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How can flexibility mechanisms reduce greenhouse gas emissions in the residential sector ?

The effect of dynamic pricing and self-consumption on CO_2 emissions.

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Abstract

Human activities are nowadays recognized by the scientific community as the most important driver of greenhouse gas emissions across the Earth's surface. As global warming and climate change are becoming increasingly important challenges to tackle, one must find ways to reduce the human's carbon footprint to strive towards net zero carbon emissions and meet the goals of the 2015 Paris Agreement.

This work addresses the impact that flexibility mechanisms have on greenhouse gas emissions in the residential sector. More specifically, it tries to determine how the CO_2 emissions of a residential consumer vary when dynamic tariffs of electricity are implemented or when self-consumption is performed using photovoltaic panels and a battery. To do so, consumption profiles are submitted to a financial optimization and the emissions are computed using various emission factors and CO_2 assessment methods.

The study shows that dynamic pricing only has a limited effect on the CO_2 emissions because of the losses that occur in the battery. Depending on the situation, these losses can either be greater or smaller than the gains obtained through the flexibility mechanism, leading to small reductions or small increases of the emissions. Photovoltaic self-consumption allows to significantly reduce the emissions because grid-consumed electricity can be replaced by self-produced electricity which releases less emissions.

Acknowledgements

First of all, I wanted to thank my supervisor, professor Emmanuel De Jaeger, for his availability during this semester and for giving me the opportunity to perform this thesis in collaboration with Laborelec.

A special thanks as well to Cathy Crunelle, for welcoming me in her research team, for her valuable advice and for allowing me to work on this very interesting subject of electricity carbon content.

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Finally I would like to express my gratitude and throw a special thanks to Louis Fichefet, for being my mentor at Laborelec and for helping me along those four months of work. His availability, comments and reviews are an important part of the reason why I was able to conduct this thesis successfully.

Cédric Desneux

Contents

Acronyms

CH_4 Methane.

CO_2 Carbon Dioxide.

EF Emission Factor.

GHG Greenhouse Gas.

GWP Global Warming Potential.

IPCC Intergovernmental Panel on Climate Change.

N_2O Nitrous Oxide.

PV Photovoltaics.

TSO Transmission System Operator.

UNECE United Nations Economic Commission for Europe.

Chapter 1

Introduction

In August 2021, the Intergovernmental Panel on Climate Change (IPCC) published the first part of its Sixth Assessment Report addressing the physical understanding of the climate system and climate change. Its summary starts with the strong message stating that *«it is unequivocal that human influence has warmed the atmosphere, ocean and land»* and that *«observed increases in well-mixed greenhouse gas concentrations since around 1750 are unequivocally caused by human activities»* [1]. Figure 1.1 illustrates the significant impact human activities and industrialization have had on carbon dioxide (CO_2) emissions in the last century. This spike in emissions compared to earlier periods is the main driver of the greenhouse effect leading to global warming today.

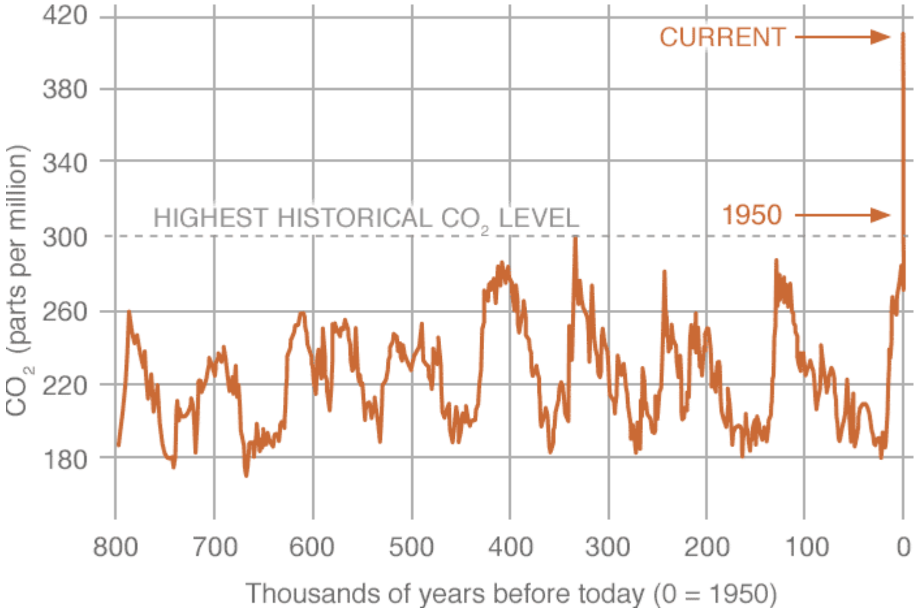

Figure 1.1: Evolution of CO_2 concentration levels on Earth. Human activities and industrialization in the last century have profoundly increased CO_2 levels in Earth's atmosphere. The measurements were obtained by reconstruction from ice cores [2].

1.1 Greenhouse effect and global warming of Earth

The greenhouse effect is the way in which heat is trapped close to Earth's surface by greenhouse gases (GHGs) [3]. Solar radiation emitted by the Sun is absorbed at the planet's surface and is then reflected as heat back towards the atmosphere and space. However, as heat is making its way back, some of it is absorbed by GHGs in the atmosphere (Figure 1.2). This natural phenomenon is needed to keep a viable temperature on Earth but the additional GHGs produced by human activities are responsible for an increased greenhouse effect leading to global warming (Figure 1.3). The most common undesirable GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide[1] (N_2O) and fluorinated gases of different categories [5] [6] [7].

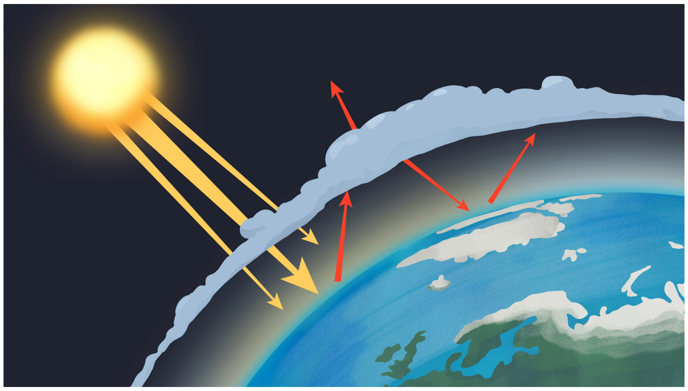

Figure 1.2: The greenhouse effect : solar radiation is reflected by Earth's surface as heat towards the atmosphere and space. GHGs in the atmosphere prevent part of the heat to escape to space, leading to increasing temperatures in the atmosphere. Figure source : [8].

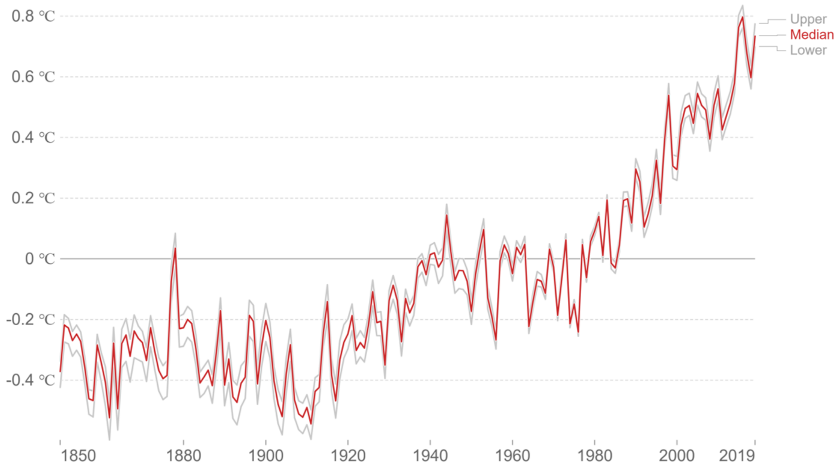

Figure 1.3: Global average land-sea temperature anomaly relative to the 1961-1990 average temperature [9]. The red line shows the median average temperature anomaly, the grey lines show the upper and lower 95% confidence intervals. Since beginning 2000, Earth's temperature has continue to increase due to the greenhouse effect : 19 of the hottest years have occurred between 2000 and 2020 [10]. Data source : Hadley Centre (HadCRUT4) [11].

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[1] Nitrous oxide is mainly emitted by agricultural activities (soil fertilization and animal waste management) [4].

1.2 Global Warming Potential (GWP)

In order to compare the impact and the respective contribution of the different GHGs to the greenhouse effect, a relative scale was developed by the IPCC since its First Assessment Report of 1990 : the Global Warming Potential (GWP). This scale measures the capacity of a certain mass of gas to absorb energy over a certain time period, relative to the absorption capacity of the same mass of CO_2 and over the same period of time. It is thus a reflection of a gas's energy absorption capacity (called radiative efficiency) and of its lifetime (how long the gas remains in the atmosphere). CH_4, for instance, has a shorter lifetime than CO_2 but a much higher energy absorption capacity, thus resulting in a higher GWP. The most common reference time period to assess the GWP is 100 years. Figure 1.4 shows a comparison of the GWPs of the most common GHGs. GWPs of fluorinated gases such as sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are not shown because they lie much higher (23500 and 16100 respectively)[2].

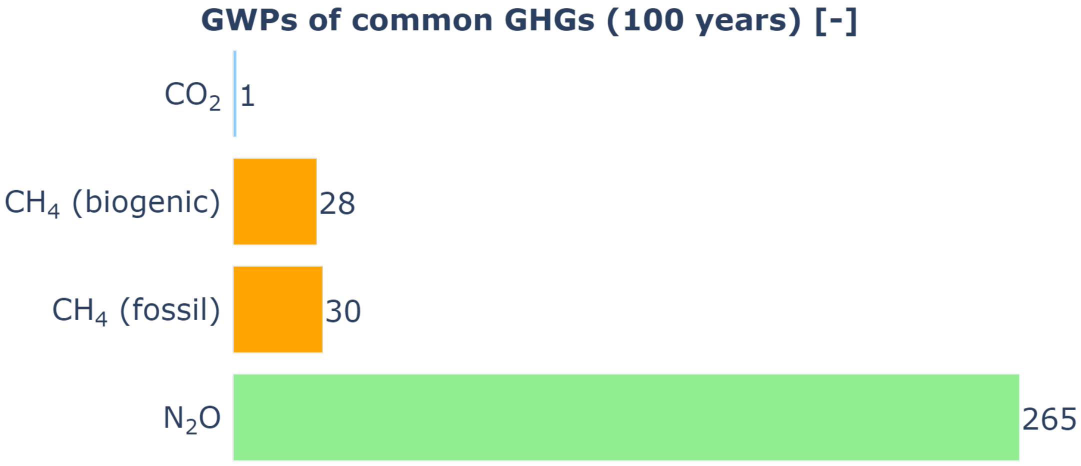

Figure 1.4: GWPs (100 years) of the most common GHGs [14]. CO_2 has a much lower GWP than CH_4 and N_2O. Fluorinated gases have really high GWPs (23500 for SF_6 for instance) and are hence not shown for clarity purposes.

The GWP thus allows to express emissions from various gases in CO_2-equivalent emissions. For instance, 1g of emitted CH_4 from fossil origin (whose GWP is 30) is equivalent to a 30g emission of CO_2. This is useful to compare the carbon footprint of processes across diverse sectors and industries such as comparing the GHG emissions of various electricity generating sources, as described in chapter 2.

Note that though CO_2 has a low GWP compared to other GHGs, it is the gas which affects the greenhouse effect the most since it is released in much higher quantities. Figure 1.5 compares the global 2019 emissions of the most common GHGs on the CO_2-equivalent scale. On this scale, one can observe that gases with the higher GWPs are actually less harmful than the ones with the lower GWPs. This explains why CO_2 is often rightfully considered as the main driver of global warming.

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[2] SF_6 is primarily used as an insulating gas for electrical applications [12] while NF_3 is commonly used in the microelectronic manufacturing industry [13].

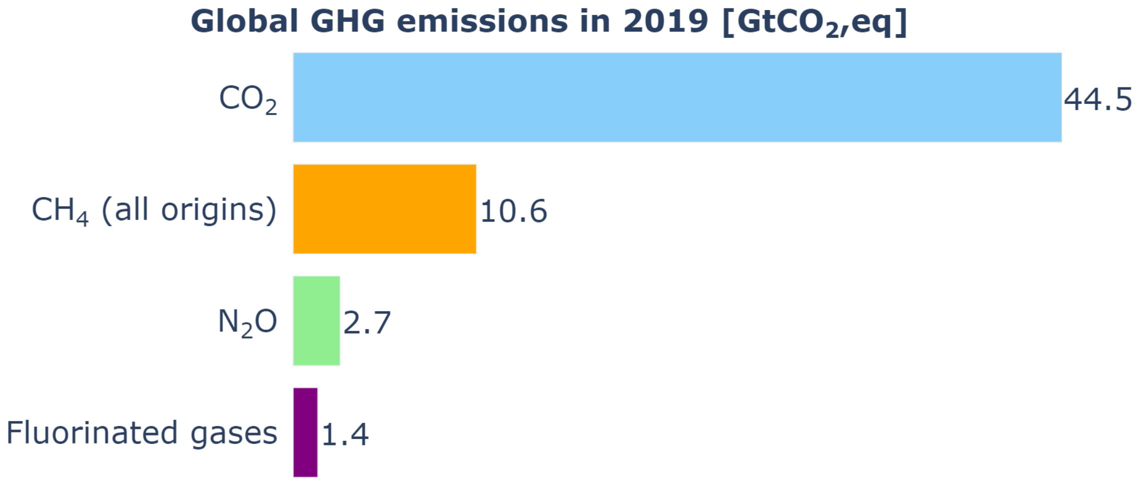

Figure 1.5: 2019 global GHG emissions [1]. On the CO_2-equivalent scale, CO_2 is the most emitted GHG. Gases with higher GWPs such as the fluorinated gases actually have a lower impact on the greenhouse effect because they are emitted in small quantities.

Chapter 2

State of the art and general concepts

This chapter describes and explains the general concepts used throughout this thesis. It firstly addresses the essential concept of electricity carbon content by dividing it in two parts : the emission factors of the different electricity generating sources on the one hand and the CO_2[1] emission assessment methods on the other hand. It then takes a closer look at typical flexibility mechanisms used in the residential sector.

2.1 Emission factors of electricity generating sources

Electricity does not release any CO_2 at the moment of consumption. However, this does not mean that electricity does not release CO_2 when it is produced[2]. In fact, the International Energy Agency (IEA) states that electricity and heat generation are responsible for 44% of global released CO_2 in 2019 (Figure 2.1). The United States Environmental Protection Agency even says that electricity alone is responsible for 25% of the GHG emissions in the country in 2020, only surpassed by transport (27%) [15]. Assessing emissions related to electricity generation is thus key to determine the impact electricity consumption really has on the greenhouse effect. In this regard, emission factors of electricity generating sources are the first important concept to understand.

The emission factor (EF) of an electricity generating source is the amount of GHG the source emits per unit of electricity produced. It is expressed in grams of CO_2-equivalent per kWh of electricity : [gCO_2,eq/kWh]. The values obtained for each source often vary in function of hypotheses taken for the various power plants. To take into account that multiple values can be computed for a same power source, three values provided by three different organizations are presented here and used throughout this study. The organizations are the *French Environment and Energy Management Agency* (ADEME[3]), the IPCC and the *United Nations Economic Commission for Europe* (UNECE). The following sections present the organizations and their respective computed EFs and compare the obtained values for each electricity source.

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[1] It is the first time that "CO_2" is used instead of "carbon" or "CO_2-equivalent" in this context. As the reader now understands the concept of GWP, all emissions will be referred to as CO_2 for simplicity reasons.

[2] Transportation losses can be accounted for in the generation part, by considering extra production to cover them.

[3] *Agence De l'Environnement et de la Maîtrise de l'Energie* in French.

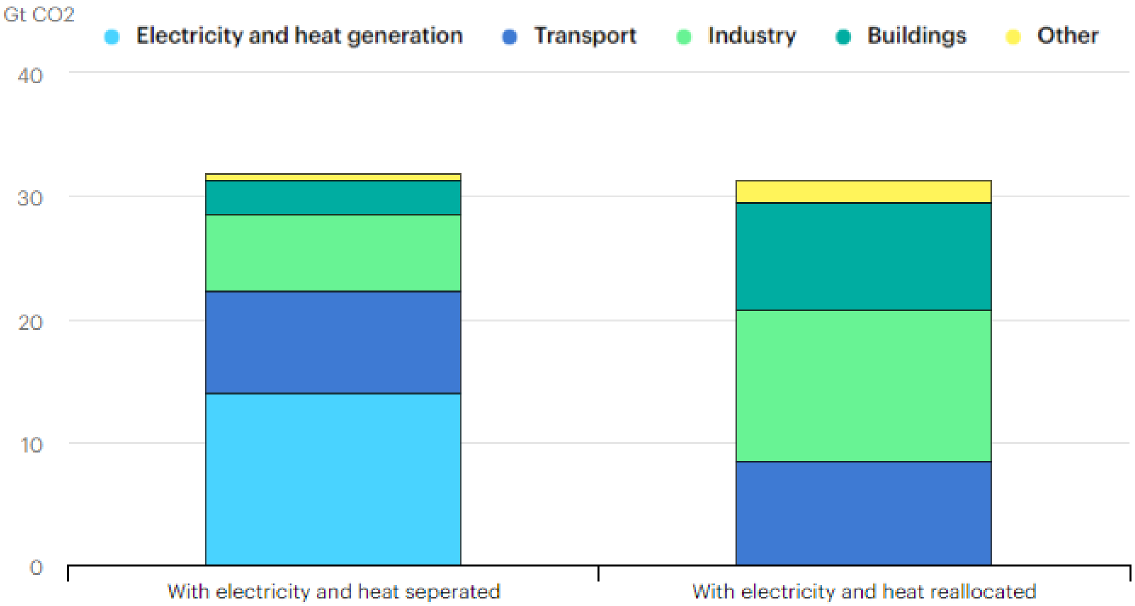

Figure 2.1: Global CO_2 emissions by sector in 2019 [16]. Electricity and heat generation emit the most with 14 $GtCO_2$ released in the atmosphere representing 44% of the total emissions.

2.1.1 EF assessment : *Base Carbone* ADEME

The ADEME is the French Environment and Energy Management Agency. The ADEME has developed its *Base Carbone* which is a *«public database of emission factors as required for carrying out carbon accounting exercises»* [17]. The EFs provided by the ADEME (shown in Figure 2.2) are obtained through life-cycle assessments and are originally computed for production plants in France[4]. They cover the following :

- **Conventional production plants** (nuclear-, gas-, oil- and coal-powered facilities) :
  - Fuel combustion (fossil fuel plants only)
  - Fuel supply (all plants)
  - Plant construction (all plants)

  Line losses are not taken into account.

- **Renewable energy sources** (hydro, wind and solar) :
  - Upstream emissions for the energy resource
  - Production chain manufacturing
  - Production chain maintenance

  The use of the energy resource is considered emission free.

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[4] However, this does not mean their use is exclusive to studies in France.

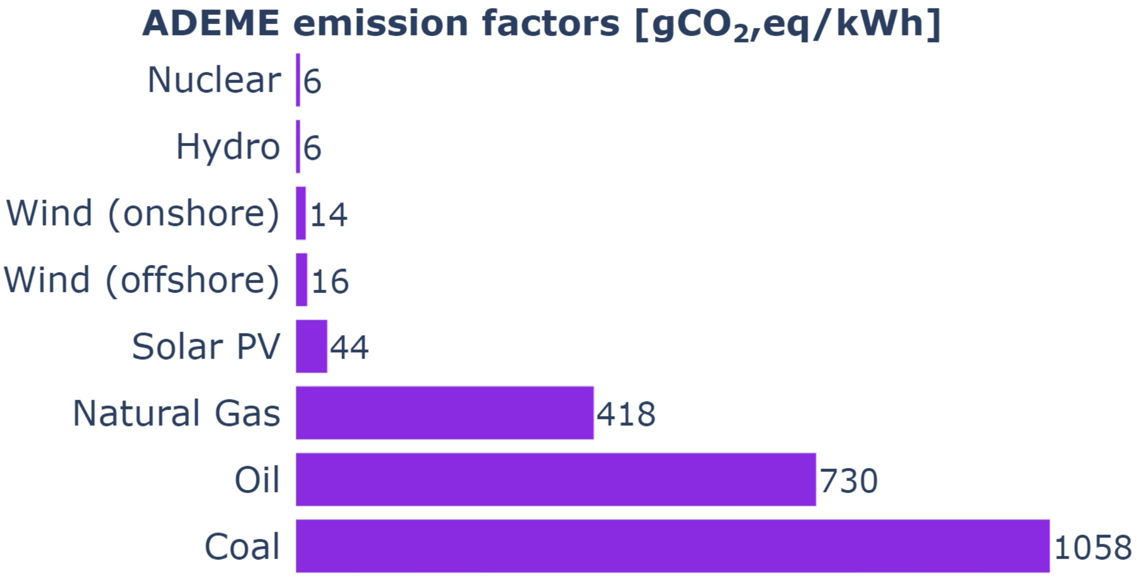

Figure 2.2: Emission factors provided by ADEME [18]. Fossil fuel power plants emit much more GHGs than renewable energy sources. Coal is the most emitting power plant type with over 1 kgCO_2,eq/kWh of produced electricity while nuclear and hydro are the least emitting (only 6 gCO_2,eq/kWh).

2.1.2 EF assessment : IPCC

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations's body for assessing the science related to climate change. Its main goal is to provide governments information to help them develop climate policies [19]. In its Fifth Assessment Report (2014), the IPCC published EFs of the most common electricity supply technologies. Figure 2.3 shows most of the published values [20].

The IPCC does not provide an EF for oil-powered plants but publishes a biomass EF of 230 gCO_2,eq/kWh. Note that this value is computed by neglecting direct emissions from the combustion process. Indeed, it is assumed that CO_2 released during combustion had been captured by the growing plants earlier in the life-cycle. Its relatively high value is thus due to the related infrastructure and supply chain emissions. Nuclear and hydro are considered to be emitting more GHGs than wind power. An additional distinction between utility scale and roof-mounted solar PV is made. Natural gas refers to Combined Cycle Gas Turbine (CCGT) plants and coal to Pulverized Coal[5] (PC) plants.

A broader comparison between the EF values across the publishing organizations is carried out further.

