_0)] = \exp[-b \times \ln(V_0 \times \theta/L)].$

280 Thus, during the restoration of the electricity energy production, the rate of the
281 electricity energy production is equivalent to

282
$$V^a = (V_0^b)^{a/b-1} \times [\theta/L]^{-b}, \quad (5)$$

283 Let us describe some basic consequences of Equation (5). First, the rate of the
284 electricity energy production V^a and the rate of electricity energy consumption V_0^b are
285 generally not equal. Second, if $\theta / L > 1$, then the rate of the electricity energy
286 production V^a is greater than the rate of the electricity energy consumption V_0^b
287 because $a / b < 1$. Under these conditions, the electricity system will have no risk of
288 collapse during the restoration of the system. Conversely, if $0 < \theta / L < 1$, the rate of
289 electricity energy consumption V_0^b will be greater than the rate of electricity energy
290 production V^a , and a blackout can be expected. Third, in our model, the values of V^a
291 and V_0^b are relative to each other, as given in Equation (5). In this approach, only the
292 relative values between V^a and V_0^b play a role. From Equation (3), it is possible to
293 estimate the value of the rate of the electricity energy consumption V_0^b at
294 equilibrium. In the transient state, it is necessary to use Equation (5).

295 A numerical code was developed in Fortran to solve Equations (1) and (2) using a
296 finite-difference method. The electricity production is relaxed by a change in the rate
297 of electricity production. For example, in Saint-Martin, the rate of the electricity
298 production V^a before the hurricane was 1.65 MWh/h, whereas the rate of electricity

299 production V^a after the hurricane was 1.08 MWh/h. An abrupt change in the rate of
300 the electricity production is necessary to simulate the observed trend.

301

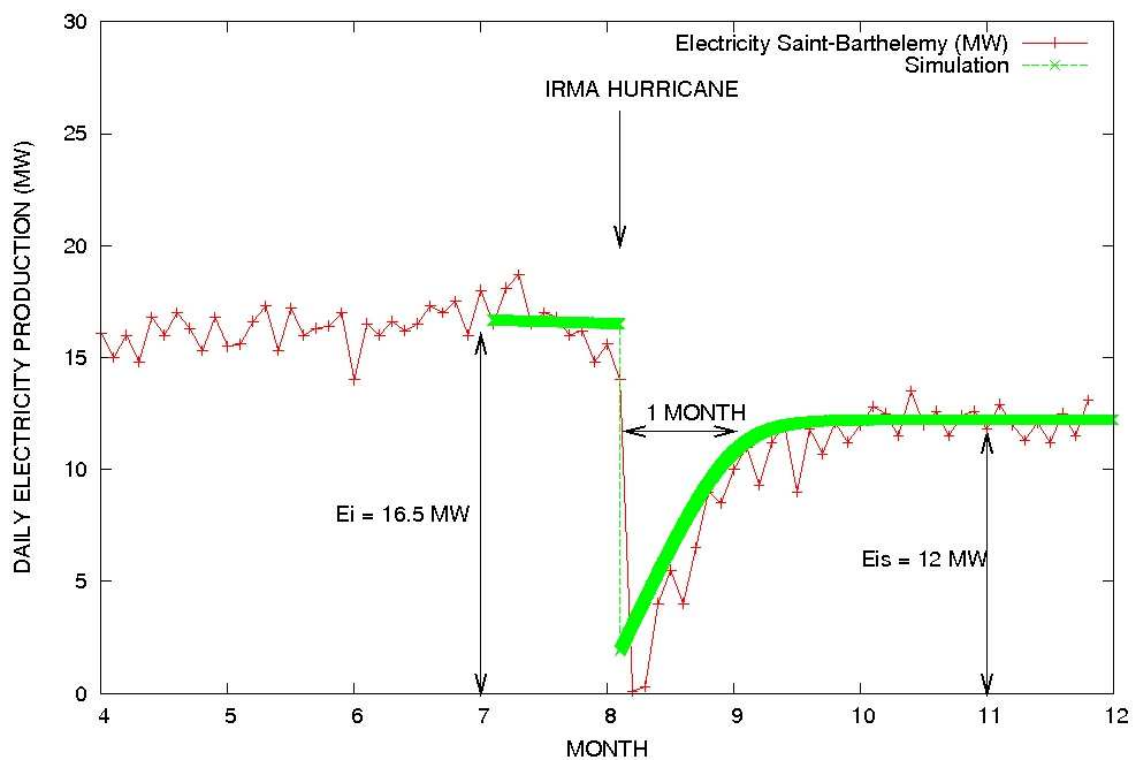
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304 4. Numerical simulations

305 The daily electricity production of Saint-Martin, Saint-Barthelemy, and Puerto Rico
306 has been simulated before and after the occurrence of a major hurricane during a
307 period of time of 8 months.

308 4.1. Saint-Martin electricity production



309

310

311 *Figure 1. Influence of Hurricane Irma on the daily electricity production of Saint-*
312 *Martin. Two stable states can be observed for the daily electricity production. The*
313 *first one is approximately $E_i = 27.5$ MW and the second one is approximately $E_{is} = 17$*
314 *MW. The second intermediate stable plateau can be observed 2 months after the*
315 *blackout due to the collapse of the electricity network. The progressive restoration of*
316 *the electricity network is simulated with $E_{max} = 56.6$ MW, $\varpi = 0.30$, $V = 0.25$*
317 *$(\text{MWh/h})^{1/a}$, $V_0 = 0.025 (\text{MWh/h})^{1/b}$, $a = -0.054$, $b = -0.063$, and $L = 0.09$ MWh. At t*
318 *$= 0$, $\theta = 1$ h.*

