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► To cite this version:

Guillaume Guimbretiere, Benjamin Pillot, Christophe Révillion, Corrie Mathiak, Romain Authier. Territorial solar baking potential: A socio-technical analysis for planning the sustainable energy transition of the bakery world. 2023. hal-04295387

HAL Id: hal-04295387

<https://hal.science/hal-04295387>

Preprint submitted on 20 Nov 2023

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Territorial solar baking potential: A socio-technical analysis for planning the sustainable energy transition of the bakery world

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Abstract

In the context of a global energy transition, heating remains a highly energy consuming process. One very virtuous and low economic cost solution for cooking is direct solar concentration oven. In this article, in order to estimate the solar baking potential of a territory, a socio-technical solar bakery's workflow model and two socio-economic indicators were developed. From real incoming solar energy as input, the model takes into account the solar oven properties and baker's time management in order to calculate bakery's bread productivity. Then, this model was applied and indicators computed for a small tropical island (Réunion, France). Results show that substantial solar bread production areas match the island population density, and that the level of solar bread production can be viable, though requiring an adaptation of the bakery sector's organization to the solar production variability.

Keywords: Artisan bakery, solar energy, spatio-temporal modeling, social-technical transition, multi-scale organization, small island

1. Introduction

Recently, the sharp rise of energy and electricity prices in France has jeopardized many small-scale commercial activities such as artisan bakeries [1]. It reveals that the energy transition framework is still in its infancy, and how the pursuit of a sustainable path must incorporate more than just the energy supply dimension [2, 3]. Political actions still look like small patches on big issues that fail to address the big picture. A typical example are variable renewable energies (VRE) being integrated into centralized electrical networks (e.g. solar & wind farms). In the short and mid-term, this is likely a good option for mitigating CO₂ emissions from the energy sector [4] and thus for combating climate change. However, in the long-term, the sustainability of such VRE systems should be questioned : They 1) are much more adapted to small-scale remote applications [5], and 2) strongly depend on mining and rare earth elements (REE) [6].

Due to its abundance and worldwide distribution, solar energy has long been identified as the main energy source from which a sustainable society could be built [7]. The current issue is that nowadays energy sources in general and solar energy in particular are mostly regarded as *power sources*, i.e. electricity generation sources [8]. Overall, the energy-centered view of the energy transition framework is too constraining as it only focuses on the *energy* part of the technical system. It is key to understand that energy is not an end in and of itself; rather, it is a means towards fulfilling a need. According to the *energy services* definition by Fell *et al.* [9], the desired end services or states are obtained or facilitated by functions performed using energy. These functions can be in part unmaterialized but in the end, it is only a hardware tool (here called technology) that can materially act on the real world and fulfill the need (i.e. obtain the desired service). Therefore, by realizing that energy has to be combined with a technology in order to obtain a final end service, it becomes clear that only by addressing both technologies and energy can a sustainable transition of our civilization be achieved. It is important to note that "technologies" adress the whole technological regime, not only the energy "production" technologies. Furthermore, when considering the place and role of the technologies in the energy transition, one has to consider that technologies are not neutral tools isolated from the social framework [10, 11]. A radical energy transition towards sustainability should only be possible once the social-technical system has been considered as a whole [12, 13]. Accordingly, a broader understanding of the systemic synergies

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and complexities implied by energy transition incites to apprehend the whole chain of energy supply, [energy] transport and [energy] consumption. It also implies social and cultural changes [14]: we must transform our manner of living; that is to think about why we need specific types of energy, and how we may find corresponding sustainable alternatives.

What does this shifted perspective of the energy transition imply on the baker's socio-technical transition towards sustainability? In fact, more than 50% of the energy consumed by a bakery is dedicated to baking [15]. If our approach is articulated around energy production technologies, it appears that the bakery oven primarily requires *heat energy*; nowadays this heat is mostly converted directly from combustion of wood [16] or fossil fuels, or from the electricity provided by the national grid using an electric oven [17]. Energy transition is traditionally regarded as an energy-centered transition [18, 19]. The energy system being multi-scalar, it is possible to make energy supply more sustainable according to different scales [4]. As a result, the current approach consists in replacing utility-scale power plants based on finite resources by renewable energy (RE) systems. Another way is to substitute the electricity supply locally, using a stand-alone RE system such as solar PV panels coupled with storage [20]. In both cases, the energy transformation chain is based on two conversions, from primary renewable energy (light, motion, etc.) to electricity and then from electricity to heat. Meanwhile, the related energy technology consumes limited materials, such as REE [6], subject to electronic failures, and complex to the extent that most of the technical maintenance cannot be performed by end users [5]. One can immediately see the limits of such an energy-centered view of the energy transition where the baking technology (the oven) is left aside (this is still an electric oven). However, bread is eventually baked in the oven, not in the power plant. A sustainable baking tech should therefore 1) be based on a one-conversion chain, i.e. from primary to heat energy, 2) use the least possible material and REE, 3) be very reliable in the long-term, and 4) be easily usable and maintainable by the bakers. The direct solar-thermal oven does fit this definition: even with the lack of a complete life cycle analysis, with no electrical part, no emissions of CO₂, GHG or small particles during operation, one can legitimately expect a high degree of sustainability for this kind of technology.

Several solar baking ovens have already been set up throughout the world [21, 22, 23, 24, 25]; in Normandie (France), a artisan bakery has been using a solar oven for commercial purposes for the past few years [26]. Solar cooking technology has been known for a very long time [27]. However, in spite of its multiple benefits, its use is not widespread among household users in developing countries due to various reasons identified by P.P. Otte [28]. Typically, criteria that influence the adoption of solar cooking are *economic, social, cultural, environmental, political* and *technical*. Unfortunately, in the design of cookstoves, engineers mostly tend to pass over usability and the needs of the targeted users in their context of use, while focusing on technical attributes only [29]. Those constraints will probably be quite different for craftsmen against household users. Since they are professionals, their motives will differ: promoters of the direct solar ovens may be more concerned by global warming while bakers may be more concerned by economic viability of the solar technology (even if they are heavily concerned by environmental impact of the baker activity). Besides, as professionals, if the business activity is viable they should also be able to better adapt their practices and time management than household users. In the case of Neoloco [26], the bakery's products and the organization of its activity have been adapted to the use of the direct solar-thermal oven.

With the sustainable transition of part of the bakery sector in mind, the direct solar baking practice needs to be upscaled to the regional scale. To do so, various obstacles have to be overcome. First, only few studies concern collective solar ovens instead of household's ones. Second, a craftsman needs to plan his activity in advance. For this, because of the variability of the solar resource, it is essential to anticipate the potential of solar bread production in the context of the bakery's location site. This solar production depends on the type of solar oven and the solar irradiation level of the site, but also on the organization of the baker's work. In this article, in order to provide some answers to the planning issues of the baker, we propose a socio-technical model for assessing the production potential of a solar baker. Then, at the territorial scale of the bakery sector, we discuss two socio-economic indicators giving information on the overlap between the consumer market and the solar producers' sector. The insights gained from the socio-technical model and the socio-economic indicators are discussed in the context of Réunion, a French department located in the south-west of the Indian Ocean, where solar energy is abundant and, according to the 2015 *Energy Transition Act*, France's energy policy is to reach full energy self-sufficiency by 2030 [30].

2. Material and methods

2.1. Réunion island

The Réunion is an island located in the Indian Ocean, about 800 km east of Madagascar (Fig. 1). With an area of 2,512 km², this territory has an ovoid shape with a diameter between 50 and 70 km. It culminates at 3 069 m on the Piton des Neiges. The terrain of Réunion is characteristic of volcanic islands with steep slopes and alluvial plains of limited size [31].

