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Anastasia Roth, Marianne Boix, Vincent Gerbaud, Ludovic Montastruc, Philippe Etur. Impact of taxes and investment incentive on the development of renewable energy self-consumption: French household's case study. *Journal of Cleaner Production*, 2020, 265, pp.121791. 10.1016/j.jclepro.2020.121791 . hal-02650430

**HAL Id: hal-02650430**

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Submitted on 29 May 2020

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**Official URL :** <https://doi.org/10.1016/j.jclepro.2020.121791>

**To cite this version:**

Roth, Anastasia<sup>ORCID</sup> and Boix, Marianne<sup>ORCID</sup> and Montastruc, Ludovic<sup>ORCID</sup> and Etur, Philippe and Gerbaud, Vincent<sup>ORCID</sup> *Impact of taxes and investment incentive on the development of renewable energy self-consumption: French household's case study*. (2020) *Journal of Cleaner Production*, 265. 121791. ISSN 0959-6526

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# Impact of taxes and investment incentive on the development of renewable energy self-consumption: French households' case study.

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## Abstract

Mutations in the energy sector are shifting the production and distribution systems from a centralized to a decentralized model. Within this context, we address the economics of grid-connected Hybrid Renewable Energy Systems (HRES) in relation with energy management strategies by considering taxes and economic regulation frameworks. Therefore, we propose a model to perform economic analysis of such HRES formulated as a MILP (Mixed Integer Linear Programming) model in the context of the French regulation. We test it on the case study of an integrated PV installation for French households' self-consumption, comparing two household sizes: a two persons household with a consumption of 4000kWh/year and a five persons household consuming 8500 kWh/year; and two solar exposures: one of 1400 h of equivalent maximum production and one of 1060 h. The main results is that the current regulation framework for incentive calculus does not encourage citizens to install a maximum of PV panels as well as it does not guarantee a uniform development of self-consumption infrastructure. Alternatively, we propose a new regulation framework in order to reverse those tendencies.

## Keywords

Hybrid Renewable Energy Systems, grid-connected, MILP, modelling, energy self-consumption.

Abbreviation	Explanation
CAPEX	Capital Expenditure
CC	Composante de Comptage = Yearly count component

CG	Composante de Gestion = Yearly administration component
CRE	Commission de Régulation de l'Énergie = Energy regulation commission
CS (fixed or variable)	Composante de soutirage = Yearly extraction component
CSPE	Contribution au Service Public d'Électricité = Contribution to electricity public service
CTA	Contribution Tarifaire d'Acheminement = Taxes for electricity delivery
HRES	Hybrid Renewable Energy System
IFER	Imposition Forfaitaire des Entreprises de Réseaux = Flat-rate taxation of Network company
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
MILP	Mixt-Integer Linear Programing
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure
PP	Payback Period
PV	Photovoltaïc panel
TURPE	Tarifs d'Utilisation des Réseaux Public de distribution d'Électricité = Rate for usage of public network of electricity distribution
TCFE	Taxes sur la Consommation Finale d'Électricité = Electricity final consumption taxes

## 1 Introduction

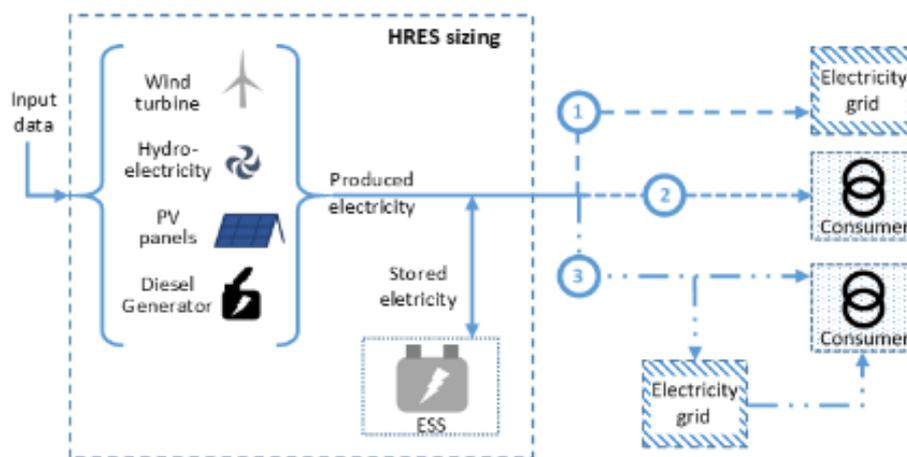
The current global warming due to anthropic activities is indisputable (Cook et al., 2013). Grubler and al. (2018) recommend to improve energy efficiency to reach the objective of 1.5°C increase of the planet, established by the COP21 (Paris). Therefore, transformations in the energy sector are mandatory, especially by increasing renewable energies' share in energy mix. This evolution fosters changes such as switching from a centralized to a decentralized model of the energy sector in developed countries. Indeed, the electricity network in most developed countries can be qualified as centralized, since a small number of big power plants produces electricity dispatched toward the final consumer through a large distribution grid. On the contrary, a decentralized model stands for multiple small power plants installed nearby consumption sites, which are most likely resilient especially when large failure occurs since the production facilities are multiple.

Therefore, developing techniques to design Hybrid Renewable Energy Systems (HRES) is an important task for facing future energy challenges. A HRES is a synergy system combining conventional and

renewable energy sources as well as storage systems if needed. A HRES can be used in different ways illustrated on Figure 1. HRES can be designed for:

1. Producing electricity entirely injected into the grid (case 1 Figure 1). This case is typically encountered from a centralized perspective.
2. Meeting the electricity demand of consumers isolated from the electricity grid (case 2 Figure 1). An undersized HRES or a curtailing electricity production are necessary, as energy surplus is not allowed (when more energy is produced than needed). Besides, one needs a backup systems, like diesel generator, in case of energy shortage (energy produced is less than energy needs)
3. Meeting the electricity demand of consumers connected to the electricity grid (case 3 Figure 1). In this case, the HRES supplies the consumer in priority. The grid connection is used as a backup in case of energy shortage as well as an evacuation in case of energy surplus.

(PLEASE INSERT FIGURE 1)



The three cases are different regarding the coupling of the supply side and the demand side. In case 1, the grid acts as an infinite reservoir of energy into which all the electricity supplied by the HRES is injected. On the contrary, for cases 2 and 3, demand side and supply side are coupled. Indeed, the supply must deliver exactly the demand, so that no blackout happens. While it has been observed that the electricity demand can be related to many determinants, either socio-economic such as

poverty, household income, age, etc. (Brounen et al. 2012; Besagni and Borgarello, 2018) or structural and geographical ones such as building size, climate, sunshine... (Filippini and Pachauri, 2004; Longhi, 2015), our contribution can only handle them through three input parameters, namely the electricity demand curve, the sunshine per year and the tariffs and taxes. These later are considered at their standard rate but they could be adapted to cases backed by some specific social policy, for instance subsidies for low-income families.

In case 2 of Figure 1 storage can be needed to balance renewables production. In Roth et al., (2019) we have proposed a flexible meta-model architecture of HRES has been proposed and it was further specified for the grass root design of a stand-alone HRES for a factory in tropical island. We have then shown that investment costs in electric storage jeopardized economic viability of HRES systems. Alternatively, thermal storage could be used instead (Lund et al., 2018). Indeed, the HRES model that we use is currently designed for electricity production but it could be expanded to include heating devices and then balance electricity and heating supply with relevant demands as coupling both is a major incentive for renewable energy development and system integration (Lund et al., 2018).

Another key aspect that challenges HRES implementation is the regulation framework. Tackling this issue is fundamental since designing HRES without taking into account local regulations might shatter the economic viability of the HRES in operation.

