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Highlights

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- A set of scenarios for 2030 and 2050 are generated
- More expensive scenarios consume less water and emit fewer greenhouse gases
- Electrical facilities can take up to 3% of the island's surface area in the long term
- Up to 2GWh of storage could be needed to reach the island's electrical autonomy

Assessment of medium and long term scenarios for the electrical autonomy in island territories: the Reunion Island case study

Agnès François^{a,*}, Robin Roche^a, Dominique Grondin^b, Michel Benne^b

^a*FEMTO-ST, Univ. Bourgogne Franche-Comte, UTBM, CNRS, Belfort, France*

^b*ENERGY-Lab, Université de La Reunion, Saint-Denis, France*

Abstract

Island territories, due to their specific energy context, are at the forefront of energy transition studies with the aim of achieving energy autonomy. This is the case of Reunion Island, where the electricity mix is currently 70 % carbon-based and where imports provide 80 % of the energy consumption. In this context, this article assesses the facilities to install in the medium and long term to progressively reduce energy imports. Several scenarios of installed power generation capacities have been studied for 2030 and 2050, associated with two scenarios for electricity consumption. Simulations are performed according these scenarios in order to define the electricity mix and the investments in new batteries and in the electricity transmission network reinforcement. For 2030, results show that a reduction in consumption compared with the trend could enable reduce costs and environmental impacts. For 2050, investments in new electricity generation technologies are essential to meet the needs of a 100 % electrified vehicle fleet. If the overall consumption does not follow an energy demand management plan, all the energy sources on the island will have to be exploited to their maximum.

Abbreviations: BAU, Business-as-usual; DSO, Distribution system Operator; EE, Energy efficiency; GHG, Greenhouse gas; IPCC, Intergovernmental panel on climate change; OTEC, Ocean thermal energy conversion; PV, Photovoltaics; SWOT, Strengths - weaknesses - opportunities - threats

*Corresponding author

Email addresses: agnes.francois@utbm.fr (Agnès François),
robin.roche@utbm.fr (Robin Roche), dominique.grondin@univ-reunion.fr
(Dominique Grondin), michel.benne@univ-reunion.fr (Michel Benne)

The energy transition will also require large storage facilities and little reinforcement in the current electricity high voltage network.

Keywords: Reunion Island, electrical autonomy, energy transition, energy management in isolated territories, renewable energy

Nomenclature

Parameters

n	Substations
s	Storage units and generators at a substation
l	High voltage lines
t	Timesteps
$d_{n,t}$	Hourly electrical demand at a substation (MW)
$\underline{g}_{n,s}$	Upper bound of nominal power of electrical generators
$c_{n,s}$	Capital cost of storage units or generators (€/MWh)
c_l	Capital cost of high voltage lines (€/MVA)
$o_{n,s,t}$	Marginal cost for storage units or generators (€/MWh)
dr	Discount rate
lf	Lifetime of a technology (years)
K_{nl}	Incidence matrix of a high voltage line at a substation
$\eta_{n,s}$	Standing losses of a storage unit
$MaxProd$	Maximum production of a sector over a year (MWh)

Variables

$\bar{g}_{n,s}$	Nominal power of electrical generators (MW)
$\bar{e}_{n,s}$	Storage nominal energy (MWh)
$h_{n,s,t}$	Hourly dispatch of a storage unit (MW)
$e_{n,s,t}$	Hourly energy stored in a storage unit (MWh)
$g_{n,s,t}$	Hourly dispatch of a generator (MW)
F_l	High voltage line capacity (MVA)
$f_{l,t}$	Hourly power flow (MW)

1. Introduction

The world is facing unprecedented climate change and the need to move away from fossil fuels is more relevant than ever. With the Intergovernmental Panel on Climate Change (IPCC) predicting that this could increase the

5 risk of conflict [1], the need to reduce this dependence involving global en-
6 ergy trade is even greater. In this context, islands face a particular energy
7 situation: they are weakly or not connected to larger grids on the continents,
8 weather conditions are sometimes extreme, intermittent energy sources are
9 locally important, and the transport and distribution of energy can be dif-
10 ficult to set up. These regions are therefore highly dependent on imported
11 resources, in particular fossil fuels, used for both electricity production and
12 transport, and their energy transition can be complicated to implement. In
13 France, the transition of these specific territories is planned since 2015. Since
14 then, the law on Energy Transition for Green Growth sets the objective of en-
15 ergy autonomy in 2030 for the french Overseas Departments and Regions and
16 in 2050 for Corsica. Located in the south-west of the Indian Ocean, between
17 the islands of Madagascar and Mauritius, Reunion Island is the most popu-
18 lated of the five French overseas departments. In 2020, more than 857 000 in-
19 habitants lived in this 2 512 km² island [2]. Regarding the development of its
20 energy transition, the territory has several strengths and opportunities, but
21 also weaknesses and threats. These are summarized in Appendix A, through
22 a SWOT analysis (Strengths - Weaknesses - Opportunities - Threats). The
23 present paper focuses on the energy transition of Reunion Island. As there
24 is a certain delay in achieving the objective of energy autonomy mentioned
25 above, what futures are currently possible for the island’s electricity system,
26 and at what cost?

27 Common subject of study for energetic studies, islands from many dif-
28 ferent countries are represented in the literature. Spain [3, 4], Denmark
29 [5], Norway [6], Turkey [7], France [8], China [9], United States [10], Greece
30 [11, 12] or Portugal [13] are among them. The objectives of a 100 % renewable
31 mix or energy autonomy are predominant in the studies. However, the meth-
32 ods used to achieve them differ: optimisation tools for future investments,
33 evaluations of hydrogen integration, simulations of different configurations
34 or specific studies on electric vehicles. Indeed, each island is unique and
35 does not start from the same point: while the Faroe islands were 41 % re-
36 newable in 2019 [5], all electricity was generated by fuel for the island of
37 Saint-Barthélemy [14]. Other more global studies present tools to assess the
38 decarbonisation of islands. They investigate the replicability of the proposed
39 means to several islands. In [15], only five buildings are modelled, while in
40 [16] and [17], eight and four European islands respectively are compared. The
41 main limitation of these studies lies in the non-openness of the models used
42 and the impossibility of reproducing the methodology followed for another

43 case study.

44 Regarding Reunion Island more precisely, several regional reports are reg-
45 ularly published, on specific sectors or on the island’s energy development
46 objectives. The PETREL report [18], from 2009, defines two scenarios for the
47 evolution of the island’s energy situation for 2020 and 2030: a business-as-
48 usual one (BAU) and another one called STARTER, reflecting the territory’s
49 objective of energy autonomy for 2030. Similarly, the SRCAE (regional air
50 climate energy scheme, 2013) [19] contains forecasts of electricity generation
51 and installed capacity. The island can also rely on its Multiannual Energy
52 Programmes [20] (PPE). This tool for steering energy policy is developed
53 jointly with national and regional authorities. The current one covers the
54 period 2023 - 2028 and proposes scenarios for consumption, production and
55 the evolution of the transport sector. All are designed to achieve the objec-
56 tives of the 2015 law, with an intermediate objective of 99% of renewable
57 energy in the electricity mix by 2028. A report of the French Agency for
58 Ecological Transition (ADEME) examines possible ways to achieve the ob-
59 jectives of the law [21]. Lastly, the EDF-SEI report [22] presents two sce-
60 narios of electricity consumption and production for 2023, 2028 and 2033.
61 EDF-SEI is the Distribution System Operator (DSO) and the division of
62 the leading national electricity producer and supplier, operating exclusively
63 in non-interconnected areas. Four articles describe the energy transition of
64 Reunion Island [23, 24, 25, 26], all based on the same modeling of the is-
65 land, but exploiting different aspects and presenting different results. The
66 main limitation of these documents is that they do not take into account
67 past predictions and do not propose long term planning. Indeed, they only
68 present medium term energy system planning, i.e. up to 2030. As the global
69 energy transition is lagging behind, the long term, i.e. 2050, is also taken
70 into account in the present study.

71 The other contributions of the present paper are first the comparison
72 of existing energy studies of Reunion Island. Based on this, new scenarios
73 for the evolution of the energy context by 2030 are defined, taking into ac-
74 count the current situation of the island. A methodology for the modelling,
75 simulation and techno-economic optimisation of these scenarios is presented,
76 summarized in Figure 1. The aim of the tools developed is to be used for
77 any island case study in the future.