With nearly 900,000 inhabitants, the island has a population density close to 350 inhabitants/km². The majority of these inhabitants are located along the coast (Fig. 1) [32]. The climate is tropical, with a hot and humid season from December to March, and a cooler and drier season from June to September. In addition, the insularity, the circulation of trade winds and the high relief of Reunion Island generate significant climatic contrasts: The windward coast (east and north) can be distinguished from the leeward coast (west and south). The windward coast receives the trade winds from the front, bringing masses of humid air which are blocked on the relief of the center of the island by pouring a great part of their rains there. In fact, the leeward coast has a much drier climate. This geographical contrast also affects the sunshine rate, the coasts and the west of the island being sunnier than the east and the center. It is therefore relevant to study in more detail the spatial distribution of solar radiation over this small area.

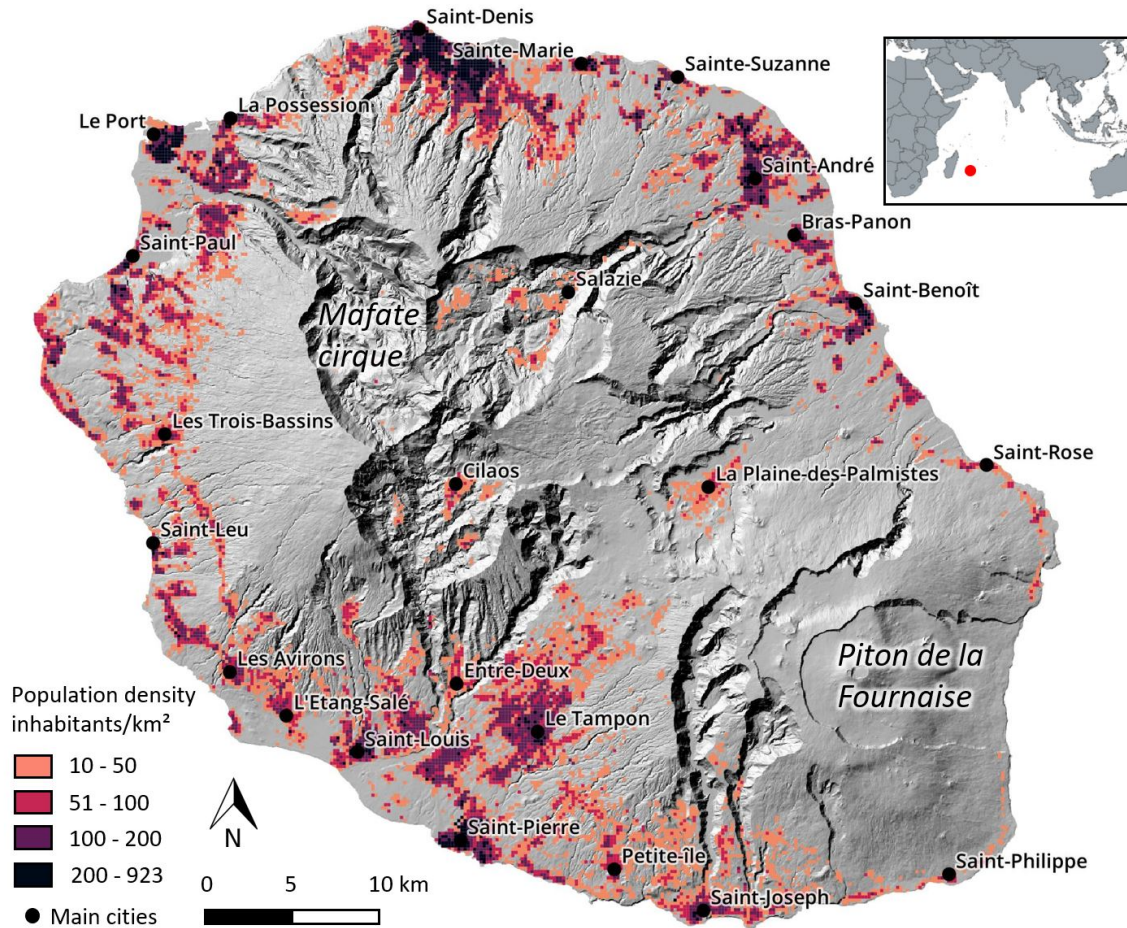


Figure 1: Population density of the Réunion Island

2.2. The solar resource

2.2.1. Direct normal solar radiation

Solar thermal bakery is mainly fueled by direct solar radiation, which is concentrated through parabolic or flat mirrors into the solar cooker's focus [22, 33]. In first instance, knowledge of both 1) spatial and 2) temporal distribution of the solar direct irradiance is essential to assess how solar baking may match the current and future behavior of potential bread consumers. Satellite-based models stand for a good trade-off between accuracy and the need for apprehending the geographical distribution of solar radiation [34]. However, all models are not equal in terms of temporal and spatial resolution as well as final precision or data access [34, 35]. The satellite-based physical model (PSM-3) developed for more than 20 years by the NREL to produce the National Solar Radiation Database (NSRDB) provides good balance between all these requirements for Réunion. Data

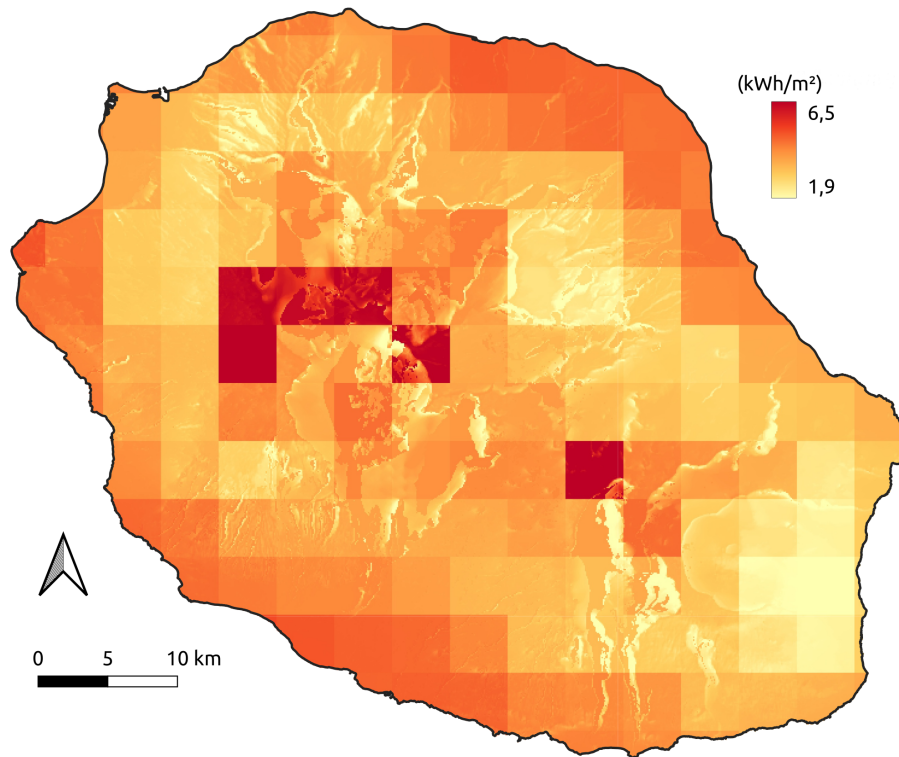


Figure 2: Daily mean shaded direct normal irradiation (in kWh/m²) for the 2017-2019 period in Réunion

access is also kept as straightforward as possible in order to get a full dataset of hourly Direct Normal Irradiance (DNI) maps in W/m², and accuracy is close to the one from other satellite-based products such as CAMS and SARA2 [34, 36], but with a better spatial resolution than those two over Réunion because of the satellite's location : NSRDB is based on the Meteosat IODC geostationary satellite against Meteosat 11 for CAMS and SARA2 over Réunion [37, 38, 39].

2.2.2. Topography shadow correction of the DNI

Another significant information for solar thermal bakery is the topography of the territory, that directly influences available direct solar radiation through terrain shadowing. In order to integrate the shading effect into the DNI maps, one can use the SRTM data released by the CGIAR-CSI, the horizon model instantiated in [40] and the solar position algorithm developed at NREL [41]. Accordingly, original NSRDB-based hourly DNI maps have been downsampled to the resolution of the 90m Digital Elevation Model (DEM) of Réunion. Finally, the result is a set of hourly shaded DNI maps over a 3 years range from 2017 to 2019; to give an idea to the reader, the daily mean direct normal irradiation (in kWh/m²) for the 2017-2019 period is depicted in Fig. 2.