2.1.3 EF assessment : UNECE

The *United Nations Economic Commission for Europe* (UNECE) is one of the five regional commissions of the United Nations. Its goal is to promote pan-European economic integration [22]. In 2021, the organization published a detailed study on integrated life-cycle assessments of electricity sources [21]. Figure 2.4 gives the EFs published in that paper. They are very similar to the ones provided by ADEME as the general EF hierarchy is the same. No

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[5] This is the most widely spread type of coal power plants across the world [21].

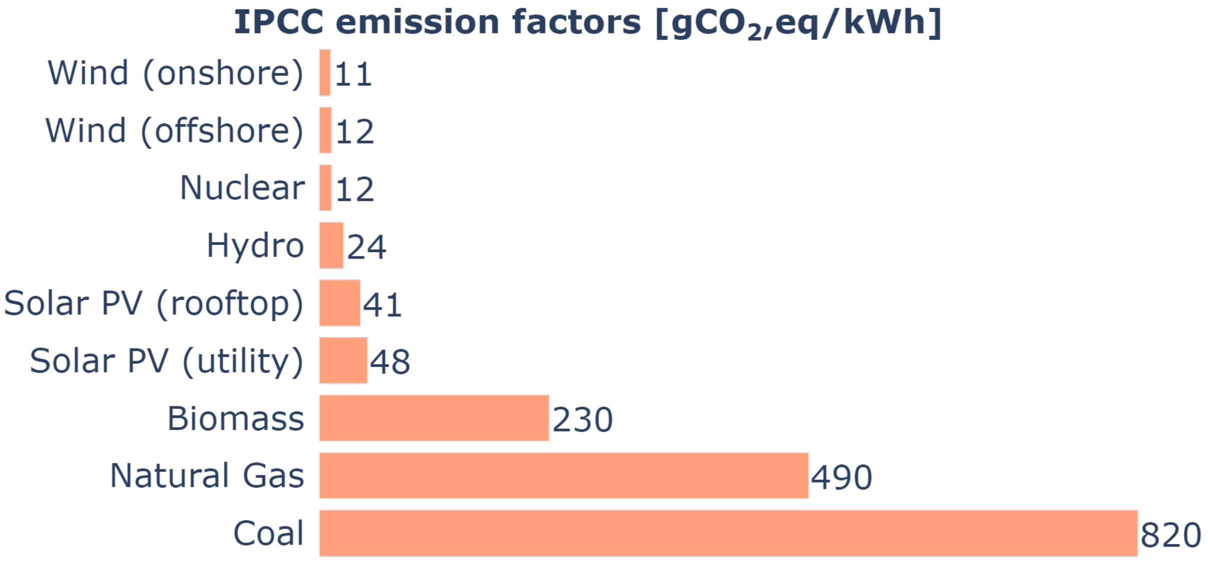

Figure 2.3: Median emission factors provided by the IPCC [20]. Fossil fuel power plants emit the most GHGs while wind power (on- and offshore) emit the fewest. Biomass plants emit a relatively high amount of CO_2 *compared to other renewable energy sources, even though the value of 230* gCO_2*,eq does not include combustion emissions. Rooftop and utility-scale solar PV installations are distinguished.*

EFs are provided for biomass- and oil-powered plants.

Additional information about some of the technologies are given in the paper and can be summarized as follows :

- Coal (1023 gCO_2,eq/kWh) : Pulverized coal (PC) without Carbon Capture and Storage (CCS), Europe, 2020
- Natural gas (434 gCO_2,eq/kWh) : Combined Cyle (CC), without CCS, Europe, 2020
- Solar PV (37 gCO_2,eq/kWh) : polycrystalline silicon PV technology[6], Europe, 2020. A small distinction is made between ground- and roof-mounted installations :
  - Ground-mounted : 36.7 gCO_2,eq/kWh
  - Roof-mounted : 37.2 gCO_2,eq/kWh

  The small variation is due to a slightly lower efficiency considered for roof-mounted PV, inducing a slight increase in emissions. However, as the two values are close to each other, the unique value of 37 gCO_2,eq/kWh is used through this study.

2.1.4 EF comparison

Globally, one can conclude that the three organizations provide similar values for most of the electricity sources. It is clear that fossil fuel power plants emit much more GHGs than renewable energy sources, except for biomass

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[6] Even though the PV technology market diversified itself in the last decade (with thin-film technologies for instance), silicon-based panels still represent the majority of PV installations, mainly due to their high efficiency compared to thin-film panels [21].

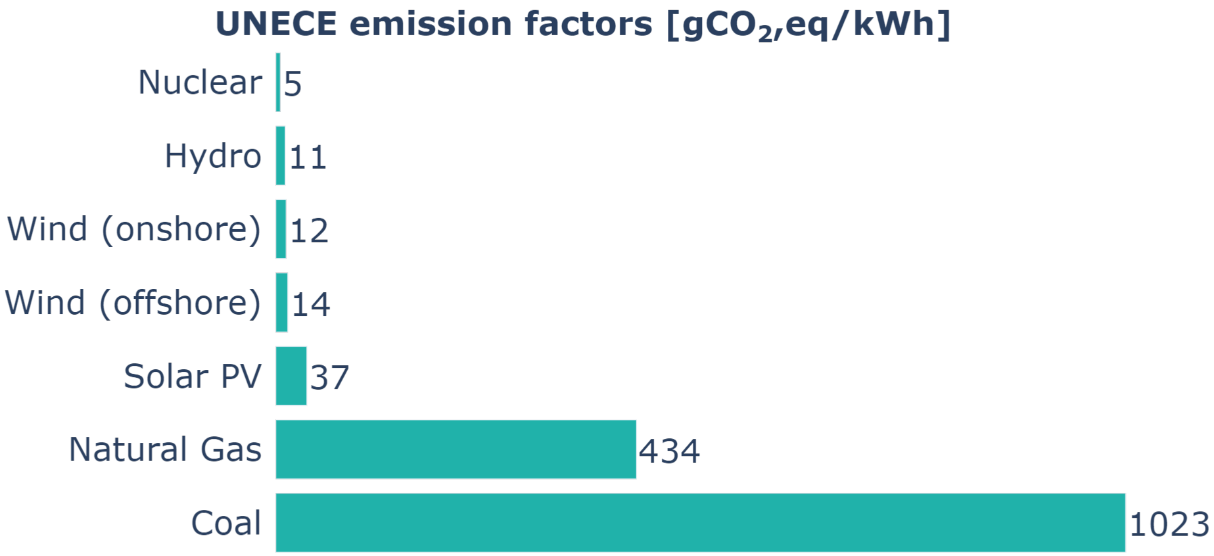

Figure 2.4: Emission factors provided by the UNECE [21]. The EF distribution is very similar to ADEME's and the same observations can thus be made.

which stands in the middle. As only one organization provides values for biomass (IPCC : 230 gCO_2,eq/kWh) and oil (ADEME : 730 gCO_2,eq/kWh), one can not perform any real comparison for these sources. For clarity purposes and coherence throughout this study, the EFs provided by the sole organization are considered globally valid (the organizations which do not provide an EF are assumed to use the same value as the organization that does). Figures 2.5 and 2.6 compare the EFs provided across all three organizations. For clarity purposes, low- and high-emitting electricity sources were split in two different graphs. Some important results stand out and must be mentioned :

- Wind power (both on- and offshore), solar PV and natural gas have similar EFs across all three organizations.
- Hydropower is the energy source where the largest variations in EFs can be observed (ranging from 6 to 24 gCO_2,eq/kWh). The most likely reason for this large range is the variation in considered amount of emitted GHGs for the plant construction. Indeed, for a hydropower plant, most of the GHG emissions are related to fossil fuel combustion during the plant construction itself [23], mainly for transportation [21]. This means that the computed EF is very site-specific and can vary quite a bit in function of the considered plant's location [21].
- The IPCC sets the coal EF (820 gCO_2,eq/kWh) about 20% lower than ADEME (1058 gCO_2,eq/kWh) and the UNECE (1023 gCO_2,eq/kWh). The UNECE provides a detail explanation on this variation. In short, it is likely that some plant efficiencies have been overestimated leading to the low value of 820 gCO_2,eq/kWh. However, as the IPCC is a widely-recognized organization, this low value is kept throughout this study for its coal EF.
- The IPCC sets the nuclear EF (12 gCO_2,eq/kWh) twice as high than ADEME (6 gCO_2,eq/kWh) and the UNECE (5 gCO_2,eq/kWh). In this case, much less computation details are provided by the organizations and one must thus accept this large gap as it is.

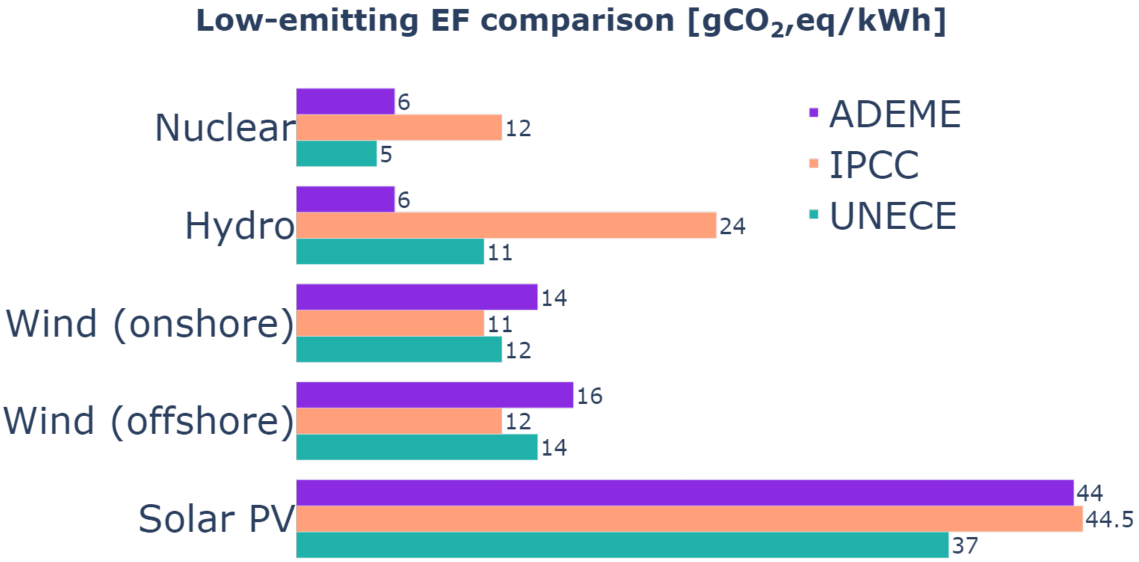

Figure 2.5: EF comparison of the low-emitting electricity sources. Wind and Solar PV yield similar EFs. Hydropower EFs vary a lot, mainly due to the variation in estimated fossil fuel combustion emissions during the plant's construction. The IPCC estimates the nuclear EF to be two times higher than ADEME's and UNECE's estimations.

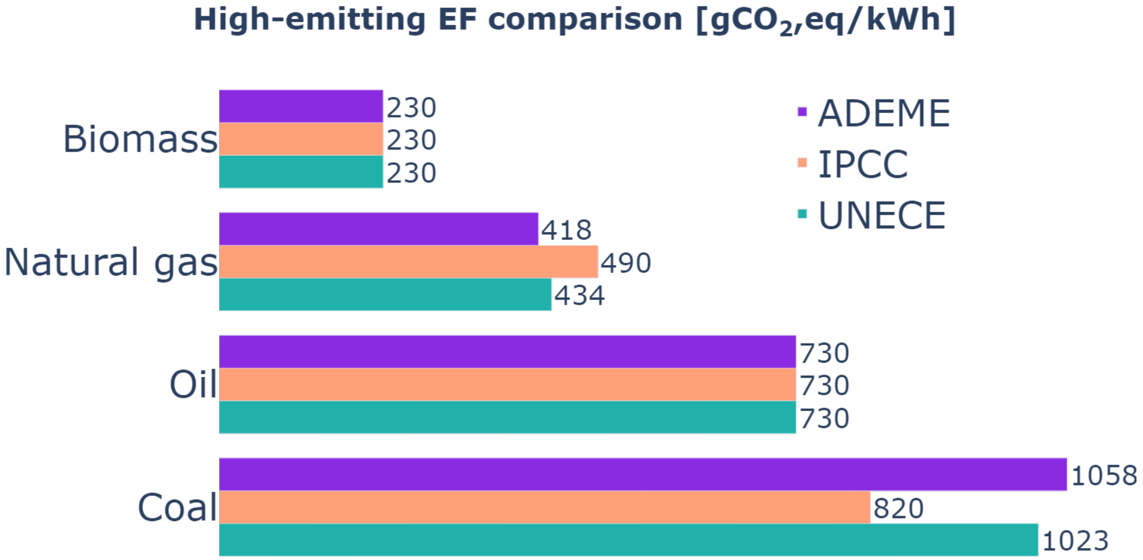

Figure 2.6: EF comparison of the high-emitting electricity sources. Biomass and oil EFs are only provided by one organization (IPCC and ADEME respectively) but their values are generalized to all organizations. Natural gas yields similar EFs. Compared to ADEME and the UNECE, the IPCC estimates that coal emits around 20% less. The main reason is a likely overestimation of coal power plant efficiencies in the works used and cited by the IPCC.

2.2 Electricity CO_2 emission assessment methods

Now that the concept of emission factor (EF) has been introduced and thoroughly explained, one can take a closer look at the various electricity CO_2 emission assessment methods[7]. These methods are used to compute the carbon content of electricity over a certain period of time or to assess the effect on carbon emissions when precise actions are taken. To identify each method's advantages and drawbacks and to compare them with each other, one can assess them through five criteria :

1. **Global emission computation** : can the method assess global emission levels ?
2. **Consumption uses computation** : is it suited to assess the carbon emissions of specific consumption uses (heating, cooking, lighting, hot water production, etc.) ?
3. **Flexibility applications** : can it help make short- or mid-term decisions to implement flexibility ?
4. **Prospective scenarios** : can it help make long-term decisions to assess future changes in the electrical grid (public policies, legal requirements, etc.) ?
5. **Data requirements** : how much data is required to apply this method successfully (low/medium/high) ?

2.2.1 Mean mix methods

Mean mix methods are the most commonly used assessment methods and consist in computing the total CO_2 emissions related to a certain production of electricity over a certain period of time (a year, a month or an hour) and divide the result by the total production over the same period. The three different time steps (yearly, monthly and hourly) lead to three different methods whose computation principle is the same but whose main goals and applications are different since the levels of precision are not the same. Let us detail the advantages and drawbacks of each of them.

Mean mix method - yearly time step

Principle and computation The mean mix method computes a yearly average of CO_2 emissions and is used by ADEME to perform some global GHG emission assessments. Equation 2.1 shows how the global electricity carbon content $Q_{CO_2,global}$ is computed using this method.

$$Q_{CO_2,global} = \frac{CO_{2,prod.} + CO_{2,imp.} - CO_{2,exp.}}{E_{prod.} + E_{imp.} - E_{exp.}} \quad [gCO_{2,eq}/kWh] \tag{2.1}$$

where $E_{prod.}$, $E_{imp.}$ and $E_{exp.}$ are respectively the total electricity produced, imported and exported from the considered territory (all expressed in [kWh]) and where $CO_{2,prod.}$, $CO_{2,imp.}$[8] and $CO_{2,exp.}$ are the related CO_2 emissions in [gCO_2,eq].

Criteria assessment The main advantage of the average mix method is to give a quick overview of the carbon emissions of a certain territory, with only few data. However, as it computes a global yearly average, this method is unable to affect some electricity consumption uses (such as heating or lighting for instance) with different emission

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[7] This section is largely inspired by ADEME's *Base carbone* [18] and [24].

[8] The importation EF can be computed as an average of the European electrical mix.

Global Emissions	Consumption Uses	Flexibility Applications	Prospective Scenarios	Data Requirements
✓	✗	✗	✗	Low

Table 2.1: Mean mix method - yearly timestep : criteria assessment

factors and thus to compare their respective carbon intensity. It is also not suited for prospective (short- and long-term) purposes. Table 2.1 summarizes the method's performance for the defined criteria.

Monthly method (mean mix method - monthly time step)

Principle and computation The monthly method uses the same principle as the yearly mean mix method, except that it computes a different carbon content (which is called the *monthly carbon content* and is noted $Q_{CO_2,i}$ for clarity) for each month.
Equation 2.2 details the computation of the monthly carbon content $Q_{CO_2,i}$:

$$Q_{CO_2,i} = \frac{\sum_{p=1}^{P} \left(P_{p,i} \cdot EF_p \right)}{\sum_{p=1}^{P} P_{p,i}} \quad [gCO_{2,eq}/kWh] \tag{2.2}$$

where p refers to a power generating unit and i to a month of the year. $P_{p,i}$ is the electricity production of power generating unit type p during month i and EF_p is the emission factor of the same power generating unit type.

Criteria assessment The main advantage of using a monthly time step is a gain in precision which allows to assess and differentiate the carbon intensity of different electricity consumption uses. Since 2019, the monthly method is the reference method used by ADEME for all calculations when distinguishing electricity uses [25]. Based on the monthly carbon content, it is possible to compute the consumption EF[9] EF_{use} with Equation 2.3 :

$$EF_{use} = \frac{\sum_{i=1}^{12} \left(Q_{CO_2,i} \cdot C_{use,i} \right)}{\sum_{i=1}^{12} C_{use,i}} = \sum_{i=1}^{12} \left(Q_{CO_2,i} \cdot C_{use,i}^{\%} \right) \quad [gCO_{2,eq}/kWh] \tag{2.3}$$

where $C_{use,i}$ is the usage electricity consumption during month i generally expressed in GWh and $C_{use,i}^{\%}$ is the monthly share of electricity consumption of the considered usage type relative to its total yearly consumption. Table 2.2 summarizes the method's performance for the defined criteria.

Global Emissions	Consumption Uses	Flexibility Applications	Prospective Scenarios	Data Requirements
✓	✓	✗	✗	Medium

Table 2.2: Monthly method : criteria assessment

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[9] This EF relates to electricity consumption uses (heating, lighting, etc.) and not to the EF of an electricity generating source like presented in the previous Chapter. To make a clear distinction between the two, EFs related to electricity usage types are referred to as consumption EFs.

RTE eCO$_2$Mix (mean mix method - hourly time step)

The hourly method works exactly like the monthly method but with a shorter time step (usually 1 hour but it can get even shorter, down to a quarter-hour). This method thus requires a substantial amount of data but has the advantage of being able to be coupled with flexibility applications. Indeed, by re-evaluating the carbon content of electricity each hour, demand-side management can be implemented in order to try to reduce CO$_2$ emissions. Technically, the method can also be used to determine the carbon intensity of consumption uses. However, it requires to know the hourly shares of consumption for each consumption use which is not easy to retrieve with this level of precision. The *French electricity transmission operator*[10] calls this method *eCO$_2$Mix* and uses it with a 30min time step to display data on its official website [26]. Table 2.3 summarizes the method's performance for the defined criteria.

Global Emissions	**Consumption Uses**	**Flexibility Applications**	**Prospective Scenarios**	**Data Requirements**
✓	✓	✓	✗	High

Table 2.3: Monthly method : criteria assessment

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[10] called *Réseau de Transport d'Electricité* in French an referred to as RTE.

2.2.2 Seasonal method

Principle and computation The seasonal method was a widely used method by ADEME before 2019. It has now been considered obsolete when it comes to distinguishing carbon emissions of various consumption uses (in favor of the monthly method) but is still interesting to understand and analyze [25].

The basic principle is to make a distinction between a base and a seasonalized part of the electrical production and consumption. By applying different carbon content factors for the base and seasonalized parts, one can affect consumption uses with EFs varying in a larger range. Indeed, the more a consumption use is specific to periods when the electricity has a large carbon content (typically heating which is important during the winter period[11]), the larger its consumption EF. For each power generating unit type, the base production part $P_{base,p}$ corresponds to the lowest monthly production reached over the year while the seasonalized part $P_{season,p,i}$ corresponds to the difference between the total monthly production and the base part.

This leads to a unique base carbon content Q_{base} (Equation 2.4) and twelve different monthly seasonalized carbon contents $Q_{season,i}$ (Equation 2.5) :

$$Q_{base} = \frac{\sum_{p=1}^{P} \Big(P_{base,p} \cdot EF_p \Big)}{\sum_{p=1}^{P} P_{base,p}} \quad [gCO_{2,eq}/kWh] \tag{2.4}$$

$$Q_{season,i} = \frac{\sum_{p=1}^{P} \Big(P_{season,p,i} \cdot EF_p \Big)}{\sum_{p=1}^{P} P_{season,p,i}} \quad [gCO_{2,eq}/kWh] \tag{2.5}$$

The same principle is applied to the electricity consumption leading to a base consumption $C_{base,u}$ and a seasonalized consumption $C_{season,u,i}$ for each use. The emission factor for each use can then easily be computed with Equation 2.6 :

$$EF_{use} = \frac{\sum_{i=1}^{12} \Big(C_{base,u} \cdot Q_{base} + C_{season,u,i} \cdot Q_{season,i} \Big)}{\sum_{i=1}^{12} \Big(C_{base,u} + C_{season,u} \Big)} \quad [gCO_{2,eq}/kWh] \tag{2.6}$$

As written before, this method allows for a larger range of consumption EFs and thus strongly penalizes consumption uses which consume highly carbonated electricity. To give a better understanding, Annex **??** compares the monthly method and the seasonal method for the assessment of consumption uses in France in 2019.

Criteria assessment The seasonal method is well-suited to assess consumption uses emissions as it was developed for this purpose. When it comes to the criteria assessment, it has the same characteristics as the monthly method (Table 2.4).

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[11] As the electricity consumption increases during the winter, more generating units are required to meet the demand. This increases peak unit electricity needs (see Section 2.2.3 on the Merit Order Curve principle) which increases the global carbon content.

Global Emissions	Consumption Uses	Flexibility Applications	Prospective Scenarios	Data Requirements
✓	✓	✗	✗	Medium

Table 2.4: Seasonal method : criteria assessment

2.2.3 Methods with prospective purposes

Methods with prospective purposes are, as their name suggests, used to assess the effect of a future change in electricity production or consumption on the carbon emissions.

Marginal method

The marginal method is a method whose purpose is to assess the effect of small changes of production or consumption on a short time scale horizon (usually 1 hour or less). To fully understand its principle, let us first introduce the **merit order curve and principle**.