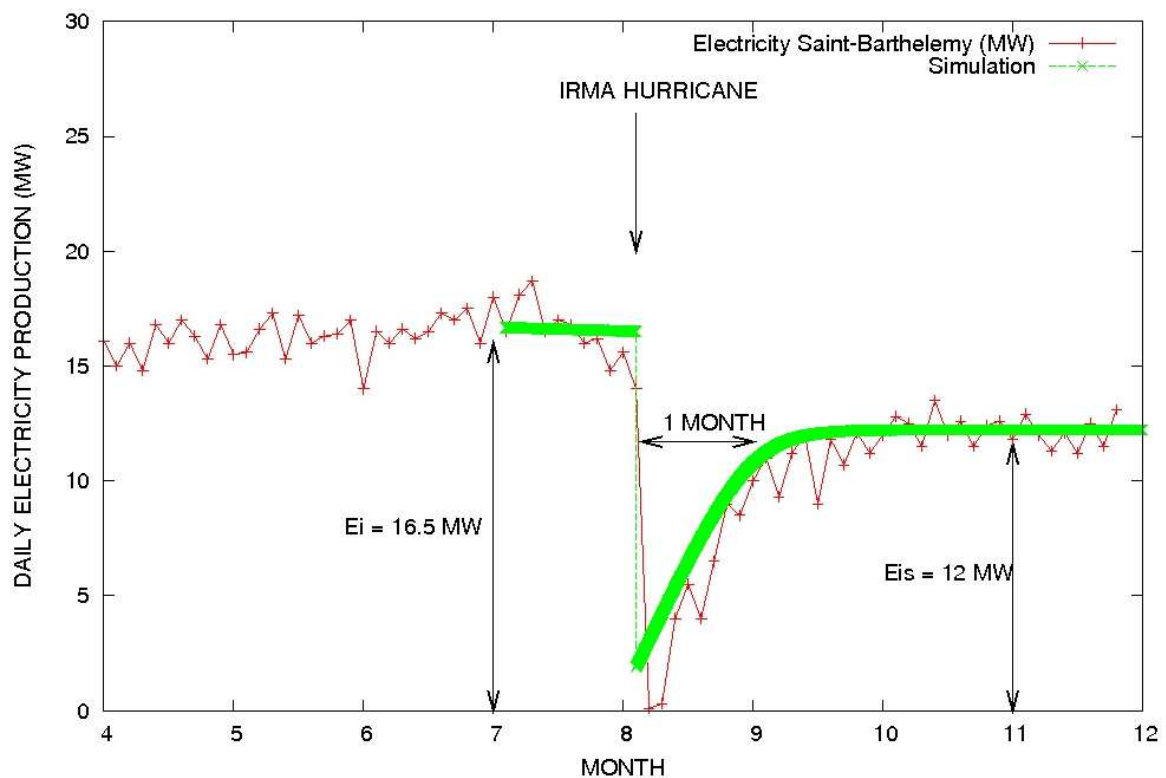
319

320 For Saint-Martin, the simulation of the daily electricity production was
321 performed using Equation (1), considering that the electricity production capacity is
322 $E_{max} = 56.6$ MW. A value of effective electricity production ratio ϖ of 0.30 was
323 considered. In the modelling of Saint-Martin, the rate of electricity energy production
324 was $V^a = 1.65$ MWh/h, the rate of electricity consumption was $V_0^b = 1.08$ MWh/h, and
325 the electricity power was $L = 0.09$ MWh. Using these parameters, the model could fit
326 the electricity production for 8 months before and after the impact of Hurricane Irma
327 (Figure 1).

328 4.2. Saint-Barthelemy electricity production

329 Even in the island of Saint-Barthelemy, located approximately 10–15 km east of
330 Saint-Martin, the electricity network was damaged by Hurricane Irma. The general
331 trend of daily electricity production shows the same pattern in Saint-Barthelemy than

332 that in Saint-Martin. Two stable periods can be observed in the daily electricity
333 production of Saint-Barthelemy, the first before the blackout and the second one
334 month after the main blackout (Figure 2). The resilience time is approximately 1
335 month from the blackout until the new stable equilibrium is reached. The first initial
336 stable daily electricity production E_i is approximately 16.5 MW. The second
337 intermediate stable equilibrium of the daily electricity production E_{is} is of 12 MW for
338 at least 3 months.



339

340

341 *Figure 2. Influence of Hurricane Irma on the daily electricity production in Saint-*

342 *Barthelemy. Two stable states can be observed for the daily electricity production.*

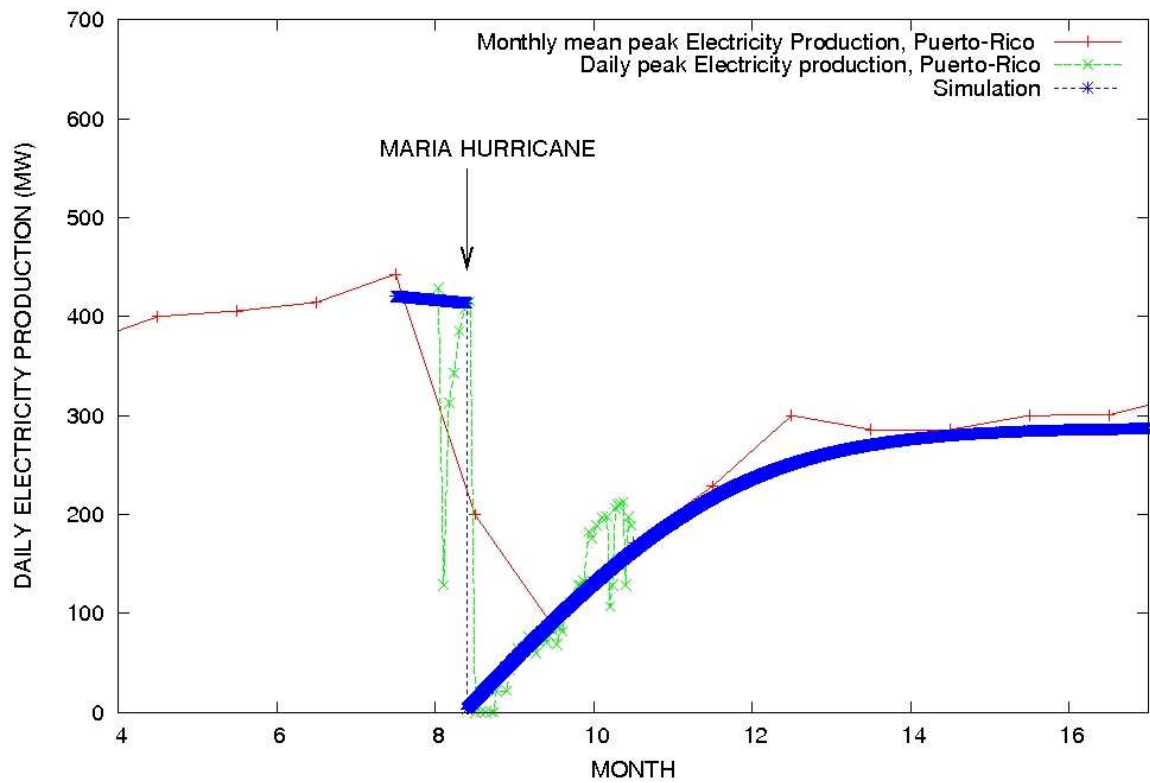
343 *The first one is approximately $E_i = 16.5$ MW and the second one is approximately E_{is}*