78 The present paper provides a common tool to better initiate the energy
79 transition of non-interconnected areas, as well as guidance for the energy
80 transition of Reunion Island in the long term. It is organised as follows:

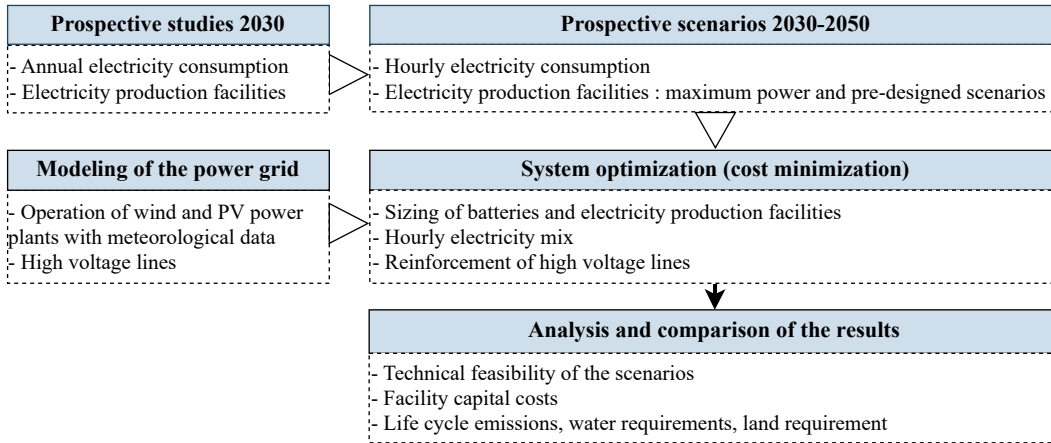


Figure 1: Flowchart of the proposed methodology.

81 after the introduction section, section 2 presents different energy situations
 82 on the island. Past forecasts for 2020, current situation and forecasts for
 83 2030 from the literature are detailed. Section 3 presents the methodology
 84 for modelling, simulating and optimising the new scenarios. These are then
 85 compared from a technical, economical and environmental point of view in
 86 Section 4. The article ends with a discussion and a conclusion in sections 5
 87 and 6.

88 2. Reunion Island energy planning comparison

89 To implement the energy transition of a territory, objectives must be
 90 set and medium and long term action plans must be adopted. These actions
 91 include investments in local electricity generation and targets for primary en-
 92 ergy consumption reduction. These two points are examined in this section,
 93 where scenarios for the evolution of electricity consumption and installed
 94 power generation capacities are compared. First, a focus on the past fore-
 95 casts of Reunion Island for 2020 is made, followed by a comparison with
 96 the current situation of the island. Then, studies proposing medium-term
 97 forecasts for the electricity mix of Reunion Island are compared.

98 2.1. Past forecasts and current situation

99 Forecasts of the evolution of the energy situation of Reunion Island have
 100 already been made in the past. In particular, two reports presented targets

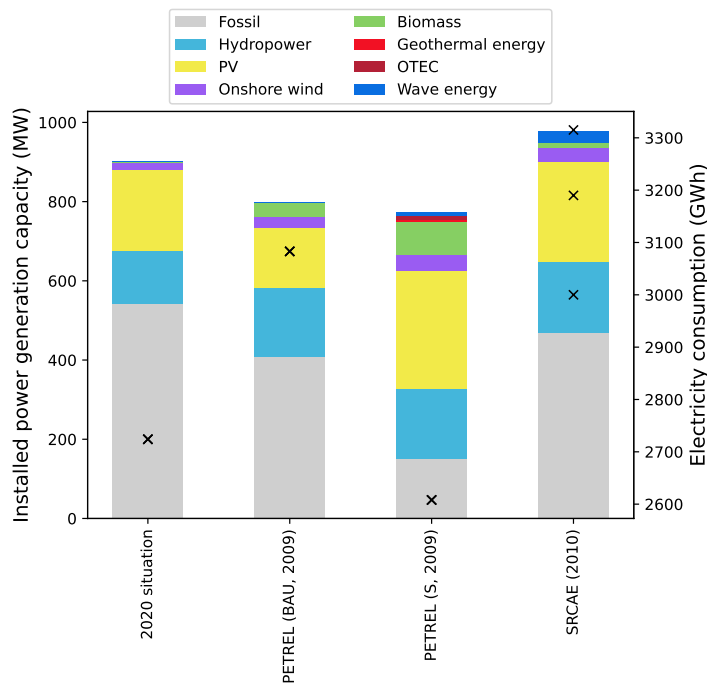


Figure 2: Comparison of the 2020 forecasts to reality. Crosses correspond to the consumption forecasts.

101 for 2020, which can be compared today and allow to assess whether their
 102 forecasts were correct [18, 19]. Both reports contain forecasts of electricity
 103 generation and installed capacity for 2020, neither of which has yet been
 104 reached in 2022. The comparison of installed power generation capacity and
 105 electricity consumption can be found in Figure 2. The “fossil” category in-
 106 cludes installations using exclusively fossil fuels but also installations using
 107 a mix of fossil fuels and biomass resources. If electricity consumption fore-
 108 casts rather well framed the reality, almost every installed power generation
 109 capacity has been overestimated. The law on Energy Transition for Green
 110 Growth from 2015 presents an intermediate target of 50 % renewable energy
 111 by 2020. This target was not reached for electricity production, as 31.3 %
 112 was from renewables, nor for primary energy consumption, as 13 % was from
 113 renewables.

114 As shown in Figure 2, power generation is currently mainly based on fossil
 115 fuels. The map of the installed capacity can be seen in Figure 3a.

116 The electricity network can rely on several thermal units; among them,

117 two coal and bagasse (the fibrous residue of sugarcane crushing) power plants
118 for a total of 210 MW are used for base loads. Work has started on converting
119 these two power plants to biomass. The bagasse part will be kept, and coal
120 will be replaced by local biomass resources and pellets imported from North
121 America. Another plant may be converted to liquid biomass, mainly rapeseed
122 oil, imported from Europe: the diesel plant of 211 MW installed in the north-
123 west of the island. Three combustion turbines, for a total of 121 MW, are
124 also installed, as well as 133 MW of hydroelectricity, 4.4 MW of biogas plants,
125 16.5 MW of wind turbines and 200 MW of photovoltaic systems (PV).

126 In Reunion Island, the electricity grid is operated by EDF-SEI. 25 substa-
127 tions are located on the island, linked together by 500 km of 63 kV lines (see
128 Figure 3b). These substations are linked to 3 500 km of 15 kV lines, mainly
129 underground. Since 2019, the maximum penetration rate of intermittent
130 renewables on the grid has been set to 35 % [20].

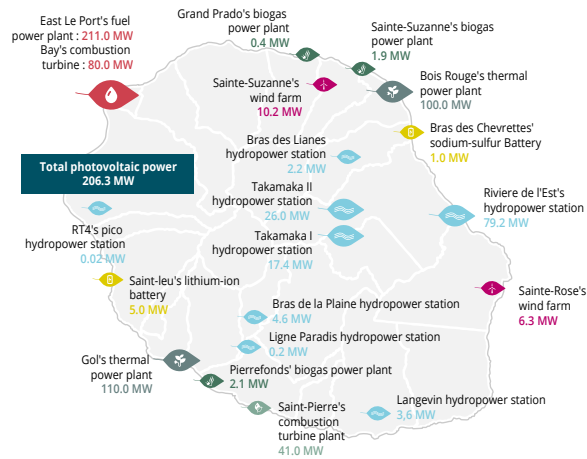
131 *2.2. Comparison of scenarios*

132 New predictions for 2030 have been made since the previous forecasts
133 presented. Several articles and reports follow the law on Energy Transition
134 from 2015 and try to estimate the evolution of the energy mix of Reunion
135 Island by 2030.

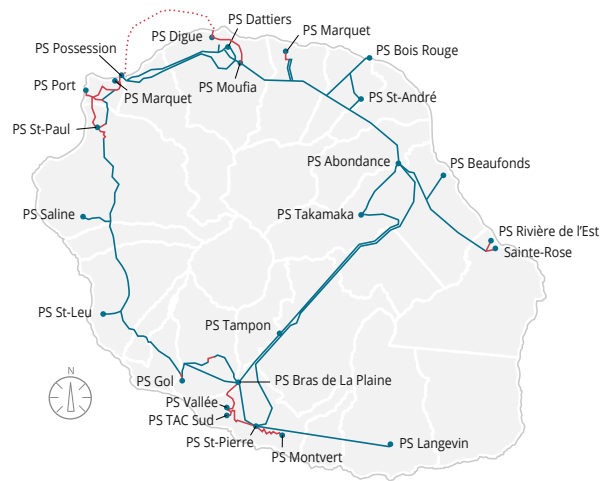
136 *2.2.1. Installed power generation capacity*

137 First, the different existing scenarios of installed power generation ca-
138 pacity for 2030 are compared. This comparison will be used as a basis for
139 defining new scenarios for the same period and for the longer term (2050).
140 The different scenarios of installed electricity generation capacity compared
141 can be found in Table B.3. The results of the comparison are shown in Fig-
142 ure 4. Two articles [23, 25] present scenarios made up of a mix of those of a
143 third one [26], but have not been plotted due to a lack of data on biomass po-
144 tential. Another article [28] details the results of one of the ADEME report's
145 scenarios [21] and thus has not been plotted.