2.3. A socio-technical solar bakery workflow model

The main objective of our study was to find out how a network of artisan bakers equipped with concentrating solar ovens could fulfill population needs for baked bread using the solar resource. Hence a socio-technical workflow model was built. It is depicted in Fig. 3 with bottom-up flow. On the left of the workflow is a downward arrow representing the evolution of need from the original need for baked bread as food: the need for baking bread leads to a need for energy which must be mobilized by a cooking technology.

The bakery's process workflow model is composed of a series of numeric filters and functions pictured in full red or green rectangles on the Fig. 3. The output data of each step is the input data of the next step and are pictured in rounded rectangles, lightly shaded red, green or blue. For instance, starting at the model's beginning: The first input in the numeric model is the solar energy time series data (yellow rounded rectangle at the bottom). After numeric filtering by the *DNI threshold* filter, only time steps with DNI value above the DNI threshold (> 700 W/m² in the present case study) are kept in the *Output Rated*

Energy time series data. This later data set is next numerically filtered through the *Number of continuous hours* filter, etc ... Now, regarding the meaning of the model in details : For solar concentration, aggregated and averaged DNI gives spatial information about what we might call the gross solar income of a given territory. But, for activities such as bread baking, the core of a successful implementation is also linked to heat supply stability. For this to happen, DNI must remain above a given threshold for a time period corresponding to the duration required for preheating the oven plus baking one batch of bread. This threshold will differ from oven to oven, depending on their specific energy focus capacity (based on mirror reflection rate and total surface, oven insulation, etc.). Therefore, the DNI is two times filtered because of the response of the solar oven to solar radiation: a first high-pass power numeric filter removes values of solar power that are under a critical threshold for heating the solar oven (the *DNI threshold* filter). A second numeric filter is related to the minimum continuous time period above the threshold of the first numeric filter so that the oven maintains the necessary temperature to bake a full batch of bread (the *number of continuous hours* numeric filter). At the output of these two filters, one obtains the number of periods in the year during which the solar oven can, if one needs it, bake a batch of bread: the *number of working periods*. Then, depending on the *baker's time management*, a *number of periods used for baking* can be set. The oven allows for a specific *quantity of bread to be baked per batch* (in kg) and from it, one can estimate the daily *productivity* (in kg/day). *Productivity* is mainly based on the daily craftsman's time management and from it, a *production* (in kg/year) can be calculated, depending on the mid (weekly) to long (yearly) time organization of the baker. This organization results from the integration of social constraints like rate consumption, food practices and the environmental constraint of solar energy availability. Different types of solar ovens can be analyzed based on this process workflow model, through parameterization of the filters: *DNI threshold*, *number of continuous hours* and *quantity of bread to be baked per batch*. Also, the model can be applied to other territories (real or model) by changing the DNI data input. In fact, the DNI and the type of solar oven define what can be called the solar baking *physical potential* of the bakery's site. Effectively, the available baking time consists of time when the baking chamber remains in a given operating temperature range. The targeted temperature range is fixed by physicochemical processes of bread baking [17, 42], and the heat comes from a physical process of solar flux conversion in the oven. In the model, the physical potential of solar baking is expressed in number of available working periods. In the following, a day is called *bakeable* when multiple continuous hours of high DNI allow for baking *at least* one batch of bread. Next, in order to analyse the physical potential of a Lytefire 11 oven (see subsec. 2.4) in Réunion, two new parameters were built from the *number of working periods* output: the *Maximum number of bakeable days per year* and the *Average production shortage per year* (see Fig. 3, at the right). These parameters are thresholds that correspond to the baker's time periods for baking bread throughout the year, and emphasize both the *frequency* and *intensity* issues of the activity. In other words, frequency is given by the number of effective bakeable days as well as the amount of time corresponding to bread shortage (*unbakeable* days). Intensity corresponds to the number of bread batches that can be baked on a given bakeable day. Shortage period is retrieved by collecting the different spans of consecutive *unbakeable days* along the year. Finally, the solar baking physical potential managed by the baker through a work strategy results in a bread daily productivity and yearly production.

2.4. The craftsman's solar bakery oven

For the present work, the Neoloco [26] solar baking setup is considered: it uses a Lytefire 11 [43], a solar oven model allowing up to 38 kg of bread to be baked per batch. The Lytefire 11 has a 11 m² surface of solar energy collection made up of 23 mirrors. Collected light is then concentrated in the oven consisting of two floors: a lower floor into which the light enters through a window, and which contains absorbent elements performing the conversion of light into heat and limiting losses by outgoing reflections. The second floor is the baking chamber to which the craftsman accesses through a door. The two floors are open to each other and the heat circulation is done by natural convection. The solar collector/concentrator and oven assembly form an integral system mounted on wheels to follow the course of the sun. All operations are carried out manually and no electricity is required to operate the oven. Following Neoloco's practice feedback, the *DNI threshold* high-pass numeric filter is set to $\text{DNI} > 700 \text{ W/m}^2$, and the *number of continuous hours* numeric filter to 3 hours: 2 hours of preheating and 1 hour of baking. The maximum load of the Lytefire 11 is 38kg of bread per batch (the *quantity/batch* filter).

2.5. The baker's work strategy

Once the solar baking physical potential is estimated through the identification of the periods allowing bread baking (the "working periods"), the baker must organize all the stages of his production so that the time of baking matches the solar oven "working period". Thus, the baker has to develop a work strategy for the short (daily) and long (yearly) term. For the daily time management, regarding our hypotheses, it is assumed that the maximum number of batches over the year is estimated by maximizing the daily number of batches up to 3 for every bakeable day. For the yearly strategy, two strategies are considered:

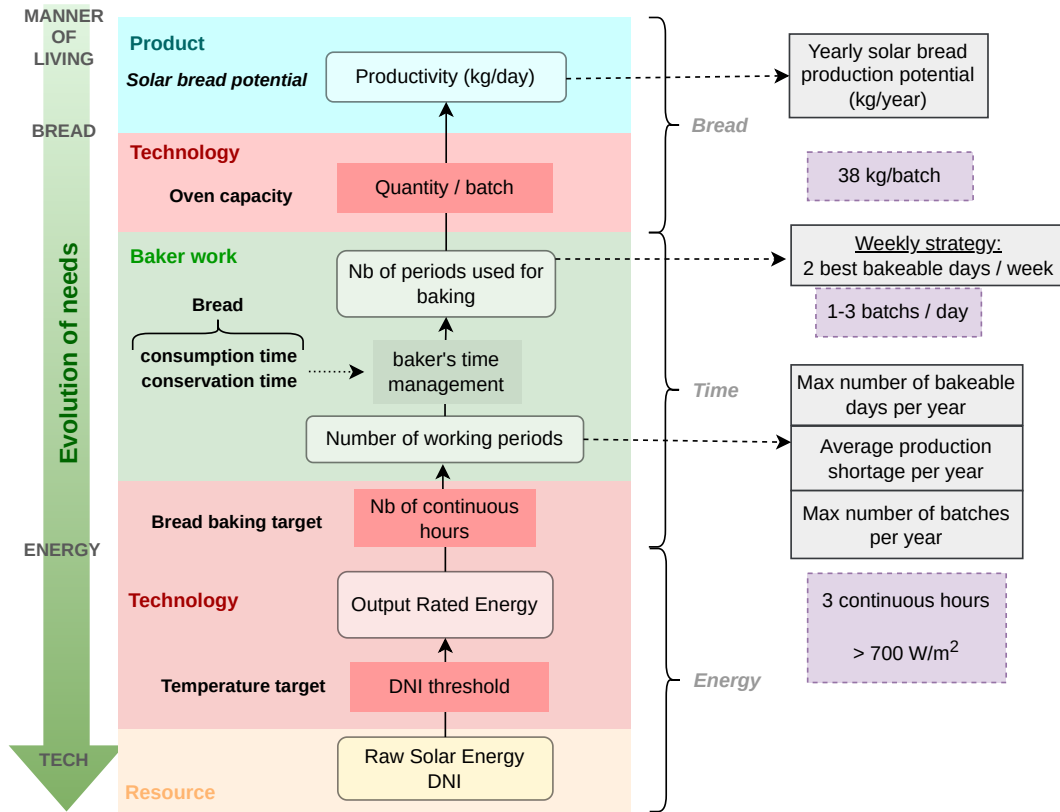


Figure 3: Direct solar bakery's process workflow. Numeric filters' values in the purple boxes are given based on the Lytefire 11 solar oven model.

the “max production strategy” and the “weekly operating strategy”. In the “max production strategy” we consider that the baker produces the maximum bread quantity allowed by the solar baking physical potential and within the limit of the adopted daily time management (max of 3 batches per day). In the “weekly operating strategy”, the baker bakes only from one to two days a week. The chosen bakeable days are days where the maximum number of batches is in the 1 to 3 range.