344 = 12 MW. The second intermediate stable plateau can be observed 2 months after the
345 blackout due to the collapse of the electricity network. The progressive resilience of
346 the electricity network is simulated with $E_{max} = 34,2$ MW, $\varpi = 0.35$, $V = 0.25$
347 $(MWh/h)^{1/a}$, $V_0 = 0.025 (MWh/h)^{1/b}$, $\theta = 1$ h, $a = -0.054$, $b = -0.07$, and $L = 0.05$
348 MWh.

349

350 4.3. Modelling Puerto Rico electricity production

351 In Puerto Rico, the transient state between Hurricane Maria and the new
352 equilibrium extended over 5 months. Equations (1) and (2) provide the estimates of
353 electricity production before and after the hurricane at each time step (Figure 3).
354 Before Hurricane Maria, the daily electricity production was approximately 400 MW,
355 whereas the daily electricity production after the hurricane was 300 MW in the stable
356 state.



357

358

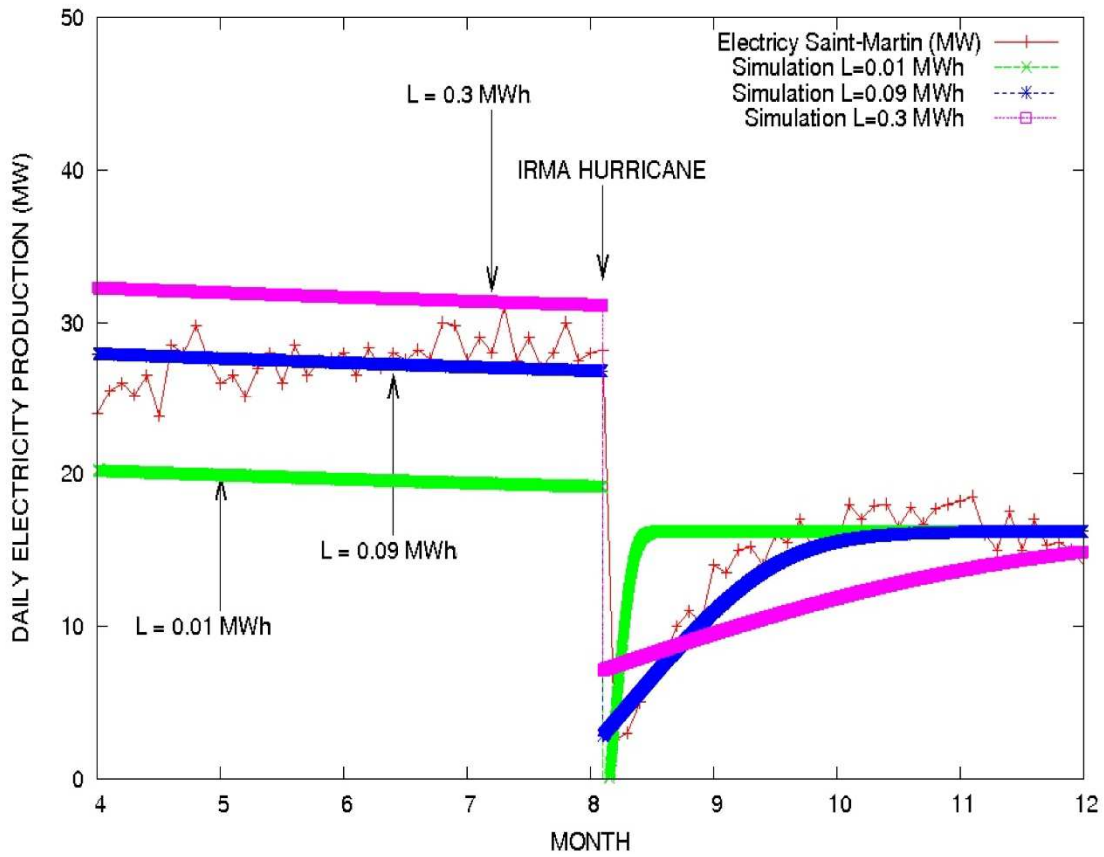
359 **Figure 3.** Influence of Hurricane Maria on the daily electricity production of Puerto
 360 Rico. Two stable states can be observed for the daily electricity production. The first
 361 one is approximately $E_i = 400$ MW and the second one is approximately $E_{is} = 300$
 362 MW. The second intermediate stable plateau can be observed 5 months after the
 363 collapse of the electricity network due to Hurricane Maria. The progressive resilience
 364 of the electricity network is modelled with $E_{max} = 6\ 000$ MW, $\tau = 0.05$, $V = 0.5$
 365 $(\text{MWh/h})^{1/a}$, $V_0 = 0.055 (\text{MWh/h})^{1/b}$, $\theta = 1$ h, $a = -0.008$, $b = -0.019$, and $L = 0.6$
 366 MWh. The monthly electricity production was divided by 30 to obtain the equivalent
 367 daily electricity production data.