146 Overall, the scenarios offer very different forecasts. While some scenarios
147 indicate zero fossil power for 2030, others maintain the installations, which
148 have not yet reached the end of their life, but specify that they will no
149 longer be used by the targeted date. Few scenarios maintain the use of fossil
150 resources in 2030, as investments in new coal power plants may be more
151 economically attractive. Regarding biomass energy, the data depend on the
152 conversion of thermal power plants, taken into account or not in the forecasts.



(a)



(b)

Figure 3: (a) Map of installed capacity in 2020 [2].; (b) Map of the high voltage electricity network [27]. Red lines are underground and submarine lines.

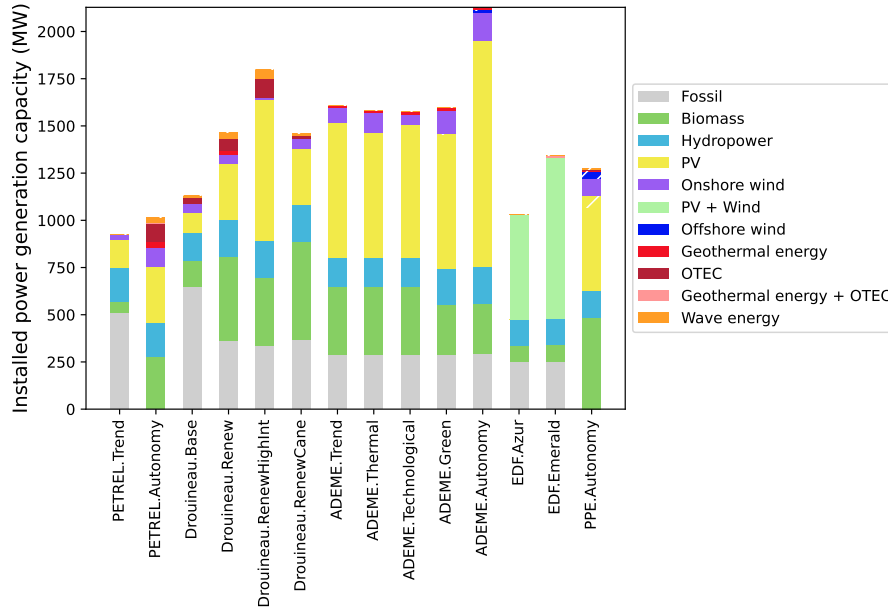


Figure 4: Comparison of scenarios for installed power generation capacity in 2030. Hatching corresponds to the high ranges of *PPE.Autonomy*.

153 The scenarios using the least biomass are those that aim for energy autonomy
 154 in 2030: to supply large power plants, the resource will necessarily have to
 155 be imported. Finally, the forecasts bet on energies not yet exploited on the
 156 island, such as offshore wind, wave energy, ocean thermal energy conversion
 157 (OTEC) or geothermal energy.

158 2.2.2. Electricity consumption

159 The other area that contains several scenarios for 2030 is electricity con-
 160 sumption. Most of the reports and articles reviewed propose two scenarios
 161 for this horizon, a trend scenario and an energy-efficiency (EE) one. Overall,
 162 the consumption targets for the island are of the same order of magnitude,
 163 as shown in Figure 5.

164 Finally, the last area studied is the consumption of electrical vehicles.
 165 In 2019, the road sector alone accounted for 34% of the consumption of
 166 imported fossil fuels in Reunion Island. Within this sector, private cars rep-
 167 resent 77% of vehicles, justifying the need for their transition. Two reports
 168 make forecasts on the electrification of the private vehicle fleet and the re-
 169 sulting additional electricity consumption [22, 21]. If the percentage of the

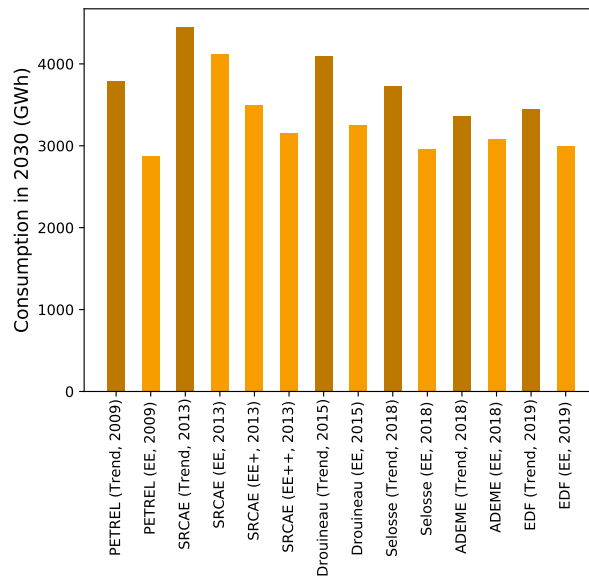


Figure 5: Comparison of the consumption scenarios.

170 fleet of individual vehicles electrified by 2030 can be different, the resulting
 171 power consumption is consistent between the two reports.

172 3. Methodology

173 After having compared various data on Reunion Island’s electricity supply
 174 by 2030, new energy scenarios will be defined; for the electricity production
 175 facilities and for the electricity consumption, for both 2030 and 2050. Indeed,
 176 after noticing the delay in relation to the forecasts for 2020, it seems difficult
 177 today to engage a complete transition of the local energy system to reach
 178 energy autonomy by 2030. In this work, autonomy will be targeted for 2050.
 179 First, the electricity consumption scenarios will be presented. The system
 180 will then be modelled and optimised to meet the introduced electricity de-
 181 mand, in order to propose optimal electricity production scenarios. These
 182 optimums will then be compared to other pre-designed scenarios, taking into
 183 account different energy policy choices in the coming years for Reunion Is-
 184 land.

185 *3.1. Modeling of electricity consumption*

186 The modelled electricity scenarios will be the basis for our optimisation.
187 Indeed, the first objective for the modelling of an electrical network is to be
188 able to satisfy the demand at each time step.

189 For 2030, the choice was made to use electricity consumption scenar-
190 ios from the ADEME report [21]: a demand of 3 080 GWh for the whole
191 island with a **EE** scenario, and a demand of 3 360 GWh with a **Trend** sce-
192 nario. The first scenario assumes a more proactive approach to managing
193 energy demand, for example through energy efficiency measures, and a more
194 optimistic view of the capacity to disseminate the associated technologies.
195 The same objectives were kept for 2050, with the assumption of an increase
196 in demand due to an increase of population and an electrification of uses
197 compensated by a more advanced demand-side management over the years.
198 As the island’s electrical network is modelled by its various substations, the
199 data introduced must be distributed there. The assumption of similar growth
200 among all substations in the long run is made. Island hourly generation data
201 are used, with typical profiles for tertiary buildings and primary residence
202 data for the residential sector, in conjunction with occupancy and appliance
203 usage data [29].

204 In parallel, consumption data of electric vehicles are required. Annual
205 data for the whole island can be obtained, based on the percentage of the
206 individual vehicle fleet electrified [21, 22]. To define an hourly load profile
207 for a typical day, EDF-SEI report [22] is used. In it, two daily profiles of
208 electric vehicle consumption in 2033 in Reunion Island are defined, the first
209 for a fleet that can be driven at 40 % and the second at 80 %. A connection
210 with the demography of the island is used for the distribution of the data;
211 the assumption of a majority of home charging is made, and the data are
212 distributed to the substations according to the number of inhabitants of
213 the island’s municipalities. For 2030, the impact of the electrification of
214 the private vehicle fleet has not been taken into account. For 2050, a fleet
215 electrified at 100 % has been considered, of which 80 % can be driven. The
216 different load profiles can be seen on Figure 6.

217 *3.2. Modeling of electricity production*

218 Together with the electrical demand, electrical production and storage
219 data are affiliated to each substation, which are connected to each other by
220 high voltage transmission lines.