2.6. From an artisan bakery to the Réunion's bakery sector

The bakery's process workflow in Fig. 3 allows for the estimation of a baker's production according to the solar oven model, the management of his working time and the solar resource of his baking site. Because of the long term work objective of gaining new insight into the sustainable development transition of the territory, one wants to have an island-wide vision of the potential of a solar-powered bakery sector. Classically, the matching between production and consumption is one of the key-points for the viability of an economic activity. Regarding consumption, in Réunion, the population is heterogeneously distributed (Fig. 1). Concerning the production, one main difference between the solar bakery compared to the classical electrified one is that the energy source is the solar radiation that is also heterogeneously distributed across the island (Fig. 2). For these reasons, two indicators were built in order to analyze the solar baking production/consumption potential match. First, following a systemic view of the territory sustainability, we argue that sole identification of the most efficient areas for solar bread production is not enough: energy and CO₂ emissions savings that may result from the solar oven utilization cannot be transferred to transporting solar bread to the consumers or the consumers to the bakery. That is why a built indicator called *Eaten Where Solar Baked* gives insight into whether bread consumption matches solar bread production in the immediate vicinity. This indicator is useful for identifying the region where even if the solar bread potential is high, the population of bread consumers is too low and the solar bread production from these regions requires transport to other areas. Based on this indicator, locations that are unsuitable for installing bakeries can be excluded. In order to assess where bakeries should

be established, a second indicator called *Solar Bread Economic Intensity* was built. This later indicator estimates whether production matches consumption and assesses the most relevant regions for a potential solar bakery economy.

2.6.1. Solar bakery sector's indicators

Here, dealing with the proximity between bakery sites for solar bread production and the consumers, a honeycomb mesh of the territory is defined and then, both indicators in every hexagonal cell are computed. The mesh resolution is based on a specific distance threshold from bakery to bread consumer. This threshold may depend on the *mobility* scenarios to be implemented, including sustainable ones where mobility-based CO₂ emissions would not balance CO₂ emissions spared through the use of a solar bakery. Small enough cells might for instance ensure *soft mobility* scenarios, where customer travels are realized on foot or by bike.

Overall, bread consumption in cell i is defined by both *frequency* and *intensity*: does an individual consume bread and how much quantity if he does? Probability p_c that consumed bread quantity will be higher than the bread produced by the solar bakery is given by:

$$p_c = P\left(q_c \geq \frac{X_p}{\eta_c}\right) \quad (1)$$

where q_c is the final quantity consumed, η_c is the number of bread consumers and X_p is the supplied bread quantity. The number of bread consumers in cell i is given by the number of inhabitants η_h in that cell and the probability that they actually consume bread. One may retrieve the probability $P_{h,c}$ of a human h to be a bread consumer c in cell i from the distribution of the ratio between the number of bread consumers and the number of inhabitants among all cells. Using the expectation of that ratio $\mathbb{E}(\eta_c/\eta_h)$, the number of bread consumers η_c^i in cell i is therefore given by:

$$\eta_c^i = \eta_h^i \cdot P_{h,c} = \eta_h^i \cdot \mathbb{E}(\eta_c/\eta_h) \quad (2)$$

where η_h^i is the number of individuals in cell i . Expectation of the ratio between number of consumers and number of inhabitants among geographic cells is given by:

$$\mathbb{E}(\eta_c/\eta_h) = \sum_i^N p_i \frac{\eta_c^i}{\eta_h^i} \quad (3)$$

where p_i is the probability of the outcome η_c^i/η_h^i and $\sum_i^N p_i = 1$. By definition, considering the expected value as the weighted average of all cell ratios, p_i can be expressed as the population weight of cell i , such as :

$$p_i = \frac{\eta_h^i}{N_h} \quad (4)$$

with N_h the total number of inhabitants. One therefore gets:

$$\mathbb{E}(\eta_c/\eta_h) = \frac{1}{N_h} \sum_i^N \eta_c^i = \frac{N_c}{N_h} \quad (5)$$

with N_c the density of bread consumers and N_h the population density in the island. Therefore, from the probability defined in Eq. (1), we can define the ‘‘Eaten Where Solar Baked’’ index $EWSB^i$ in cell i :

$$EWSB^i = P\left(q_c^i \geq \frac{X_p^i N_h}{\eta_h^i N_c}\right) \quad (6)$$

where X_p^i is the produced bread quantity in cell i , and q_c^i the final quantity consumed in cell i . The *EWSB* index stands for the probability that the local production of solar bread in cell i is actually consumed in cell i . Accordingly, from a sustainability perspective, the bread is eventually baked and consumed in a sustainable manner, i.e. solar bread is supplied to the consumers through sustainable trips. Next, the ‘‘Solar Bread Economic Intensity’’ index $SBEI^i$ in cell i is defined as the product between the expected rate of return of the bread production and the *EWSB* index:

$$SBEI^i = X_p^i \cdot \alpha \cdot EWSB^i \quad (7)$$

where α is the rate of return (€) of 1 tonne of bread. The *SBEI* index expressed in € per cell underlines among the best *EWSB* sites which one are the best for a sustainable economic bakery’s activity; that is the sites where a significant solar bread production can actually be consumed in the surroundings.

2.6.2. Bread consumers in Reunion

To calculate both solar bread indicators described in the next section, a specific population location data is used. This set is calculated from population data on administrative entities, the population being distributed over all buildings of more than 20 m² located in these entities, proportionally to the size of the buildings [32]. Accurate information is retrieved from this data and allows for calculating the number of inhabitants η_h and number of bread consumers η_c among the cells in which a potential solar bakery could be implemented. Hypotheses about bread consumers profile have been simplified, with yearly individual consumption of bread taken as a normal distribution $N(\mu, \sigma)$ with $\mu = 50$ kg [44] and $\sigma = 20$ kg.

2.6.3. Reference bakeries

A survey to 63 french bakeries (2008-2010) [15] shows that on average, 53% of the energy consumed by the bakeries is for baking. The average energy consumption for baking depends of the fuel type of the oven : ≈ 26000 kWh/y for electric ovens, ≈ 63000 kWh/y for gas ovens, and ≈ 98000 kWh/y for fuel oil ovens. In 2022, we conducted a series of interviews with bakers. Elements are summarized in Table 1: *Neoloco* is a solar baker located in Europe (Normandie, France). *Le pain nourricier* (LPN), *Au coin du levain* (ACDL) and *Cassava* are bakeries located in Réunion. All of them bake sourdough breads.