In this paper, we perform an economic analysis of HRES. Section 2 shows how literature has accounted for economic regulation framework in grid-connected HRES design. The heterogeneity of the proposed methods and their incompleteness under the light of the French complex regulations are discussed, with a particular emphasis on the inclusion or not of taxes. In section 3, a generic economic assessment model for a grid-connected HRES as in Figure 1 is developed. Building upon the literature proposals while taking into account taxes, it is deemed suitable for many countries. Section 4 describes how the model is specified as a Mixed-Integer Linear Programming (MILP) problem for the French tariffs and tax regulation on self-consumption. Finally, in section 5, the MILP optimization

model is solved for the case study of French households willing to implement energy production devices, such as photovoltaic panels for self-consumption. This approach consists in estimating how the actual regulation framework encourage people to install self-consumption facilities in their house, and to propose alternative if not. In this paper, a focus is done on the French context but the approach is generic and can be used in other context.

## 2 Literature overview

When designing HRES, two main questions have to be answered: how to produce electricity and how much does it cost?

Regarding the production issue, it comes to the design of HRES in general, including grid-connected ones; and many studies can be found in the literature. Most of the time, HRES design requires the use of optimization techniques. In the category of heuristic optimization techniques, one finds studies using Genetic Algorithm (GA) (Guinot et al., 2013), Particle Swarm Optimization (PSO) (Mohamed et al., 2017), Cuckoo Search (CS) (Nadjemi et al., 2017) or fuzzy logic (Giallanza et al., 2018). The strength of these techniques is the possibility to model accurately the non-linear behaviour of some physical elements of HRES such as batteries, converter, fuel cell, etc... However, they can be time consuming to implement and solve, they are often sensitive to penalty functions and they usually give under-optimal results compared to deterministic optimization. Hence, other faster optimization techniques have been investigated such as MILP like in Atia and Yamada, 2016a; Rigo-Mariani et al., 2017; Scheubel et al., 2017. To some extent, MILP models are inaccurate due to the linear modelling they involve, but it is acceptable in the case of grassroots design as we have shown in Roth et al. (2019). In both categories of optimization techniques that we cited, one can perform mono-objective or multi-objective studies (Eriksson and Gray, 2019). We notice that some studies take into account the environmental impact of the designed solutions (Saedpanah et al., 2020; Theodosiou et al., 2015); a concern we will take care of in section 5. In addition to these models, Sinha and Chandell, (2014) reviewed existing ready-to-use software for designing HRES. The

widely used software is 'HOMER pro' developed by the National Renewable Energy Laboratory (NREL) in USA and used in Fodhil et al. (2019) for the optimization of a PV-diesel-battery HRES in Algeria. It is connected to several popular databases for technical aspects, consumption data or meteorology, which offers a user-friendly experience. Other in-house tools compete with HOMER, like in (Prabatha et al., 2019) where a new software based on a combinatory ranking method is proposed. Nevertheless, these approaches, including HOMER, do not implement optimization capability so, resulting solutions are likely to be under-optimal.

When focusing on the economic analysis of grid-connected HRES, four aspects need to be modelled: infrastructure costs with the so-called Capital expenditure (CAPEX) and Operational expenditure (OPEX), tariff of the energy sold to the grid, tariff of the energy bought from the grid, and important as well, taxes applicable to energy bought and sold to the grid. Obviously, papers addressing the first aspect have also to address the other ones but they only do so partially. For instance, Islam (2018) used HOMER to assess technically and economically the capability of HRES to supply office building in the south of France. They consider a fixed price of 0.18€/kWh for the energy bought from the grid to supply building consumption and a fixed price of 0.1018€/kWh for the energy sold to the grid. Yet, in many countries, including France, energy is bought from the grid at a variable price, depending on hours (peak, off-peak hours) and season (winter or summer) when consumption occurs; and energy sold to the grid must comply with a complex regulation framework that cannot be handle with a fixed price only. While French regulation is one of the most complex, as we'll show later, there are also simpler regulations elsewhere. In some countries using fixed prices for both selling and purchasing electricity are suitable in the economic model applicable in Algeria (Nadjemi et al., 2017). Hernández et al. (2019) and Cucchiella et al., (2015) also used fixed prices for Spain and Italy respectively, but it is questionable since other studies use variable prices for these countries (Gonzalez et al., 2015; González et al., 2018). Variable prices for energy bought to the grid are used for Malaysia (Subramani et al., 2019) but with no possibility to sold energy to the grid. A mix of fixed and variable prices are applicable in Shangaï (Liao et al., 2019) and with restrictions in France (Rigo-

Mariani, 2014). Among these works, not even one considers taxes in their economic analysis, which is a strong simplification in the economic model of self-consumption. Hence, we propose below a generic model for the economic analysis of grid-connected HRES to gather all these strategies in one.

### 3 Generic model for economic analysis of grid-connected HRES

In order to assess the economic viability of grid-connected HRES we propose a generic model based on the Net Present Value (*NPV*) of the system:

$$NPV = CAPEX_{tot} - Grant + \sum_{n=1}^N \frac{OPEX_{tot}(n) - Gain_{tot}(n)}{(1+i)^n} \quad (1)$$

*NPV* quantifies the balance between the investment in the HRES infrastructure (capital and operational expenditures) and the money earned for running the HRES over  $N$  years.  $n$  is the index of the current year and  $i$  is the discount rate. *Grant* is the grant for investment, which can account for subsidies given to producers for their investment in renewable installation, like in France.  $Grant = 0$  if the local regulation gives no subsidies.

We define  $CAPEX_{tot}$  as the sum of the capital expenditures of each element:

$$CAPEX_{tot} = \sum_{j=1}^{NbElem} CAPEX_{ElemList\{j\}} \quad (2)$$

Where  $NbElem$  is the number of elements in a list, denoted  $ElemList\{j\}$ , that contains all HRES' elements' name. An element is a wind turbine, a diesel generator, a battery storage, a PV, a junction, .... (Roth et al., 2019).

The  $OPEX_{tot}$  is a vector of  $N$  elements giving the sum of operational expenditures of each element for every years:

$$\forall n \in \llbracket 1; N \rrbracket, OPEX_{tot}(n) = \sum_{j=1}^{NbElem} OPEX_{ElemList\{j\}}(n) \quad (3)$$

$Gain_{tot}(n)$  is a vector of  $N$  elements representing the money earned from selling energy to the grid ( $Gain_{soldNRJ}(n)$ ) and the saved money on the electricity bill ( $Gain_{onElecBill}(n)$ ):

$$\forall n \in \llbracket 1;N \rrbracket, Gain_{tot}(n) = Gain_{soldNRJ}(n) + Gain_{onElecBill}(n) \quad (4)$$

$Gain_{soldNRJ}(n)$  is a vector of  $N$  elements composed of the raw gain on sold energy ( $RawGain_{soldNRJ}(n)$ ) and the taxes ( $Taxes_{soldNRJ}(n)$ ):

$$\forall n \in \llbracket 1;N \rrbracket, Gain_{soldNRJ}(n) = RawGain_{soldNRJ}(n) - Taxes_{soldNRJ}(n) \quad (5)$$

$Gain_{onElecBill}(n)$  is a vector of  $N$  elements and is the difference between the electricity bill without the HRES ( $ElecBill_{ref}(n)$ ) and the one with the HRES ( $ElecBill_{new}(n)$ ). Note that  $\forall n \in \llbracket 1;N \rrbracket$ ,  $ElecBill_{ref}(n) > ElecBill_{new}(n)$  since the HRES energy production goes in priority to the consumer, which reduces the amount of energy taken from the grid, thus lowering the electricity bill.

Therefore, we have:

$$\forall n \in \llbracket 1;N \rrbracket, Gain_{onElecBill}(n) = ElecBill_{ref}(n) - ElecBill_{new}(n) \quad (6)$$

$ElecBill_{ref}(n)$  values are an input given by the model user.  $ElecBill_{new}(n)$  is the sum of a fixed part ( $Fixed_{part}(n)$ ), usually for the subscription of the electricity contract, and a variable part which is a function of the hourly consumption ( $Variable_{part}(n)$ ) and taxes ( $Taxes_{onElecBill}(n)$ ):

$$\forall n \in \llbracket 1;N \rrbracket, ElecBill_{new}(n) = Fixed_{part}(n) + Variable_{part}(n) + Taxes_{onElecBill}(n) \quad (7)$$

In the following section, we use this generic model for the economic assessment of grid-connected HRES in the context of the 2017 French regulation on self-consumption.