Merit order curve and principle The merit order can be defined as «*the sequence in which power plants are designated to deliver power, with the aim of economically optimizing the electricity supply*» [27]. Each hour, the power generating units are classified from lowest to highest bid (price at which the unit agrees to sell its electricity[12]) and are then aggregated to form the electricity supply curve. The intersection between this curve and the demand curve determines the market clearing price and volume. Figure 2.7 illustrates this concept.

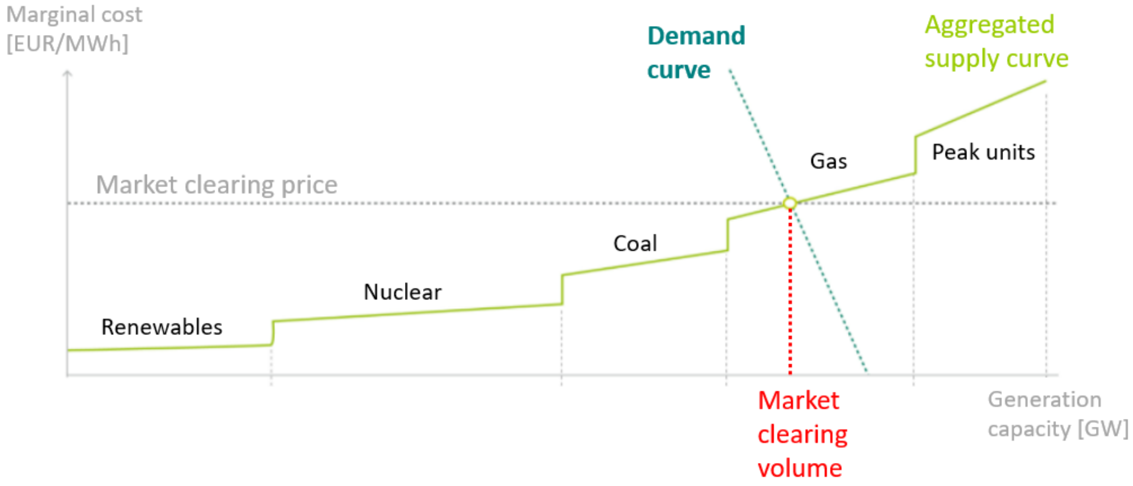

Figure 2.7: Merit order principle and electricity clearing mechanism illustration [27]. Each hour, producers are classified from lowest to highest bidder to create the aggregated supply curve. Its intersection with the demand curve then determines the market clearing price and volume.

As can be seen on Figure 2.7, renewable energy producers bid the lowest selling price. This is due to their very low marginal cost. Physically, this can be understood because additional wind or sun does not yield an additional

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[12] Practically, bidding its marginal cost is the most common procedure. However, negative bids can occur, especially in case of high renewable production. Conventional producers then sometimes prefer to pay to deliver their electricity rather than shutting down their operations.

cost. Theoretically, one could say that renewables have a 0€/MWh marginal cost. In practice however operation and maintenance activities lead to a low and slowly-increasing supply curve. Nuclear comes in second place and is then followed by thermal plants using fossil fuels (coal, gas, oil, etc.). Their bids are high because they usually have a high marginal cost, partly due to governmental carbon-related taxes and partly because increasing their capacity requires an increasing amount of fuel.

Marginal method principle The main idea of the marginal method is to suppose that a small change in electricity consumption only affects the last-selling power generating unit in the merit order[13]. Using Figure 2.7 as illustration, it means that a increase/decrease of 1 MW of electricity demand would lead to a increase/drop of production of 1 MW with the gas power plant only (the production with renewable energy sources, nuclear and coal would not vary). From a CO_2 point of view, this leads to much larger emission ranges as the additional/saved electricity is affected with a high carbon content (the EF of the last generating unit instead of an average EF of all the generating sources). Physically, the marginal method reflects the reality more closely than the mean mix methods.

Criteria assessment The marginal method can be a very powerful tool to model flexibility but it is also important to mention that **it is practically very difficult to assess which is the last-called generating unit in the merit order**. This explains why precise technical models of the method are currently lacking. As said earlier, this method is good to assess small variations in production or consumption but can definitely not be generalized to larger variations or long-term evolutions of the consumption and production profiles. This means it is unable to compute global emissions. Just like the mean hourly method, it is possible to determine consumption uses EFs but it requires a substantial amount of data. Table 2.5 summarizes the method's performance for the defined criteria.

Global Emissions	Consumption Uses	Flexibility Applications	Prospective Scenarios	Data Requirements
✗	✓	✓	✗	High

Table 2.5: Marginal method : criteria assessment

Incremental method

Computation and principle The incremental method can be seen as a long-term marginal method. It assesses the combined impact of both a significant evolution of the electrical mix (production variation) and a significant change in consumer behavior (consumption variation). The variation in production sources leads to a variation in CO_2 emissions (ΔCO_2) while the variation in consumer behavior leads to a change in electricity demand ($E_{dem.}$). The carbon content (Q_{CO_2}) can then be computed as given in Equation 2.7 :

$$Q_{CO_2} = \frac{\Delta CO_2}{\Delta E_{dem.}} \tag{2.7}$$

Figure 2.8 illustrates the principle of the incremental method.

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[13] This ideal interpretation is a good approximation but does not perfectly match the reality. Indeed, a change in consumption actually affects all power generating units which leads to a new aggregated and slightly modified electricity supply curve.

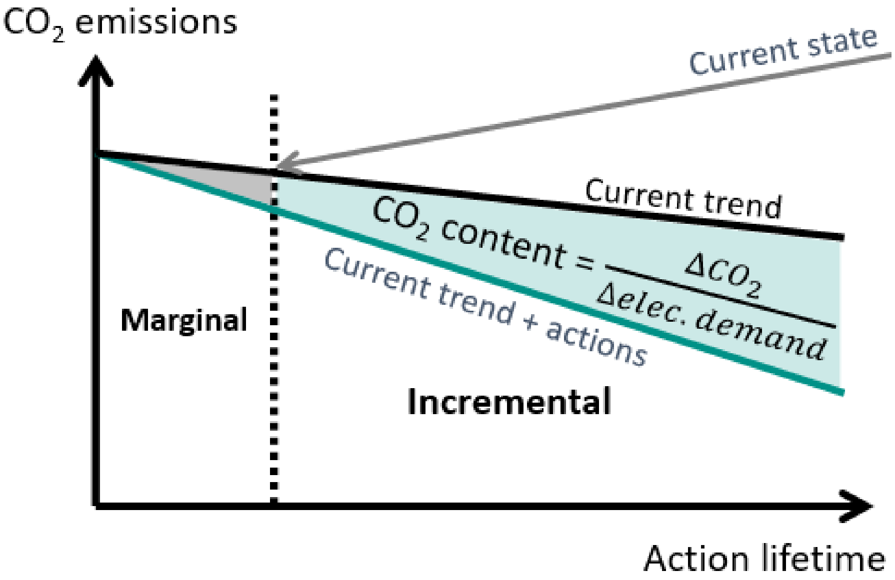

Figure 2.8: Illustration of the incremental method. By comparing a current trend with a scenario including actions, one can estimate variations in electrical production and consumption. Using these variations, it is possible to compute the carbon content of electricity [24].

Criteria assessment The incremental method's prospective aspect relates to a much longer time horizon (usually multiple years or even decades) than the marginal method. It is thus suited to compare long-term prospective scenarios[14] rather than to implement short-term flexibility. It is also important to point out that that the results obtained with the incremental method are highly dependent on the selected prospective scenarios. And some long-term parameters such as energy policies, economic growth or future electricity prices are not always easy to estimate with precision. Therefore, the incremental requires detailed studies of potential scenarios and a good amount of information and data. Table 2.6 summarizes the method's performance for the defined criteria.

Global Emissions	Consumption Uses	Flexibility Applications	Prospective Scenarios	Data Requirements
✗	✓	✗	✓	High

Table 2.6: Incremental method : criteria assessment

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[14] A typical application of the incremental method is to assess the impact of a public policy on the electrical market [25].

2.3 Electrical flexibility in the residential sector

This short section addresses the concept of electrical flexibility in the residential sector. When it comes to electrical power, flexibility is defined as «*the possibility to adjust the electrical consumption or production of an installation or process*» [28].

Electrical flexibility can be split in three different types :

1. **Production flexibility :** increase/decrease in the production of power plants (large fossil fuel or nuclear plants but also renewable energy sources or emergency generators for instance).
2. **Consumption flexibility :** also called **demand response**, refers to a temporary increase/decrease in electrical consumption in the industry (a large industrial process put on hold for instance) or in households (electrical boiler starts heating up water at a precise point of time).
3. **Storage flexibility :** charging/discharging of devices which can store and release energy when needed (pumped hydropower plants, domestic batteries, flywheels, etc.).

When addressing electrical flexibility in the residential sector, it mainly refers to consumption and storage flexibility. To implement flexibility, three elements are usually necessary : a driver (or goal), a mechanism and an asset.

2.3.1 Flexibility driver

The driver is the reason why flexibility is implemented. In other words, it is the goal the producer or consumer wants to achieve by integrating flexibility in his behavior. Some examples are :

- A large industrial factory reduces its consumption to help **balance the grid** and **restore the grid frequency** to its nominal value.
- A home-owner wants **to reduce his grid-dependency** and decides to install PV panels on his roof.
- A small business owner buys a domestic battery to **keep sensitive electrical processes running** in case of a black-out.

Even though these flexibility drivers might seem very different, it is quite clear that, in each case, the main goal is to reduce costs or increase income. Cost optimization is thus almost always the reason why one tries to implement flexibility.

2.3.2 Flexibility mechanisms

When combined with a driver, flexibility mechanisms allow for an adaptive behavior of the electrical production or consumption. Keeping in mind that the main goal of residential consumers is to decrease their electricity bill, one can present two main flexibility mechanisms in the residential sector : variable pricing and self-consumption.

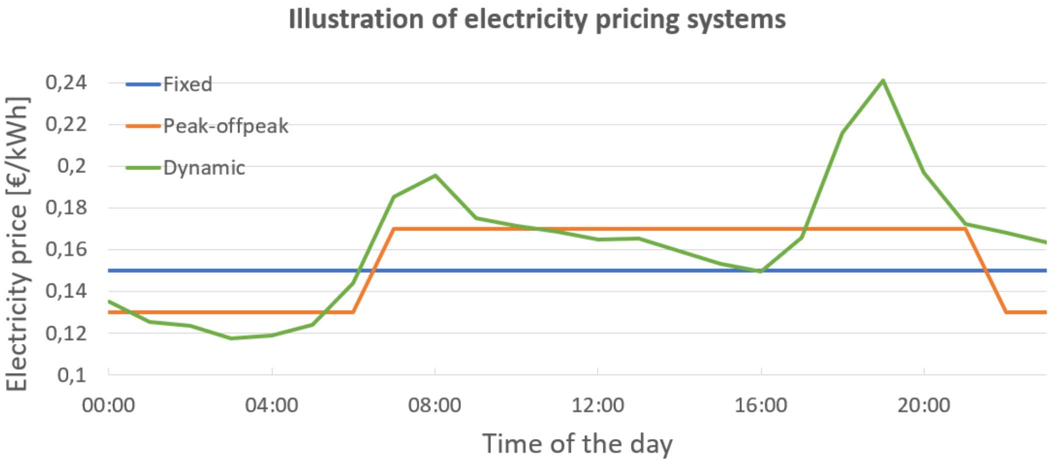

Figure 2.9: Illustration of various electricity pricing systems. In this illustrative example, each system can sell the cheapest but also the most expensive electricity, depending on the time of the day.

Variable pricing of electricity

As its names suggests, variable pricing is the way by which the final price (the one that the final consumer pays to its electricity supplier) varies along time (hour, day or week), as opposed to a fixed price which always stays the same. By consuming its electricity when its cheaper, the consumer can reduce its total cost. The way the price varies depends on the type of tariff the consumer is subscribed to.

Peak/off-peak tariff The most common type of variable pricing is the peak/off-peak[15] tariff which sets a different price for day- and night-consumption. Peak prices can for instance apply from 7:00 until 22:00 and off-peak prices from 22:00 until 7:00 the next day. Extra variations can be implemented during the week-end from which off-peaks tariffs are applied, regardless of the time of the day. In Belgium, it is the Distribution System Operator (DSO)) who decides upon the exact specifications of the tariff [29].

Dynamic tariff Dynamic pricing is a type of variable pricing for which the electricity price is computed every hour based on the electricity price on the wholesale markets. Equation 2.8 describes a potential implementation of dynamic pricing :

$$P_{cons,h} = \Big(A + B \cdot P_{DAM,h}\Big) + T \tag{2.8}$$

where $P_{cons,h}$ is the consumer's electricity price at hour h, $P_{DAM,h}$ is the electricity price on the day-ahead market at hour h, A and B are adjustment parameters fixed by the DSO and T represents taxes and extra costs for the consumer. Dynamic pricing allows for a much more volatile electricity price than a traditional bi-hourly day rate and can thus lead to substantial cost savings for flexible consumers. Figure 2.9 illustrates the various pricing systems.

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[15] Sometimes referred to as *bi-hourly day rate*.

Self-consumption

Electricity self-consumption is defined as «*consumption by one or more consumers of electrical energy from production facilities close to and associated with those of consumption*» [30]. A typical example in the residential sector is the direct consumption of electricity produced by PV panels connected to a household. Small wind turbine generators can also be used but are less common as they take up more space than PV panels which can easily be installed on the roof[16]. If the panels produce more electricity than the quantity consumed at a certain time, power can be injected to the grid in return of a compensation. Figure 2.10 illustrates the concept of self-consumption for a household.

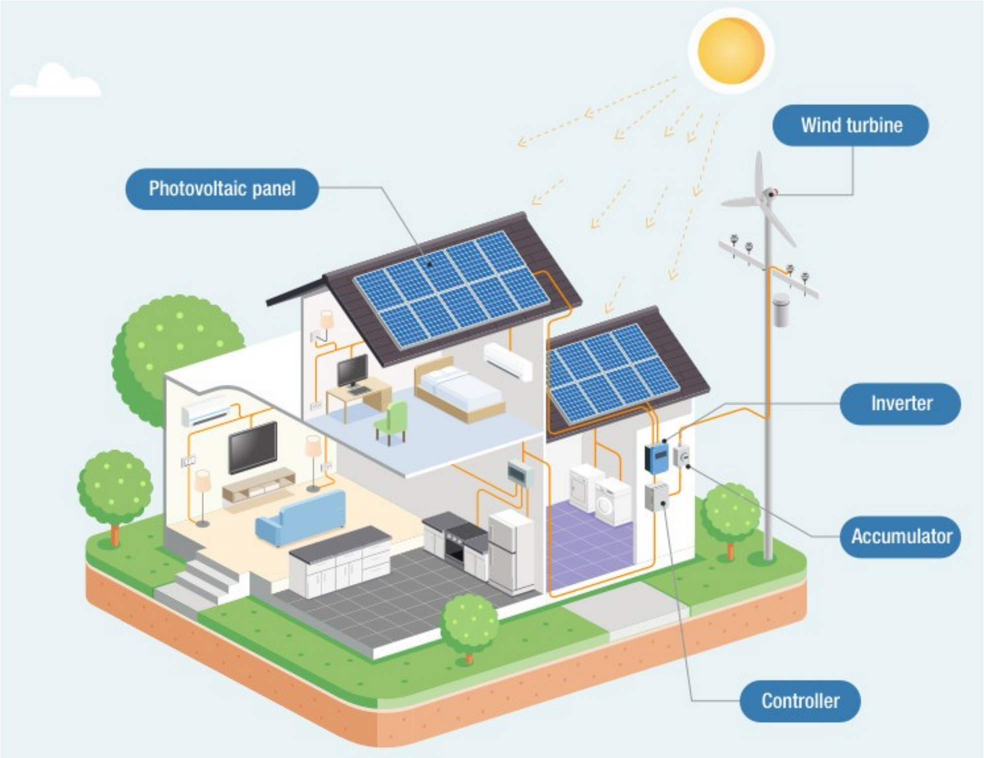

Figure 2.10: Illustration of electrical self-consumption [31]. The PV panels and the small wind turbine produce electricity which is directly consumed by the household they are associated with and connected to. The accumulator (battery) can store electricity surplus and release it when needed.

2.3.3 Flexibility assets

In the residential sector, flexibility assets are electric equipment which can be actively managed to provide grid services or optimize consumption for instance. They are the elements which physically allow for a flexible behavior. Usually they are physical items which can store and release electricity when needed. Common examples include Battery Electric Storage Systems (BESS), electric vehicles, heat pumps, etc. Though very useful when they are coupled with flexibility mechanisms, flexibility assets are not always required to implement flexibility. For instance, many households are equipped with PV panels without a domestic battery.

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[16] Wind turbines can also run into urban permit issues.

Chapter 3

Global study methodology

The main goal of this study is to identify the impact that flexibility mechanisms have on CO_2 emissions, considering various CO_2 emission assessment methods and emission factors. A simple example to illustrate how the emissions can vary is shown in Figure 3.1. Three different profiles consuming the same amount of electricity can be responsible for various amounts of emissions. To modify a consumption profile, flexibility mechanisms need to be implemented. This Chapter defines and justifies all the choices that are made to reach this goal of flexibility implementation. Figure 3.2 illustrates the global methodology used throughout this study.

The methodology steps are the following :

1. Define the **temporal context** of the study. In other words, select relevant study periods (and their duration).
2. Define the **geographical context** of the study. This comes down to selecting relevant countries.
3. Select generic **electricity consumption profiles**, ideally matching with the selected studied period(s) and country(ies).
4. Select relevant **flexibility mechanisms** (and their respective flexibility assets), implement them using data which matches with the selected studied period(s) and country(ies) and obtain modified consumption profiles using a **simulation tool.**
5. Select relevant **CO_2 emission assessment methods** and couple them with EFs to compute the instantaneous CO_2 content of electricity (a *CO_2 signal*) based on the instantaneous electricity production data.
6. Compute the CO_2 emission variations between the reference and modified total emissions, then **analyze and discuss the results**.

This chapter is all about detailing the first five steps and justifying the different choices that were made. The following chapter tackles step number 6 by presenting the results of the study and by analyzing them thoroughly.

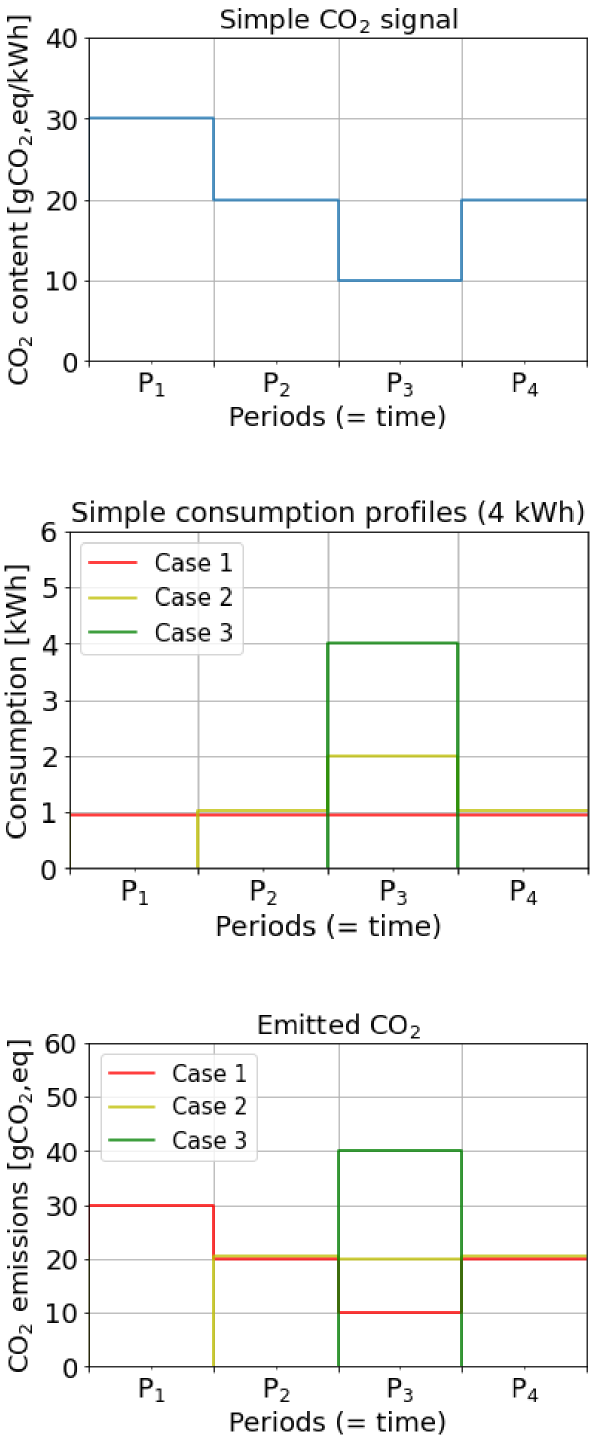

Figure 3.1: A simple illustration of how consumption profiles with similar consumption levels can lead to different CO_2 *emission levels. All consumption profiles consume 4 kWh of electricity along the four periods. However, case 2 (yellow) reduces emissions from 80 to 60* gCO_2*,eq compared to the case 1 (red). Case 3 (green) reduces emissions to 40* gCO_2*,eq (this actually corresponds to the minimum amount of emissions one could get for this example). The third graph is computed by multiplying the two first ones with each other.*

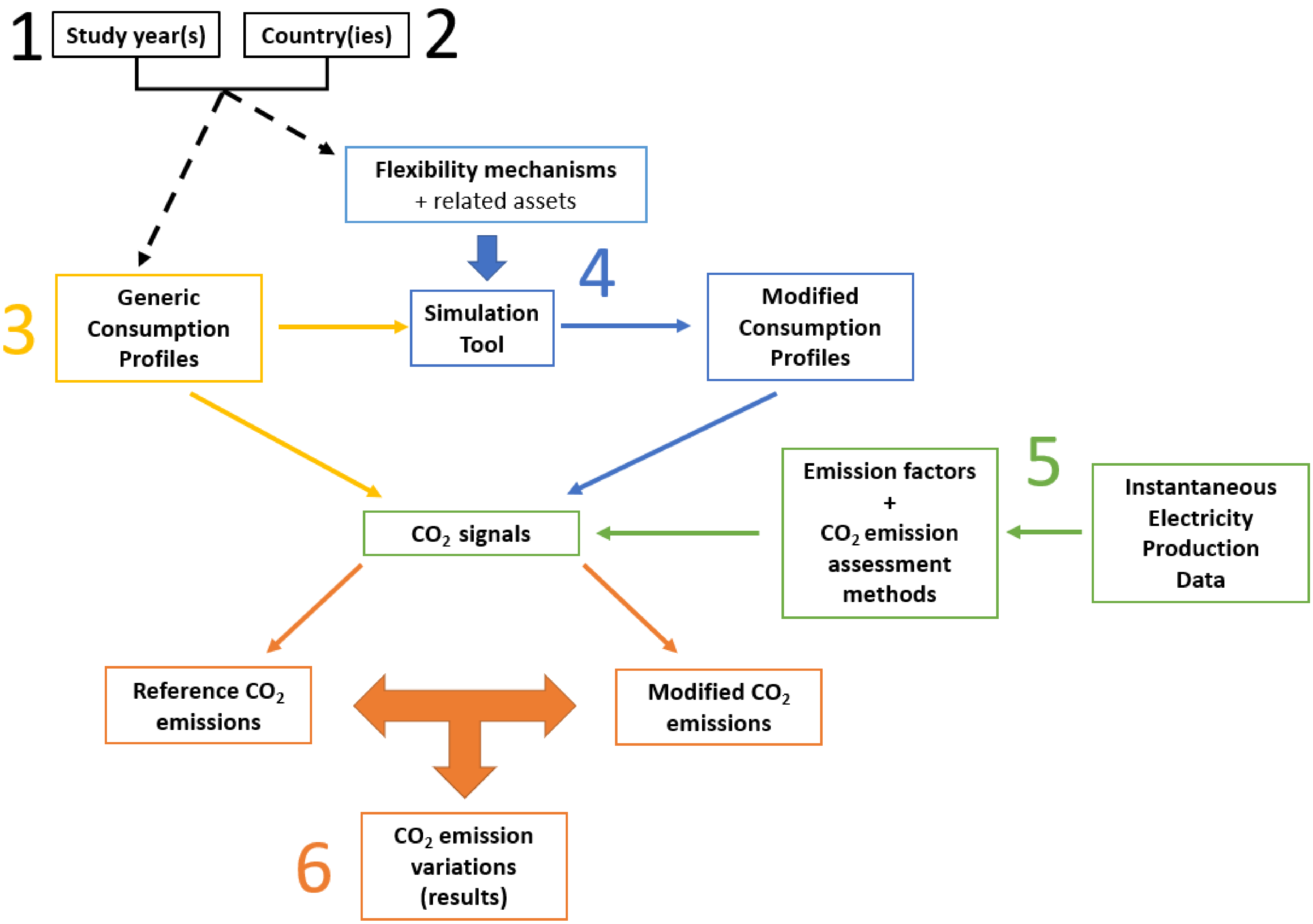

Figure 3.2: Global study methodology.