Name	Location	Fuel	Sales model	Work strategy (baking days/week)	Yearly production ¹ (tons/year)	Price range (€/kg)
Neoloco	Normandie (France)	Sun or Wood	Pre-sale & bread deposit	1	7-8	6-10
Le pain nourricier	Entre-Deux	Wood	Market place	2	6	6-12
Au coin du levain	Sainte-Marie	Electricity	Shop	3	12-15	8-15
Cassava	Saint-Paul	Electricity	Shop	5	16-20	–

¹ Yearly production is calculated from daily or weekly with a year equal to 50 weeks

Table 1: Reference bakeries data

3. Results and discussion

This work targets an estimation of the solar baking potential of a territory depending on its solar energy and population context. Since solar baking is a solar technology, first a gross estimation can be made from the cumulative data of incoming solar energy (Fig. 2): in the first subsection, such gross estimation is discussed. To go further, in the second and third subsections, the results of the ‘‘maximum production strategy’’ and ‘‘weekly operating strategy’’ described in subsection 2.5, are respectively discussed. For both strategies, first the solar baking physical potential from a purely energy and technology point of view without taking into account the current population distribution, is discussed. Then, the solar baking socio-technical potential by mapping the *Eaten Where Solar Baked* and *Solar Bread Economic Intensity* indicators, that take population density into consideration, is discussed.

3.1. Solar baking potential from DNI data

Regarding solar variability, the “Daily mean shaded DNI map” (Fig. 2) shows an heterogeneous spatial distribution of the solar energy in the range 1.9 - 6.5 kWh/m². As a gross estimation of the solar bakery potential, the most irradiated areas are expected to have the highest potential: the highest DNI values are located in the northeast and west coasts, as well as in the southwest. The slopes of the summits receive little solar radiation due to shadowing effect, while the Piton de la Fournaise volcano in the south-east gets the lowest DNI potential because of micro climate effects. Ultimately, the high summits of the island and the cirque of Mafate are the regions with the highest solar potential. It is important to underline the large size of the satellite pixels projected on a territory with very sharp and rugged field. Future work will engage into enhancement of these satellite-based data, as well as comparison with data from ground stations.

3.2. The maximum production strategy

Remember that in the “maximum production strategy”, the baker produces the maximum bread quantity allowed by the solar baking physical potential and in the limit of the adopted daily time management : 3 batches per day maximum.

3.2.1. Solar baking physical potential

Once DNI was identified for the period, the related thresholds (subsection 2.3) for solar bread production were derived. “Max number of bakeable days”, “production shortage” and “Max number of batches” are respectively depicted in Fig. 4a, Fig. 4b and Fig. 4c. “Maximum solar bread production” is then derived from the range of batches (1-3) per bakeable day combined with the maximum quantity baked per batch. In Lytefire 11 user guide, the batch quantity range is given between 30 and 38 kg, and the result when the batch is set to 38 kg is described in Fig. 4d. It is interesting to note that while the DNI map of Fig. 2 gives information about spatial distribution of the solar resource, the set of figures in Fig. 4 actually gives more insight into the temporal variability of the solar radiation, and thus into the bread production we may derive from it. Color scales are bicolor gradients with tipping values chosen at significant thresholds: for the “max number of bakeable days” map, the tipping value is 175 days which is close to half a year. For the “average production shortage” map, the tipping value is 5 days which is the shelf life of a sourdough bread. For the “max number of batches” map, the tipping point is 280 batches which is close to half the maximum value on the island. 280 batches is also $\frac{1}{4}$ of the theoretical maximum number of batches (i.e. $1095 = 3 * 365$) and 75% of the theoretical maximum of bakeable days per year (i.e. 365).

As explained in the introduction, it is important to note that the need for energy is not a need per se but a need directly connected to a social service through a technological tool using energy. In the case of the solar bakery, the *bakery's process workflow* transforms energy and raw materials into baked bread using a direct concentration solar oven. Therefore, this process transfers the issue of solar variability to the issue of temporal and spatial variability of bread production. The maps in Fig. 4 represent several parameters that allows for the consequences of this variability on the production potential of solar bread and its regularity across Réunion to be taken into account. Regarding the various parameters of the solar bread production potential (Fig. 4): essentially, the thresholds maps rather fit the DNI maps (Fig. 2); the sunniest areas are those where there is the largest “max number of bakeable days per year”, the lower “average production shortage per year”, the “maximum number of batches per year” and therefore ultimately the greater “bread production potential”. However, the quantitative outcome is significantly different with a solar bread production range being two times the DNI range. In more details:

- The *max number of bakeable days per year* map (Fig. 4a) shows that in the areas exhibiting the highest number of bakeable days (in green), baking can be performed more than half of the days a year.
- The *average production shortage per year* map (Fig. 4b) shows that except in the Piton de la Fournaise volcano area at the south-east (in pink), in the rest of the island there is less than 5 consecutive unbakeable days in average. In a nutshell, it means that baking can be performed at least once a week. It is compatible with some sourdough bakery's business model like the Neoloco one [26].
- The *max number of batches per year* map (Fig. 4c) shows that in the area where the number of bakeable is greater than 175 (more than half of the days a year), the number of batches is well above 175: two or three batches per day should be a common situation.
- The *solar bread production potential* map (Fig. 4d) shows information close to the *max number of batches per year* map: in order to obtain the solar bread quantity, the number of batches are just multiplied by the oven capacity of : 38kg per batch. Nevertheless, on one hand this map gives the bread quantity in tons that can be directly compared to a typical

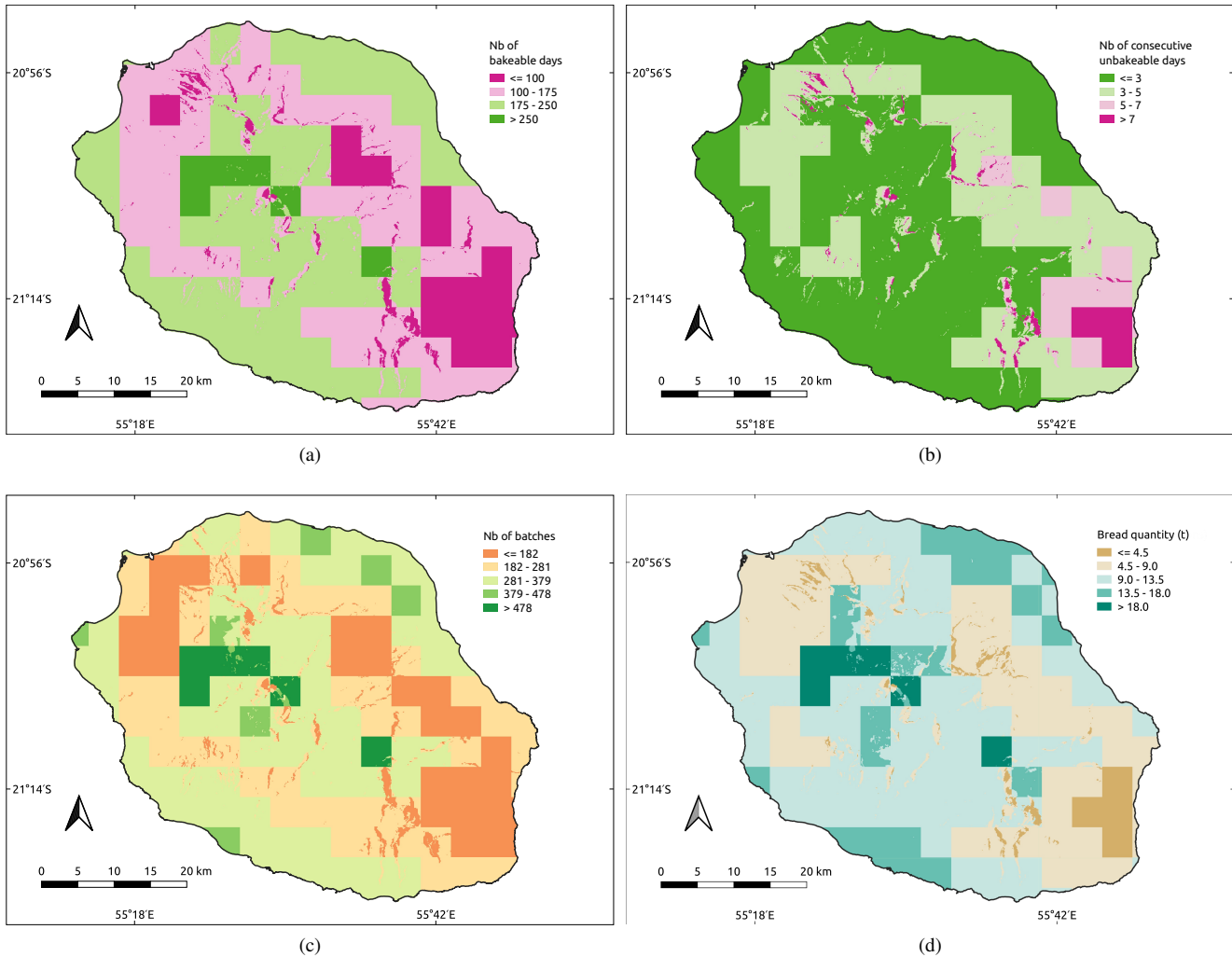


Figure 4: Solar bread production thresholds in Réunion following the maximum production strategy. (a) Max number of bakeable days per year, (b) Average production shortage per year, (c) Max number of batches per year, and (d) Max yearly solar bread production.

bread production or consumption. On the other hand, the bread quantity scale's levels are chosen in order to identify sites in the sunniest areas where the solar bread production potential is the best: the summits and the Mafate mountain cirque at the island's center are the most relevant areas. On the coast, Sainte-Marie, Sainte-Suzanne (north-east) and Saint-Pierre (south) are the best populated areas for solar baking.