## 4 MILP model for self-consumption French regulation

### 4.1 The French context

In 2017, for the first time in Europe, the French government promulgated a law allowing energy self-consumption as cases 2 and 3 in Figure 1. We consider two kinds of self-consumption:

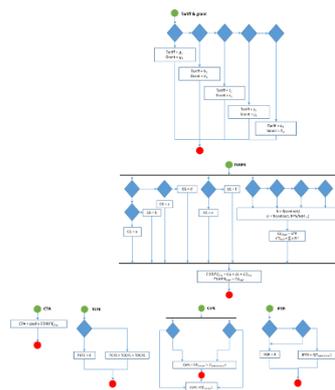
- Individual self-consumption: the electricity consumer is the owner of electricity production infrastructure and consume its own production of electricity.

- Collective self-consumption: a group of electricity consumers consumes and buys electricity to a local electricity production infrastructure owner.

Each of the two cases is subjected to a specific regulation. In this paper, we only focus on individual self-consumption since the collective case depends on other aspects, such as governance that cannot be taken into account in our proposed mathematical model.

French regulation is not straightforward since tariffs, taxes and grants are calculated through a stepwise waterfall of “if... then... else” conditions. The government established tariffs, taxes and grants structures for the energy sold to and bought from the grid in the context of self-consumption as shown on Figure 2.

(PLEASE INSERT FIGURE 2)



There are five taxes:

- *Tarifs d’Utilisation des Réseaux Publics de distribution d’Electricité (TURPE)* : it covers costs handle by the national electricity distributor.
- *Contribution Tarifaire d’Acheminement (CTA)*: it covers costs generated by electricity transport.
- *Taxes sur la Consommation Finale d’Electricité (TCFE)* : it concerns the local tax system.

- *Contribution au Service Public d'Electricité* (CSPE): this tax helps funding public service duty of ENEDIS (formerly EDF, which was the historic national electricity supplier), namely the obligation to buy renewable energy to producer at fix prices.
- *Imposition Forfaitaire sur les Entreprises de Réseaux* (IFER): it taxes electricity producers.

This regulation structure can be modelled as a MILP problem since it is stepwise and linear with respect to the production and the energy management of the HRES. As far as we know such a MILP-implemented approach has never been proposed in the literature for the full regulation structure, but for Rigo-Mariani (2014) in an earlier simplified version. In the next two subsections, we detail the MILP formulation of Figure 2 tariffs and taxes structure of the energy sold to the grid and of the energy bought from the grid respectively.

## 4.2 Tariffs and taxes structure of energy sold to the grid

As shown in equation (5) the money earned from selling electricity to the grid is modelled as follow:

$$\forall n \in \llbracket 1;N \rrbracket, \quad Gain_{soldNRJ}(n) = RawGain_{soldNRJ}(n) - Taxes_{soldNRJ}(n)$$

First of all, let's consider the  $RawGain_{soldNRJ}(n)$  which refers to Figure 2a, while  $Taxes_{soldNRJ}(n)$  refer to Figure 2b).

### 4.2.1 Model of the raw gain on the sold energy

The *Commission de Régulation de l'Energie* (CRE) (Energy Regulation Commission) is a French institution that is in charge of fixing the prices of electricity and gas. The CRE has defined the price of electricity sold to the grid by decree in May, 9<sup>th</sup>, 2017 as well as grant for investment, as a function of of rated power ( $Rated_{power}$ ) into five classes indexed by k.

$RawGain_{soldNRJ}(n)$  is calculated as:

$$\forall n \in \llbracket 1;N \rrbracket, \forall k \in \llbracket 1;5 \rrbracket, \quad RawGain_{soldNRJ}(n) = E_{sld,tot}(n).Tariff_k$$

where  $E_{sld,tot}(n)$  is the total amount of energy sold to the grid during the year  $n$  and  $Tariff_k$  the  $k$ -class tariff corresponding to the rated power of the HRES. But, in the HRES design problem,  $E_{sld,tot}(n)$  will be a variable as well as  $Tariff_k$  since it is function of  $Rated_{power}$  which is also a variable, according to the stepwise waterfall structure (Figure 2a). So, we need to linearize the calculation of  $RawGain_{soldNRJ}(n)$  as:

$$\forall n \in \llbracket 1;N \rrbracket, RawGain_{soldNRJ}(n) = \sum_{k=1}^4 Tariff_k \cdot E_{sld,tot}^k(n) \quad (8)$$

Where  $Tariff_k$  gives the tariff corresponding to the category  $k$  and  $E_{sld,tot}^k$  is a vector storing variables about the energy sold to the grid at tariff  $k$ .

We use a set of binary values  $z_{sld,k}$  to ensure that  $E_{sld,tot}^k(n) = 0$  (and  $z_{sld,k} = 0$ ) when  $Rated_{power}$  is not in the category  $k$  and  $E_{sld,tot}^k(n) = E_{sld,tot}(n)$  (and  $z_{sld,k} = 1$ ) otherwise. Here is now the way to determine  $z_{sld,k}$  and  $E_{sld,tot}^k(n)$ . Let's denote the rated power threshold of the  $k$  tariff class by  $Rated_{pwrLim,k}$ . In order to determine their value we first need to find which tariff  $k$  concerns the current  $Rated_{power}$ :

$$\forall k \in \llbracket 1;3 \rrbracket P_{sld,k^+} - P_{sld,k^-} = Rated_{power} - Rated_{pwrLim,k} \quad (9)$$

$$\forall k \in \llbracket 1;3 \rrbracket 0 \leq P_{sld,k^+} \leq (1 - y_{sld,k}) \cdot BigM1 \quad (10)$$

$$\forall k \in \llbracket 1;3 \rrbracket 0 \leq P_{sld,k^-} \leq y_{sld,k} \cdot BigM1 \quad (11)$$

With  $P_{sld,k^+} \in \mathbb{R}^{3+}$ ,  $P_{sld,k^-} \in \mathbb{R}^{3+}$ ,  $y_{sld,k} \in \{0,1\}$  and  $BigM1$  a big positive value. Thus, if  $Rated_{power} > Rated_{pwrLim,k}$  then  $y_{sld,k} = 0$ ,  $P_{sld,k^-} = 0$  and  $P_{sld,k^+} \neq 0$ . On the contrary if  $Rated_{power} < Rated_{pwrLim,k}$  then  $y_{sld,k} = 1$ ,  $P_{sld,k^-} \neq 0$  and  $P_{sld,k^+} = 0$ . When  $Rated_{power} = Rated_{pwrLim,k}$ ,  $y_{sld,k}$  can be equal to either 0 or 1. One sets  $y_{sld,k} = 1$  as a default value, so that  $Rated_{power}$  is set in the category  $k$ . Then, we determine the value of  $z_{sld,k}$ :

$$z_{sld,1} = y_{sld,1} \quad (12)$$

$$\forall k \in \llbracket 2;3 \rrbracket z_{sld,k} = y_{sld,k} - y_{sld,k-1} \quad (13)$$

$$z_{sld,4} = 1 - y_{sld,k} \quad (14)$$

Finally, we obtain the value of  $E_{sld,tot}^k(n)$ :

$$\forall k \in \llbracket 1;4 \rrbracket, \forall n \in \llbracket 1;N \rrbracket, 0 \leq E_{sld,tot}^k(n) \leq z_{sld,k} \cdot BigM2 \quad (15)$$

$$\forall k \in \llbracket 1;4 \rrbracket, \forall n \in \llbracket 1;N \rrbracket, E_{sld,tot}^k(n) \leq E_{sld,tot}(n) \quad (16)$$

$$\forall k \in \llbracket 1;4 \rrbracket, \forall n \in \llbracket 1;N \rrbracket, E_{sld,tot}(n) - BigM2 \cdot (1 - z_{sld,k}) \leq E_{sld,tot}^k(n) \quad (17)$$

With  $BigM2$  a big positive value.