368

369 4.4. Influence of a , b , L , V , and V_0

370 The parameters a , b , L , V , and V_0 of Equations (1) and (2) influence the electricity
371 energy production. Simulations show that the electricity power L has a strong
372 influence on the electricity production (Figure 4). The higher the electricity power L
373 is, the higher the offset between the two stables “plateaus” of electricity production E_i
374 and E_{is} . Furthermore, the higher the electricity power L is, the longer the resilience
375 time t_r (Figure 4). A value of effective electricity power $L = 0.05$ MWh was used to
376 simulate the electricity production in Saint-Barthelemy, of 0.09 MWh in Saint-Martin,
377 and of 0.6 MWh in Puerto Rico (Table 2). The higher the system (i.e., initial electricity
378 production), the higher the electricity power L (see Tables 1 and 2). Even if the
379 effective electricity power L is not strictly linearly proportional to the initial system
380 capacity (or to the number of inhabitants), a link may exist that it could be interesting
381 to investigate in further studies with more data (Tables 1 and 2).

382



383

384 **Figure 4.** Influence of electricity power L on electricity energy production E . Other

385 parameters used in the modelling: $E_{max} = 56.6$ MW, $\tau = 0.30$, $V = 0.25$ (MWh/h) $^{1/a}$,

386 $V_0 = 0.025$ (MWh/h) $^{1/b}$, $\theta = 1$ h, $a = -0.054$, $b = -0.063$.

387 The dimensionless constants a and b also play a significant role in the result of

388 Equation (1). The constants a and b are negatives. The smaller the value of $|b|$ is, the

389 higher the offset between the two stable values of the electricity production E_i and E_{is}

390 (Figure 5A, Table 1). In this study, $|b|$ is equal to 0.070 in Saint-Barthelemy (Figure

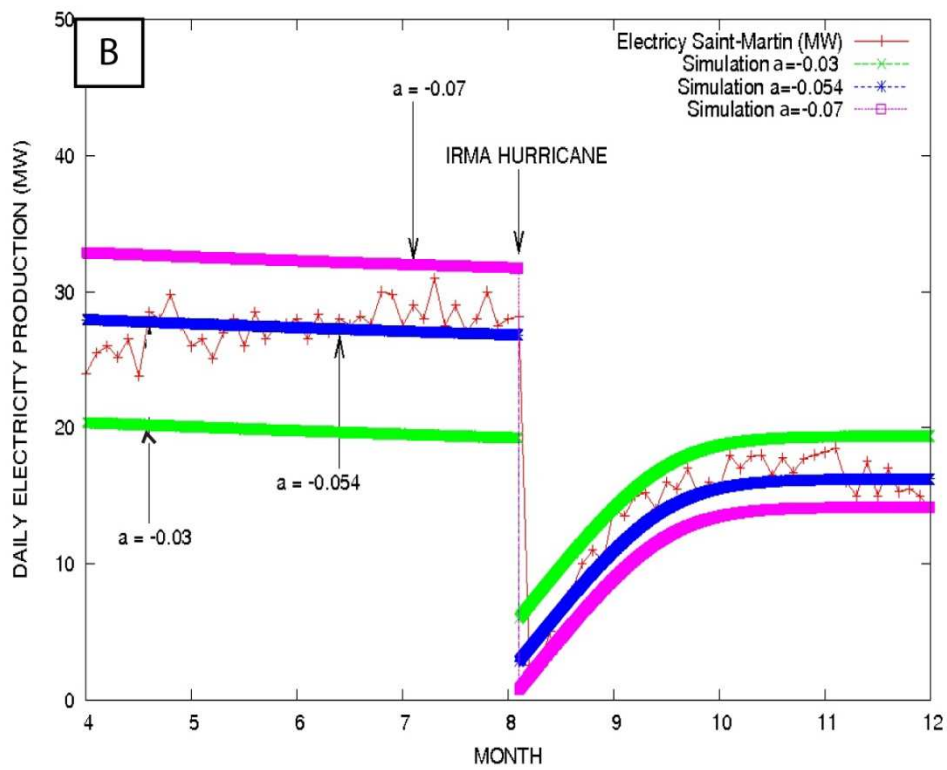
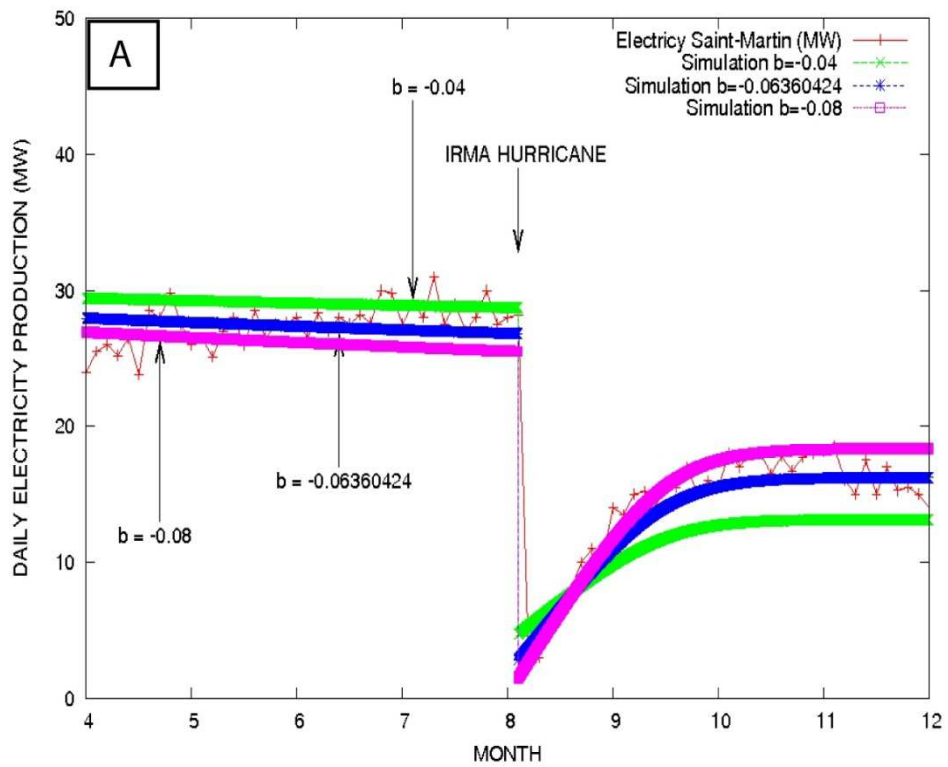
391 2), 0.063 in Saint-Martin (Figure 1), and 0.019 in Puerto Rico (Figure 3). The smaller