3.2.2. Solar baking socio-technical potential

Here, the study is positioned in the context of the 2023 population density and soft mobility system (bicycles and pedestrians). Obviously, it is not the scenario of the whole mobility system shift to soft mobility because the current distribution of the population on the island is highly dependent on the dominant mode of transportation, which is the private car. It is likely that a whole transition to a soft mobility system would lead to a change in the distribution of the population on the island. Soft mobility is considered only for solar bread collection, because it would be counterproductive to reduce electrical energy consumption and polluting emissions with solar baking while transferring this energy consumption to polluting trips required for collecting the bread. Moreover, the soft mobility framework is deeply sustainable and robust, even when facing with a context of energy crises which affect not only energy required for baking bread, but also mobility.

The spatial distribution of both the *EWSB* and *SBEI* index over Réunion is depicted in Fig. 5, for hexagonal cells of 500 m

radius and a fixed rate of return $\alpha = 8 \text{ €/kg}$.

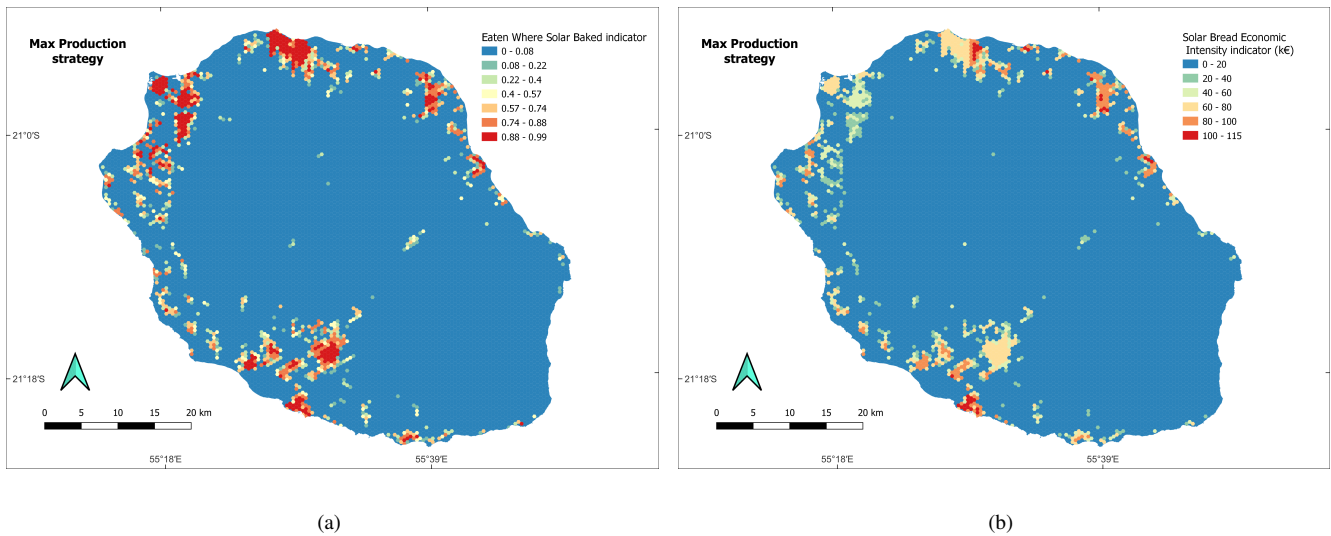


Figure 5: (a) *Eaten Where Solar Baked* and (b) *Solar Bread Economic Intensity* indicators in Réunion

The *EWSB* index (Eq. 6, Fig. 5a) gives information on the ability of the population to consume the entire solar bread production in an area very close to the solar bakery site. It is an accessibility index showing how accessible a batch of bread would be to the surrounding consumers when it is actually produced. The index range is from 0 (the bread is not consumed) to 1 (all bread is consumed). High accessibility does not mean that the solar bakery would eventually be viable, but only that the bread which is effectively produced is highly accessible to the local consumers. Globally, without surprise, the *EWSB* indicator map shows high index values in the area where the population density is the highest: in the cities of the north (Saint-Denis), the north-west (Le Port), the east (Saint-Andre and Saint-Benoit), and the south (Saint-Louis, Saint-Pierre and Le Tampon). The high potential solar bread production areas of the center of the island (see Fig. 4d) where population density is very low exhibit very low *EWSB* values.

The *SBEI* index (Eq. 7, Fig. 5b) shows the areas where the solar bread production is the highest AND can be consumed in the immediate vicinity of the solar bakery site. It gives combined information about solar bread production and accessibility, and hence shows how viable a solar bakery might be. Viability is defined locally, that is the density of potential consumers is computed from the number of inhabitants and surface area of each pre-defined cells. Finally, it is important to note that obviously the resulting map does not give a full realistic view of *how much* a solar bakery might be viable locally, because of the simplified hypotheses about individual consumption, the rate of return, etc. However, it gives a very interesting relative information about the most suitable locations for developing solar baking in the island. These most suitable locations are especially in cities of Saint-Pierre, Saint-Andre, Saint-Benoît and the eastern part of Saint-Denis. Finally, Le Tampon, Le Port and the western part of Saint-Denis where the *EWSB* index is high are not suitable places for solar baking because of the too low solar bread production potential.

A detailed discussion of the map is beyond the scope of this paper, but one can note here the sharp split-up between west Saint-Denis and east Saint-Denis. This pattern is probably due to the large size of the DNI pixels (see Fig. 2). No higher resolution DNI map is currently available, but as said previously (see section 3.1), we will study the pixel size effect in future works.

3.3. The weekly operating strategy

Remember that the “weekly operating strategy” consists in baking at most two days a week. The chosen bakeable days are days with the maximum number of batches in the range 1-3 (see Fig. 3 at right). This solar baker organization comes from the consideration of breads’ types that the artisan can bake: for instance, Neoloco bakes sourdough breads one day a week. The sourdough breads are long shelf life breads (3 to 5 days) compare to only yeast breads (1 to 2 days), and they suit the solar baking variability.

3.3.1. Solar baking physical potential

Fig. 6 shows the maps of the *solar bread production potential* for the weekly strategy. According to this strategy, the baker manages his time with at least 5 days a week dedicated to activities besides baking. Following the solar energy availability, the baker could possibly bake only one day a week or consider some weeks with no production. One can compare this map with the map corresponding to the maximum production strategy (Fig. 4d). The color scales are the same. The map of Fig. 6 shows that globally, the best area for solar baking remains the same with the weekly strategy as for max production strategy: the coast, especially the north-east, and in a lesser extent the south.