#### 4.2.2 Model of the grants on the sold energy

We define the grant for investment as follow:

$$Grant_{sld} = \sum_{k=1}^4 Grant_{sld}^k \cdot z_{sld,k} \quad (18)$$

#### 4.2.3 Model of the taxes on the sold energy

Now, let's consider the  $Taxes_{soldNRJ}(n)$ . When selling energy to the grid, producers need to pay the so-called taxes *Imposition Forfaitaire sur les Entreprises de Réseaux* (IFER) proportionnal to  $Rated_{power}$  :

$$IFER = IFER_{cost} * 0.8 * Rated_{power} \quad (19)$$

but there exists a tax exemption below a threshold of rated power (denoted  $Rated_{pwrLim,IFER}$ ) and also above a limit of self-consumption (denoted  $E_{sld,csmd,tot}$ ). In order to linearize the first condition on rated power, we define  $y_{IFER,1} \in \{0,1\}$  a binary that indicates the position of  $Rated_{power}$  with respect to  $Rated_{pwrLim,IFER}$ . We define it such as if  $Rated_{power} \leq Rated_{pwrLim,IFER}$  kW then  $y_{IFER,1} = 0$  and if  $Rated_{power} \geq Rated_{pwrLim,IFER}$  kW then  $y_{IFER,1} = 1$ :

$$P_{IFER1^+} - P_{IFER1^-} = Rated_{power} - Rated_{pwrLim,IFER} \quad (20)$$

$$0 \leq P_{IFER1^+} \leq (1 - y_{IFER1}) \cdot BigM3 \quad (21)$$

$$0 \leq P_{IFER1^-} \leq y_{IFER1} \cdot BigM3 \quad (22)$$

With  $P_{IFER1^+} \in \mathbb{R}^+$ ,  $P_{IFER1^-} \in \mathbb{R}^+$  and  $BigM3$  a big positive value.

To linearize the second condition on the self-consumed energy, we name  $y_{IFER,2}(n) \in \{0,1\}$  a vector of  $N$  binaries that indicates the position of the total amount of energy produced during the year  $n$  (denoted  $E_{prod,tot}$ ) by the energy self-consumed during the year ( $E_{slfcsmd,tot}$ ). Thus,  $\forall n \in \llbracket 1;N \rrbracket$ ,  $E_{prod,tot}(n) \geq E_{slfcsmd,tot}(n)$  and if  $E_{prod,tot} > E_{slfcsmd,tot}$  then  $y_{IFER,2} = 1$  whereas if  $E_{prod,tot} = E_{slfcsmd,tot}$  then  $y_{IFER,2} = 0$ :

$$\forall n \in \llbracket 1;N \rrbracket P_{IFER2^+}(n) - P_{IFER2^-}(n) = E_{prod,tot}(n) - E_{slfcsmd,tot}(n) \quad (23)$$

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq P_{IFER2^+}(n) \leq y_{IFER2}(n) \cdot BigM4 \quad (24)$$

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq P_{IFER2^-}(n) \leq (1 - y_{IFER2}(n)) \cdot BigM4 \quad (25)$$

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq y_{IFER2}(n) \leq E_{prod,tot}(n) - E_{slfcsmd,tot}(n) \quad (26)$$

In order to determine whether the producer is subject to IFER, we need to linearize the product of  $y_{IFER1}$  and  $y_{IFER2}$  and collect the value in  $z_{IFER}(n) \in \{0,1\}$  a vector of  $N$  binaries:

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq z_{IFER}(n) \leq y_{IFER1} \quad (27)$$

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq z_{IFER}(n) \leq y_{IFER2}(n) \quad (28)$$

$$\forall n \in \llbracket 1;N \rrbracket y_{IFER1} + y_{IFER2}(n) - 1 \leq z_{IFER}(n) \quad (29)$$

Finally, we define the values of  $Taxes_{soldNRJ}$  as the linearization of the product of  $z_{IFER}$  by  $IFER$ :

$$\forall n \in \llbracket 1;N \rrbracket, 0 \leq Taxes_{soldNRJ}(n) \leq z_{IFER}(n) \cdot BigM5 \quad (30)$$

$$\forall n \in \llbracket 1;N \rrbracket, Taxes_{soldNRJ}(n) \leq IFER_{cost} * 0.8 * Rated_{power} \quad (31)$$

$$\forall n \in \llbracket 1;N \rrbracket, IFER_{cost} * 0.8 * Rated_{power} - (1 - z_{IFER}(n)) \cdot BigM5 \leq Taxes_{soldNRJ}(n) \quad (32)$$

### 4.3 Tariffs and taxes structure of energy bought from the grid

In this section, we specify the model of the electricity bill (equation (7)) in the self-consumption French context:

$$\forall n \in \llbracket 1;N \rrbracket, \quad ElecBill_{new}(n) = Fixed_{part} + Variable_{part}(n) + Taxes_{onElecBill}(n)$$

The fixed part ( $Fixed_{part}(n)$ ) is given by the subscription fee of the electricity contract with the supplier. Besides, this fee usually includes some taxes that need to be retrieve in order to put it in variable  $Taxes_{onElecBill}(n)$ . We will detail these taxes in the case study.

The variable part of the electricity bill ( $Variable_{part}(n)$ ) depends on the hourly consumption. In France, the price of the consumed electricity also depends on time slots (usually peak hours and off-peak hours for households). The contract between a consumer and a supplier stipulates the time slots and the corresponding prices. Again some taxes are included in these prices, so in the case study we will specify it and added to the  $Taxes_{onElecBill}$ . To calculate  $Variable_{part}(n)$  we need to multiply the time series of electricity prices by the time series of the electricity demand:

$$\forall n \in \llbracket 1;N \rrbracket, \quad Variable_{part}(n) = \sum_{t=H.(n-1)+1}^{H.n} E_{csm d}(t). Price_{csm d}(t) \quad (33)$$

With  $H$  the number of time step in a year,  $E_{csm d} \in \mathbb{R}^{nH+}$  a vector of  $H.N$  elements giving the consumed energy and  $Price_{csm d} \in \mathbb{R}^{nH+}$  a vector of  $H.N$  elements representing the price of the consumed energy.

In the French regulation, there are four taxes that consumers need to pay on their electricity bill:  $CTA$ ,  $TCFE$ ,  $TURPE$  and  $CSPE$  and. The  $CTA$  tax is fixed and the three others are described in the following sections.

#### 4.3.1 TURPE tax model

The TURPE tax is updated regularly by the CRE institution. As we focus on households, we will model the TURPE for low voltage consumers (less than 250 V) (ENEDIS, 2017). TURPE is composed of three

fixed elements:  $CG, CC, CS_{fixed}$ . They are parameters and are defined by the grid operator (ENEDIS, 2017) and one variable element:  $CS_{variable}$ . Thus:

$$\forall n \in \llbracket 1;N \rrbracket \text{TURPE}(n) = CG + CC + CS_{fixed} + CS_{variable}(n) \quad (34)$$

Regarding high voltage consumers, there are other fixed and variable elements. Some of them cannot be linearized. But, since they depend on the energy management and not on the design of the HRES, they can be set as parameters of the model.

$CS_{variable}(n) \in \mathbb{R}^{n+}$  and is defined as:

$$\forall n \in \llbracket 1;N \rrbracket CS_{variable}(n) = \sum_{s=1}^{NbTslot} coef_c^s \cdot E_{csmd,tot}^s(n) \quad (35)$$

Where  $NbTslot$  is the number of time slots stipulated in the electricity contract,  $s$  is the index of the current time slot,  $coef_c^s$  are coefficient for each time period and are defined in (ENEDIS, 2017),  $E_{csmd,tot}^s$  is the energy consumed during each time slot  $s$ .