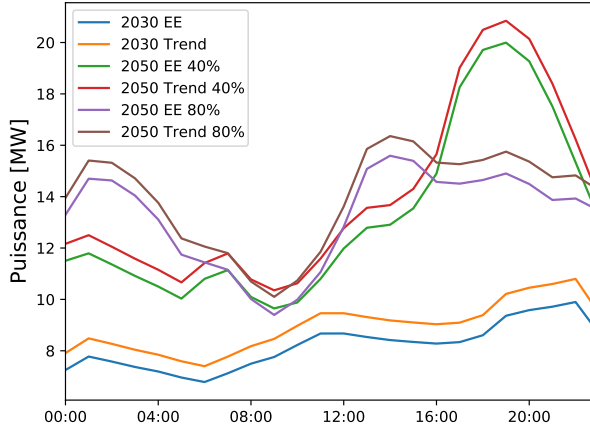


Figure 6: Load on one of the substations on a weekday, depending on the simulated consumption scenario. The 2050 scenarios both have a 100 % electrified private vehicle fleet, of which 40 % or 80 % can be driven.

221 The power generation capacity installed at each substation will be opti-
 222 mised in the first instance. To do this, a maximum power is defined for each
 223 sector for each modelled horizon. For 2030, the PPE [20] forecasts have been
 224 taken for all the existing energy sectors on the island, except for PV: for this
 225 sector, the average of the forecasts of the compared literature scenarios is
 226 taken as the upper bound. For 2050, the existing sectors are maximised by
 227 their potential [21] as defined in the literature. Three new sectors are also
 228 considered for this horizon: offshore wind, geothermal and OTEC. Their in-
 229 stalled capacity is maximised respectively by the high range given by the
 230 PPE for 2028 [20], the only potential evaluated and half of the potential
 231 defined [21]. The distribution of installed capacity at the different subst-
 232 ations is carried out using data from [21]. The data for 2030 were distributed
 233 according to the capacity of each substation. For 2050, no restrictions were
 234 considered.

235 The resulting scenarios will thus be economically optimal and technically
 236 feasible. They will then be compared with seven pre-designed scenarios,
 237 three for 2030 and four for 2050, detailed next, which describe likely futures
 238 depending on policy decisions taken in the coming years. In particular, hav-
 239 ing pre-defined power generation scenarios allows other features of the power
 240 system to be studied with reduced computation time. The resulting elec-
 241 tricity mix of all the scenarios will be composed during the simulation and
 242 optimisation of the system. Regarding the scenarios for 2030, only electricity

243 production technologies currently used on the island have been developed.
244 The current situation of the island is considered and is taken as a basis of
245 the three scenarios. Imports of fossil or renewable resources are considered,
246 in line with the projects currently developed on the island.

- 247 • The **Trend** scenario follows the guidelines of the PPE [20]. This sce-
248 nario is named as such because the decisions taken in the energy sector
249 in the coming years will most likely be based on this report. PV and
250 wind installations increase significantly and small hydroelectric projects
251 are being carried out. Current coal - bagasse plants are converted to
252 100 % bagasse (almost 70 % of the installed capacity will be supplied
253 by imports) as well as current diesel engines to liquid biomass (almost
254 all supplied by imports). The bioethanol combustion turbine is main-
255 tained, as well as current biogas plants. Some biomass projects are
256 considered, such as new biogas plants or projects for the recovery of
257 refuse-derived fuel.
- 258 • In the **80 to 90 % renewable** scenario, only the current coal - bagasse
259 plants are converted to 100 % bagasse and the diesel engines keep work-
260 ing with heavy fuel oil (211 MW). Indeed, work on the conversion of
261 the first plants has already started, but for the second plant, a public
262 consultation on the conversion project has just been completed. PV
263 installations are developed according to the average of the compared
264 scenarios, as well as hydropower. The average of the lowest values of
265 the compared scenarios is retained for wind power: the installed capac-
266 ity of the sector has not increased since 2008, but repowering projects
267 are currently being carried out. The additional biomass and biogas
268 projects of the previous scenario are maintained. This scenario con-
269 siders a medium-term future where the planned energy transition has
270 been delayed and thermal power is still present on the island.
- 271 • Finally, the **100 % renewable** scenario follows the same pattern as the
272 previous scenario, except that the current diesel engines are converted
273 to liquid biomass by 2030, as planned by the Region. This scenario pro-
274 poses the same renewable electricity mix target as the Trend scenario.
275 The situation is however different because data from the comparison of
276 studies in the literature were used.

277 For the 2050 scenarios, the three new technologies considered above for
278 power sizing will be integrated, with their upper limits introduced as installed

279 power. The whole power generation system will be taken from scratch and
280 no imports of fossil or renewable resources are considered.

- 281 • The **Base** scenario develops OTEC and geothermal energy as new base
282 production energies. The maximum of the potential [21] for photo-
283 voltaic and biomass facilities is considered. Regarding the hydraulic
284 capacity, the one used in the last scenario of the ADEME report is
285 chosen. Finally, because of the local weaknesses of the sector, the wind
286 capacity is only doubled compared to the previous 80 - 90 and 100 %
287 renewable scenarios for 2030. This also corresponds to the average of
288 the highest values of the compared scenarios. This scenario allows to
289 assess a situation where base production is largely developed.
- 290 • In the **Intermittent** scenario, offshore wind is the only new production
291 sector developed. PV, hydropower and biomass capacities are the same
292 as the previous scenario. Only wind power is revised upwards, taking
293 the highest value possible from the scenarios from the literature. This
294 scenario allows to assess a situation where intermittent power genera-
295 tion is predominant.
- 296 • The **Decarbonised** scenario is a mix of the two previous scenarios,
297 with the end of the biomass sector (thermal power plants, incinerators,
298 combustion turbines), excluding bioenergy (electricity production by
299 methanization). The installed capacities of geothermal, OTEC and PV
300 are the same as in the first scenario and those of onshore and offshore
301 wind are the same as in the second scenario. Hydraulics takes the value
302 of the maximum potential [21], as well as biogas. Indeed, every possible
303 facility will be required in order to compensate the end of the biomass
304 sector. Today, the island's two coal - bagasse power stations are being
305 converted to 100 % biomass. However, local reserves are not sufficient to
306 ensure equivalent electricity production, and imports are planned. By
307 aiming for local electricity production in 2050, biomass production will
308 have to be reduced. Moreover, it is possible that sugar cane cultivation,
309 which produces bagasse, will be abandoned in the future to make way
310 for other food crops. Indeed, the island has to import many food
311 resources; in 2021, more than 118,000 tonnes of agricultural products
312 were imported into Reunion Island [30]. This scenario therefore assesses
313 the impacts of a long-term situation in which the biomass sector would
314 only be represented by biogas plants in Reunion Island.

315 • Finally, the **Combined** scenario is also a mix of the first two scenarios,
 316 and is made up of all the upper bounds of the production sectors defined
 317 in the power sizing part. The objective of this scenario is to evaluate
 318 the impacts of an energy system where all local energies are exploited
 319 to their maximum.

320 The summary of installed capacities by scenario can be seen on Figure 7.

321 3.3. Optimisation problem

322 In order to assess the technical feasibility of the previously introduced
 323 scenarios, size the optimal scenarios and optimise the electricity mix in each
 324 case, the operation of the Reunion Island electrical system is simulated for
 325 2030 and 2050 with an economic optimisation.

326 The following notations are adopted: n for the substations, l for the
 327 high voltage lines, t for the timesteps (every hour of year 2050) and s for
 328 the different generators and batteries at a substation. Input data are: the
 329 hourly electrical demand ($d_{n,t}$ in MW), the nominal powers of the electrical
 330 generators if not optimised ($\bar{g}_{n,s}$ in MW) or their upper bound ($\underline{g}_{n,s}$ in MW)
 331 and meteorological data (wind, temperature, radiation) for the operation of
 332 the PV and wind facilities.

333 The optimization variables are: the nominal energy of the batteries ($\bar{e}_{n,s}$
 334 in MWh), their hourly dispatch and stored energy ($h_{n,s,t}$ in MW and $e_{n,s,t}$ in
 335 MWh), as well as the hourly operation of the power generation technologies
 336 ($g_{n,s,t}$ in MW) and the potential reinforcements of the high voltage lines (F_l
 337 in MVA). The hourly operation of intermittent power generation technologies
 338 is not optimized; all the possible energy produced is recovered. The nominal
 339 powers of the electrical generators ($\bar{g}_{n,s}$ in MW) are optimization variables
 340 in the case of the power sizing part of the study.