3.1 Temporal context

3.1.1 Simulation period length and resolution

When it comes to the the temporal context, it is decided from the get-go that carried simulations are going to be annual. Indeed, studying the impact of GHG emissions has only limited interest if it only relates to short time periods or to a specific period of the year (season or month for instance). Additionally, as the main goal is to implement flexibility on a short time-scale, the temporal resolution of the study is set at a quarter-hour (15 min). This means that all the processed data must be provided with a **15 min time-step** in order to perform the simulations properly.

3.1.2 Study years selection

In order to be able to compare different years with each other, two years were selected as reference periods for the simulations. When selecting the study years, the main criteria to take into account are the amount of time that has passed since them (the most recent the year, the most sense and impact the results have) and the availability of complete data[1] for each of them. After investigation, it appears that the two most recent years with complete data are **2018** and **2019**.

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[1] The nature of all the needed data is specified further in this chapter.

3.2 Geographical context - country(ies) selection

In order to select an interesting geographical case, one must compare different countries and select the ones that are suitable for the study, based on different criteria. Before touching on those criteria, a first preselection is made : only Western European countries are considered (with the exception of Romania and Australia, for reasons that will be explained later-on). This decision is taken in order to bring down the analyzed countries to a reasonable amount and to make sure all of them have a well-developed electrical transmission and distribution network, making them eligible for global flexibility mechanisms. The preselected countries are the following (listed in descending order of total annual electrical production in 2020) : Germany, France, United Kingdom, Italy, Australia, Spain, Belgium and Romania. The criteria on which the final selection is made are the following :

1. Production data
2. Current electrical mix
3. Flexibility potential
4. ENGIE group interests
5. Electrical mix relevancy in the future

The sections hereunder explain and justify the relevance of each assessment criterion. Each country is then assessed in details and given a qualitative grade (-, 0, + or ++) to compare them and finally select the ones which are the most interesting to study. The final two selected countries are **France** and **Germany**.

3.2.1 Production data

A. Criterion definition and justification In order to quantify the instantaneous CO_2 content of electricity, detailed data on the electrical production sources (preferably with a short time-step) is needed. As all the preselected countries have different Transmission System Operators (TSO), the available data varies from one to another. An assessment of the available information is thus required to make sure that a coupling with flexibility is conceivable.

B. Country assessment grades

European Network of Transmission System Operators for Electricity (ENTSO-E) data Before getting into the individual TSOs it is worth mentioning that the ENTSO-E collects and publishes all the electricity generation, transportation and consumption data and information for the European market. It is a great central data source but the available information can only be downloaded day by day and the time step (1 hour) might be too long to use for flexibility applications.

Individual TSO Table 3.1 gives a general overview of the TSOs operating in the different preselected countries. The level of detail, the time step and the «downloadability» are all checked in order to make sure to have complete and easily accessible data. Each country is given a grade combining their performance for all three subcriteria.

Country	TSO(s)	Detailed centralized data ?	Easily downloadable ?	Time Step [min]	Assessment score
Germany	TransNetBW - TenneT DE Amprion - 50Hertz	✓	✓	15	++
France	Réseau de Transport de l'Electricité (RTE)	✓	✓	30	+
United Kingdom	National Grid ESO	✓	✓	30	+
Italy	Terna	✗ ⟶ ENTSO-E data			0
Australia	Australian Energy Market Operator (AEMO)	✗ ⟶ no data			-
Spain	Red Eléctrica de España	✓	✗ (day-by-day only)	10	+
Belgium	Elia	✓	✓	15	++
Romania	Transelectrica	✓	✓	60	+

Table 3.1: Electricity generation data assessment. Germany and Belgium provide the most detailed data (time-step shorter than 30min and easily accesible). No precise data could be retrieved for Australia.

3.2.2 Current electrical mix

A. Criterion definition and justification The electrical mix has a direct impact on the CO_2 content of the produced electricity. A more varied mix should naturally give better results when coupled with flexibility mechanisms. As an example, one can take a look at the Norwegian electrical mix (Figure 3.3). For the past 30 years, it has been largely dominated by hydroelectricity. This means that a change in consumption through flexibility mechanisms only has very few chances to yield significant CO_2 emission reductions, due to the very homogeneous and lowly carbonated mix. More varied production facilities are in this regard more interesting and should give more interesting results.

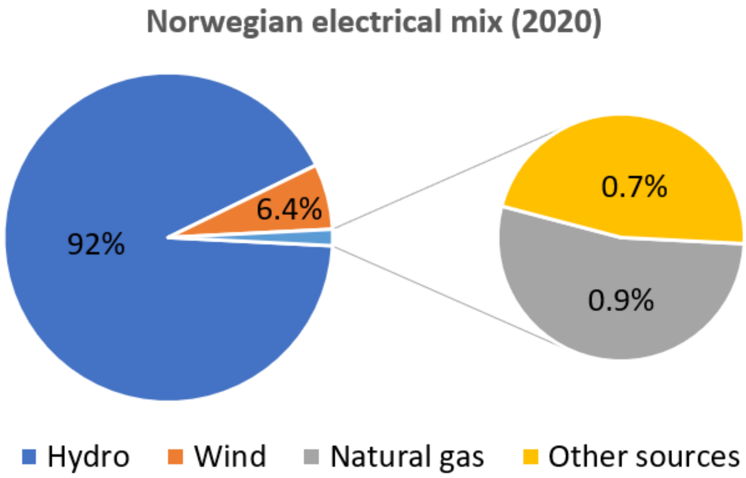


Figure 3.3: Norwegian electrical mix (2020) [32]. The production is largely dominated by renewable energy (mainly hydropower but also wind). Fossil power plants account for only a very small share of the total mix (less than 1%).

B. Country assessment grades Figure 3.5 shows the electrical mixes of all the preselected countries in 2020 [33]. The year 2020 was chosen as reference in this part because it was the most recent year with complete data. However, that year was particular due to Covid-19 and worldwide lockdowns. In order to check whether 2020 was representative compared to previous years, data for 2019 was analyzed as well. Despite a global smaller production in 2020 (see Figure 3.4), no significant difference in the shares of production could be identified (see Figure 3.6 for Germany, see Figure C.1 in Appendix C for the other countries.) and one can thus conclude that 2020 can be used as reference electrical mix for all countries. The precise data is given in Table C.1 in Appendix C. Based on the variety of the mixes, a grade is assigned for each country in Table 3.2. France, Italy and Australia are given a "-" due to low level of variety and the dominance of a certain production type (nuclear power in France, natural gas in Italy and coal in Australia). The Belgian mix is more varied but still keeps large chunks of production with nuclear power and natural gas. Germany, the UK, Spain and Romania are much more varied with multiple production types (at least 4) accounting for more than 10% of the total production, thus getting a "++" grade.

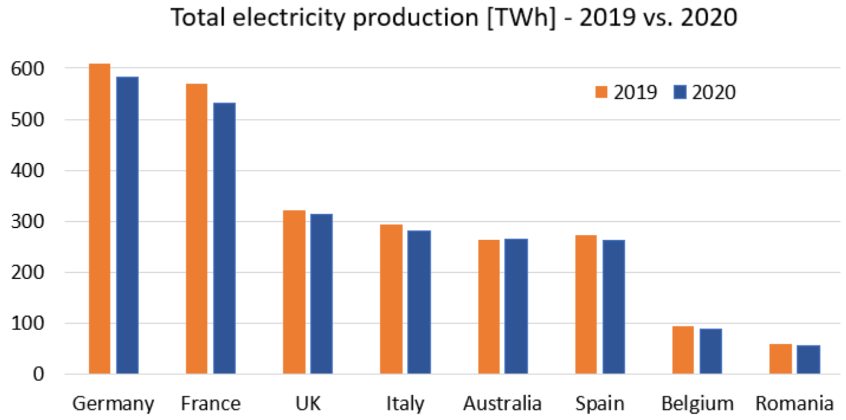
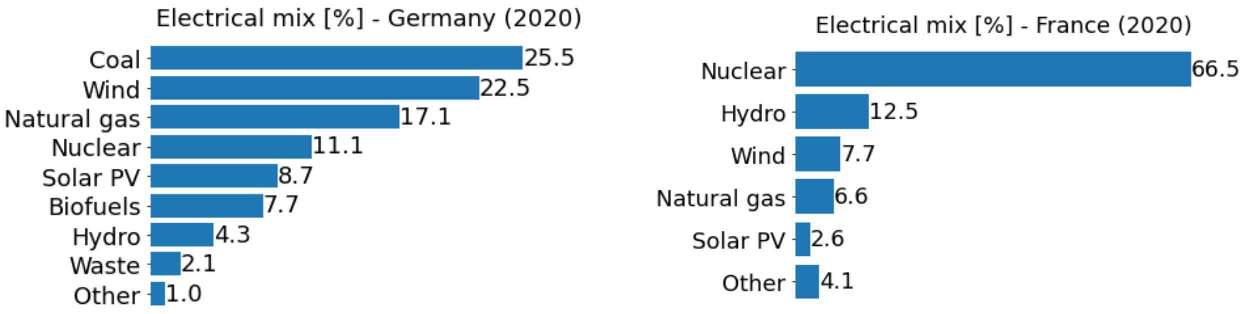
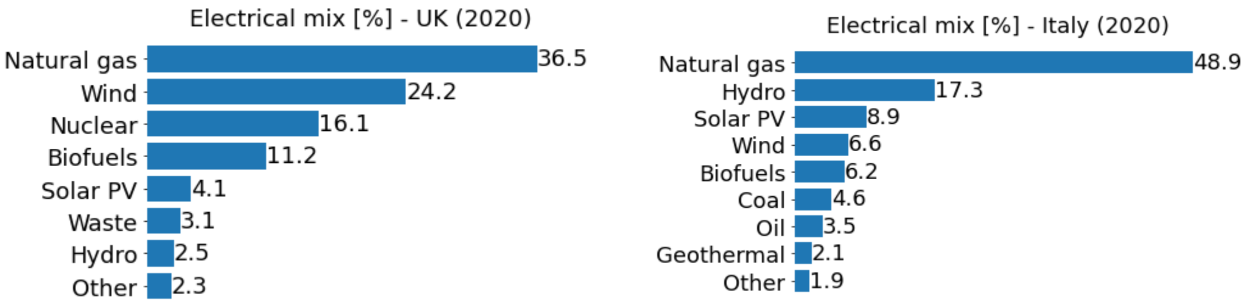


Figure 3.4: Total electricity production in 2019 and 2020 for preselected countries [33]. In 2020, Germany and France lead with more than 500TWh each. The UK, Italy, Australia and Spain follow with productions ranging from 260 to 315TWh. Belgium and Romania produce the least with 89 and 56TWh respectively. One can observe that the total production was smaller in 2020 than in 2019, due to the pandemic.



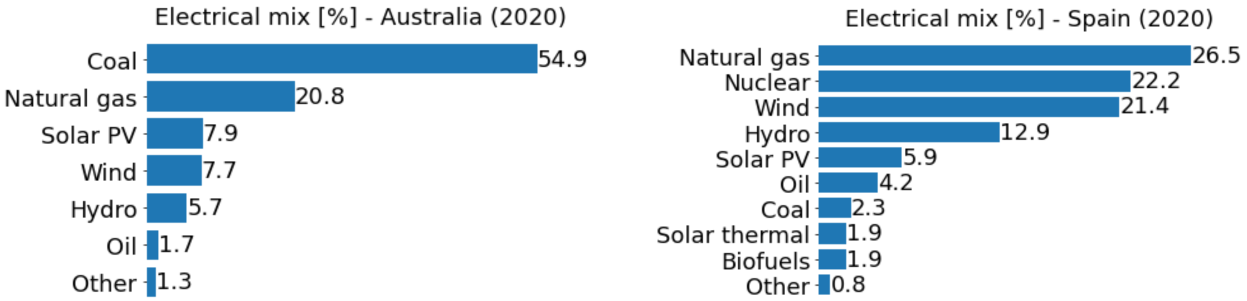
(a) Germany - 582 TWh

(b) France - 532 TWh



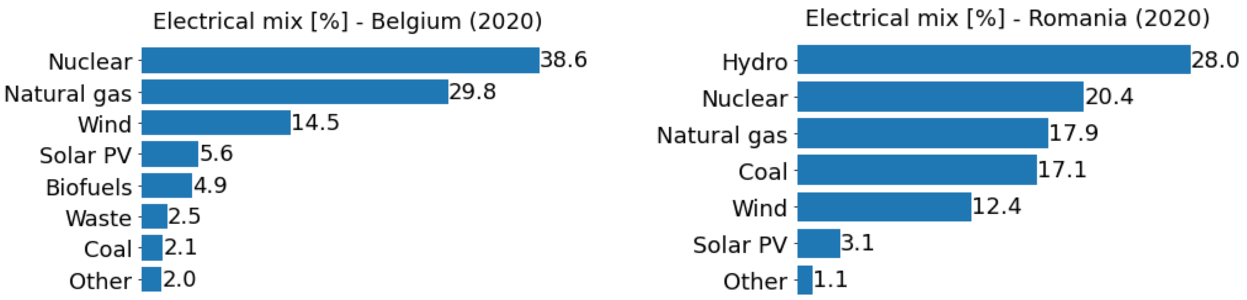
(c) United Kingdom - 313 TWh

(d) Italy - 281 TWh



(e) Australia - 265 TWh

(f) Spain - 262 TWh



(g) Belgium - 89 TWh

(h) Romania - 56 TWh

Figure 3.5: Electrical mixes of the preselected countries in 2020 [33].

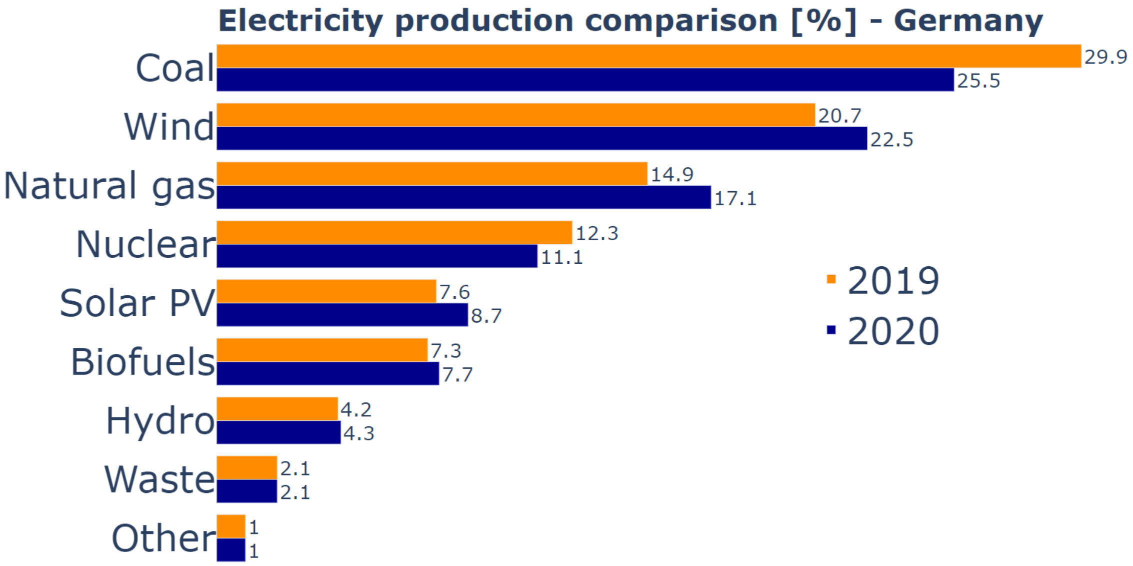


Figure 3.6: German electrical mix comparison 2019 vs. 2020 [%]. The shares of electrical generation do not vary much from 2019 to 2020 (only a few %). One can thus conclude that the Covid-19 lockdowns did not have a significant impact on the electricity generation distribution.

Country	**Assessment score**
Germany	++
France	-
United Kingdom	+
Italy	-
Australia	-
Spain	++
Belgium	+
Romania	++

Table 3.2: Electrical mixes assessment scores. France, Italy and Australia have a mix largely dominated by a certain generation type. Germany, Spain and Romania have the most varied mixes.

3.2.3 Flexibility potential

A. Criterion definition and justification This criterion and its related analysis is directly taken from a study performed by *DELTA-EE* [34], a Scottish energy research and consultant company. It assesses the flexibility potential in each country as well as the expected evolution of demand-side flexibility in the next coming years. It groups two sub-criteria which both address multiple topics and answer some questions related to flexibility :

1. Local flexibility and energy communities :
    - Is collective self consumption allowed ?
    - Is there a national framework for citizen energy communities ?
    - Is there a national framework for renewable energy communities ?

- Is Distribution System Operator (DSO) flexibility commercial ?
- Are there DSO flexibility trials?

2. Future of flexibility :
    - Potential market size of flexibility
    - Markets opening to demand-side flexibility by 2025
    - 2030 renewable targets
    - Target dates to join European market coupling

B. Country assessment grades The Delta-EE study uses a 1-5 scoring system for both sub-criteria (local flexibility and future of flexibility). Table 3.3 gives those scores and infers a grade used in this comparative study.

Country	Local flexibility and energy communities	Future of flexibility	Assessment score
Germany	2	3	0
France	4	3	++
United Kingdom	5	3	++
Italy	3	4	++
Australia	not studied	not studied	0
Spain	1	4	0
Belgium	2	2	-
Romania	1	3	-

Table 3.3: Flexibility potential assessment [34]. Australia is given a "0" by lack of information (the Delta-EE study only covers the European market). France, the UK and Italy have great flexibility potentials while Belgium and Romania are quite limited. Germany and Spain present mitigated flexibility possibilities.

3.2.4 ENGIE Group interests

A. Criterion definition and justification This thesis is performed in the context of broader projects carried out at ENGIE Laborelec. Therefore, the study of specific countries should ideally yield added-value for the company. Some countries present more value than others for Laborelec and this has to be taken into account when selecting the case study. It is in this regard that Australia and Romania are analyzed as well : both countries host an ENGIE business-to-customer (BtoC) entity and are thus potentially interesting cases.

B. Country assessment grades This criterion adds value to the countries where ENGIE has BtoC entities. Table 3.4 thus assigns a "++" to those countries (except for Romania where BtoC activities are limited) and a "0" to the other ones.

3.2.5 Electrical mix relevancy in the future

A. Criterion definition and justification As the electrical production facilities are undergoing fast and ever-going changes, one must verify how the current electrical mix of a country relates to its planned evolution and thus the corresponding mix in the 5 to 10 next years. Public policies and phase out plans can have a significant

Country	**Assessment grade**
Germany	0
France	++
United Kingdom	0
Italy	++
Australia	++
Spain	0
Belgium	++
Romania	+

Table 3.4: ENGIE interests assessment scores.

impact on a country's electrical mix in only a few years. The study of a country which has plans to radically change its electrical mix in the near future can therefore have limited relevancy. As explained further, this criterion is secondary and is finally not taken into account when selecting the studied countries.

B. Country assessment grades After doing some research, it appears that this criterion is not as important as originally thought. Indeed, the literature [35, 36, 37, 38, 39, 40] shows that all the electrical mixes will vary significantly in the next-coming decade (coal phase-out plans, increase of renewables, etc.). It has thus been decided to not take this criterion into account.

3.2.6 Final comparison and selection

Table 3.5 summarizes the scores of each country and gives them a final grade. Australia and Italy are given a «-» and a «0» respectively, mainly because to the limited availability of electricity generation data. Spain and Romania get a «+». Germany, France, the UK and Belgium are all given a «++». As it has been decided to select two countries, the final selection must be seen as a choice of two countries which could present variable results complementing each other. In this regard, **France** was chosen for its huge importance for ENGIE and its high flexibility potential coupled with **Germany** for its varied electrical mix and detailed data. As both countries have very different electrical mixes, the results should vary quite a bit and provide some interesting insights.