392 the system size (i.e., initial energy distribution) is, the higher is $|b|$. There is an effect

393 of $|b|$ on the increase in the electricity production rate after the collapse. The higher

394 $|b|$ is, the higher will be the increase in electricity production after the hurricane. The
395 higher $|a|$ is, the higher will be the offset between the two stable values of the
396 electricity production E_i and E_{is} (Figure 5B).

397



398

399 *Figure 5. Influence of the adimensional constants b and a on the electricity energy*

400 *production. (A) Influence of the adimensional constant b on the electricity*

401 production, $a = -0.054$, (B) Influence of the adimensional constant b on the
 402 electricity production, $b = -0.063$. The other parameters used in the modelling are
 403 $E_{max} = 56.6$ MW, $\tau_0 = 0.30$, $V = 0.25$ (MWh/h)^{1/a}, $V_0 = 0.025$ (MWh/h)^{1/b}, $\theta = 1$ h, and
 404 $L = 0.09$ MWh.

405 The higher the parameter V is, the faster the electricity production reaches the
 406 intermediate stable electricity production E_{is} (Figure 6A). The resilience time of the
 407 system increases when V increases. In the calculation, $V = 0.25$ (MWh/h)^{1/a}. However,
 408 the absolute value of V is less important in the model than the ratio between V and
 409 V_0 . There is an analytic relation between these two parameters at equilibrium, or
 410 when $\tau_0 = E / E_{max}$ is constant. V_0 is always smaller than V in the three cases studied,
 411 and the ratio V / V_0 ranges from 9.1 to 10 (Table 2). The variation in V_0 generates a
 412 translation of the electricity production. The higher the value of V_0 is, the higher will
 413 be the electricity production E (Figure 6B). The influence of this parameter can
 414 apparently be counterintuitive. However, this can be interpreted considering that a
 415 bigger country with a higher electricity production E has a higher rate of electricity
 416 consumption as well.

417 **Table 2.** Main characteristics of the territories and parameters used

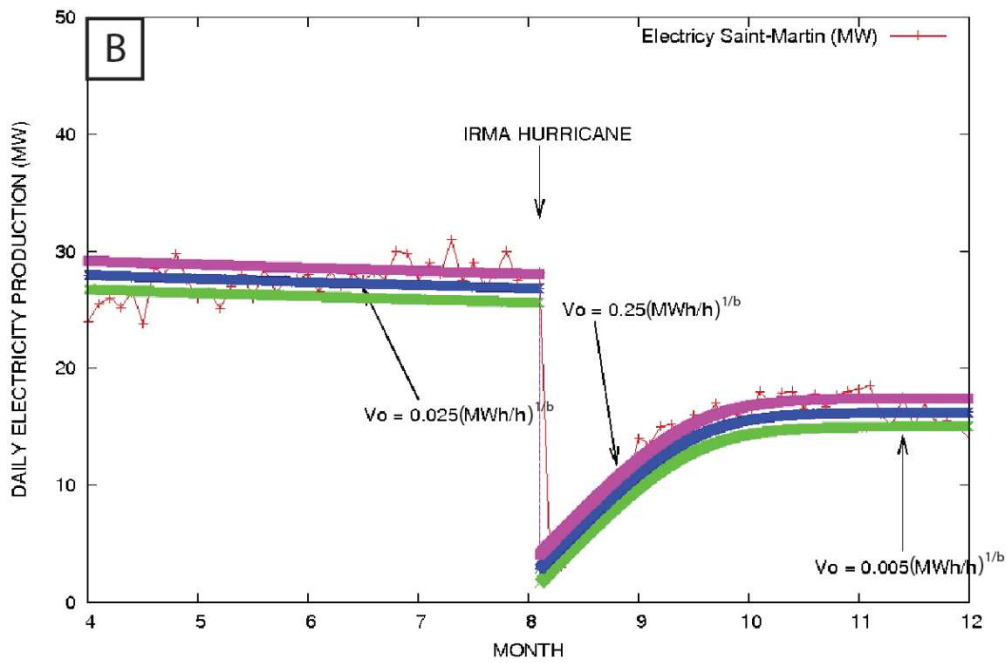
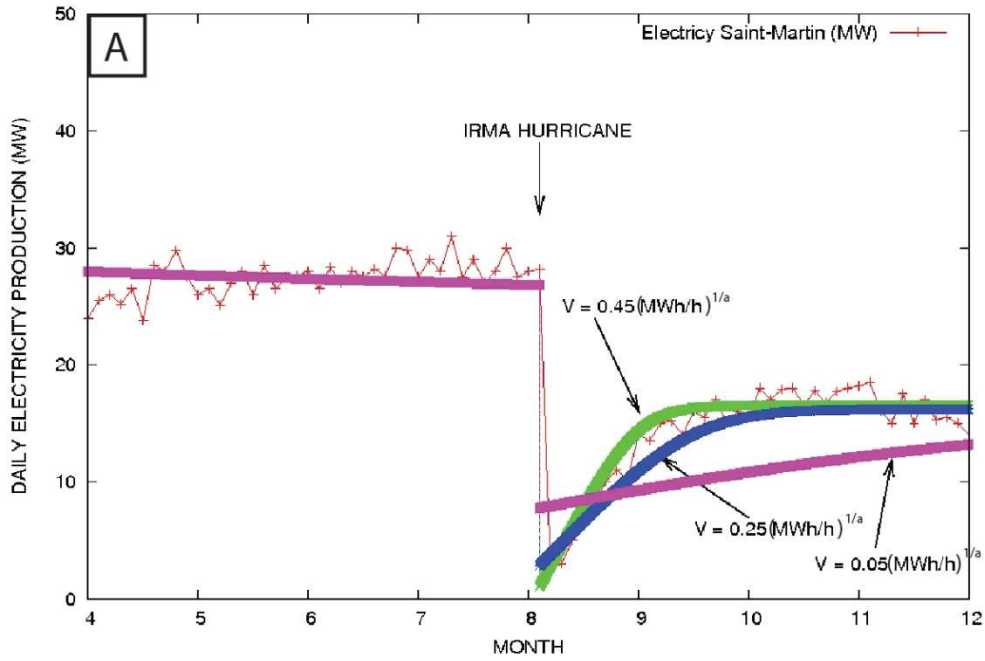
Caribbean island	Inhabitants	Gross Domestic Product (Euro/capita)	Characteristic Electricity Production L (MWh)	Plateau Combined Parameter $a+b$	Electricity Prod./Consum. Rate Ratio V/V_0	Electricity Production Ratio (effect./max.) τ_0
Saint-Barth.	10 000	40 000	0.05	-0.124	10	0.35
Saint-Martin	35 000	16 600	0.09	-0.117	10	0.3