341 These variables are subject to a Mixed Integer Linear Programming (MILP)
 342 algorithm, minimizing the investment costs on batteries ($c_{n,s}$), power lines
 343 (c_l) and generators if required ($c_{n,s}$), as well as the operating costs of gener-
 344 ators and batteries ($o_{n,s,t}$). The objective function is expressed in Eq. (1):

$$\min \sum_{n,s} [c_{n,s}\bar{e}_{n,s} + c_{n,s}\bar{g}_{n,s}] + \sum_l c_l F_l + \sum_t \sum_{n,s} [o_{n,s,t}g_{n,s,t} + o_{n,s,t}h_{n,s,t}] \quad (1)$$

345 To express capital costs in annual costs, the annuity factor $\frac{1-(1+dr)^{-lf}}{dr}$ was
 346 used, where dr is the discount rate and lf the lifetime of the technology [31].

347 The satisfaction of the demand, with the power flow $f_{l,t}$ in MW and K_{nl}
 348 the incidence matrix of line l at substation n is defined by Eq. (2):

$$\sum_s g_{n,s,t} + \sum_s h_{n,s,t} - \sum_l K_{nl} f_{l,t} = d_{n,t} \quad (2)$$

349 For the optimisation of the size of the installed generation power capaci-
 350 ties, Eq. (3) is implemented:

$$\bar{g}_{n,s} \leq \underline{g}_{n,s} \quad (3)$$

351 The operation of the batteries is defined in Eq. (4), with $\eta_{n,s}$ the standing
 352 losses, considered zero in the modeling of this study. No efficiency losses for
 353 power going into and out of the storage are considered.

$$e_{n,s,t} = \eta_{n,s} e_{n,s,t-1} - h_{n,s,t} \quad (4)$$

354 A constraint for limiting the annual production of a sector has been in-
 355 troduced in Eq. (5)

$$\sum_t g_{n,s,t} \leq \text{MaxProd} \quad (5)$$

356 Indeed, some electrical productions are limited, like hydropower or biomass,
 357 according to available local resources. These limits (*MaxProd* in MWh)
 358 have been set according to data from the literature.

359 The necessary reinforcement of high voltage lines are defined by Eq. (6).
 360 The current limit of apparent power of the lines was defined with data from
 361 [21].

$$|f_{l,t}| \leq F_l \quad (6)$$

362 To implement the model, the Python for Power System Analysis (PyPSA)
 363 framework [32] is used. The optimisation problem is solved with Gurobi [33].

364 4. Results

365 4.1. Technical comparison

366 Different results were obtained from the optimisation of the simulated sys-
 367 tem. The sizing of power generation facilities when optimised, the electricity
 368 produced per sector and per substation, the required size of the batteries
 369 and their operation, and the required reinforcement of the high voltage lines

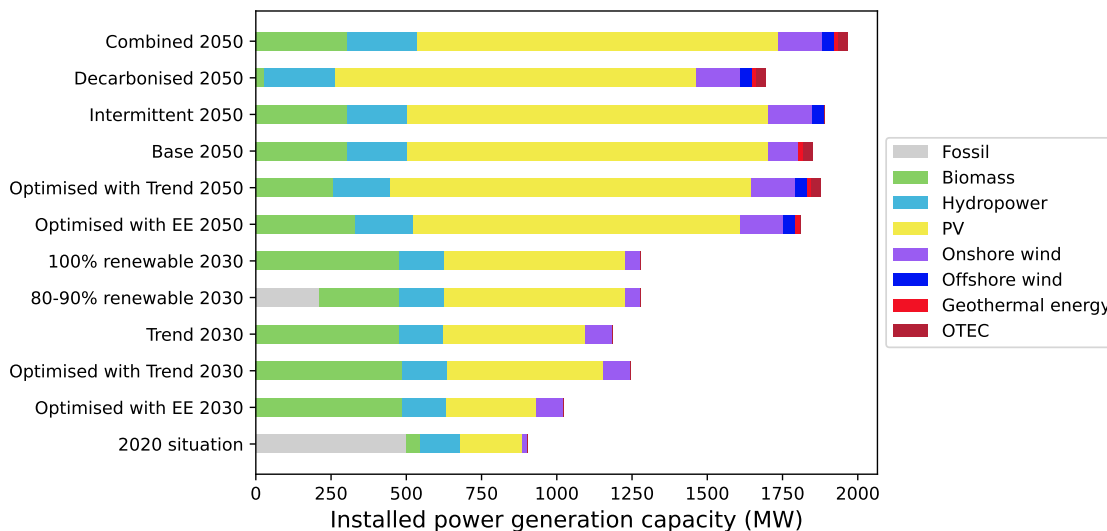


Figure 7: Installed capacities (MW) for the 2030 and 2050 scenarios.

370 were displayed. The sizing of the electricity generation scenarios was made
 371 for 2030 and 2050, in order to satisfy the two consumption scenarios chosen.
 372 The results of this sizing are shown in Figure 7. The other results for the
 373 simulation of the power system over the year are shown in Table 1, together
 374 with the simulation results of the pre-designed scenarios.

375 For the sizing of installations for 2030, in both consumption cases, wind
 376 installations are prioritised over PV installations, although the prices of the
 377 latter are higher. This is justified by the minimisation of storage needs in
 378 order to smooth out PV production. No reinforcement of the grid power lines
 379 will be necessary in the medium term.

380 For all three pre-designed scenarios, larger amounts of batteries are re-
 381 quired with the EE power consumption scenario. With a higher share of
 382 intermittent energy in the electricity mix and lower electricity demand, en-
 383 ergy can be stored when it is not consumed. Conversely, the Trend con-
 384 sumption scenario consumes more intermittent energy, leaving the missing
 385 demand filled by controllable generation. However, batteries are not used in
 386 the same way depending on the demand; while relatively small batteries (2 -
 387 5 MWh) are installed at all substations with the Trend scenario, larger bat-
 388 teries (up to 70 MWh) are installed at less than half of the substations in the
 389 other scenario. These are shown in Figure 8a. These include the substations

Scenario	Battery need, EE (MWh)	Line reinforcement, EE (MVA)	Battery need, Trend (MWh)	Line reinforcement, Trend (MVA)
Optimised 2030	0	0	168.5	0
Trend 2030	21.856	0	0	0
80-90% ren. 2030	184.51	0	88.15	0
100% ren. 2030	184.51	0	88.15	0
Optimised 2050	1746	11	1924	13
Base 2050	1747	4	x	x
Intermittent 2050	2342	0	x	x
Decarbonised 2050	x	x	x	x
Combined 2050	2342	0	2041	5.2

Table 1: Results of the simulations of every production scenario with every consumption scenario. Crosses mean that the system is not technically feasible.

390 where the five largest photovoltaic capacities have been added. The other
391 substations concerned have either PV power additions or low installed power
392 (around 10 MW). For the latter, the battery allows the electricity produced at
393 another station to be stored to meet local demand. This shows the advantage
394 of the sizing of the electricity production facilities: the storage requirements
395 are optimised with the two consumption scenarios proposed. In the case of
396 the Trend consumption scenario, storage requirements are greater with the
397 sizing of the facilities because of the lower installed capacity of hydroelectric
398 power.

399 Looking at the 2050 horizon, the Trend and EE consumption scenarios
400 are different than for 2030, as the additional demand for electric vehicles
401 is taken into account here. Once again, installations are sized to minimise
402 the need for electrical storage. It should also be noted that the geothermal
403 potential is required in both electricity consumption scenarios. In the case
404 of the Trend consumption scenario, the OTEC installation is essential to
405 meet demand. Thus, with regard to the pre-designed scenarios, the Base
406 and Intermittent scenarios are not feasible in combination with the Trend
407 consumption scenario. Moreover, the Decarbonised scenario is not feasible
408 with both consumption scenarios. In both case, demand is too high to be
409 met by the installed capacities defined in the scenarios. While storage is
410 needed in all feasible simulations, less is required for pre-designed scenarios
411 where reinforcement is needed on the electricity transmission network. This

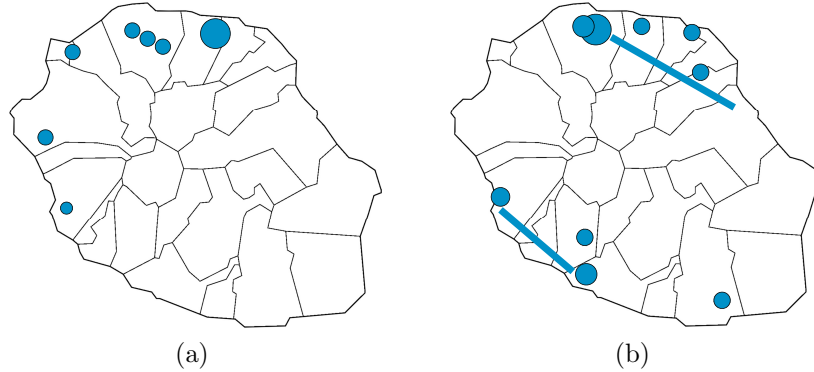


Figure 8: Comparison of requirements for battery and line reinforcement; (a) 2030 scenarios.; (b) 2050 scenarios.