	Modelling data	**Current mix**	**Flexibility potential**	**ENGIE interests**	**Global grade**	**Selected ?**
Germany	++	++	0	0	++	✓
France	+	-	++	++	++	✓
United Kingdom	+	+	++	0	++	✗
Italy	0	-	++	++	**0**	✗
Australia	-	-	0	++	-	✗
Spain	+	++	0	0	+	✗
Belgium	++	+	-	++	++	✗
Romania	+	++	-	+	+	✗

Table 3.5: Global country comparison. Australia and Italy are given a "-" and a "0" respectively, mainly because to the limited availability of electricity generation data. Spain and Romania get a "+". Germany, France, the UK and Belgium are all given a "++". Finally, France and Germany are selected.

3.3 Consumption profiles

3.3.1 General requirements

To run the simulations, the reference electricity consumption profiles are an essential piece of data. The most important aspect of those profiles is that they must reflect the reality as closely as possible and they should ideally match with the specified temporal and geographical context of the study (France and Germany in 2018 and 2019 and with a 15-min time-step). A secondary aspect is the amount of studied profiles. Indeed, the more profiles, the more interesting and reliable the results can be.

3.3.2 Selection

The available database available for use for this thesis is made of 2335 belgian profiles from 2013. Their total yearly consumption ranges from 30 to roughly 100 000 kWh. As this range is very large and does not really matches with traditional household consumption values[2], the database has been reduced to **1854 profiles consuming between 1000 and 8000 kWh of electricity yearly**. Figure 3.7 shows the selected profile's distribution over this consumption range. The majority of the profiles fall in the 2000-4000 kWh range which makes it a good pool to work with. Additionally, there are still a good amount of small (below 2000 kWh) and big (above 4000 kWh) consumers we can analyze to find out how the total yearly consumption affects the final results. It should be mentioned that those profiles provide quarter-hourly data. This means that each profile contains the exact amount of consumed electricity for each quarter-hour of the year. Figure 3.8 illustrates the instantaneous consumption of one profile on the 30^{th} of October[3].

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[2] The Federal Statistical Office of Germany (Destatis) estimates that the average total electricity consumption per household in Germany in 2018 was 3113 kWh. This number varies in function of the household size : 1943 kWh for a one-person household, 3221 kWh for a two-person household and 4978 kWh for a three-and more person household [41].

[3] As written above, the consumption profiles are originally from 2013. However, as 2018 and 2019 were the selected study years, the profile timestamps were modified to match these years.

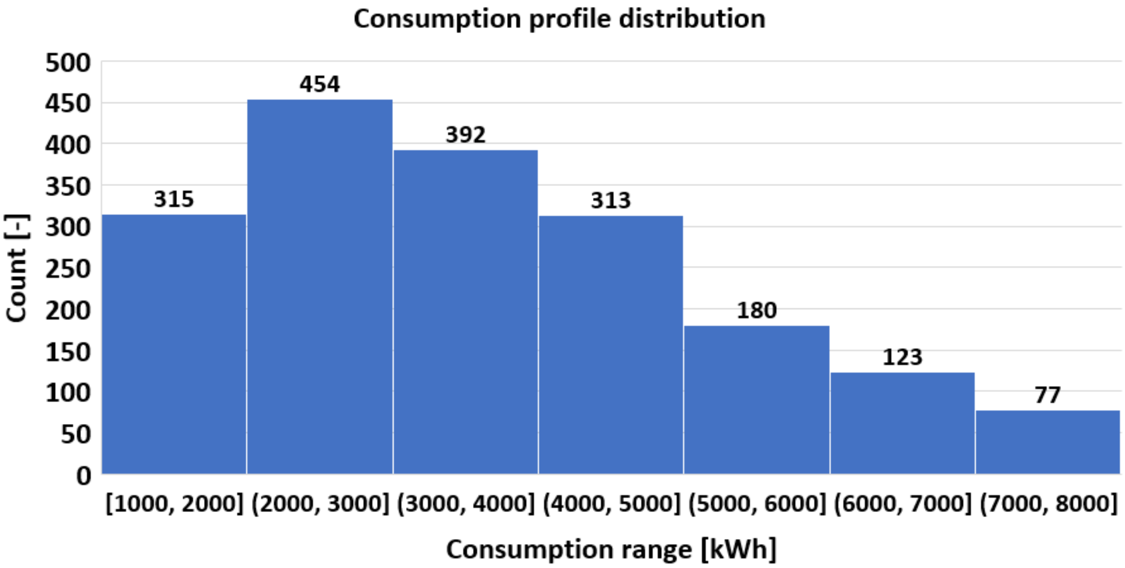

Figure 3.7: Selected consumption profile's distribution. Most of the profiles fall in the range 2000-4000 kWh which matches the average household consumption values. Small and big consumers (below 2000 and above 4000 kWh of consumed electricity) are also interesting to analyze to see how they perform when it comes to emission reductions compared to average consumers.

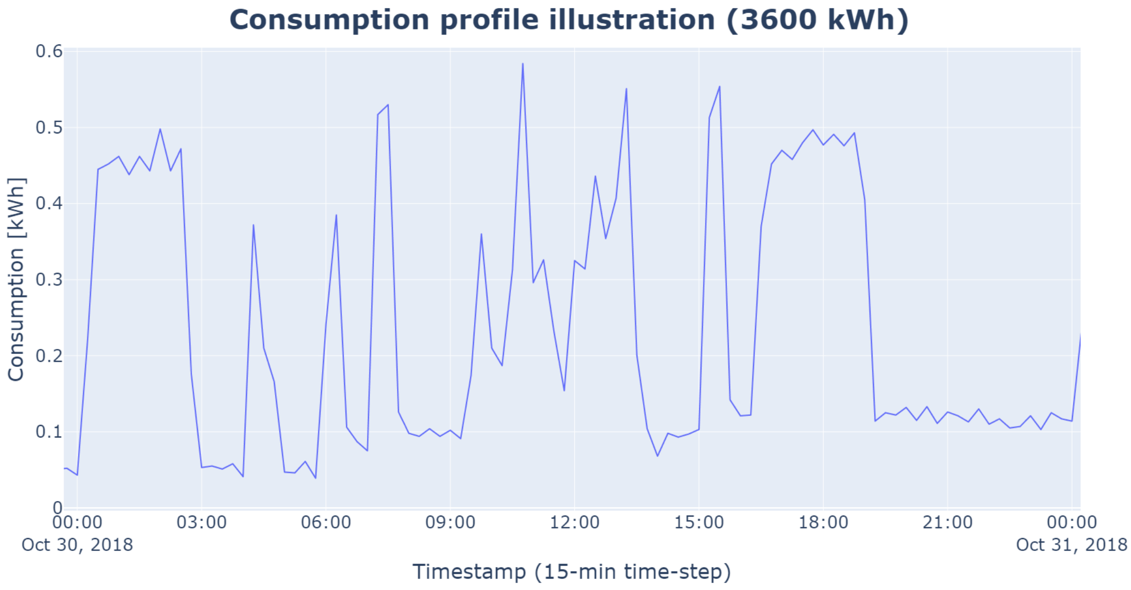

Figure 3.8: Illustration of the instantaneous consumption of one profile (total yearly consumption of 3600 kWh). The day (October, 30th) was chosen at random. The data gives the electricity consumed each quarter-hour, for the whole year.

3.4 Flexibility mechanisms and simulation tool

Now the general context of the study is determined and the consumption profiles are specified, one must decide upon the flexibility mechanisms to implement (and the related assets that are needed) in order to obtain modified grid consumption curves. As explained in Chapter 2, the two main flexibility mechanisms in the residential sector are variable pricing of electricity and self-consumption. More precisely, the two main type of simulations carried out in this work are **dynamic pricing** and **PV self-consumption**. Before getting into the specifics of each mechanism and how each simulation type is implemented (necessary data, choices made, hypotheses taken, etc.), one should first take a look at the available simulation tool. In this case, the software used to perform the simulations is a Python library developed at Laborelec called **ESyPAC**.

3.4.1 Simulation tool : ESyPAC

ESyPAC is an internally-developed simulation tool at Laborelec which allows to perform technico-economical and sensitivity analyses on residential electrical systems. The in-house Python package can have many different applications. Some examples are :

- Assessing the impact of adding an electric vehicle in the home on the consumption profile.
- Assessing the impact of tariff on consumption behavior and energy bill.
- Assessing the flexibility available in electric storage water heaters.

ESyPAC modelling ESyPAC uses models of typical residential electrical assets to perform its simulations. The following assets are available : communities[4], homes, PV installations, batteries, hot water tanks, electrical vehicles, heaters and heat pumps, air-conditioning systems and swimming pools. Figure 3.9 represents a complete model which can be implemented : a community is made of multiple homes. Each home can be using a specific electricity pricing system (= a tariff) and can contain various sub-assets. Each sub-asset can be defined with a specific consumption/production profile and technology. Flexible assets such as PV systems, batteries, EVs and hot water tanks can also interact with each other.

ESyPAC simulations Once the complete simulation model is defined, a controller (with possibly an optimization horizon) and a time-step must be chosen. The controller can either be sequential or optimizer. The **sequential controller** is simply an ordered list of asset-specific controllers. The order is indeed important, because it defines which assets will bring flexibility in priority (namely when the PV produces electricity locally). The **optimizer controller** solves a linear optimization problem. The optimizer either optimizes the self-consumption percentage or the consumer's electricity bill (which is computed based on the tariff assigned to the home asset) for each optimization horizon timeframe[5]. Results provided by the simulation are then given with the specified time-step and include updated global consumption profiles of the homes, electricity costs and specific assets production/consumption profiles (for instance the charge/discharge curve of the implemented batteries). Figure 3.10 illustrates the global implementation of a simulation on ESyPAC.

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[4] Communities are special assets which can contain multiple homes, to share PV installations for instance.

[5] Assuming an optimization horizon of 24h, the optimizer will optimize the desired aspect (self-consumption rate or total cost) on this time horizon by controlling the behavior of the assets properly. It thus assumes that the information (electricity price, future PV production, etc.) is known in advance for this period of time.

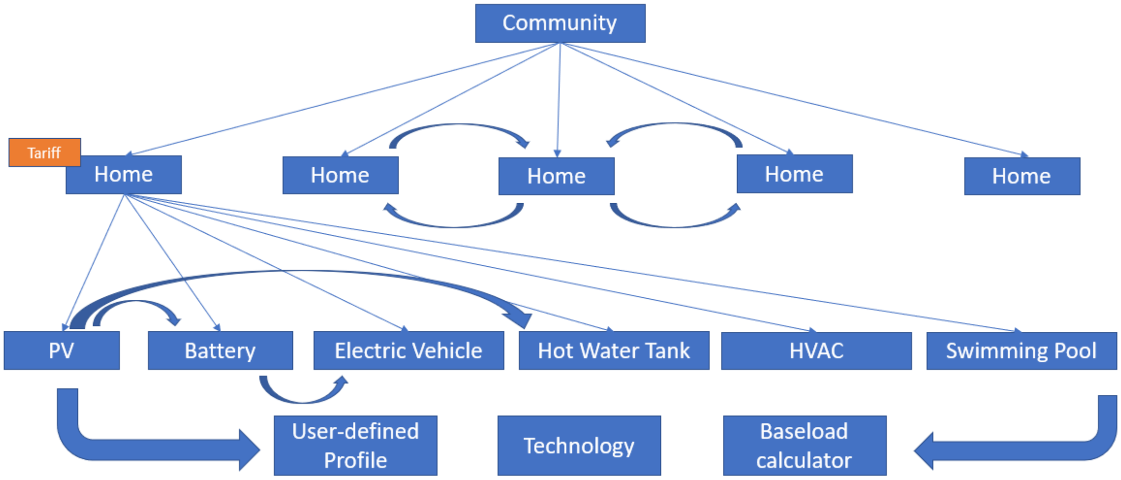

Figure 3.9: ESyPAC generic modelling example. Communities contain multiple homes which can in turn contain various sub-assets. Flexible assets such as PV systems and batteries can interact with each other. All sub-assets can have their own consumption and production profiles which can be specified by the user.

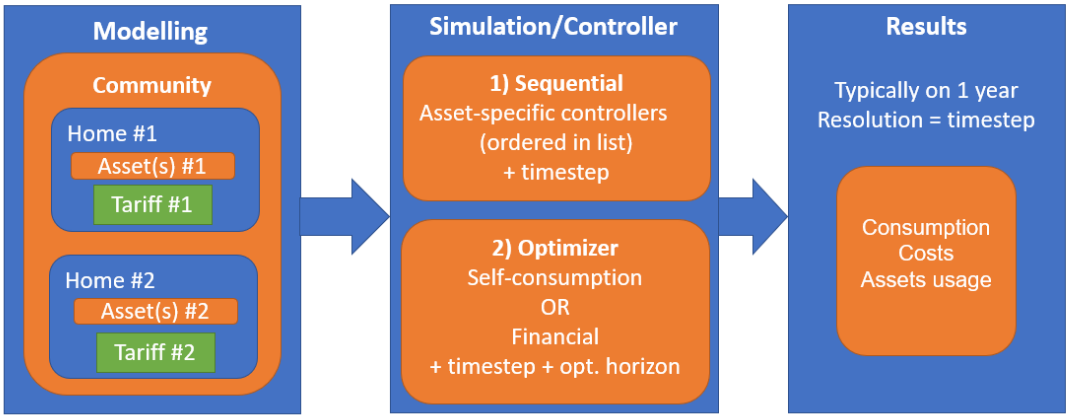

Figure 3.10: ESyPAC generic simulation example. The model (here a community containing two homes) is coupled with a controller type (sequential or optimizer) to provide results (modified consumption profile, electricity price, asset-specific results) with a resolution which matches the specified time-step.

3.4.2 Mechanisms implementation

Based on ESyPAC's requirements to run its simulations, one can now have a clear view of the required data and the underlying hypotheses to perform the desired study. The first choice made for this study is to not use the *community* asset and limit each simulation to 1 home. Indeed, the interaction between multiple homes is not part of the the scope of this work and there is thus no reason to include such behavior in the simulations. Additionally, three more choices must be made :

1. What sub-assets does the home contain ?
2. What tariff is the home submitted to ?
3. Which type of simulation controller is used ?

	Sub-assets	Tariff	Controller Type
Dynamic Pricing	Stationary battery	Dynamic	Financial Optimizer
PV self-consumption	Stationary battery + PV installation	Bi-hourly	

Table 3.6: Overview of the simulation specifications.

Table 3.6 gives a quick overview of the answers to these three questions for both flexibility mechanisms. The following sections detail each element, first by taking a look at the ones that are common to both mechanisms (namely the battery and the controller) and secondly by tackling elements relating to one mechanism only.

3.4.3 Common elements : stationary battery and controller

Stationary battery

The stationary or domestic battery is the flexible asset by excellence. It provides full flexibility with very few constraints (compared to an EV's battery for instance which must be charged at certain times and is not always available at home to provide the required flexibility). The battery can interact with the grid and with the PV installation to charge itself. It can then store energy before being consumed by the home, later-on. The chosen parameters for the battery are shown in Table 3.7. The capacity, peak power and efficiency were all chosen to represent a generic average stationary battery one can find on the market today[6]. The allowed depth of discharge (DoD) is fixed at 100%. This was chosen to have an effective 10 kWh of available storage in the battery [7].

Energy capacity [kWh]	Peak power [kW]	Round-trip efficiency [%]	Depth of discharge [%]
10	5	90	100

Table 3.7: Overview of the stationary battery's specifications.

Controller type

The financial optimizer controller is chosen. This choice relates to the discussion about the main flexibility driver in Chapter 2, namely cost optimization. The optimization horizon is set at 24 hours. When performing an annual simulation, ESyPAC thus optimizes the electricity grid consumption for each 24-hour period by deciding how much electricity is drawn from the grid (and thus paid) during each quarter-hour of that day. To optimize the cost, the software thus assumes it knows the electricity price, the house consumption (which is the generic consumption profile provided as input data) and the PV production (if applicable) for the next 24 hours. It then selects the financially optimal behavior and interactions between the grid, the battery, the PV system (if applicable) and the house consumption.

3.4.4 Dynamic pricing : the dynamic tariff

The dynamic tariff used for the dynamic pricing is obtained using Equation 3.1, already introduced in Chapter 2 :

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[6] For comparison, Table D.1 in Appendix D gives the specs of some commercial batteries available on the market today.

[7] In ESyPAC's simulation, the capacity and depth of discharge parameters work in pair (an 8 kWh battery with 100% DoD works exactly the same as a 10 kWh battery with 80% DoD).

$$P_{cons,h} = \Big(A + B \cdot P_{DAM,h}\Big) + T \tag{3.1}$$

where $P_{cons,h}$ is the consumer's electricity price at hour h (expressed in [EUR/kWh]), $P_{DAM,h}$ is the electricity price on the day-ahead market at quarter-hour h (expressed in [EUR/kWh]), A and B are adjustment parameters fixed by the DSO and T represents taxes and extra costs for the consumer in [EUR].

Spot prices $P_{DAM,qh}$ The day-ahead market prices are found on Strommarktdaten (German electricity market database [42]) and are updated each hour. Data is retrieved for France and Germany for both study years (2018 and 2019). Such spot prices are expressed in [EUR/MWh] and usually vary between 30 and 80 EUR/MWh. To use them in Equation 3.1 they must be converted to EUR/kWh.

Adjustment parameters A and B The adjustment parameters A and B are set at 0 and 1 respectively. This allows to get an electricity price which is equal to the market price, not considering the taxes.

Taxes and extra costs T The taxes are computed based on French electricity taxes (both for France and Germany). They are made of multiple components such as transport and distribution taxes[8], contribution taxes[9] and VAT. Their total value adds up to 0.10 EUR/kWh but does not matter as the main goal is not to compute precise cost gains but to investigate CO_2 emissions.

Final dynamic formula Based on previous comments, the dynamic pricing formula reads as follows :

$$P_{cons,h} = P_{DAM,h} + 0.10 \tag{3.2}$$

Figure 3.11 illustrates how the final electricity price varies in France in 2018 on October 30th using this Equation. The main trend which can be observed is that electricity is cheaper at night and during the afternoon while it gets more expensive in the morning and during the early evening.

3.4.5 PV self-consumption : PV installation and bi-hourly tariff

A. Bi-hourly tariff

As opposed to the dynamic pricing tariff, a bi-hourly day rate tariff is applied for the self-consumption simulations. The same taxes apply as for the dynamic pricing but now there is only a distinction between a day- and night-tariff. The off-peak period is set from 23:00 until 7:00 in the morning the next day. The total peak price is set at 0.16 EUR/kWh while the off-peak price is set at 0.12 EUR/kWh[10].

B. PV installation

To compute the PV production at each time-step, ESyPAC needs to know how big the PV installation is, how much irradiation the installation is submitted to and the total efficiency of the system.

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[8] Called *TURPE* in French for *Tarif d'Utilisation du Réseau Public d'Electricité*.

[9] Called *CSPE* in French for *Contribution au Service Public de l'Electricité*.

[10] A question that might arise is whether those prices are realistic in today's energy context. The answer is "not really". Those prices are quite low compared to the real electricity prices today but, again, the absolute prices do not matter much in this study, as the main goal is to compute CO_2 reductions and not cost gains.

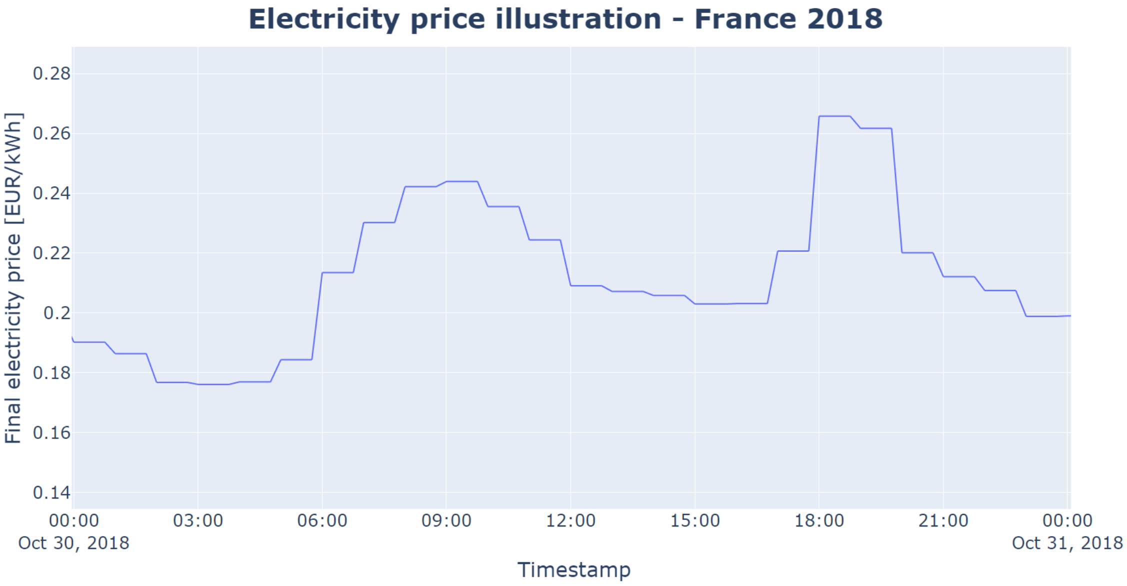

Figure 3.11: Dynamic electricity price illustration in France on October 30th 2018 using the defined formula. One can observe that the price varies from about 0.18 to 0.26 EUR/kWh depending on the time of the day. Electricity is cheaper at night and during the afternoon while it gets more expensive in the morning and during the early evening.

PV installation size The power of the PV installation is set at 4 kilowatt-peak (kWp) which corresponds to an average residential PV installation. The watt-peak is a measure of the power of PV installations. It represents the maximum theoretical electrical power a panel can produce under standard conditions[11] [44].

Solar irradiation : location selection To be as precise as possible, one must use real historical solar irradiation to compute the produced electricity by the panels. As irradiation depends on the geographical context, multiple locations in France and Germany are considered to provide a broad analysis and distinguish locations with high irradiation from locations where the sun shines less. To try to identify locations with different irradiation characteristics, one can base the analysis on climate zones.