#### 4.3.2 CSPE tax model

In the context of self-consumption, if the rated power of the HRES is under a limit (denoted  $Rated_{pwrLim,CSPE}$ ) or if the total energy produced by the HRES is inferior to  $E_{prodTotLim,CSPE}$  then the consumer only pays the CSPE tax on the energy bought from the grid ( $E_{bght,tot}$ ). Else, the CSPE tax is payed at the rate  $Cost_{cspe}$  on the total energy consumed ( $E_{csmd,tot}$ ) (the one taken from the grid plus the one produced thank to the HRES). We linearize this two-level condition in the same way we linearized the one on IFER:

$$P_{CSPE1^+} - P_{CSPE1^-} = Rated_{pwrLim,CSPE} - Rated_{power} \quad (36)$$

$$0 \leq P_{CSPE1^+} \leq y_{CSPE1} \cdot BigM6 \quad (37)$$

$$0 \leq P_{CSPE1^-} \leq (1 - y_{CSPE1}) \cdot BigM6 \quad (38)$$

With  $P_{CSPE1^+} \in \mathbb{R}^+$ ,  $P_{CSPE1^-} \in \mathbb{R}^+$ ,  $y_{CSPE1} \in \{0,1\}$  and  $BigM6$  a big positive value. When  $Rated_{power} \leq Rated_{pwrLim,CSPE}$  then  $y_{CSPE1} = 1$  and when  $Rated_{power} \geq Rated_{pwrLim,CSPE}$  then  $y_{CSPE1} = 0$ . Therefore,  $y_{CSPE1}$  gives the value of the first condition. Then:

$$\forall n \in \llbracket 1;N \rrbracket, P_{CSPE2^+}(n) - P_{CSPE2^-}(n) = E_{prodTotLim,CSPE} - E_{prod,tot}(n) \quad (39)$$

$$\forall n \in \llbracket 1;N \rrbracket, 0 \leq P_{CSPE2^+}(n) \leq y_{CSPE2} \cdot BigM7 \quad (40)$$

$$\forall n \in \llbracket 1;N \rrbracket, 0 \leq P_{CSPE2^-}(n) \leq (1 - y_{CSPE2}) \cdot BigM7 \quad (41)$$

With  $P_{CSPE2^+} \in \mathbb{R}^{n+}$ ,  $P_{CSPE2^-} \in \mathbb{R}^{n+}$ ,  $y_{CSPE2} \in \{0,1\}$  and  $BigM7$  a big positive value. When  $E_{prod,tot}(n) \leq E_{prodTotLim,CSPE}$  then  $y_{CSPE2} = 1$  and when  $E_{prod,tot}(n) \geq E_{prodTotLim,CSPE}$  then  $y_{CSPE2} = 0$ . Therefore,  $y_{CSPE2}$  give the value of the second condition.

To collect the value of the two-level condition in the vector of  $N$  binaries  $z_{CSPE}(n)$ , we need to linearize the product of  $y_{CSPE1}$  by  $y_{CSPE2}$  :

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq z_{CSPE}(n) \leq 1 - y_{CSPE1}(n) \quad (42)$$

$$\forall n \in \llbracket 1;N \rrbracket 0 \leq z_{CSPE}(n) \leq 1 - y_{CSPE2}(n) \quad (43)$$

$$\forall n \in \llbracket 1;N \rrbracket 1 - y_{CSPE1}(n) + 1 - y_{CSPE2}(n) - 1 \leq z_{CSPE}(n) \quad (44)$$

If  $y_{CSPE1} = 0$  or  $y_{CSPE2} = 0$ , then  $z_{CSPE} = 0$ .

We define the value of the  $CSPE$  as:

$$\forall n \in \llbracket 1;N \rrbracket, CSPE(n) = CSPE_{tmp1}(n) + CSPE_{tmp2}(n) \quad (45)$$

Where  $CSPE_{tmp1} \in \mathbb{R}^{n+} = Cost_{cspe} \cdot E_{bght,tot}$  and  $CSPE_{tmp2} \in \mathbb{R}^{n+} = Cost_{cspe} \cdot E_{csmd,tot}$ :

$$\forall n \in \llbracket 1;N \rrbracket, 0 \leq CSPE_{tmp1}(n) \leq (1 - z_{CSPE}(n)) \cdot BigM8 \quad (46)$$

$$\forall n \in \llbracket 1;N \rrbracket, CSPE_{tmp1}(n) \leq Cost_{CSPE} \cdot E_{bght,tot}(n) \quad (47)$$

$$\forall n \in \llbracket 1;N \rrbracket, Cost_{CSPE} \cdot E_{bght,tot}(n) - BigM8 \cdot z_{cspe}(n) \leq CSPE_{tmp1}(n) \quad (48)$$

$$\forall n \in \llbracket 1;N \rrbracket, 0 \leq CSPE_{tmp2}(n) \leq z_{CSPE}(n).BigM8 \quad (49)$$

$$\forall n \in \llbracket 1;N \rrbracket, CSPE_{tmp2}(n) \leq Cost_{CSPE} \cdot E_{csmd,tot}(n).dt \quad (50)$$

$$\forall n \in \llbracket 1;N \rrbracket, Cost_{CSPE} \cdot E_{csmd,tot}(n) - BigM8 \cdot z_{cspe}(n) \leq CSPE_{tmp2}(n) \quad (51)$$

### 4.3.3 TCFE tax model

The *TCFE* tax is used to subsidize local administrations. It is composed of two parts, one for the town and one for the French department (equivalent to a county):

$$\forall n \in \llbracket 1;N \rrbracket TCFE(n) = TCCFE_{coef} \cdot E_{bght,tot}(n) + TDCFE_{coef} \cdot E_{bght,tot}(n) \quad (52)$$

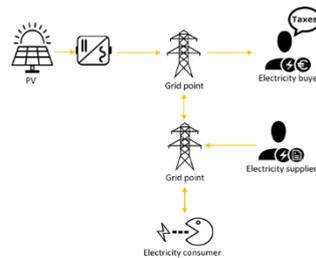
Where  $TCCFE_{coef}$  and  $TDCFE_{coef}$  are parameters of the problem that are set by the French government<sup>1</sup>. For big consumers that must subscribe to a contract above  $TCFE_{lim}$ , they are exonerated from *TCFE*.

In the next section, we will use the generic model as well as the MILP model to assess the economic viability of HRES in the context of French households.

## 5 Case study presentation

Figure 3 displays a scheme of the self-consumption infrastructures composed of photovoltaic panels on the house roof to supply the household electricity consumption. The HRES is made of a single element, aggregating the PV and the inverter.

(PLEASE INSERT FIGURE 3)



<sup>1</sup> <https://www.impots.gouv.fr/portail/taxe-sur-la-consommation-finale-deelectricite-tcfe>

One can remark that no storage capacity are included in this HRES under study. Like others, we have previously stressed out the current exaggerated investment cost of battery storage that makes their use unprofitable nowadays (Roth et al., 2019). Hence, we have disregarded any storage here in order to focus discussions on self-consumption regulation framework. When electricity production is below the household electricity demand, the household buys electricity to the electricity supplier; when electricity production exceeds the consumption, the extra production can be sold to the electricity buyer or curtailed. Being encouraged by the 2017 regulation in France, self-consumption infrastructures are likely to multiply. Nevertheless, it is worth questioning whether it enables a reduction of French households environmental impact and whether the current grant for installation is encouraging citizens to install a maximum of rated power for their self-consumption installations and where is it needed. Hence, to perform this case study, we will consider four scenarios, mixing various localization and exposure: one favourable - the city of Carcassonne in the South of France with South exposure and one unfavourable – the city of Ruch on the middle of the West coast with a West exposure. The Carcassonne time series represents 1400 hours of equivalent maximum production while the one of Ruch represents 1060 hours. According to SOLARGIS map (SOLARGIS, 2019) this later value is also representative of the energy potential available in 900 km north of Carcassonne, with a south exposure.