412 concerns the Base scenario with EE consumption, and the Combined scenario
 413 with Trend consumption. The same line requires an increase of 4 MVA for the
 414 first simulation and 3 MVA for the second. The second simulation requires
 415 a second increase of 2.2 MVA for another line. These same two lines need
 416 to be reinforced when sizing installations. They connect substations where
 417 large storage is required, due to a high PV potential or a large number of
 418 connected power generation facilities. These are shown in Figure 8b. The
 419 other substations concerned by large storage (+ 100 MWh) are connected to
 420 high electricity consumption (commune of Saint Denis), high PV potential, or
 421 high or low installed power, all energies combined. The substations requiring
 422 the least additional storage are mainly the substations connected to large
 423 hydraulic installations and having no connected electricity consumption.

424 The impacts of a 100 % electrified fleet of which only 40 % are controllable
 425 can be noticed in the storage requirements. Indeed, with an EE scenario, a
 426 need of + 7 % in storage is noticed, and for a Trend scenario a need of +
 427 8 %. The results on the lines or on the electrical generation are globally not
 428 impacted.

429 4.2. Investment costs comparison

430 The scenarios introduced can first be economically compared. Facility
 431 capital costs allow a comparison of the economic investments required in order
 432 to reach the targeted horizon. The data used for the calculations can be
 433 found in Table C.4. Data for line reinforcement were taken from [21].
 434 Regarding the 2030 scenarios, only facility capital costs for new electricity

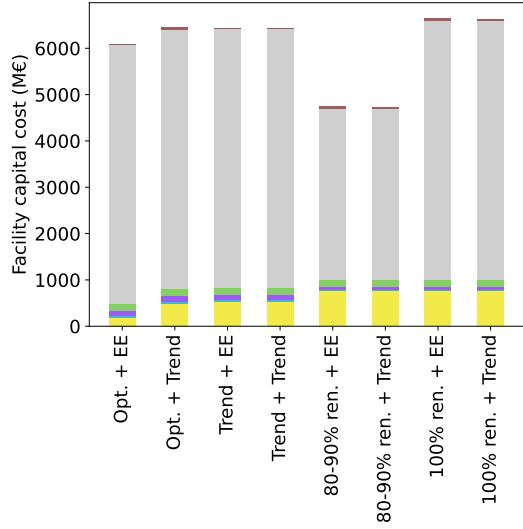
435 generation capacity compared to the current situation are considered. Invest-
436 ments are almost similar for the sizing scenarios and the Trend and 100 %
437 renewable pre-designed scenarios, as can be seen on Figure 9a, as the installed
438 capacity data are close. The main difference with the 80 - 90 % renewable
439 scenario is in the investment for the conversion of diesel engines to liquid
440 biomass [34]. Comparing the 2050 scenarios, the four scenarios have fairly
441 similar investment costs in facilities (see Figure 9b). The costs of reinforcing
442 the network are not shown in the diagrams, being in the region of a hundred
443 thousand euros for the lines concerned.

444 *4.3. Environmental comparison*

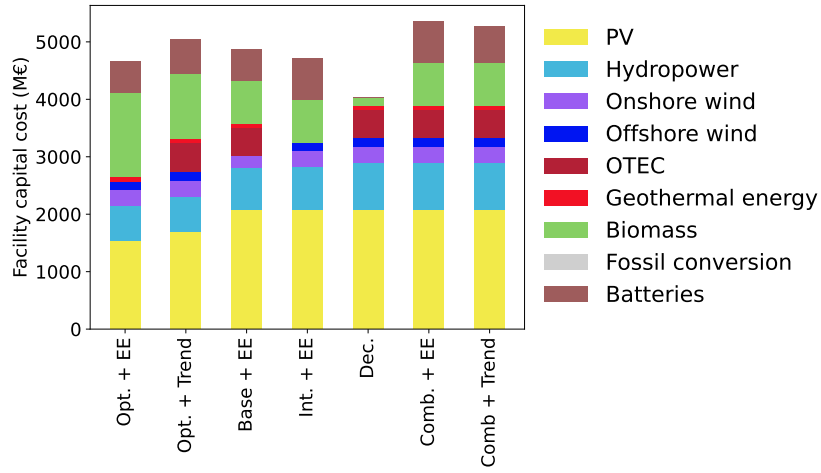
445 The scenarios presented can also be compared from an environmental
446 perspective. The data used for the calculations can be found in Table C.5.

447 Land requirement is first observed, because of the limited availability of
448 this resource on the island. Comparing the 2030 scenarios, both the 80 -
449 90 % renewable and 100 % renewable pre-designed scenarios require almost
450 six square kilometers, one more than for the remaining scenarios. Indeed,
451 the footprints of hydroelectric and photovoltaic systems are larger than those
452 of wind power plants for an equivalent capacity, which explains the differ-
453 ence. Looking at the 2050 scenarios, the Combined scenario would require
454 84 km² of land, namely 3 % of the island's surface. In comparison, the De-
455 carbonised scenario would require only 50 km². As this horizon is considered
456 from scratch, the current installations on the island would be included in this
457 total, unlike the scenarios for 2030.

458 Considering a second resource with limited availability on the island, the
459 use of water is studied. This criteria is about the water taken from the
460 environment by the electrical installation during its construction and its op-
461 eration, and not returned to its original source [35]. PV is the only technology
462 where the water requirement during operation is zero. Moreover, the water
463 consumed during the manufacturing of the panels could be neglected at the
464 local level, as the panels have to be imported. For the 2030 horizon, the
465 results are similar between the scenarios. Between a Trend consumption
466 scenario and an EE one, 100 additional cubic decameters of water are re-
467 quired, regardless of the installed power pre-designed scenario, as shown in
468 Figure 10a. Looking at the other horizon, the optimised scenario with the
469 Trend consumption scenario comes out on top, due to a higher use of local
470 biomass resources than the other scenarios, as can be seen in Figure 10b.



(a)



(b)

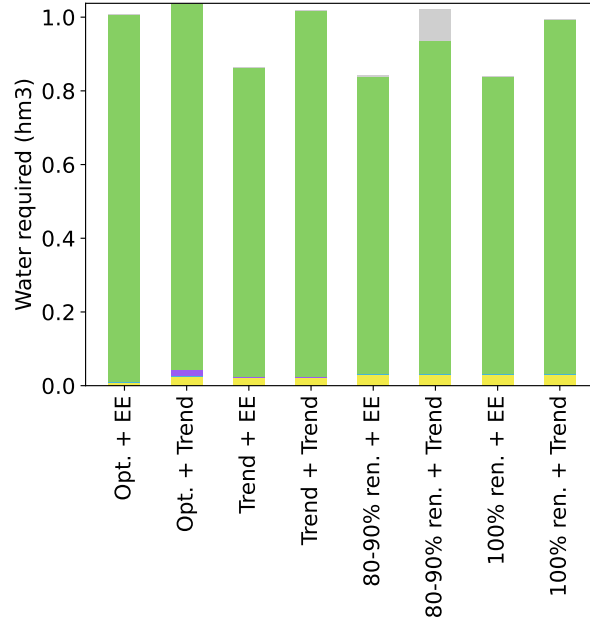
Figure 9: Comparison of facility capital costs of the different scenarios; (a) 2030 scenarios; (b) 2050 scenarios.

471 In both figures, the impact of biomass is predominant, requiring more wa-
472 ter during its operation. Moreover, over both horizons, the optimised sizing
473 scenarios consume more water than the pre-designed scenarios. Thus, if the
474 former had been optimised according to this water consumption criterion,
475 different results would have been obtained.