A climate zone is a world area or region distinguished from a neighbor by a major physical climatic characteristic that is of global scale [45]. Figure 3.12 shows the different climate zones in France and Germany. France is divided into 3 zones : zone H1 with a semi-continental climate, zone H2 with an oceanic climate and zone H3 with a Mediterranean climate. Germany is divided into two main zones : a temperate zone in the east (in green on Figure 3.12b) and a colder continental zone in the west (in blue on Figure 3.12b). For each country, 3 locations were chosen in the various climate zones to analyze their effective climate based on the temperature :

- France :
    1. Semi-continental climate (H1) location : Lille (green dot on Figure 3.12a)
    2. Oceanic climate (H2) location : Poitiers (orange dot on Figure 3.12a)

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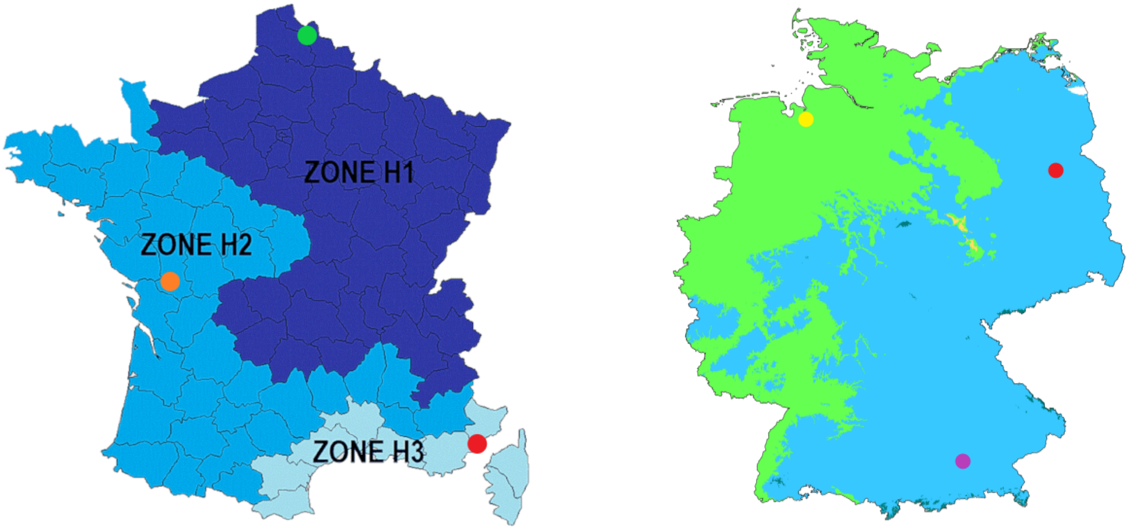
[11] The standard conditions are the following : a solar irradiation of 1000 W/m^2, an ambient temperature of 25°C, an air density of 1.5 kg/m^3 (clear sky) and an incidence angle perpendicular to the plane of the panel [43].

3. Mediterranean climate (H2) location : Cannes (red dot on Figure 3.12a)

- Germany :
  1. Temperate climate location : Bremen (yellow dot on Figure 3.12b)
  2. Continental climate location 1 : Berlin (red dot on Figure 3.12b)
  3. Continental climate location 2[12] : Munich (purple dot on Figure 3.12b)



(a) Climate zones and locations in France. *(b) Climate zones and locations in Germany.*

Figure 3.12: Climate zones and pre-selected locations to find solar radiation references. Eventually, only the French locations are kept as references.

Figure 3.13 shows the 72h moving averages of the French location's temperatures during 2018. One can observe that the temperature in Cannes is consistently the highest. Though it is not as obvious, the temperature in Lille is globally the lowest of all three along the year. This confirms the presence of the three climate zones in France and one can thus validate these locations as references to get different solar irradiation profiles in France.

Figure 3.14 shows the 72h moving averages of the German location's temperatures during 2018. As opposed to what is observed in France, there is no significant distinction between the three location's temperatures. This leads to the hypothesis that Germany is considered as uni-climate in this work. Additionally, Figure 3.15 shows that Lille's temperature mimics quite effectively the temperatures in Germany[13]. Therefore, Lille is set as reference location for the irradiation data for Germany. This aims at reducing the amount of required data and avoids complications when performing the simulations. Later-on this can also be useful to compare results which have been produced with the exact same irradiation profile but with different electrical mixes.

Solar irradiation : data The data for solar irradiation is retrieved from the same source as for the temperatures, namely the Photovoltaic Geographical Information System (PVGIS). It is a tool belonging to the European

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[12] Two different locations were picked for this zone because it seemed surprising to have similar climates and thus temperatures with such latitude variation

[13] Its temperature is a bit higher in the winter and a bit lower in the summer but the trend and values are similar.

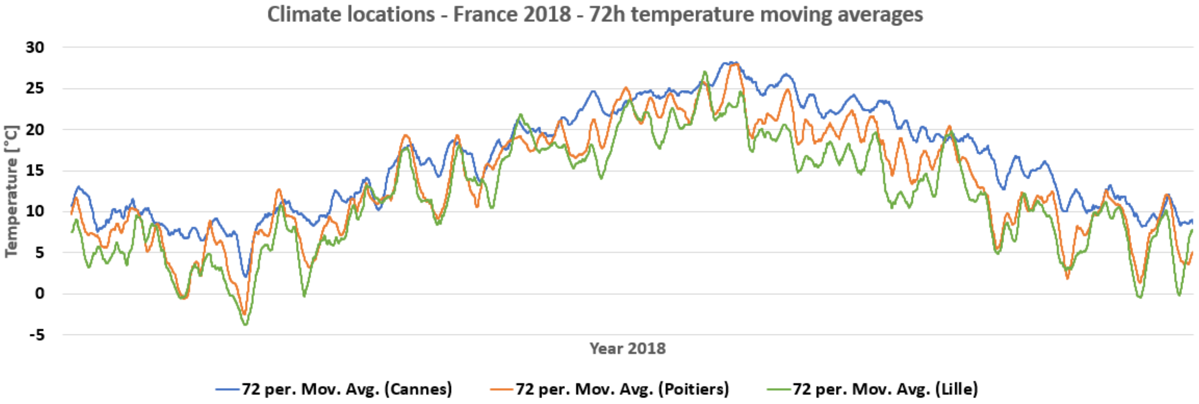


Figure 3.13: France 2018 - 72h temperature moving averages for the three selected locations [46]. Cannes consistently has a higher temperature than the two others while Lille is colder than Poitiers. This confirms the three climate zones in France.

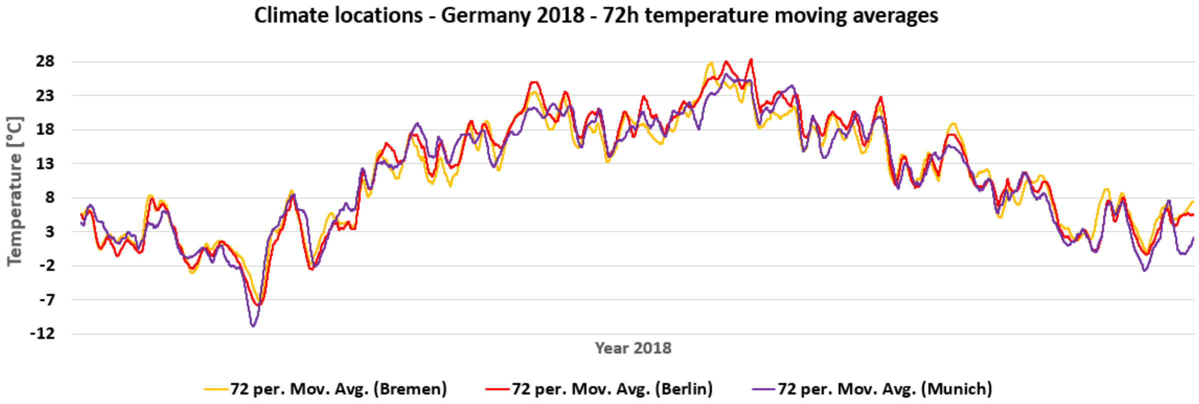


Figure 3.14: Germany 2018 - 72h temperature moving averages for the three selected locations [46]. No real distinction can be made between the three locations which leads to the hypothesis that Germany can be considered as a unique climate zone.

Commission which «*provides information about solar radiation and photovoltaic (PV) system performance for any location in Europe and Africa, as well as a large part of Asia and America*» [46]. Besides solar irradiation, the tool also computes the amount of electricity produced by a PV installation (for which multiple parameters can be user-defined) based on the irradiation the location is submitted to. Table 3.8 summarizes the parameter selection of this work. The most important parameter is the system loss, set at 14%. This value is the reference value in PVGIS and is assumed to take all losses into account. Some of those can be losses in cables and power inverters or even dust and shade on the panel. The other important choice is to consider that the PV installation has a perfect mounting slope and azimuth angle. In other words, the panels are automatically inclined and oriented to produce the maximum power along the year based on the radiation data. Note however that this slope and angle are fixed for the complete year and are not adjusted at each time-step.

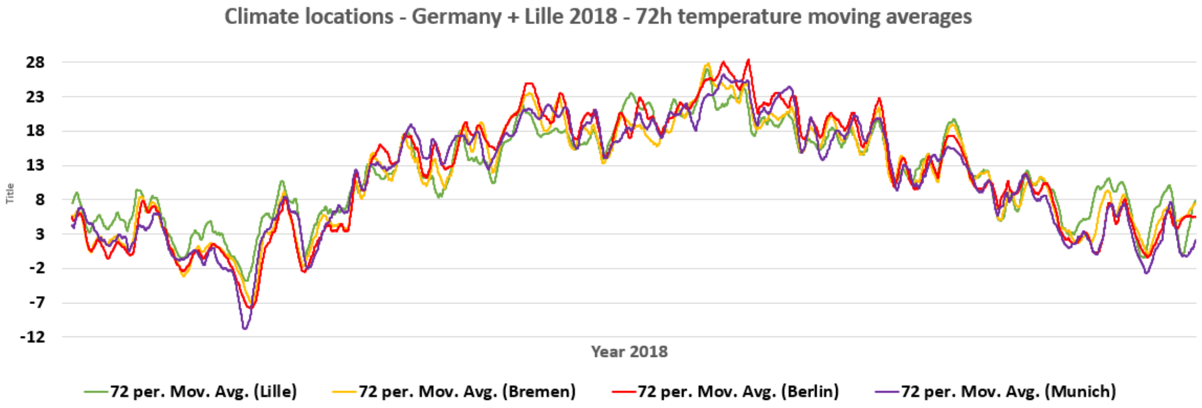


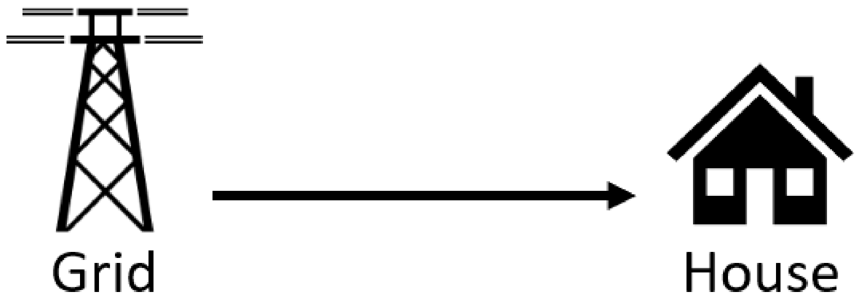
Figure 3.15: Germany and Lille 2018 - 72h temperature moving averages for the three selected locations [46]. Lille has similar temperatures as the three German locations. To ease the simulations, Lille is selected as reference solar radiation location for Germany.

PV technology	**System Loss [%]**	**Mounting Slope**	**Mounting azimuth angle**
Crystalline silicon	14	Optimized	Optimized

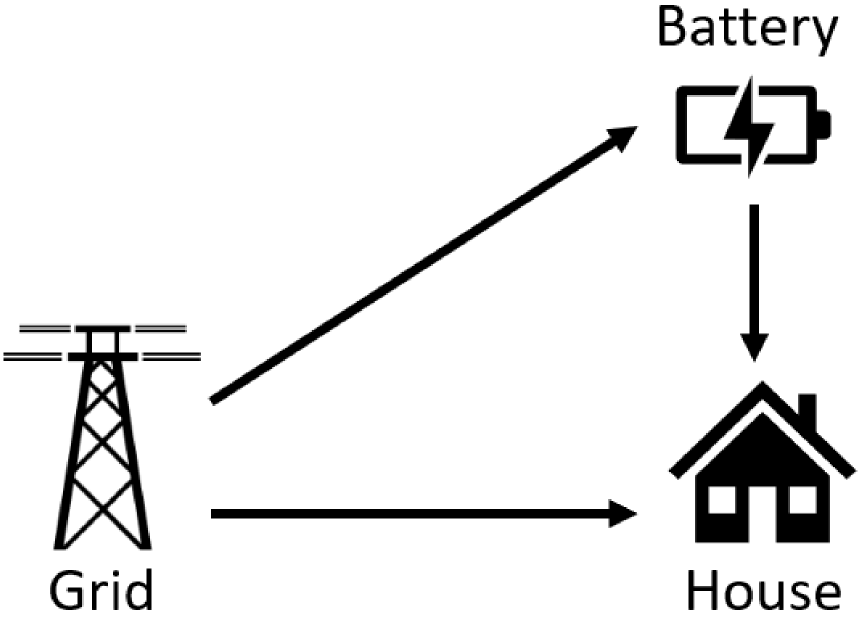
Table 3.8: PVGIS parameters summary.

3.4.6 System overview

Figures 3.16 and 3.17 represent the reference and modified system for each flexibility mechanism. In each case, the modified version includes the battery which allows to either store electricity from the grid or from the PV system (in the case of self-consumption) before being consumed by the house. An important point is that the house consumption is the reference consumption profile in both the reference and modified setups (this consumption is considered as fatal and can not be modified). The difference in CO_2 emissions is thus computed by using the reference and modified **grid** consumption profiles.

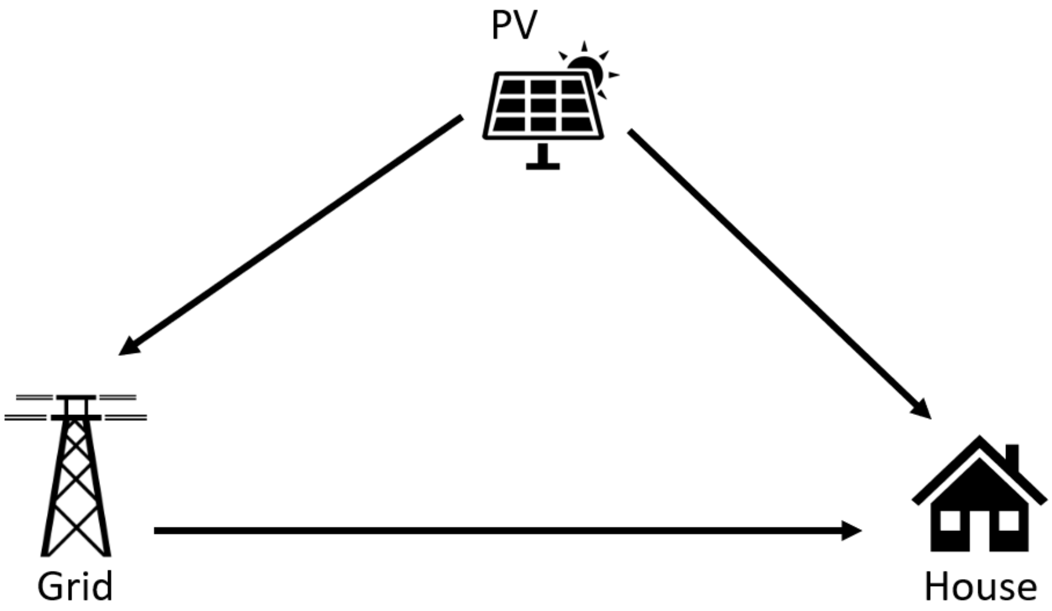


(a) Reference system for dynamic pricing. The grid consumption profile is the same as the house consumption profile as their is no element which allows for a decoupling between the two.

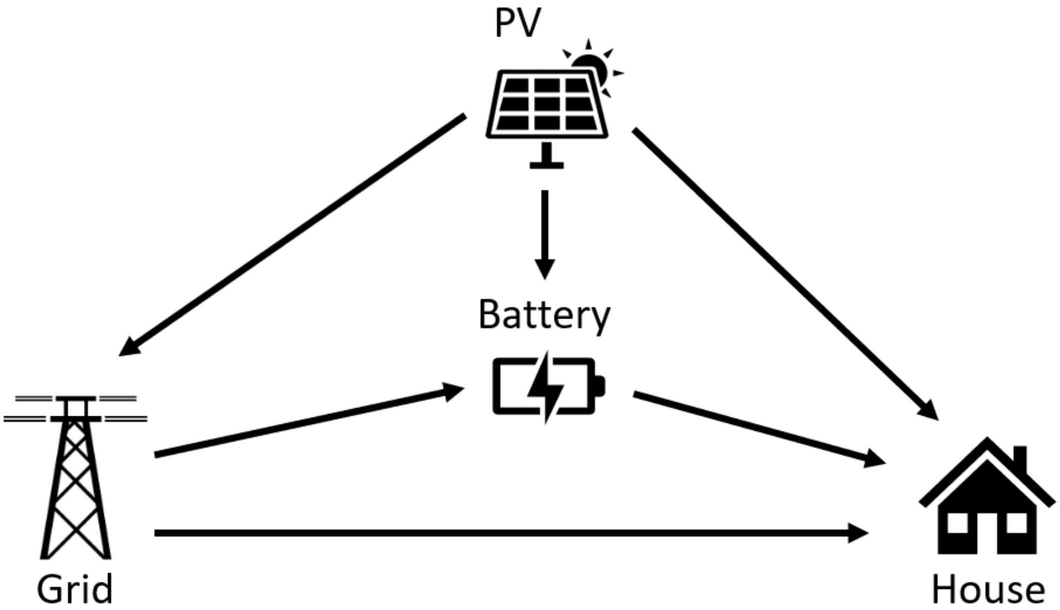


(b) Modified system for dynamic pricing. The battery is added. The grid consumption is now modified because electricity can be stored in the battery before being consumed by the house.

Figure 3.16: Reference and modified systems overview for the dynamic pricing mechanism.



(a) Reference system for self-consumption. The grid consumption profile is not the same as the house consumption because the PV system is already capable of delivering power to the house.



(b) Modified system for self-consumption. The grid consumption profile is modified from the reference case because of the battery which allows three extra power flows : from the PV system to the battery, from the grid to the battery and from the battery to the house.

Figure 3.17: Reference and modified systems overview for the self-consumption mechanism.

3.5 CO_2 signal computation

Once the modified consumption profiles are obtained, one must combine them with an instantaneous CO_2 signal (the CO_2 content of electricity at each time-step) in order to compute the total yearly emissions. This CO_2 signal is computed using relevant CO_2 assessment methods and emission factors. This section explains the selection of the methods and EFs and provides a simple example on how the CO_2 signals are computed in this study, depending on the chosen method. Note that the methods developed in this work do not take into account imports and exports. Only the production data is used to compute each country's instantaneous CO_2 signal. As a result, the carbon content in Germany is more important than the carbon content in France.

3.5.1 EF selection

As explained in chapter 2, EFs of electricity sources are the amounts of GHG these sources emit per unit of electricity produced. In this study, all the EFs presented earlier are used, in order to compare results and discuss how they can affect the final results. Their values are shown in Figures 2.5 and 2.6 in chapter 2 and are given in Table 3.9 below for exhaustivity purposes.

	Nuclear	**Hydro**	**Wind (onshore)**	**Wind (offshore)**	**Solar PV**	**Biomass**	**Natural gas**	**Oil**	**Coal**
ADEME	6	6	14	16	44	230*	418	730	1058
IPCC	12	24	11	12	44.5	230	490	730*	820
UNECE	5	11	12	14	37	230*	434	730*	1023

Table 3.9: EFs used in this study in [gCO_2,eq/kWh]. Values with a star are taken from the only organization which provides an EF for the respective electricity source (biomass (provided by IPCC) and oil (provided by ADEME)).

3.5.2 Assessment methods selection

Based on the information provided in chapter 2, one can summarize the different assessment methods with Table 3.10. As already explained, to be relevant for this study, the selected methods must be able to reflect the effect of short-term flexibility actions and consumption modification on global emissions by computing a dynamic CO_2 signal. For this reason, the selected methods are the **hourly mean mix method** and the **marginal method**.

	Global Emissions	**Consumption Uses**	**Flexibility Applications**	**Prospective Scenarios (long-term)**	**Data Requirements**	**Selected ?**
Mean mix (yearly)	✓	✗	✗	✗	Low	✗
Mean mix (monthly)	✓	✓	✗	✗	Medium	✗
Mean mix (hourly)	✓	✓	✓	✗	High	✓
Seasonal	✓	✓	✗	✗	Medium	✗
Marginal	✗	✓	✓	✗	High	✓
Incremental	✗	✓	✗	✓	High	✗

Table 3.10: CO_2 assessment methods global summary.

3.5.3 CO_2 signal computation example

To properly illustrate how the CO_2 signal is computed for each assessment method, a basic example is described in this section, focusing on 4 different quarter-hours in Germany in 2018 (January, February, March and April 1^{st} from 12:00 until 12:15). For this example, the electricity production data is given in Table 3.11. January 1^{st} has a very high onshore wind production which allows for a lower production with coal power plants, which should thus lead to a lower CO_2 content for that quarter-hour. March 1^{st} and April 1^{st} have very similar production distribution and have a lower coal production than February 1^{st}, mainly due to a higher amount of solar PV. One can expect that February 1^{st} has the highest CO_2 content.

	Nuclear	**Hydro**	**Wind (onshore)**	**Wind (offshore)**	**Solar PV**	**Biomass**	**Natural gas**	**Oil**	**Coal**	**TOTAL**
Jan 1^{st} 12:00 - 12:15	1252 (7.6)	563 (3.4)	7958 (48.5)	822 (5.0)	1640 (10.0)	1254 (7.6)	626 (3.8)	270 (1.7)	2038 (12.4)	**16422**
Feb 1^{st} 12:00 - 12:15	2264 (11.6)	970 (5.0)	4787 (24.5)	1001 (5.1)	1590 (8.1)	1277 (6.5)	1590 (8.1)	271 (1.4)	5812 (29.7)	**19562**
Mar 1^{st} 12:00 - 12:15	1937 (8.7)	417 (1.9)	6439 (29.0)	955 (4.3)	4615 (20.8)	1238 (5.6)	1468 (6.6)	247 (1.1)	4876 (22.0)	**22193**
Apr 1^{st} 12:00 - 12:15	1977 (13.7)	530 (3.7)	3875 (26.8)	290 (2.0)	2085 (14.4)	1236 (8.6)	891 (6.2)	279 (1.9)	3270 (22.7)	**14433**

Table 3.11: German production data ($P_{p,qh}$) from 2018 to illustrate the assessment method's implementation. Values are given in [MWh]. Numbers in parentheses are the percentage of the production filled by the respective electricity source at that time.