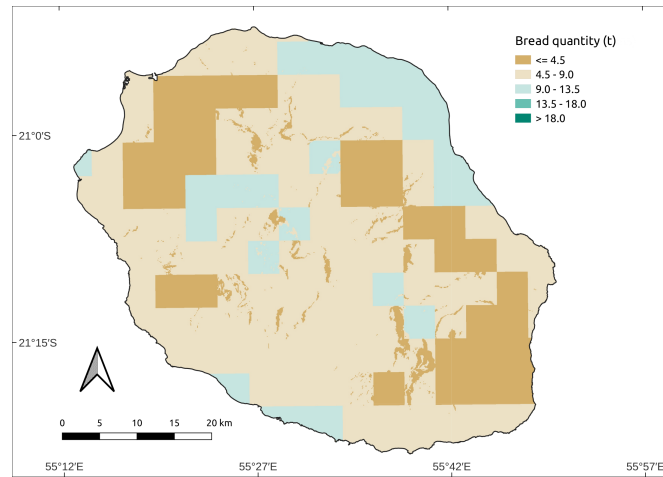


Figure 6: Yearly solar bread production for a weekly operating strategy in Réunion

Fig. 7 plots the yearly solar bread production of the weekly strategy versus the production of the max production strategy (black dots). Lines are empirical references that correspond to a percentage of the max production strategy minus one ton: the blue, yellow, red and green lines respectively correspond to a percentage of 100, 70, 60 and 50%. The trend of the production switch between the maximum and the weekly strategies is linear with a 1 tonne systematic decrease (about 26 batches). First, one can see that all the locations are between the 100% (blue dashed) and the 50% (green dashed) lines. Next, one immediately distinguishes a first group of locations where the production is very high according to the max production strategy (between 16 and 23 t/y), and falls down between 8 and 11 t/y based on the weekly strategy. The production of these locations is very impacted by the implementation of the weekly strategy: points are close to the 60% line (dotted red), while the scatter plot of all other locations is centered on the 70% line (dotted yellow). However, the production of the locations following the weekly strategy are close to the maximum theoretical production of 11,856 kg ($38 * 3 * 2 * 52$). The maximum theoretical production with the maximum production strategy is 41,610 kg ($38 * 3 * 365$) and almost every site under study is below half this value. Finally, for a weekly strategy where more than 70% of the time (5 days out of 7) is dedicated to other activity than baking, in the majority of places considered for solar baking, the average decline of the maximum production is only of 30% minus 1 t.

In order to compare the calculated solar productions to those of existing bakeries, the yearly productions of reference bakeries (subsection 2.6.3) are reported on the plot by mean of bakeries' names located on the axis at their respective range production. The solar production matches well the bakeries' production : Neoloco and LPN level of production (their work strategy is based on one baking day per week) can be reached with the weekly strategy. The level of production of ACDL (3 baking days per week) and Cassava (5 baking days per week) can be reached with the maximum production strategy.

3.3.2. Solar baking socio-technical potential

The soft mobility context is the same as for the "max production strategy" and the spatial distribution of both the *EWSB* and *SBEI* indexes over Réunion is depicted in Fig. 8. Fig. 8a shows the mapping of the *EWSB* index for the weekly strategy. With the weekly strategy, a lower amount of bread is produced (see the the *solar bread production potential*, Fig. 6) and an increase of the *EWSB* is mechanically expected. This is the case: areas where the *EWSB* index was the highest for the *max production strategy* still stand for higher values according to the weekly strategy, and the low value areas of the coast in the

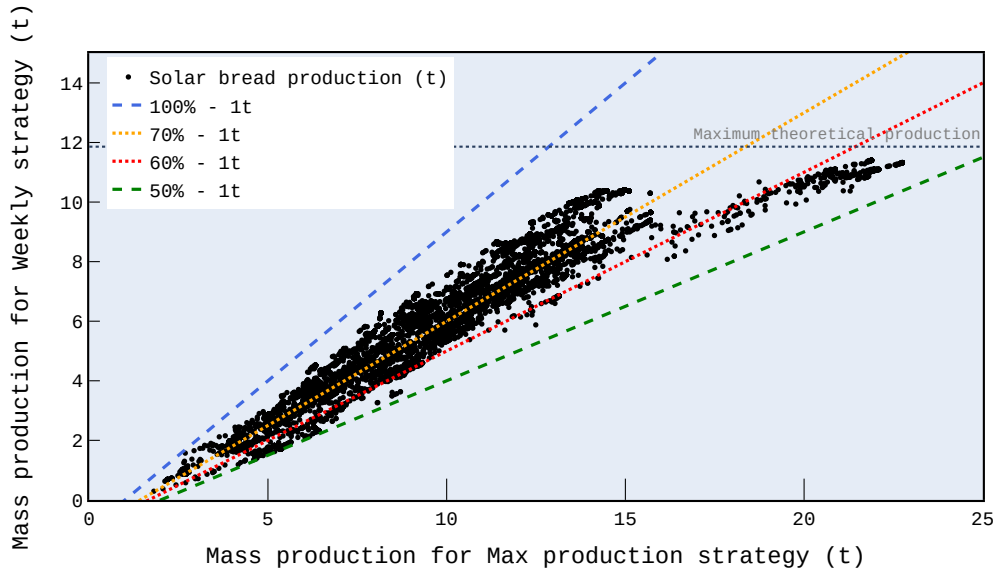


Figure 7: Mass production for the weekly strategy vs mass production for the max production strategy (black dots). Colored dotted lines are empirical references (see text) and the grey dotted line shows the maximum theoretical production level with the weekly strategy.

“max production strategy” show higher values in the “weekly operating strategy”. Globally, with the “weekly strategy”, all solar bread baked along the inhabited coast of Réunion should eventually be consumed.

Fig. 8b shows the *SBEI* index’s map for the weekly strategy. Compared to the maximum production strategy map (Fig. 5b), the decline of the *SBEI* index between both strategies in areas where it was formerly the most significant is only 30 % in average (from 100-115 k€ in Fig. 5b, to 64-81 k€ in Fig. 8b). Globally, the most suitable areas lie in the same color level and are the same as for the “max production strategy”: the eastern part of Saint-Denis, cities of Saint-Pierre, Saint-Andre and Saint-Benoit. But even more interesting, north-east areas that had intermediate suitability in the “maximum production strategy” (in orange in Fig. 5b) are now the best areas (in red) in the weekly strategy, following a decline of only 20 % in average (80-100 k€ range to 64-81 k€ range) or less on some points.

Fig. 9 plots the *EWSB* index versus the solar bread production for all the hexagonal cells and for both the max and weekly production strategies (respectively blue and red dots). For the max production strategy, the sites that produce more than 15 t or less than 5 t exhibit *EWSB* index values close to zero: they are irrelevant for solar baking. For the weekly strategy, irrelevant sites for solar baking are those corresponding to a production higher than 10 t or lower than 2 t. Hence we assume that the most robust organization for the bakery sector should consider a work strategy with site production between 5 and 10 t per year (with the Lytefire 11 oven). This range of production includes the production of Neoloco and LPN. The production level of ACDL can be reached with the max production strategy in some areas showing a high *EWSB* index. The production level of Cassava cannot be reached in Réunion when produced bread is consumed in close vicinity (*EWSB* index close to zero), for the sustainable mobility scenario.

Based on the average energy consumption for baking introduced in subsection 2.6.3 (≈ 26000 kWh/year for electric ovens) and the average ratio of direct emissions per electrical kWh consumed in 2019 in Réunion (719 gCO₂/kWh) [45], a rough estimation of the saved gCO₂ emissions with a solar weekly strategy can be performed: considering that 26000 kWh/year corresponds to 6 electrical baking days per week, the emission of a classical “electrical” french bakery in Réunion with a 2 days weekly strategy is $719 \times 26000/3 \approx 6.2$ tCO₂.