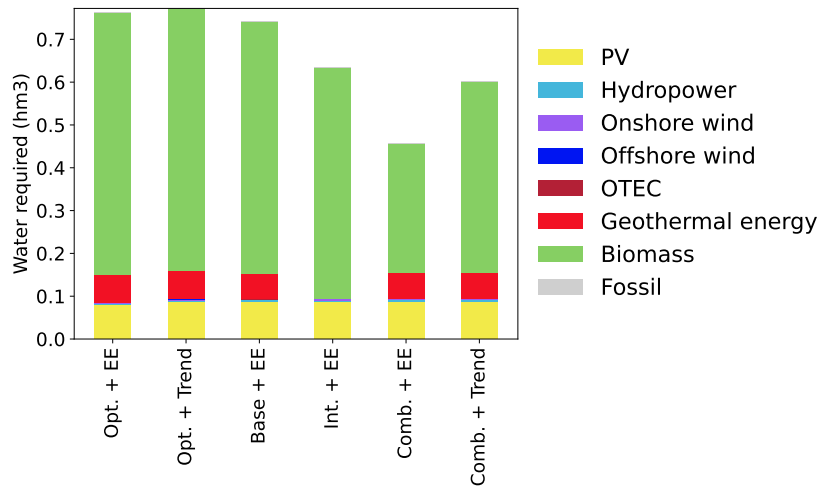
476 Lastly, life cycle greenhouse gas (GHG) emissions are depicted to assess
477 the environmental impact of the scenarios. Among them, CO₂, CH₄ and
478 NO₂ emissions, all measured in CO₂ equivalence. For the study, emissions
479 from electrical installations were assessed, as well as electricity generation
480 emissions over the simulated year. As expected, for 2030 the 80 - 90 %
481 renewable energy scenario with the Trend consumption scenario is the one
482 emitting the most GHG emissions over the life cycle of the new facilities, as
483 shown in Figure 11a. These emissions amount to 124 kilotonnes of CO₂eq,
484 while the only direct CO₂ emissions for electricity production were 1 922
485 kilotonnes in 2019 [27]. Moreover, with this same installed capacity scenario,
486 switching from the Trend electricity consumption scenario to the EE one leads
487 to a decrease of 71 kilotonnes of CO₂eq. Indeed, during the optimization,
488 only the production costs of the power generation facilities were considered.
489 Thus, the use of the diesel power plant in this scenario is in the minority, as
490 the import costs are high compared to the maintenance costs of the facilities
491 using local resources. The impacts of future biomass imports could not be
492 assessed, since their introduction is scheduled for 2024.

493 As for water requirements, in the long term the optimised sizing scenar-
494 ios have highest life-cycle GHG emissions, with almost 39 kilotonnes of CO₂
495 emitted. Once again, if they had been optimised according to this crite-
496 rion, different results would have been obtained. The pre-designed scenario
497 Combined with an EE consumption would be the one with the lowest CO₂
498 emissions, with 19 kilotonnes, as shown in Figure 11b. Once again, the im-
499 pact of the biomass industry is predominant in both figures, emitting the
500 most during its operation.

501 The comparison of the different criteria can be seen in Figure 12. Each
502 criterion is standardized according to the minimum and maximum results of
503 each scenario. The more outwardly oriented the simulation, the greater the
504 impacts are.

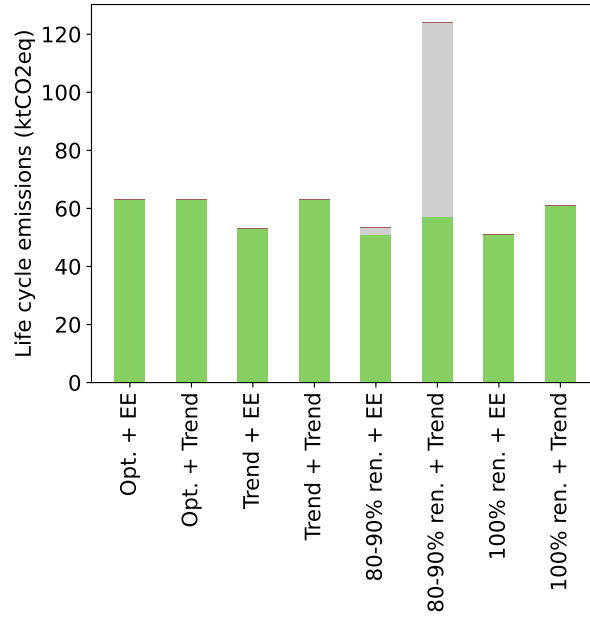


(a)

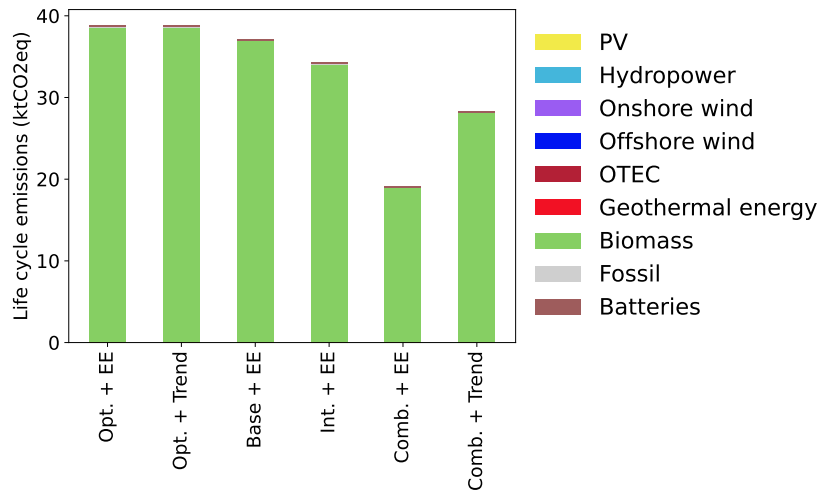


(b)

Figure 10: Comparison of the water volume needed in the different scenarios.; (a) 2030 scenarios.; (b) 2050 scenarios.



(a)



(b)

Figure 11: Comparison of life cycle emissions of the different scenarios.; (a) 2030 scenarios.; (b) 2050 scenarios.

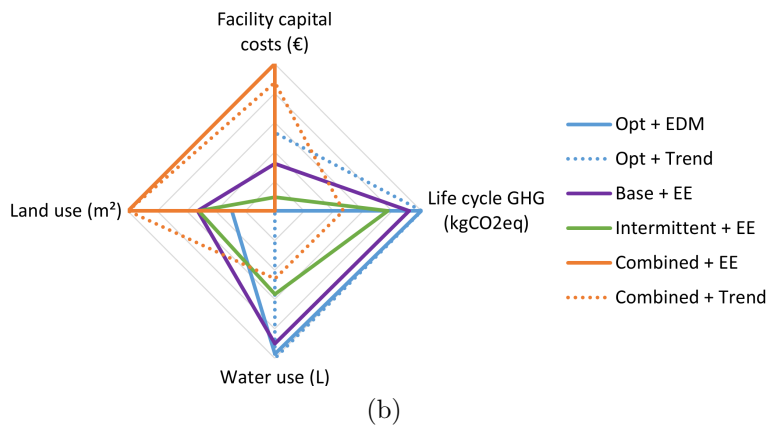
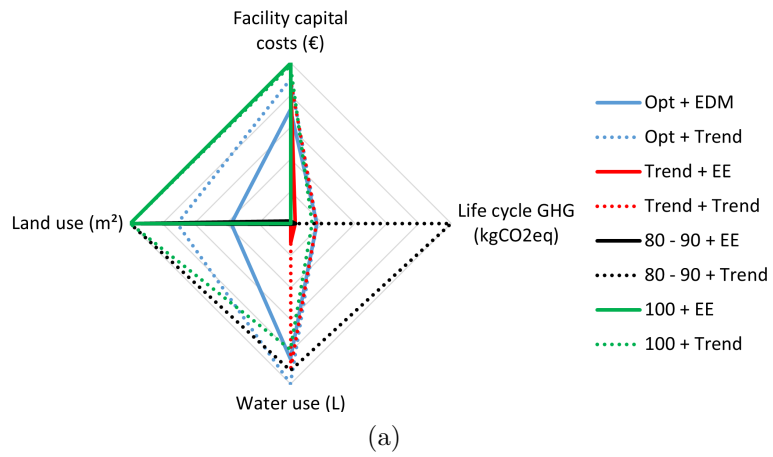


Figure 12: Representation of the different simulations on the selected criteria. Results are normalised on each criterion for each horizon; (a) 2030 simulations; (b) 2050 simulations.

505 5. Discussion

506 The scenarios introduced for 2030 and 2050 have been simulated, and
507 results were obtained and detailed. It has been demonstrated that, in order
508 to satisfy a steady long-term electricity demand with a fully electrified vehicle
509 fleet in Reunion Island, it is necessary to mobilise all possible electricity
510 production technologies. If this is not possible, electricity consumption will
511 have to be at least below the level of the EE scenario introduced in the present
512 study. Then, between one scenario or another, the impacts are close, with the
513 capital cost of the facilities being globally related to land use and life-cycle
514 GHG emissions related to water use (for 2050). If the biomass sector was
515 no longer used for electricity generation, electricity consumption would have
516 to decrease even more, below 4 GWh annually, including the consumption
517 of electric vehicles. To achieve this long-term horizon, decisions will have
518 to be made in the medium term. If the total cessation of fossil power from
519 2030 implies a significant decrease in life cycle GHG emissions, it has a
520 consequential cost. One of the best path to follow would be to maintain one
521 of the thermal power plants with a decrease in consumption. All indicators
522 would be at their minimum, except the use of land, which could be considered
523 negligible in relation to the needs in 2050.