We will also consider two kinds of households: one of 2 persons with a consumption of 4000 kWh/year and one of 5 persons with a consumption of 8500 kWh/year.

Below we explain the various parameters of the model and the objective function used in the MILP problem.

## 5.1 Time model

The time step is one hour and is denoted by  $dt = 1 h$ . The time horizon is therefore  $H = 8760 h = 1 year$ . Thus, the current time denoted  $t$  lies between  $1 \leq t \leq 8760$ . The calculus is done over the

8760 time steps and results are replicated over  $N = 20$  years which corresponds to the PV lifetime.

Hence, the current year denoted  $n$  is in between  $1 \leq n \leq 20$ .

## 5.2 PV and inverter

The PV production is modelled as follow:

$$\forall t \in \llbracket 1;nH \rrbracket, P_{prod,PV}(t) = (Nb_{PV} \cdot P_{unit,PV}(t) - P_{curt,PV}(t)) \cdot Eff_{inv} \quad (53)$$

With  $P_{prod,PV} \in \mathbb{R}^{nH+}$  a variable of the problem that refer to the time series of the power delivered by the HRES.  $P_{unit,PV}$  is the time series of the production of one PV and it is a parameter of the problem. The unit time series are obtained thanks to the software PVsyst (PVsyst, 2019) for the two aforementioned localization in the incline plan of the rooftop ( $18^\circ$ ), with 1400 hr for Carcassonne and 1060 hr for Ruch.  $Eff_{inv}$  is the inverter's energy efficiency which is consider as constant and equal to 94%.  $Nb_{PV} \in \mathbb{N}$  is the number of PV to install, it is a variable of the problem. Finally,  $P_{curt} \in \mathbb{R}^{nH+}$  is the curtailment of the production, it is also a variable of the problem and cannot exceed the production:

$$\forall t \in \llbracket 1;nH \rrbracket, 0 \leq P_{curt,PV}(t) \leq P_{prod,PV}(t) \quad (54)$$

The total amount of energy produced by year is:

$$\forall n \in \llbracket 1;N \rrbracket, E_{prodTot,PV}(n) = \sum_{t=H \cdot (n-1)+1}^{nH} P_{prod,PV}(t) \cdot dt \quad (55)$$

Finally, the number of installed PV is in between 0 and a maximum denoted  $Nb_{max,PV}$ :

$$0 \leq Nb_{PV} \leq Nb_{max,PV} \quad (56)$$

## 5.3 Electricity consumer

ENEDIS, the French electricity supplier, publishes each year annual time series of load coefficients with 30 min time steps<sup>2</sup>. These time series are given for several categories of consumers (residential, professional, high and low voltage...). By multiplying these time series by the annual consumption of

<sup>2</sup> <https://www.enedis.fr/coefficients-des-profils>

the two households considered and by dividing each time step by the sum of all the coefficients of the time series, we obtain a load curve typical for each household. In this case study, we will consider the load coefficients time series labelled “RES11\_BASE” which correspond to a residential consumer of more than 6 kVA.

#### 5.4 Electricity buyer

The electricity buyer purchases electricity to the producer and then acts as an electricity supplier to sell it to consumers.

The model of the electricity buyer is given by equations from 8 to 32. Table 1 gives the different tariffs and grants affected to the k class of rated power.

Table 1. Electricity sold to the grid prices

Index k	Rated power class	Tariff [c€/kWh]	Grant [€/kWp]
1	$Rated_{power} \leq 3kW$	10	400
2	$3 kW < Rated_{power} \leq 9 kW$	10	300
3	$9 kW < Rated_{power} \leq 36 kW$	6	200
4	$36 kW < Rated_{power} \leq 100 kW$	6	100
5	$100 kW < Rated_{power}$	CRE call for bids or electricity markets	0

According to Table 1, under 100 kW of rated power, the tariff is 10 c€/kWh until 9 kW and 6 c€/kWh until 100 kW. Above 100 kW the producer must participate to a call for bids of the CRE institution to get a tariff or to sell its production on electricity markets. Usually, the producer will try to obtain a tariff from CRE above the expected mean price of electricity markets in order to make more profits. This process of biddings is difficult to model in a MILP formulation and we do not model it. Moreover, the case study will focus on households, therefore the rated power of producing installations will be under 100 kW most of the time. Therefore, we will focus only on the first four rated power groups.

Table 2 gives the parameters of IFER tax.

Table 2. Values of the electricity buyer parameters

Parameter	Value
$Rated_{pwrLim,IFER}$	100 kW
$IFER_{cost}$	7400 €/MWh

## 5.5 Electricity supplier

The model of the electricity supplier is the one given from equations 33 to 52. The annual electricity reference bill  $ElecBill_{ref}$  is of 874 € for the 2 persons households and of 1662 € for the 5 persons households. The subscribed power for the grid connexion is 9 kVA for both households. The tariff structure of the consumed energy depends on the considered time slot: off-peak period (from 3 to 6 AM, from 1 to 3 PM and at 9 PM) or peak period (from 10 PM to 2 AM, from 7 AM to 12 AM and from 4 PM to 8 PM). The price of consumed energy ( $Price_{csm d}$ ) is fixed by the decree of October, 4<sup>th</sup>, 2018. For our households, it is of 0.1579 €/kWh in peak period and 0.1228 €/kWh in off-peak period. These prices include the variable part of the TURPE given by the  $coef_c^S$  introduced in the equation (35). The  $coef_c^S$  values are given by (ENEDIS, 2017): in peak periods it equals 3.89 c€/kWh and in off-peak periods it is of 2.38 c€/kWh. Thus,  $Price_{csm d}$  equals 0.119€/kWh in peak periods and 0.099 €/kWh in off-peak periods. Otherwise, the decree of October, 4<sup>th</sup>, 2018 also defines the subscription rate at 151.34 €/year which includes the fixed TURPE part ( $TURPE_{fixed} = CG + CC + CS_{fixe} = 16.56 + 19.80 + 61.65 = 97.92$  values from (ENEDIS, 2017)). So, the subscription is of 53.42€/year without the TURPE. Table 3 recall all the value of the parameters of the electricity supplier.

Table 3. Values of the electricity supplier parameters

Parameter	Value	Unit
$Fixed_{part}$	53.42	[€/year]
$CG$	16.56	[€/year]
$CC$	19.80	[€/year]
$CS_{fixe}$	61.56	[€/year]
$CACS$	0	[€/year]

$TCCFE_{coef}$	8.5	[€/MWh]
$TDCFE_{coef}$	4	[€/MWh]
$CTA$	26.48	[€/year]
$Rated_{pwrLim,CSPE}$	100	[kWp]
$E_{prodTotLim,CSPE}$	240	[GWh]
$Cost_{CSPE}$	22.5	[€/MWh]
$TCFE_{lim}$	250	kVA

## 5.6 Objective function and economic assessment

The generic model presented in section 3.1 is used to assess the economic viability of the four scenarios of the case study: a household of 2 persons in Ruch, a household of 5 persons in Ruch, a household of 2 persons in Carcassonne, a household of 5 persons in Carcassonne. The objective function is defined by the maximisation of the function in equation (1):

$$f_{obj} = \max(NPV) = \max(CAPEX_{tot} - Grant_{sld} + \sum_{n=1}^N \frac{OPEX_{tot}(n) - Gain_{tot}(n)}{(1+i)^n}) \quad (57)$$

With the discount rate  $i = 7\%$

Regarding equation (2) and (3) only one HRES element, namely the PV element, is considered in the case study since the PV CAPEX and OPEX include the one of the inverter. Thus:

$$CAPEX_{tot} = CAPEX_{PV} = 0.8 * Rated_{power} \quad (58)$$

$$OPEX_{tot} = OPEX_{PV} = 0.03 * CAPEX_{PV} \quad (59)$$

Moreover, we will use two economic indicators:

- The Payback period (PP) which is the  $N$  that makes NPV null. The more PP is high the less the project is interesting.
- The Internal Rate of Return (IRR) which is the  $i$  that makes NPV null. The more the difference between the discount rate and the IRR, the less the project bears some risk. A typical value of the discount rate that we will use is 7%.