Mean hourly method implementation

The mean hourly method is straightforward and easily implemented. One should note that the time-step is reduced to 15 min to match the temporal resolution of the study. However that does not change how the method works and Equation 2.2 can easily be adapted as follows :

$$Q_{CO_2,qh} = \frac{\sum_{p=1}^{P}\left(P_{p,qh} \cdot EF_p\right)}{\sum_{p=1}^{P} P_{p,qh}} \quad [gCO_{2,eq}/kWh] \tag{3.3}$$

where $Q_{CO_2,qh}$ is the electricity carbon content for quarter-hour qh, $P_{p,qh}$ is the electricity production of power generating unit type p during quarter-hour qh and EF_p is the emission factor of the same power generating unit type. Using the EFs from Table 3.9 and the production data from Table 3.11, one can compute the related CO_2 contents shown in Figure 3.18. As expected, the lowest carbon contents are obtained for the quarter-hour in January and the highest for the quarter-hour in February. One can also observe that the IPCC systematically gives lower values. This is due to its coal EF (820 gCO_2,eq/kWh) which is smaller than the ADEME's and UNECE's (1058 and 1023 gCO_2,eq/kWh respectively).

Marginal method implementation

Implementing the marginal method is a more difficult challenge to tackle. Indeed, the marginal method assumes that the electricity carbon content is solely determined by the last power generating unit in the merit order (see

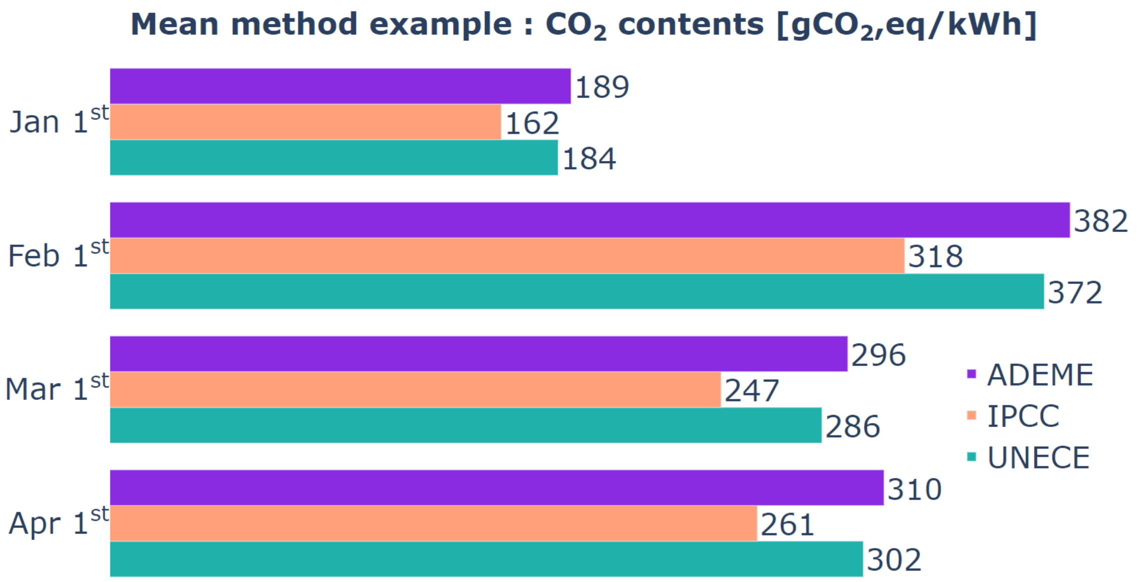


Figure 3.18: Computed carbon contents using the mean mix method. The results are as expected (lower values in for January and higher values for February). The IPCC gives smaller carbon contents due to its lower coal EF.

Figure 2.7 in chapter 2 for the details). However, determining this production unit is very difficult in practice. The available data towards finding this information is scarce and one must thus define a methodology which tries to replicate the method as closely as possible.

One way to do this is to assume that the last called power generating unit is either always a coal-fired plant, an oil-fired plant or a gas-fired plant. Indeed, it is safe to say that renewable energy sources and nuclear plants are not fixing the market price, as their respective marginal costs are quite low. The hypothesis taken in this study for the marginal method is to assume that **the marginal carbon content of electricity is a weighted sum of the carbon contents of the three most-emitting electricity sources**, namely gas, oil and coal. In other words, one applies the mean mix method, but only considering these three types of power plants. Table 3.11 can then be simplified into Table 3.12. The computed CO$_2$ contents are shown in Figure 3.19.

	Natural gas	**Oil**	**Coal**	**TOTAL**
Jan 1st 12:00 - 12:15	626 (21.3)	270 (9.2)	2038 (69.5)	**2934**
Feb 1st 12:00 - 12:15	1590 (20.7)	271 (3.5)	5812 (75.8)	**7673**
Mar 1st 12:00 - 12:15	1468 (22.3)	247 (3.7)	4876 (74.0)	**6591**
Apr 1st 12:00 - 12:15	891 (20.1)	279 (6.3)	3270 (73.6)	**4440**

Table 3.12: Simplified German production data ($P_{p,qh}$) from 2018 to illustrate the marginal method's implementation. Values are given in [MWh]. Numbers in parentheses are the percentage of the production filled by the respective electricity source at that time. One can observe that the three production sources have similar shares in each case, which should lead to carbon contents close to each other.

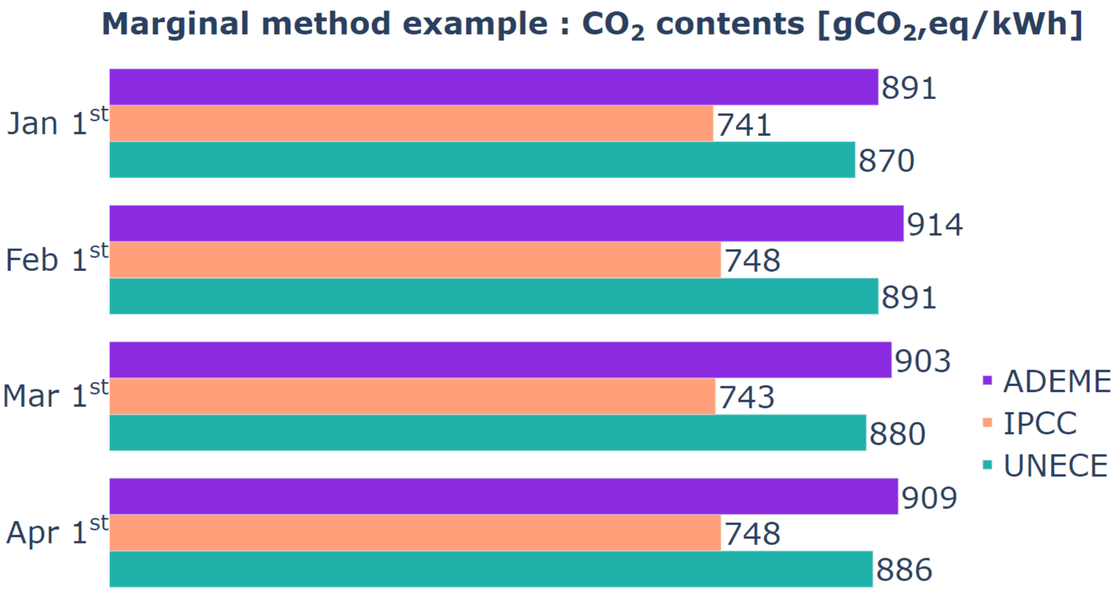


Figure 3.19: Computed carbon contents using the marginal method. Though they are much higher than for the mean mix method, the values are very close to each other due to a similar production shares distribution in each case. Again, the IPCC gives smaller carbon contents due to its lower coal EF.

The marginal method provides much higher CO_2 contents than the mean mix method. This is due to its nature which assumes that only the last called power generating unit sets the electricity carbon content. In this example, the marginal method does not provide very diverse results because the production distribution between oil-, coal- and gas-powered plants is similar for the four selected quarter-hours.

Chapter 4

Results and analyses

This chapter presents the results of the simulations carried out in this thesis. First, the dynamic pricing flexibility mechanism is investigated, followed by the PV self-consumption mechanism. In each case, the global observations and results are presented and are then explained and analyzed. The chapter ends with a discussion putting into perspective the relative importance of each flexibility mechanism. In this chapter, France is sometimes referred to as **FR**, Germany as **GE**, the mean mix method as **MEAN**, the marginal method as **MARG**, 2018 as **18** and 2019 as **19**.

4.1 Dynamic pricing

4.1.1 Global observations

Figures 4.1 and 4.2 show the global CO_2 variations due to the implementation of dynamic pricing[1]. The following observations can be made :

1. The effect of dynamic pricing on the CO_2 emissions is limited : the results range from a maximum emission reduction of about 8% (MEAN FR18) to a maximum increase of around 10% (MARG FR18).
2. With the mean mix method, emissions are reduced in France (both in 2018 and 2019). In Germany, they slightly increase in 2018 and very slightly decrease in 2019.
3. With the marginal method, emissions increase in all cases (from 4 to 10%). No significant changes can be observed between the countries and the years, except for France in 2018 for which the emissions increase is higher.
4. Variations in the results due to the EF organizations (ADEME, IPCC and UNECE) are much smaller than variations due to the selected method, year and country.

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[1] The results are here separated by CO_2 assessment method. The same results are shown in Appendix E where they are separated by country and by study year.

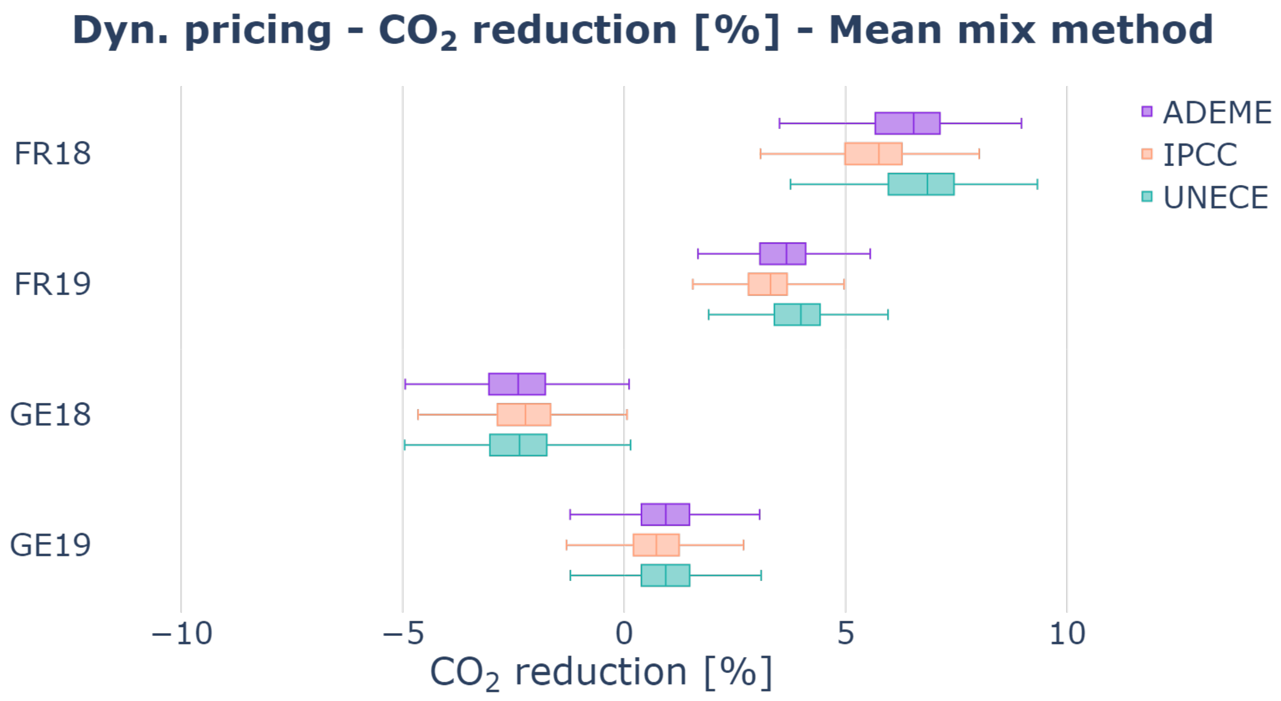

Figure 4.1: Global results - dynamic pricing - mean mix method. CO_2 emissions are reduced by 3 to 9% in France and stay the same in Germany. The EF organizations do not provide substantial differences in the estimated CO_2 variation.

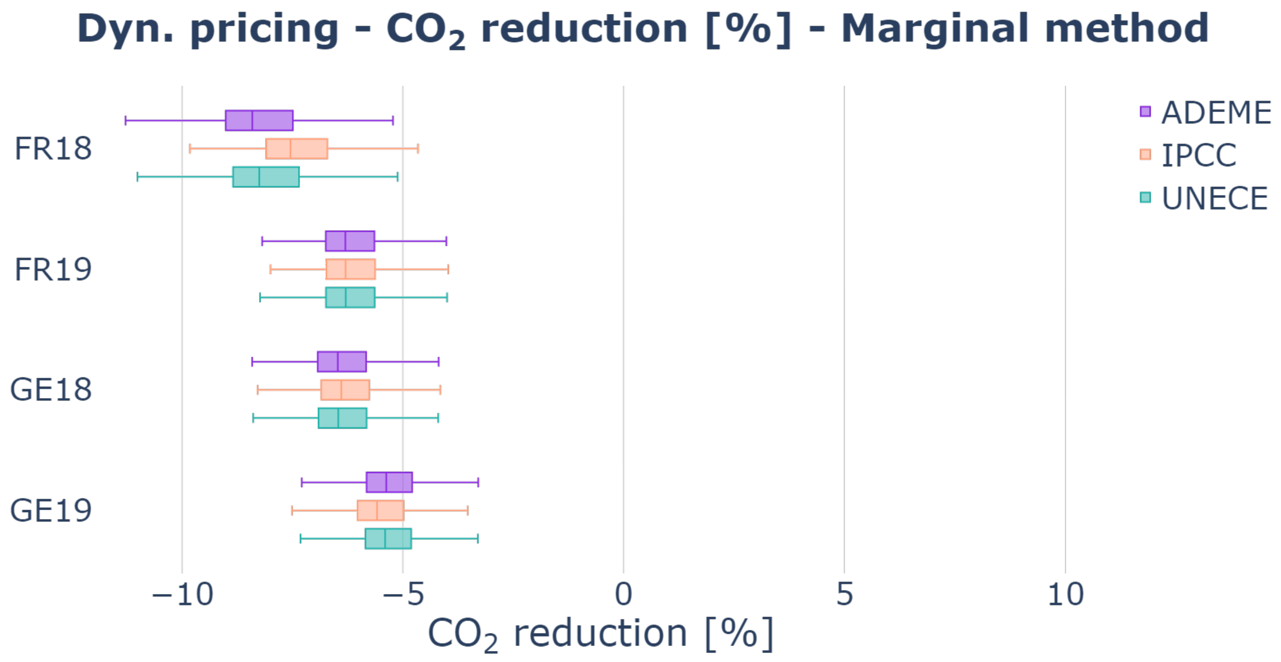

Figure 4.2: Global results - dynamic pricing - marginal method. CO_2 emissions increase in both France and Germany by 5 to 10%. The EF organizations do not provide substantial differences in the estimated CO_2 variation.

The limited CO_2 reductions (and even the increase in emissions in most of the cases) computed for the dynamic pricing mechanism is due to the combination of two phenomena, which are developed below :

1. **The battery losses lead to a total consumption increase yielding additional emissions.**
2. **The financial optimization only leads to the consumption of cleaner electricity in the case of the mean method.**

4.1.2 Battery losses

A. Global results

As the battery's efficiency is set at 90%, some of the battery-stored electricity is lost during the process of charging and discharging. Because the total house consumption is fixed, this leads to an increase in total drawn electricity from the grid over the year which in turn leads to additional CO_2 emissions. Figure 4.3 shows the percentage of additional consumption for the different cases. One can see that this over-consumption varies between 4 and 8%. It is slightly higher in France than in Germany and is also slightly higher in 2018 than in 2019. Note that the global values of over-consumption are smaller than 10% because some of the electricity is not stored in the battery and flows directly from the grid to the house.

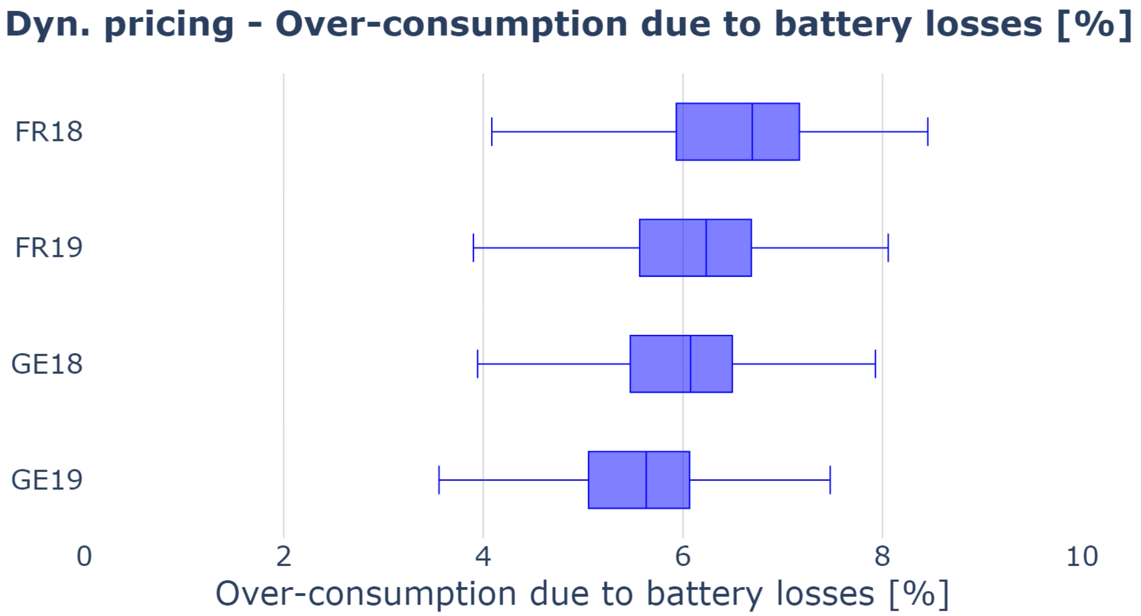

Figure 4.3: Global over-consumption due to battery losses for the different cases. The over-consumption consistently varies between 4 and 8%.

B. Profile distribution

Figure 4.4 shows how the over-consumption is distributed across the consumption profiles in France in 2018. An almost-linear decrease of the over-consumption can be observed when the total electricity consumed over the year increases. This happens because of the limited capacity of the battery. Indeed, Figure 4.5 shows that the higher the total consumption, the lower the amount of electricity the battery can store (relatively to the total consumed electricity). Less electricity stored means lower over-consumption and in turn lower additional emissions. One can thus conclude that **small consumption profiles are more penalized by over-consumption because it represents a higher share of their total reference consumption.** The same conclusions can be made for 2019 and Germany (see Appendix E for the complete results).

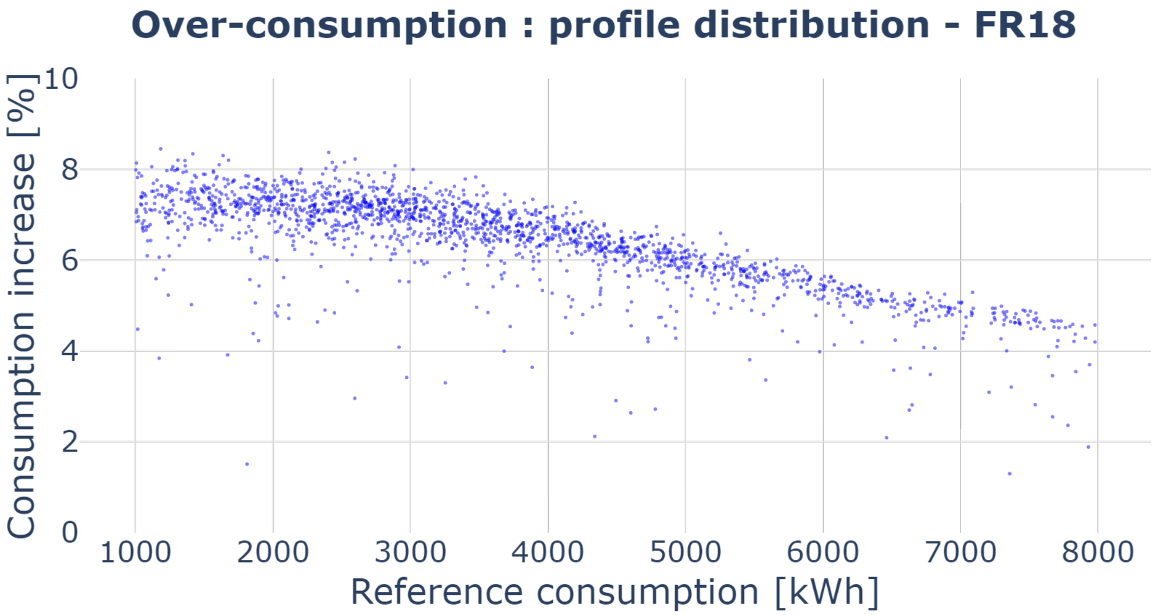

Figure 4.4: Over-consumption distribution in France in 2018. The consumption increase gets smaller as the consumption profile get larger.