524 In the simulation of the 2030 scenarios, the new capacities to be installed
525 per substation have not been uniformly distributed: the substations capaci-
526 ties were considered. As a result, some substations have not been allocated
527 any additional power by 2030, although in some cases there is potential.
528 This may justify the need for batteries in some places. In addition, some
529 of these batteries may be large (290 MWh). In the medium and long term,
530 hydrogen storage could be introduced, in order to evaluate the economic and
531 environmental use of this type of storage in such a system.

532 In the work presented, only a few comparison criteria were considered;
533 others could have been considered as well, which would have led to differ-
534 ent conclusions [36]. For example, the use of specific metals and materials
535 could have been observed. This criterion is important when considering the
536 environmental and social impact of extracting certain metals or manufac-
537 turing certain materials. The results could have also been different if the
538 impact of climate change was included in the modeling. For the simulation
539 of the photovoltaic and wind models, weather data from 2019 were used. The
540 production of these energies could vary greatly in the future, and may well
541 increase or decrease. Similarly, the production limitations of the hydro and

542 biomass sectors were determined using the literature. Here again, the pro-
543 duction is uncertain in the future due to climate change. Other uncertainties
544 exist and can hardly be evaluated in such a model, such as new energy laws
545 or new conflicts. The latter can jeopardize the current fossil imports, but also
546 the future imports of pellets or oil. Energy reliability was also not studied
547 in the paper.

548 A similar work could be done in other territories. Even if each island
549 has its own conditions and data [14, 37], the methodology set up in this
550 article is replicable and the developed optimisation model can be used for
551 any non-interconnected area by changing the input data. Some modifications
552 would be necessary to model islands connected to the mainland, as is the
553 case of Corsica for example, in order to consider an import and export of
554 electricity to an external market. Each study on a different territory would
555 lead to different results, and it would thus be interesting to compare the costs
556 and environmental impacts involved in the transition required by the law on
557 Energy Transition for Green Growth to the French islands to achieve energy
558 autonomy.

559 **6. Conclusion**

560 In the present study, different scenarios have been investigated for the
561 evolution of Reunion Island’s power system for 2030 and 2050, with a view
562 to achieving electrical autonomy in the latter period. Simulations have shown
563 that, from a GHG emissions point of view, the conversion of the current fossil
564 power plants is impacting. However, it has not been possible to assess the
565 impact of the imports planned as offsets, since their introduction is scheduled
566 for 2024. Incidentally, following an EE plan for electricity consumption could
567 reduce costs and environmental impacts, although further studies would be
568 required to evaluate the wider economic and societal impacts.

569 To achieve energy autonomy, new sources of electricity production will have
570 to be developed. The development of geothermal energy, ocean thermal en-
571 ergy conversion and offshore wind turbines has been studied in the work
572 presented. The reduction of the biomass sector could be considered in the
573 future, but it must be accompanied by a strong decrease in electricity con-
574 sumption. The future of these sectors and their long-term role in Reunion’s
575 energy context is a major source of uncertainty, which should be resolved in
576 the decisions taken in the short or medium term.

577 The present study has shown that energy transition must be supported
578 by significant storage facilities. Although only batteries have been consid-
579 ered in the present work, the use of hydrogen storage will be employed in a
580 future work, to consider longer-term storage to complement short-term bat-
581 tery storage. Moreover, a modeling of the storage in the form of energy was
582 carried out in the study. As these are very solicited, a power modeling will
583 be carried out later in order to compare the two systems.
584 Hydrogen will also be introduced to decarbonise the rest of the road trans-
585 port sector; in the present study, heavy transport vehicles, such as buses
586 or trucks, have not been taken into account to achieve energy autonomy in
587 2050. The decarbonisation of the aviation and maritime sectors will be also
588 be studied in future work.
589 Lastly, social impact of electric autonomy was not measured in the presented
590 paper. It is necessary to assess the acceptance and local impacts of some new
591 electricity production methods or storage facilities. This will be the subject
592 of further work in the continuation of the study, as well as the social impact
593 of energy autonomy as a whole.

594 **CRediT authorship contribution statement**

595 **Agnès François:** Conceptualization, Methodology, Software, Formal
596 analysis, Writing - Original Draft. **Robin Roche:** Conceptualization, Writ-
597 ing - Review and Editing, Supervision, Project administration. **Dominique**
598 **Grondin:** Conceptualization, Writing - Review and Editing, Supervision.
599 **Michel Benne:** Conceptualization, Writing - Review and Editing, Supervi-
600 sion.

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604 0035) and the Region Bourgogne Franche-Comté.

605 **Appendix A. Characteristics of the territory**

606 See Table A.2.

Table A.2: SWOT analysis of the territory.

Strengths	Weaknesses
<ul style="list-style-type: none"> - Dense hydrographic network (400GWh every year for two decades) - Good photovoltaic potential (200GWh every year since 2013) - Geothermal potential - Marine energy potential (ocean thermal energy conversion, wave energy, offshore wind turbines) - Tropical climate (negligible heat demand) 	<ul style="list-style-type: none"> - Cyclonic episodes - Dependence on imports - Isolation of the island - Waste exportation - Limited land
Opportunities	Threats
<ul style="list-style-type: none"> - National energy policy - Train or tramway potential (cite, cite) 	<ul style="list-style-type: none"> - Energy dependency

Table B.3: List of the scenarios of installed power generation capacity.

Source	Publication year	Original scenario name	New scenario name	Specificity
[18]	2009	-	PETREL.Trend	Business-as-usual
[19]	2013	STARTER	PETREL.Autonomy	Achieving energy autonomy by 2030
[26]	2015	-	SRCAE.Trend	Business-as-usual
		BASE	Drouineau.Base	Business-as-usual
		RENEW	Drouineau.Renew	100 % renewable electricity generation in 2030
		RENEW-HighInt	Drouineau.RenewHighInt	100 % renewable electricity generation in 2030 with greater increase in photovoltaic and marine energy
		RENEW-Cane	Drouineau.RenewCane	100 % renewable electricity generation in 2030 with decline of the sugar industry
[21]	2018	Trend	ADEME.Trend	Business-as-usual
		Thermal advantage	ADEME.Thermal	Economic context favourable to conventional energy
		Technological advantage	ADEME.Technological	Access to new renewable energy production technologies
		All green lights	ADEME.Green	100 % renewable electricity generation in 2030
		Towards energy autonomy	ADEME.Autonomy	Achieving energy autonomy by 2030
[22]	2019	Azur	EDF.Azur	Soft energy transition
		Emerald	EDF.Emerald	Strong energy transition
[20]	2020	-	PPE.Autonomy	Almost 100 % renewable electricity generation in 2030

607 **Appendix B. Scenarios of installed power generation capacity**

608 See Table B.3.

609 **Appendix C. Data used for the modelling**

610 See Tables C.4 and C.5.

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Generation technology	Investment (€/kW)
PV Residential	1900
PV Tertiary	1550
PV Ground	1000
PV Canopy	1230
Hydropower Pumped storage, dam	3800
Hydropower Run-of-the-river, irrigation and sewage networks	2000
Hydropower Drinking water network	5200
Onshore wind	2000
Offshore wind	3500
OTEC	16200
Geothermal energy	5350
Biomass Biogas plant	5400
Biomass Bagasse thermal power plant	2200
Biomass Small thermal power plant	2200
Biomass Waste-to-energy plant	7850
Batteries	310 €/kWh

Table C.4: Investment data used [21, 28, 38].

Table C.5: Sustainability criteria data used [35, 39, 40, 41].

Generation technology	Life cycle GHG (kgCO ₂ eq/MW)	Life cycle GHG (kgCO ₂ eq/GWh)	Water use (L/MW)	Water use (L/GWh)	Land use (m ² /MW)
PV					
Residential, tertiary	92	0	72952	0	1561
PV	92	0	72952	0	1561
Ground, canopy					
Hydropower	53	0	16587	208	190606
Pumped storage, run-of-the-river					
Hydropower	53	0	16587	208	190606
Dam					
Hydropower	53	0	16587	208	190606
Water systems					
Onshore wind	39	0	11048	2020	3950
Offshore wind	41	0	3660	130	31
OTEC	0	0	16587	208	31
Geothermal energy	49.9	0	18000	500000	18391
Biomass	0	35000	16587	553000	120236

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