Puerto Rico	3 100 000	27 000 ¹	0.6	-0.027	9.1	0.05
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418 ¹ International Monetary Fund (dollars converted to euros; <https://www.imf.org>)

419

420



421

422 *Figure 6. Influence of parameters V and V_0 on electricity energy production. (A)*
423 *Influence of parameter V on electricity production in Saint-Martin, $V_0 = 0.025$*
424 *(MWh/h)^{1/b}. (B) Influence of electricity energy consumption V_0 on electricity*
425 *production, $V = 0.25$ (MWh/h)^{1/a}. Other parameters in the simulation: $E_{max} = 56.6$*
426 *MW, $\tau = 0.30$, $\theta = 1$ h, $a = -0.054$, $b = -0.063$, and $L = 0.09$ MWh.*

427

428 **5. Discussion**

429 *5.1. Hurricane destructive power and resilience of electricity production*

430 In Puerto Rico, the influence of two hurricanes was observed in 2017 (Figure 3).
431 The electricity production was reduced by 30% of the initial electricity capacity of
432 Puerto Rico after Hurricane Irma (6 September) and it appeared to return
433 “elastically” (i.e., linearly and rapidly) to the initial state (Figure 3). The electricity
434 network and economic activities were not completely destroyed by the first
435 hurricane Irma. This could explain why two weeks after the first hurricane, the
436 electricity production was at the same level of 400 MW as the initial one (Figure 3).
437 This was not the case following Hurricane Maria. The electricity production was
438 reduced by more than 90% in this second case and the restoration was slower. The
439 electricity production was not impacted in the same way by the two hurricanes. The
440 higher the lowering of the electricity production during the hurricane, the longer the
441 time required to reach the new equilibrium. The electricity production restoration is

442 expected to depend on (1) the electrical network system rebuilding, i.e. the
443 production capacities, (2) the restoration of social and economic activities, i.e.
444 consumption/demand. During crisis, anticipating production and consumption of
445 electricity is complex and is a conundrum. The restoration rate of the electricity
446 production depends on the electricity production capacity as well as the rate of
447 electricity production and consumption (see Equation 1 and Figures 4 to 6). The
448 results suggest that the restoration of the electricity production is not linear and that
449 the restoration rate of the electricity production depends on the amount of initial
450 destruction. Furthermore, it depends on the adaptation and coping capacities as well
451 [32]. In Puerto-Rico, the restoration of the electricity production was of 75% of pre-
452 hurricane electricity production, 4-5 months after Maria hurricane. Simultaneously,
453 night-time lights data in Puerto-Rico were only 55-60% of those observed before
454 Maria hurricane suggesting that electricity was not fully restored [17]. Water
455 distribution or communication networks depends from electricity network causing
456 significant disagreement when outage or network collapse occurred. Consequently,
457 health, social and economic activities could be significantly affected by outage or
458 electricity network collapse [e.g. 2,17]. Social and economic activities decrease could
459 also cause electricity production decrease as observed during COVID-19 pandemic
460 [55]. After one year of Hurricane Maria, electricity production of Puerto Rico attained
461 the same values of approximately 400 MW. Nevertheless, the gross domestic product
462 (GDP) of Puerto Rico was slightly lower in 2017 and 2018 than in 2016, suggesting

463 that economic activity was not fully re-established to the level before Hurricane
464 Maria [33], even if the electricity production was almost completely restored.

465

466 *5.2. Electricity production equilibrium*

467 A decrease of approximately 25% of the electricity production was observed in
468 Saint-Barthelemy and Puerto Rico, from the initial stable phase when $E = E_i$ until the
469 new equilibrium phase after the collapse when $E = E_{is}$ (Figure 2 and 3; Table 1). In
470 both cases, there was an approximate constant number of inhabitants before and
471 after the hurricane. This reduction can be explained by a reduction in the activity of
472 restaurants and shops, along with other social and individual activities (schools,
473 administration, etc.). Buildings where these activities take place had been damaged
474 [34,1,35].