## 6 Results and discussion

### 6.1 Environmental impact

In order to assess the environmental impact of the infrastructure of the Figure 3, we use Life Cycle Assessment (LCA) results of 1 kWh produced by building integrated PV and 1 kWh produced by the French electrical mix. The LCA data come from the software SimaPro (SimaPro, 2019) and the database EcoInvent 3 (EcoInvent, 2019) using the Impact2002+ method. Table 4 gathers the impacts coefficients. It is important to notice that in the EcoInvent 3 database, the LCA data for the French electricity mix focuses only on the electricity production and discards the building phase of the production facilities. In order to keep consistency, we also have to discard the building phase of PV from the LCA, although this phase is likely very impactful.

Table 4. LCA coefficients for integrated to building PV and French electricity mix

Final category	Impact category	PV	French electricity mix
Human health	Human toxicity [kg C2H3Cl eq/kWh]	2,54E-03	1,37E-03
	Respiratory effects [kg PM%2.5 eq/kWh]	1,03E-04	8,94E-05
	Ionizing radiation [Bq C_14 eq/kWh]	1,21	79,84
	Ozone layer depletion [kg CFC-11 eq/kWh]	1,52E-08	8,81E-08
	Photochemical oxidation [kg C2H4 eq/kWh]	5,56E-05	1,90E-05
	<b>Total de la catégorie [μPt/kWh]</b>	<b>12,41</b>	<b>12,42</b>
Ecosystem quality	Aquatic ecotoxicity [kg TEG in water/kWh]	9,71	31,45
	Terrestrial ecotoxicity [kg TEG in soil/kWh]	2,66	2,92
	Aquatic acidification [kg SO2 eq/kWh]	5,40E-04	4,67E-04
	Aquatic eutrophication [kg PO4 P-lim/kWh]	5,57E-05	7,36E-06
	Terrestrial acid/nutr [kg SO2 eq/kWh]	1,47E-03	1,40E-03
	Land occupation [m2 terres arables/kWh]	1,33E-03	1,62E-03
	<b>Total de la catégorie [μPt/kWh]</b>	<b>1,79</b>	<b>2,04</b>
Climate change	Global warming [kg CO2 eq/kWh]	6,77E-02	8,60E-02
	<b>Total de la catégorie [μPt/kWh]</b>	<b>6,84</b>	<b>8,69</b>
Ressources	Non-renewable energy [MJ d'énergie primaire/kWh]	1,00	11,38
	Mineral extraction [MJ surplus/kWh]	3,67E-02	3,89E-03
	<b>Total de la catégorie [μPt/kWh]</b>	<b>6,84</b>	<b>74,92</b>

TOTAL [ $\mu$ Pt/kWh]	27,88 (-28%)	98,07
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From these data, one can notice that 1 kWh produced with PV or with the French electricity mix are equivalent regarding human health impact in the EcoInvent 3 database. Indeed, if the French electricity mix is more impactful on ionizing radiation impact category since the French electricity mix is dominated by nuclear energy, the PV production is more harmful on other impact categories of human health. Nevertheless, on the three other final categories the PV electricity production is more benign to environment as it reduces by 28% the electricity consumption environmental impact of French households. Therefore, the more the rated power of the PV infrastructure installed, the less the environmental impact will be.

Computations are done on a computer of 8 Go of RAM and an Intel Core i5 of 7<sup>th</sup> generation cadenced at 2.5 GHz. We use CPLEX (IBM, 2019) to solve the problem of 227 891 variables and 149 119 constraints.

## 6.2 Profitability analysis of self-consumption

Table 5 gathers the two economic indicators, payback period PP and internal rate of return IRR of the four scenarios. Notice that according to Table 1 the sold electricity price is reduced above 9 kWp (Kilowatt-peak) from 10 c€/kWh to 6 c€/kWh. Table 6 shows that above a rated power of 9 kWp, the facilities are not profitable before the PV lifetime (20 years), on the less favourable case (Ruch location) without the grant or for a 2-person household with the grant. Therefore, one can infer that when the energy potential is low, it is not interesting to install more than 9 kWp in France for self-consumption. Even on a high energy potential spot, like Carcassonne, the PP of the 2-person household is above 20 years and the IRR equal or less than the discount rate of 7% for rated power above 9 kWp. Regarding households of 5 persons the energy consumption is higher, so economy on the electricity bill grows. Thus, the system is profitable even above the 9 kWp for the Ruch location with a grant and whatever the grant for Carcasonne.

Table 5. PP and IRR of the four scenario

Rated power [kWp]			1.6	3.2	4.8	6.4	8	9.6	11.2	12.8
Ruch 2 persons	Without grant	PP [year]	10	11.5	13	14	14.5	>20	>20	>20
		IRR [%]	13	11	10	10.3	9.5	3.3	2.8	2.4
	With grant	PP [year]	4	7.1	7.2	7.3	7.4	>20	>20	>20
		IRR [%]	28	20	19	18	17	6.7	6.1	5.5
Ruch 5 persons	Without grant	PP [year]	9	9.1	9.2	10	12	>20	>20	>20
		IRR [%]	13.9	13.7	12.7	11.9	11.2	6.6	5.9	5.3
	With grant	PP [year]	4	5	5.5	6	6.2	12.5	14	15
		IRR [%]	29.8	23.3	21.9	20.7	19.9	10.6	9.7	9
Carcassonne 2 persons	Without grant	PP [year]	7.2	8	8	8.8	9	20	>20	>20
		IRR [%]	19	16.5	15.4	14.7	14.3	7	6.5	6.2
	With grant	PP [year]	3	4	4.8	4.9	5	12	13	13.1
		IRR [%]	39	28	26	25	24	11	10.5	10.1
Carcassonne 5 persons	Without grant	PP [year]	6	6.1	7	7.5	7.8	13	14.5	15
		IRR [%]	21.3	19.7	18.1	17	16.3	10.1	9.4	8.8
	With grant	PP [year]	3	3.5	4	4.2	4.5	8.5	9.5	10
		IRR [%]	43.6	32.3	29.9	28.3	27.2	14.8	13.9	13.2

While profitability seems globally ok for self-consumption, the impact of the grant given once, at installation, requires further attention. Under 9 kWp, the grant on investment helps reduce the PP on every scenario. Interestingly, whatever the location, the grant is not necessary since the IRR values without grant are already above the reference discount rate of 7%. This comment is strikingly illustrated for the Carcassonne location with IRR value being never below 14.3% and reaching up to 43.6%. It also holds to a lesser extent for the Ruch location with IRR ranging from 9.5% to 29.8%.

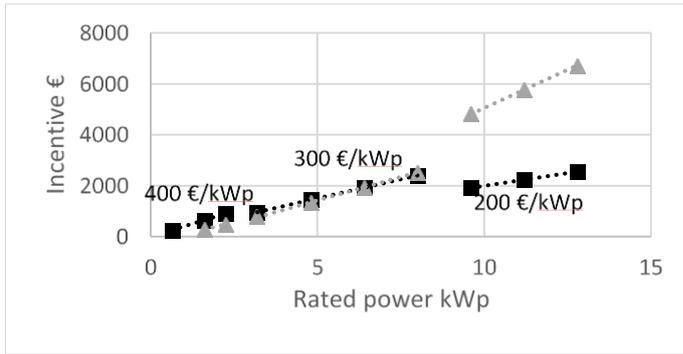
Moreover, Table 5 shows that the French citizens are not encouraged to install a maximum of rated power thus reducing their environmental impact (see section 4.1), since the PP increases and IRR decreases with the rated power. In other words, the profit decreases with the rated power. A new environmental policy should be proposed to reverse this trend.