In conclusion, the results of a simple weekly strategy show that both local optimization of the solar baker’s time management and global optimization of the solar bakery sector can be performed in order to exploit the maximum of the solar bakery potential. For this, technology and workflow have to adapt to the solar resource variability in time and space, instead of adapting the energy production system to the technology and workflow already in place. In the weekly strategy, 5 days a week are released for other activities and the whole coastal area of the island (except the south-east volcano) becomes suitable

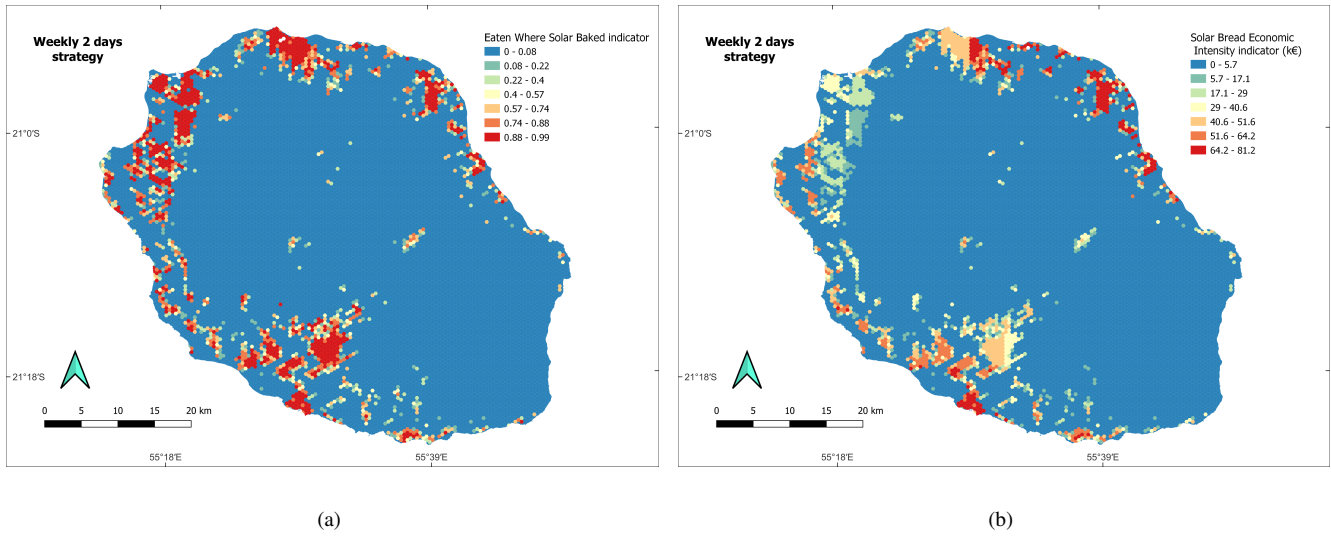


Figure 8: (a) *Eaten Where Solar Baked* and (b) *Solar Bread Economic Intensity* index for a weekly operating strategy in Réunion

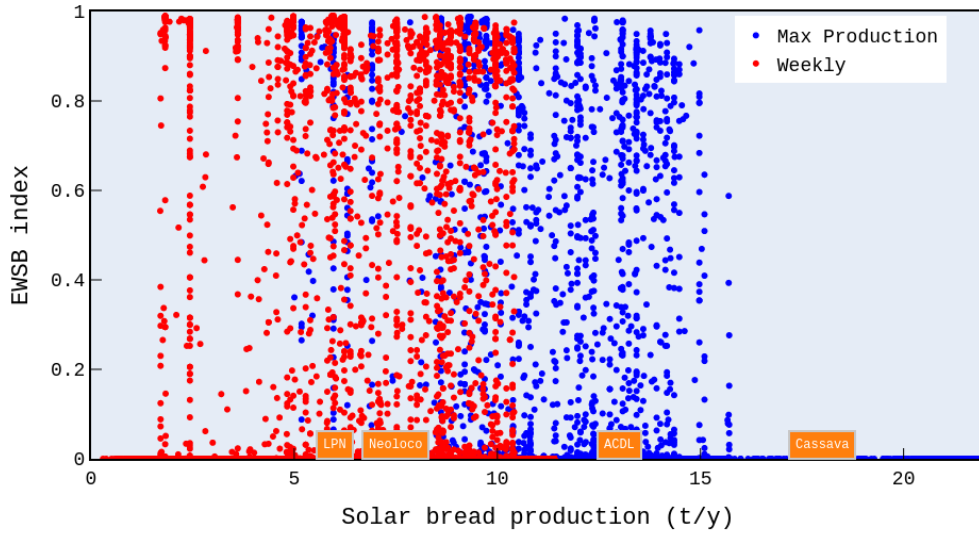


Figure 9: EWSB index vs production for both strategies

for solar baking.

4. Conclusion

This article reports a methodology based on a socio-technical approach to a direct solar economy. First, a solar bakery workflow model was developed for assessing solar bread production based on 1) the solar energy resource, 2) the solar oven technology and 3) the baker's time management. This model allows the solar bread production potential of a territory to be estimated, and was applied to Réunion island. Second, we defined two socio-economical indexes that identify the best

locations for solar bakeries based on the radical sustainability perspective of slow mobility. This approach is based on a shift from the traditional view of energy transition as an energy-centered concept, to a focus on the *energy - technology - society* system. Based on this socio-technical view of the energy transition, the corresponding solar bakery workflow model shows how it is not energy which is eventually produced, but *baking time* for bread production. In this way, even if the direct solar baking is a very sustainable option for baking and energy consumption management, it can hardly be taken into account in the energy mix calculation. Similarly, it is not rigorously possible to calculate energy savings as it was shown how an appropriate implementation of the direct solar bakery technology would impact both the baker's time management and the organization of the whole bakery sector: the shift from a part of the electrical bakery sector to direct solar baking cannot be reduced to the sole replacement of the electrical oven by direct solar ovens.

That is why the *EWSB* and *SBEI* indexes were calculated for a slow mobility scenario. However, even in this case, one is still looking at energy transition as a substitution of *fuel tap*, while the results strongly suggest that consuming *solar bread* would necessarily be different from the current consumption of *electrical bread*. If the heat energy fuel tap is only substituted, one implicitly considers that a solar bakery can deliver the exact same service as a current classical bakery. This is very unlikely, precisely because of the inherent volatile nature of direct solar radiation against the dispatchable nature of electrical supply. In order to look beyond sole substitution, one must understand how changes in bread consumer's behavior could meet the new paradigm of the solar baker's activity.

As an example, in Réunion, by considering one or two full bakeable days a week, i.e. with at least 6 continuous hours for bread production, a solar bakery could significantly enhance its viability. But it would require to bake a different type of bread on those specific days, a bread that could be stored and consumed during a greater period of time. In some way, this solar bread would serve as a bio-chemical storage of the solar radiation. It could address a current need for long-term bread storage, as well as a new manner of living that would have been co-constructed between the baker and its community of consumers. Different groups of consumers may be considered even within the same community, whose behavior would match the different bakery's ways and days of operating. Short-term or long-term bread consumption, and conservation, emphasize how solar radiation variability might be handled by the solar baker, without even considering another dispatchable backup resource. Apprehending this *social time* (see Fig. 3) is fundamental for ensuring a win-win between both production time and consumption time, and eventually promoting solar bakeries over electrical ones. This aspect sheds light on the *social-cultural dimension* of energy transition and on how it ultimately affects energy service sustainability.

In conclusion, the direct solar economy is radically sustainable compared to any other energy systems, and even if it cannot be implemented for all crafts or industries, it is a very interesting socio-technical alternative for the bakery sector's transition towards sustainability. Geographical aggregation is common strategy to mitigate variability from VRE power systems across territories [46]. One may apply the same idea regarding the bakery sector when solar energy is considered the main supply. It would ask for an economic reorganization where artisan bakeries are economically interconnected, e.g. belong to the same corporation. In Reunion, it makes sense as meteorological conditions are extremely variable over short distances. For small areas, and associated with soft mobility, it would then be theoretically possible for one solar bakery to run and compensate the lack of solar energy of the other ones. Another potential solution is to use mobile solar ovens pulled on trailers, so the production site can follow the sun. To keep the solutions sustainable, it must obviously be associated with short distances and soft mobility. Also, as with seasonal fruits, bread could be considered to be a product that is produced and consumed only at specific times during the year, though weekly or biweekly strategies ensure bread's availability almost over the entire year.

5. Acknowledgements

The authors would like to thank the CNRS and the IRD for their financial support through the MITI interdisciplinary programs.

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