475 In Saint-Martin, the decrease of 38% in electricity production from $E = E_i$ to $E = E_{is}$
476 was higher than that in Puerto Rico and Saint-Barthelemy (Figure 1 and Table 1). The
477 electrical network was almost completely restored after 1.5 months. Nevertheless, the
478 restoration of electricity production took longer (Figure 1), suggesting that other
479 processes played a role. The remarkable reduction in electricity production was also
480 due to the reduction in economic activities. Unemployment increased by 18.5% in
481 2017 [36]. The number of hotels, guest houses, and apartments was limited in Saint-
482 Martin because owing to their damage. There was a decrease of 25.9% in the number
483 of tourists visiting the island from 2016 to 2017 [36]. By comparison, the number of

484 tourists decreased by approximately 13% from 2016 to 2017 in Saint-Barthelemy [34].
485 The reconstruction of touristic infrastructures of Saint-Martin was not completed, to
486 allow increases of tourism in 2018 and 2019. The tourism industry represents
487 approximately 55% of the economic activity in Saint-Martin [36]. Furthermore,
488 Puerto Rico has a more diversified economy than Saint-Martin.

489

490 *5.3. Migration and electricity production*

491 It has been estimated that approximately 7 000 to 8 000 inhabitants left Saint-
492 Martin after the hurricane [18,37]. The reduction of 20–23% of the children in public
493 schools of Saint-Martin corresponds to the reduction of between 7 000 and 8 000
494 inhabitants on a population of 35 000 [36,37]. The cause of this migration is mainly
495 related to unemployment and difficulties of housing after the destruction caused by
496 Irma.

497 Analogous to Saint-Barthelemy and Puerto Rico, where a decrease of 20–25% of
498 the electricity production was observed after the hurricane (Table 1), a decrease of
499 approximately 20–25% of the electricity production in Saint-Martin could be
500 expected. Taking into account the global reduction of 38% of the electricity
501 production in Saint-Martin, it can be expected that the 13–18% of the electricity
502 production decrease is attributed to the migration of 7 000 to 8 000 inhabitants.

503 Historically, migration has been observed to occur in the Caribbean islands
504 following environmental disasters (hurricanes, earthquakes) and economic or social

505 crises (wars, dictatorships) [38,39]. Haiti experienced various migration phases
506 during the last decades [40]. Saint-Martin and Saint-Barthelemy experienced various
507 migrations in or out of their territories during the last two centuries [41] as well.
508 During the 1986–1990 period, there was an increase in the population of Saint-Martin
509 from 8 000 to 28 000, which was mainly due to the influx from France after a new tax
510 law was enacted in France, along with that from Haiti and the Dominican Republic
511 [42,29,8].

512 The abrupt decrease in electricity energy production is not specific to hurricanes
513 and may also be caused by earthquakes or other natural hazards (floods). The
514 intensity of the reduction depends on the amplitude of the catastrophe. The pattern
515 of the electricity production curves can be interpreted with Equations (1) and (2). The
516 time between the catastrophe and the new equilibrium depends on (i) the time to
517 rebuild the electricity network, (ii) the time to reconstruct the infrastructures that
518 consume the electricity, (iii) the time necessary for people who leave, to return, and
519 (4) the time required to restore the economy. These times shown to be mixed in the
520 electricity production curves.

521

522

523 *5.4. Economy resilience and electricity energy production*

524 If the undercapacity of electricity production can limit the development of
525 economic activity, the slowdown of socio-economic activities can slowdown
526 electricity production restoration after major hurricanes. In Saint-Martin, the

527 electricity production capacity of the production units was re-established after
528 approximately 25 days–1 month. Saint-Martin electricity production has a smaller
529 restoration rate E_{is} / t_r than that of Saint-Barthelemy and Puerto Rico (Table 1). The
530 slow rate of restoration of electricity energy production was not limited only by
531 public electricity infrastructure.

532 Additionally, the electricity resilience ratio was higher in Saint-Barthelemy than
533 in Saint-Martin (Table 1). This is in agreement with previous studies that observed
534 that electricity energy recovery rates were slower for low-income populations than
535 for other groups (moderate-income to high-income) in Puerto Rico [17]. Indeed,
536 Saint-Martin has a smaller GDP per capita than that of Saint-Barthelemy and Puerto
537 Rico (Table 2). The correlation between wealth (GDP per capita) and resilience
538 indicators (resilience ratio) suggests that the capacity of a territory to restore
539 electricity production is not independent of its wealth. This could depend on the
540 difference in initial resistance of buildings and infrastructure, but also on the funding
541 available for reconstruction (credit, insurances, solidarity funds, etc.) [43,44]. The
542 correlation between wealth and adaptation to natural hazard has been suggested by
543 several studies [45,46]. Collective organization and education could also play a role
544 independently of wealth [47,48]. Build back better get mobilized in the recovery
545 effort after Maria and Irma in the Caribbean [2,19,49] but some difficulties can be
546 observe during the reconstruction phase [7].

547 Nevertheless, the discrepancy in electricity production per inhabitant between
548 Saint-Martin and Saint-Barthelemy has not increased after the hurricane. Prior to the

549 hurricane, there was an electricity production of 1.65 kW/inhabitant in Saint-
550 Barthelemy, higher than the 0.78 kW/inhabitant in Saint-Martin. Electricity
551 production per inhabitant is higher when the gross domestic product (GDP) is higher
552 (Table 2). After Hurricane Irma, the electricity production was of 1.2 kW/inhabitant
553 in Saint-Barthelemy for 10 000 inhabitants, whereas in Saint-Martin it was of 0.63
554 kW/inhabitant, considering a population of approximately 27 000 inhabitants (after
555 the displacement of 8 000 inhabitants outside of Saint-Martin). The electricity
556 production per capita was 2.1 times higher in Saint-Barthelemy than in Saint-Martin
557 prior to the hurricane, and it was approximately 1.9 times higher after the hurricane.
558 Evidently, the hurricane did not change the gap in electricity production per capita
559 between Saint-Barthelemy and Saint-Martin. The small decrease from 2.1 to 1.9 is due
560 to uncertainties in the real number of inhabitants present after the hurricane:
561 temporary displacement from Saint-Barthelemy could also have occurred [50] and
562 the real number of inhabitants in Saint-Martin could be difficult to quantify due to
563 the porous frontier with Sint-Maarten [39].