### 6.3 A new environmental policy

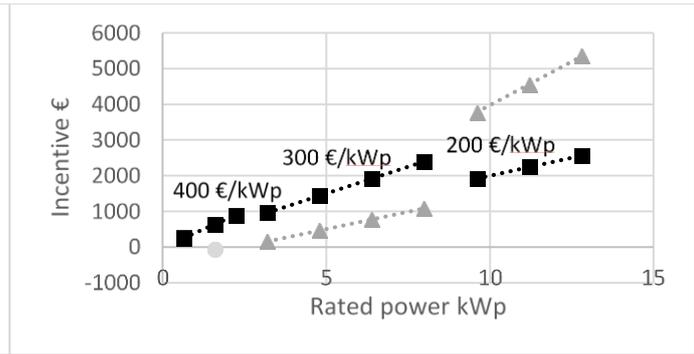
In France in 2010, the photovoltaic market for households was fast-growing thanks to the economic support by the government. At that time, the payback period PP was around 7 years and it was the decisive factor for many private persons. In 2010 the French government suddenly changed its economic support, which shattered the PV market. Now, with the 2017 self-consumption regulation, the market should recover, but according to the PP and IRR values discussed above, it appears that the French government budget allocated for incentives could be used more evenly in regards with the location and household composition and more efficiently to promote renewable energies. To corroborate this statement, Table 6 and Table 7 (in appendices) gather grants and gain/cost ratio for Ruch and Carcassonne respectively. The CAPEX, OPEX, bill saving and gain from sold energy to the grid are also given in appendices (Table 8). On every scenario, with or without grants, the gain/cost relation decreases with the rated power. In other words, the system cost increases faster than the gain, which explains the reason why the IRR decrease and the PP increase.

As an alternative, we propose a new grant calculus to reverse this trend and to favour environmental impact reduction. We consider the PP of 7 years as a reference to encourage citizens to install self-consumption systems. Then, we seek the necessary grant to make NPV equal to zero with  $N = 7 \text{ years}$  and perform a linear regression:  $ax + b$  with  $a \in \mathbb{R}^+$  in c€/kWh and  $b \in \mathbb{R}$  in €. Results are displayed in Figure 4.

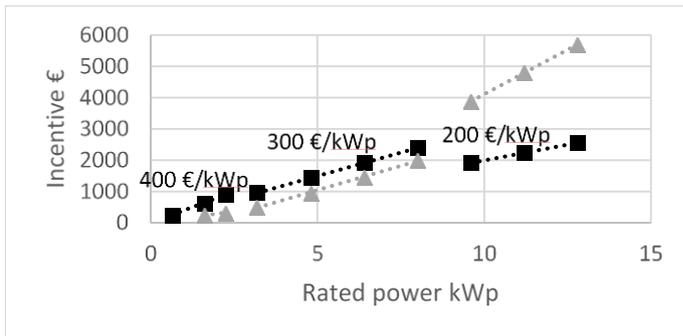
(PLEASE INSERT FIGURE 4)



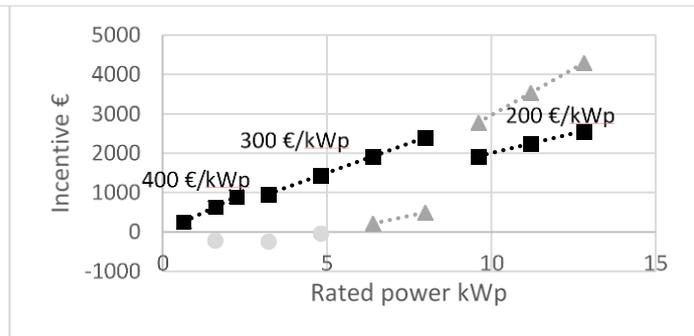
a) Ruch, 2 persons



b) Carcassonne, 2 persons



c) Ruch, 5 persons



d) Carcassonne, 5 persons

■ Current incentive    ▲ New incentive    ● Non necessary incentive

Unlike the non-monotonous current grant, the new one is always increasing with rated power (grey lines always go up). When changing from a 2-persons households to a 5-persons one, the grant decreases since the 5 persons households originally makes more profit than the 2-persons one (magnitude on incentive scale is lower). Similarly, the sunniest place, much more favoured in terms of energy potential, receives a reduced grant. Especially, in Carcassonne for low rated power (1.6 kWp for 2 persons and 1.6 to 4.8 kWp for 5 persons) the grant is null (light grey) since the PP is under 7 years without any grant (Table 6). Finally, it is noticeable that the grant calculus is more sensitive to the localisation and available sunshine than to the household composition.

## 7 Conclusion

This paper focuses on grid-connected HRES. The literature overview shows that the economic assessment of such HRES is incomplete and lacks genericity. Therefore, we propose a generic model

to perform economic assessment of grid-connected systems. Then, we specify it as a MILP model in the context of the 2017 French regulation encouraging self-consumption. Finally, we study the case of two types of households – one of 2 persons and the other of 5 persons – equipped with PV panels and located in either Ruch (unfavourable sunshine) or Carcassonne (favourable sunshine). We have shown that the higher the rated power of the system, the lower the environmental impact of the household will be. We have also demonstrated that the current grant for investing in household PV does not encourage private persons to install a maximum of rated power and that it does not guarantee a uniform development of self-consumption infrastructure across the country. Thus, we propose a methodology to find the appropriate grant calculus to reverse those tendencies.

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Table 7. Grant and gain/cost relation for Carcassonne

Rated power [kWp]		1.6	3.2	4.8	6.4	8	9.6	11.2	12.8	
Carcassonne 2 persons	Without grant	Grant [€/kWp]	0							
		Gain/Cost [%]	19.4	17.5	16.7	16.1	15.8	10.7	10.4	10.2
	Current grant	Grant [€/kWp]	400	300	300	300	300	200	200	200
		Gain/Cost [%]	34	25.9	24.6	23.8	23.4	13.6	13.3	13.0
	New grant	Grant [€/kWp]	0	0.194x - 461			0.491x - 940			
		Gain/Cost [%]	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6
	Carcassonne 5 persons	Without grant	Grant [€/kWp]	0						
			Gain/Cost [%]	21.3	20.0	18.7	17.9	17.3	12.8	12.3
Current grant		Grant [€/kWp]	400	300	300	300	300	200	200	200
		Gain/Cost [%]	37.5	29.6	27.7	26.4	25.6	16.3	15.6	15.1
New grant		Grant [€/kWp]	0		0.175x - 906		0.472x - 1752			
		Gain/Cost [%]	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6

Table 8. CAPEX, OPEX, Gain and bill saving details

Rated power [kWp]		1.6	3.2	4.8	6.4	8	9.6	11.2	12.8
Ruch 2 persons	CAPEX [€]	1 280	2 560	3 840	5 120	6 400	7 680	8 960	10 240
	OPEX [€/year]	38.4	76.8	115	154	192	230	269	307
	Gain [€/year]	43	169	314	456	619	465	559	653
	Bill saving [€/yeat]	178	238	265	280	290	297	302	306
Ruch 5 persons	CAPEX [€]	1 280	2 560	3 840	5 120	6 400	7 680	8 960	10 240
	OPEX [€/year]	38.4	76.8	115	154	192	230	269	307
	Gain [€/year]	5	81	196	328	468	368	458	549
	Bill saving [€/year]	225	376	456	506	540	565	585	600
Carcassonne 2 persons	CAPEX [€]	1 280	2 560	3 840	5 120	6 400	7 680	8 960	10 240
	OPEX [€/year]	38.4	76.8	115	154	192	230	269	307
	Gain [€/year]	79	267	470	676	885	657	783	909
	Bill saving [€/year]	210	254	273	284	292	298	302	306
Carcassonne 5 persons	CAPEX [€]	1 280	2 560	3 840	5 120	6 400	7 680	8 960	10 240
	OPEX [€/year]	38.4	76.8	115	154	192	230	269	307
	Gain [€/year]	16	148	327	520	720	554	677	801
	Bill saving [€/year]	302	448	509	544	568	586	600	611