564 Electricity energy production is a short-term indicator of destruction and
565 reconstruction of the electricity network, but also of social and economic activities.
566 The restoration of electricity production is not influenced only by the reconstruction
567 of the electricity network. It indicate also the resilience of social and economic
568 activities. The reduction in social and economic activities generates a reduction in
569 electricity production several months after the electricity network has been
570 reconstructed. A growth of social and economic activities during months after major

571 hurricane cause an increase of electricity energy production. A composite indicator of
572 economic and social activity $ESA = E/E_i$ (from equation 1) could permit to compare
573 the short-term resilience between different islands after major hurricanes. Long-term
574 resilience after a disaster, adaptation [15,51], mal-development [49] or mis-adaptation
575 [52] of societies to their environment are probably not entirely independent from
576 energy production evolution, but their relations are more complex than for short-term
577 resilience. The role of sustainability [19], of social and technological evolution [52,53]
578 must be taken into account for long-term evolution. The development of renewable
579 energy (geothermal energy, eolian energy, solar energy) in Caribbean islands after
580 2017 disasters offer a possibility to progressively increase resilience [19,54].
581 Nevertheless, “Build back better” and reorganization after disasters could also
582 reinforce existing patterns of mal-development favouring inequality [49,44].

583 During past decades, reduction in the electricity production in the Caribbean
584 islands has been correlated with economic or social events, suggesting a causal link.
585 For example, a reduction in the electricity production and a decrease of tourism in
586 the Caribbean islands occurred (i) after the subprime mortgage crisis in 2008, (ii) after
587 the September 11 terrorist attacks in 2001, and (iii) during the coronavirus epidemic
588 (Covid-19) in 2020. Nevertheless, these three events did not impact the infrastructure
589 in the Caribbean islands (no destruction of electricity networks, hotels, houses, cars,
590 or boats), and they differ from major hurricane impacts on electricity production. A
591 specific pattern, different from the one after major hurricane, is observed.

592 *5.5. Anticipating electricity production*

593 Mathematical modelling and parameters calibration allow us to predict
594 electricity production in three Caribbean islands after a major hurricane. New major
595 hurricane impact on electricity production in these three islands could be anticipate
596 few days after electrical network collapse to predict how will evolve electricity
597 production considering almost similar parameters to those used for Irma and Maria
598 hurricanes. In case of storm or class 1-4 hurricanes on Saffir-Simpson scale, the
599 efficiency of the model has not been demonstrated. Interaction between electrical
600 network restoration on one side, with economic and social activities growth in the other side
601 could be different after major hurricanes. Limitation to use this model is also related to
602 potential evolution of social and technical change. After Irma hurricane, part of the
603 aerial electricity network of Saint-Martin has been buried (underground power lines).
604 Vulnerability of the electrical network has been reduced by this way. Growth of
605 individual electricity generator and development of individual photovoltaic panel
606 could change electricity consumption after major hurricanes favouring resilience of
607 specific groups and potentially hiding part of electricity consumption that occurred
608 outside of the electrical network.

609 Prediction of electricity production of others Caribbean islands after a major
610 hurricane depends to the information available about local electricity network
611 (E_{max} , ϖ), but also to our ability to estimate parameter a , b , V , V_0 , and L and their
612 uncertainty. These later parameters depends of economic (GDP) and demographic
613 (number of inhabitants) indicators as suggested by preliminary results, but further
614 studies are necessary and uncertainty is still very high.

615 The ability of the model to predict electricity production out of islandic context is
616 not demonstrated. For non-insular electrical network, restoration of electricity
617 production should depend to better interconnections and transport facilities.
618 Consequently, the model presented in this study is probably not efficient.

619 **6. Conclusions**

620 We investigated the evolution of electricity energy production after major
621 hurricanes occurred in 2017 in three Caribbean islands: Saint-Martin, Saint-
622 Barthelemy, and Puerto Rico. Following these hurricanes, the electricity energy
623 production decreased abruptly. The full restoration of electricity production depends
624 from the full restoration of the electricity infrastructure as well as from the full
625 restoration of social and economic activities. A resilience time of several months (1
626 month $< t_s < 5$ months) was necessary to attain a new electricity energy production
627 equilibrium E_{is} that was lower than the initial electricity energy production E_i . The
628 resilience time t_r appeared to be proportional to the electricity energy production
629 capacities before the collapse, whereas the other resilience indicators were
630 proportional to the wealth (GDP). The new stable electricity production E_{is} ranged
631 between 25 and 38% less than the initial electricity production. This reduction in
632 electricity production is mainly due to a decrease in the electricity consumption per
633 capita. The reduction in electricity energy consumption per capita was 20–25%,
634 suggesting a decrease in the social and economic activities of approximately 20–25%
635 during the post-disaster equilibrium phase. Nevertheless, in the case of Saint-Martin,

636 part of the reduction in the electricity energy production was due to a reduction of
637 the population owing to their migration outside the islands. The migration of
638 approximately 8000 inhabitants from Saint-Martin reduced the electricity energy
639 production E by 13–18%. The electricity production can be used as an indicator of the
640 resilience of social and economic activities, as well as to evaluate the migration that
641 could hard to evaluate. Mathematical modelling of electricity production could be a
642 useful tool to predict electricity restauration and resilience in Caribbean islands after
643 major hurricanes.

644

645 **Declaration of interest:** none

646 **Acknowledgement:** This work was supported by French National Agency for
647 Research [ANR RELEV]. The funding source had no involvement in the design and
648 interpretation of the data in the writing of the report.

649

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