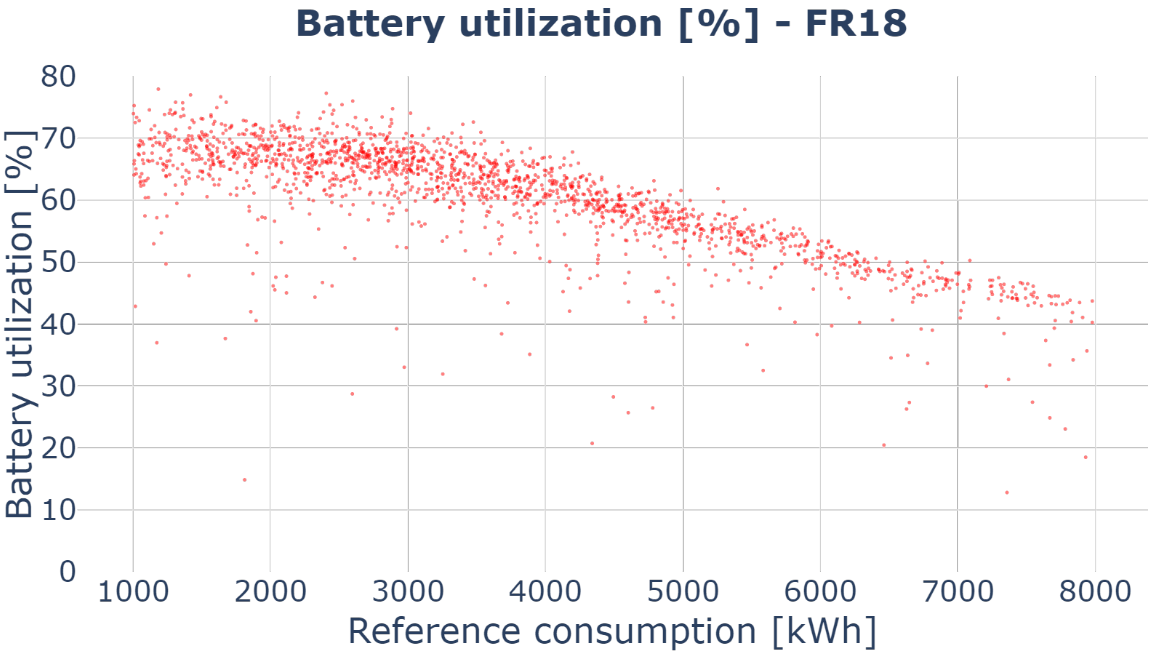

Figure 4.5: Battery utilization distribution in France in 2018. this represents the amount of electricity that goes through the battery, relatively to the total house consumption. The larger the consumption profile, the smaller the fraction of electricity that can be stored in the battery because of its limited capacity.

4.1.3 Correlation between electricity price and CO_2 content

In chapter 2, Figure 2.7 (merit order curve) showed that, in principle, higher electricity prices mean higher CO_2 contents of electricity because of the use of more carbon-intensive power sources. A way to check this is to find the correlation coefficient between the day-ahead spot market price and the computed CO_2 signals. Table 4.1 gives these correlation coefficients. For the mean method, correlations are moderate (close to strong in 2019). Using the mean method, optimizing the cost should thus result in lower CO_2 emissions. For the marginal method, correlations are not significant and there is thus no reason for the CO_2 emissions to decrease when using the implemented marginal method.

		2018	**2019**
MEAN	**FR**	0.62	0.70
	GE	0.61	0.69
MARG	**FR**	0.11	0.27
	GE	-0.05	0.20

Table 4.1: Correlation coefficients between DAM spot prices and computed CO_2 signals. For the mean method, correlations are moderate (close to strong in 2019). For the marginal method, correlations are not significant.

4.1.4 Marginal method

A. Global results

As their is no correlation between the electricity price and its CO_2 content, results for the marginal method are only driven by the over-consumption phenomenon. This results in a net increase of CO_2 emissions, by around the same amount as the observed over-consumption (see Figure 4.6).

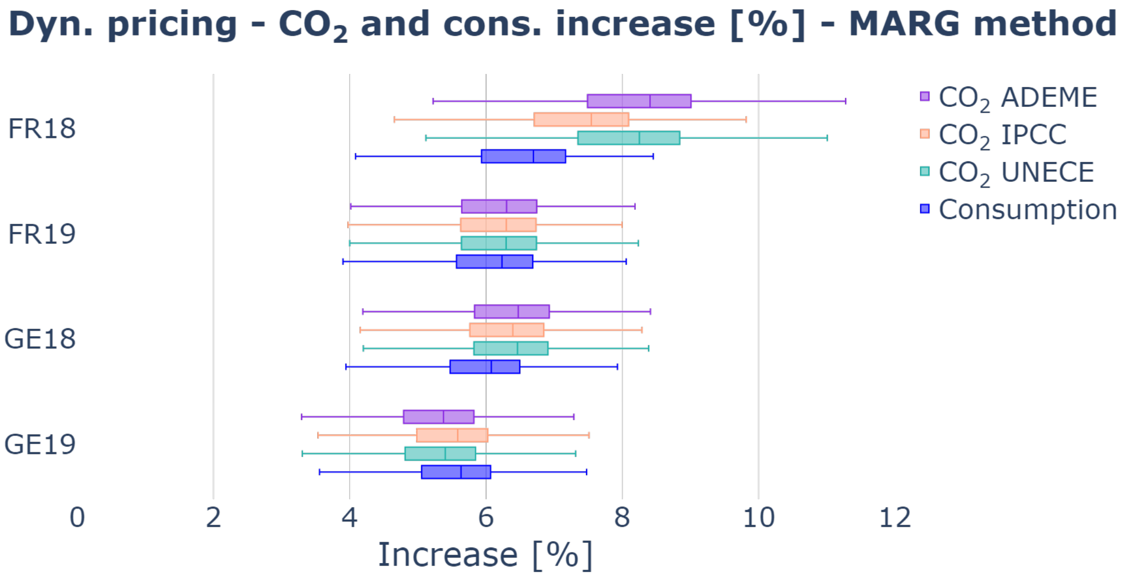

Figure 4.6: Marginal method : the CO_2 increase matches with the consumption increase.

B. Profile distribution

The distribution over the different profiles is shown for France in 2018 in Figure 4.7[2]. Small consumption profiles undergo a higher emission increase, due to the over-consumption phenomenon. This emission increase gets smaller as the consumption profile gets bigger.

4.1.5 Mean method

A. Global results

In the case of the mean method, the correlation coefficients show that there is a visible link between spot price and CO_2 content. Optimizing the cost should thus result in a decrease in CO_2 emissions. Figure 4.1 shows that this is indeed the case in France but not in Germany. A potential reason for this could be that over-consumption cancels out the CO_2 savings in Germany, while it does not in France. The difference could then be due to the fact that over-consumed electricity in Germany has a higher carbon content relatively to its global mean mix than it is the case in France.

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[2] Complete results are in Appendix E.

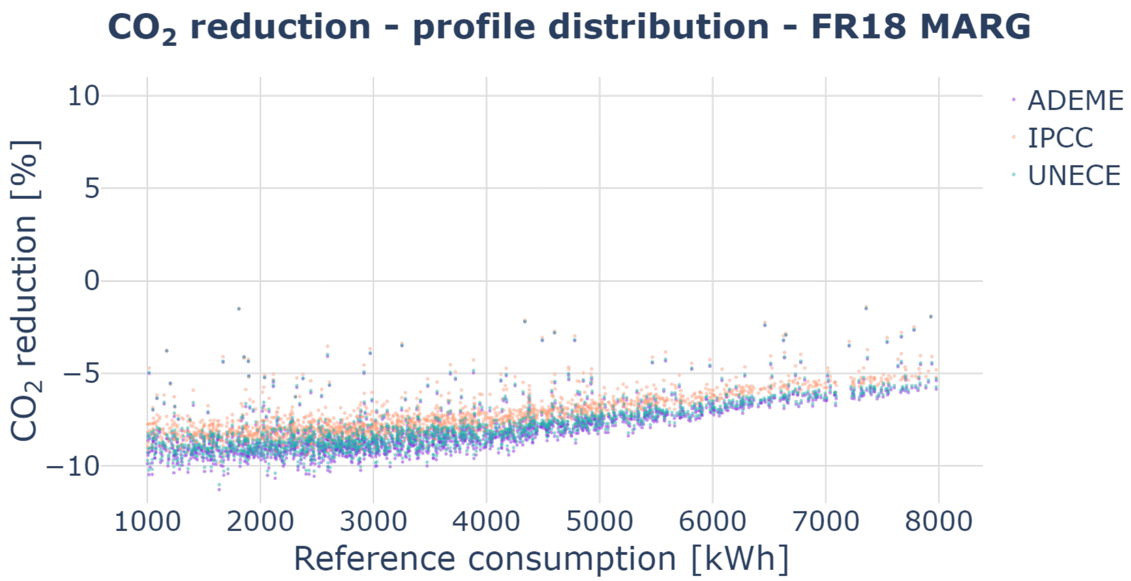

Figure 4.7: Marginal method profile distribution in France in 2018. The emission increase gets smaller as the consumption profile gets bigger because bigger profiles are less sensitive to over-consumption.

B. Profile distribution

Figures 4.8 and 4.9 show the profile distribution results for the mean method in 2018. In France, the CO_2 reductions get smaller as the consumption profile increases. This happens because the reduction in emissions due to flexibility is more important than the increase due to over-consumption : the more the battery is used, the more one can take advantage of the lower CO_2 contents, despite the higher consumption. In Germany, the emissions are almost constant across the consumption profile range. Again, this shows that the CO_2 reduction due to flexibility is cancelled out by the over-consumption phenomenon : the more a profile consumes, the less it takes advantage of lower CO_2 contents but also the less it over-consumes.

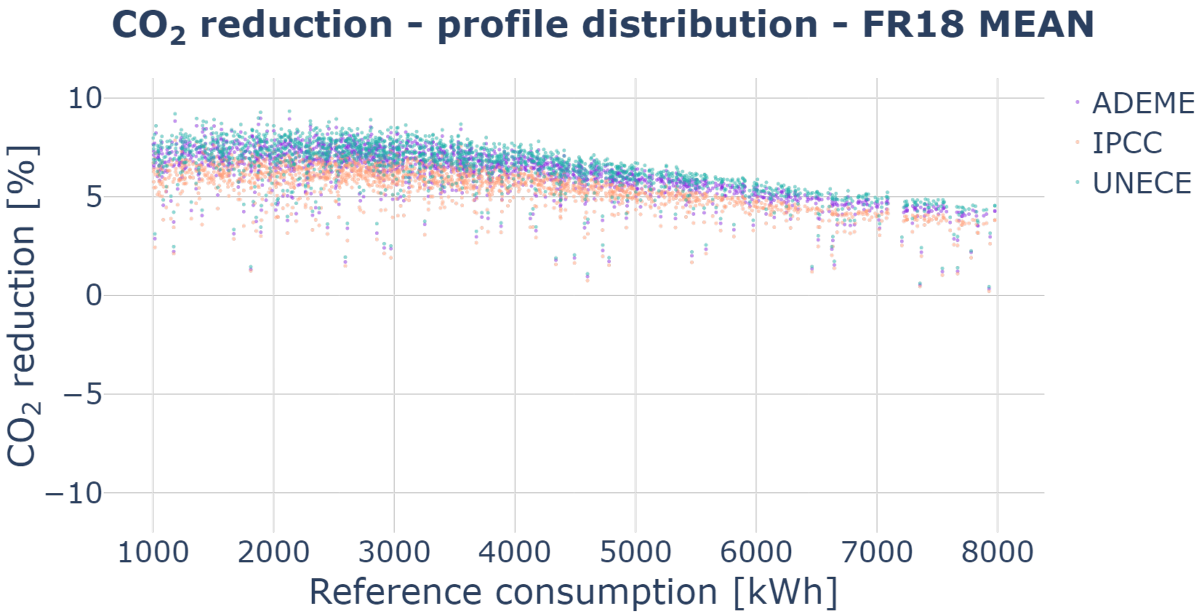

Figure 4.8: Mean method profile distribution in France in 2018. The CO_2 reductions get smaller as the consumption profile increases. This happens because the reduction in emissions due to flexibility is more important than the increase due to over-consumption.

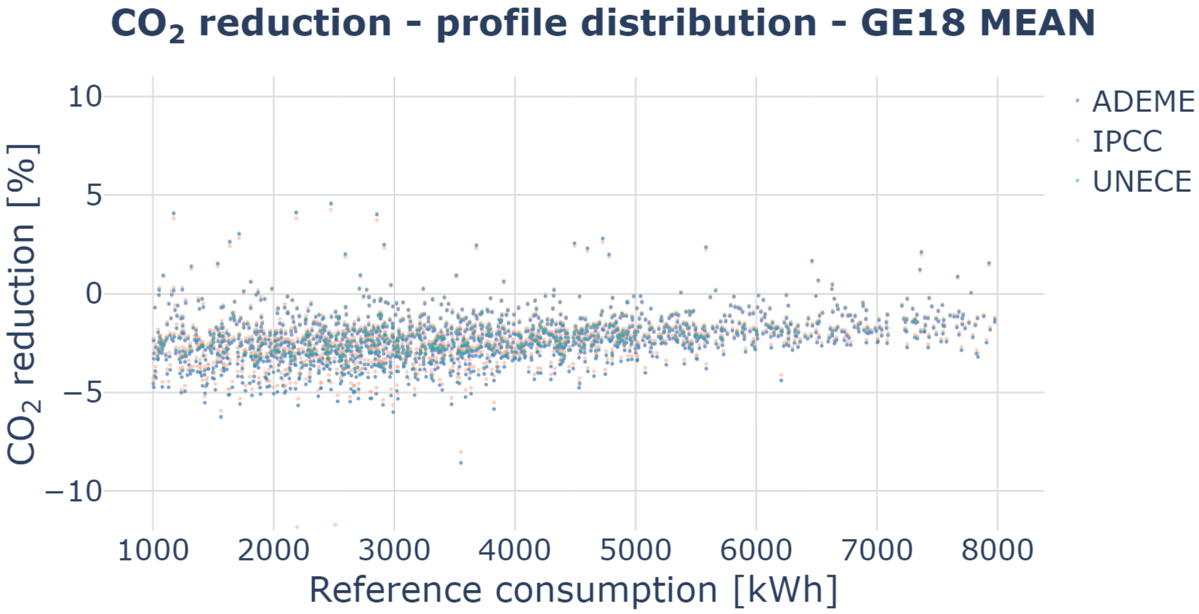

Figure 4.9: Mean method profile distribution in Germany. The emissions are almost constant across the consumption profile range. This shows that the CO_2 reduction due to flexibility is cancelled out by the over-consumption phenomenon.

4.2 Self-consumption

This section starts by comparing and analyzing results for France and Germany using the same PV location (Lille). It then takes a look at the variability of the results depending on the irradiation levels by using the three different PV locations in France (Cannes, Poitiers and Lille).

4.2.1 Global observations

Figures 4.10 and 4.11 show the global CO_2 variations due to the implementation of self-consumption[3]. The following observations can be made :

1. The marginal method (in both France and Germany) and the mean method in Germany give significant and widespread CO_2 emission reductions, ranging from 10 to 55%. For those cases, variations due to the EF organization are negligible compared to the global reduction.
2. The mean method in France (see Figure 4.15 further down for a more precise illustration) provides different results depending on the EF organization. The IPCC EFs allow for the most important reduction (1% to 10%), closely followed by the UNECE (increase of 0.5% to reduction of 8.5%) and finally by the ADEME (increase of 4% to reduction of 2.5%). Reductions are more important in 2018 than in 2019.

The reason behind these results is that the financial optimization leads to a **significant increase in self-consumption percentage when the battery is integrated to the system.** Indeed, as self-consumed electricity is considered to be free, the controller maximizes the consumption of self-consumed electricity, either by supplying it directly to the house or by storing it in the battery if the latter is not full.

4.2.2 Self-consumption variations

Figure 4.12 shows the reference (without battery) and optimized (with the battery and controller) self-consumption percentages[4]. The selected country has no impact here as they are both submitted to the same tariff and given the same PV production files (Lille). For both 2018 and 2019, **the self-consumption percentage increases by 30% when the battery is added to the system.** There is no significant difference between 2018 and 2019. Figure 4.13 shows how the self-consumption rates are distributed across the consumption profiles in 2019[5] : they decrease when the total consumption increases. However, the increase in self-consumption due to the battery implementation is constant up to consumption profiles of 6000 kWh from where the increase slightly reduces.

4.2.3 Effect of self-consumption increase

If the self-consumption percentage increases by roughly 30% when adding the battery, the percentage of grid-consumed electricity decreases by the same amount (battery losses aside). **The carbon content of the additional self-consumed electricity thus shifts from being submitted to the grid carbon content in the reference case to being given the PV emission factor in the modified system with the battery.**

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[3] The results are here separated by CO_2 assessment method. The same results are shown in Appendix F where they are separated by country and by study year.

[4] In this context, the self-consumption rate is the share of total consumption which is covered by the PV installation. As an example, a house consuming a total of 2000 kWh of which 1500 kWh come from its own PV installation has a self-consumption rate of $\frac{1500}{2000} = 0.75 = 75\%$.

[5] 2018 results are in Appendix F.

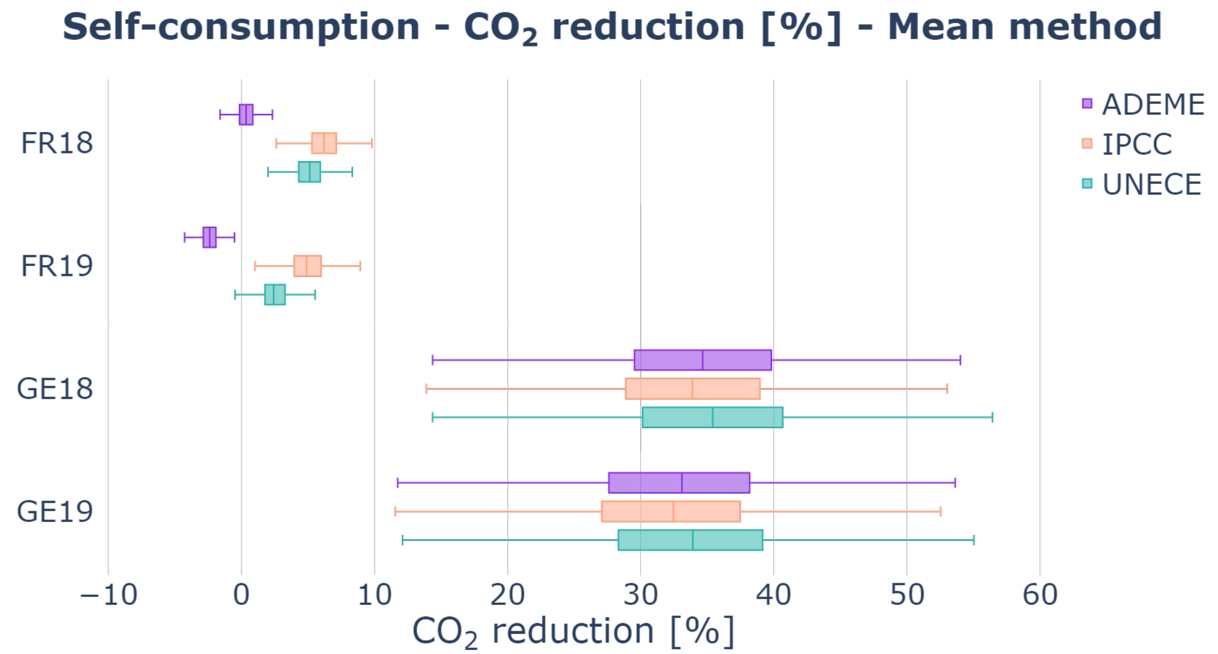

Figure 4.10: Global results (PV location : Lille) - self-consumption - mean mix method : CO$_2$ reductions are significant in Germany. In France the reductions are much smaller and depend on the EF organization.

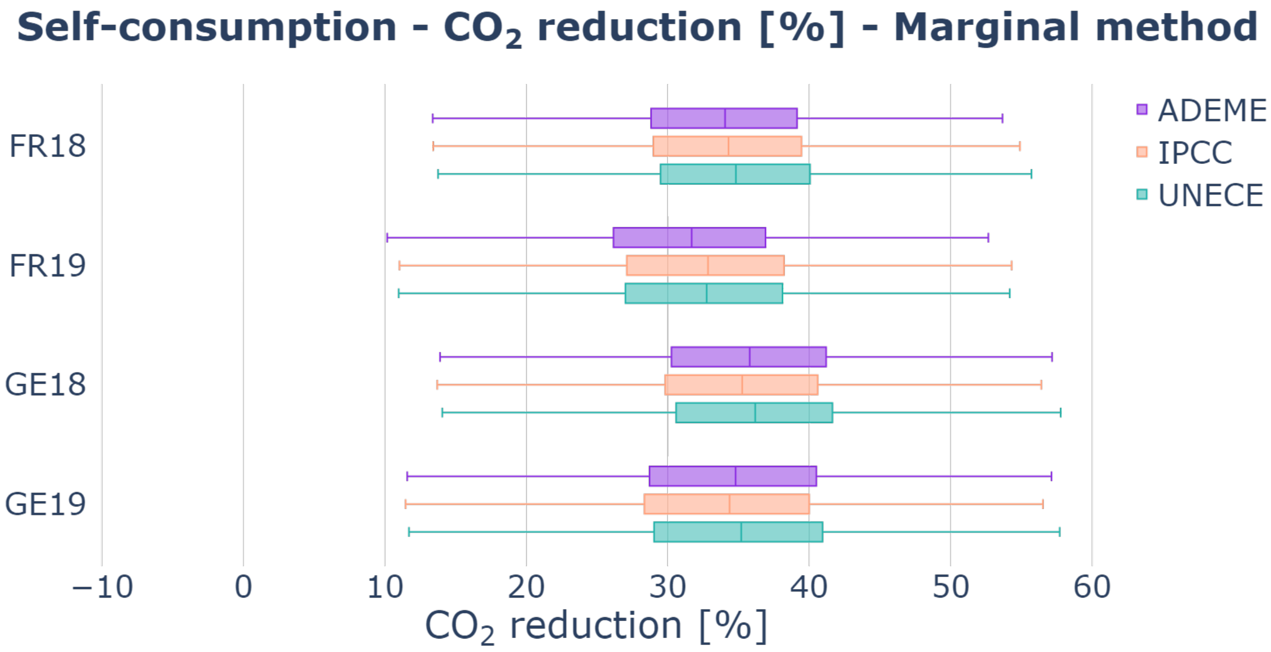

Figure 4.11: Global results (PV location : Lille) - self-consumption - marginal method. CO$_2$ reductions are significant for both France and Germany in 2018 and 2019.

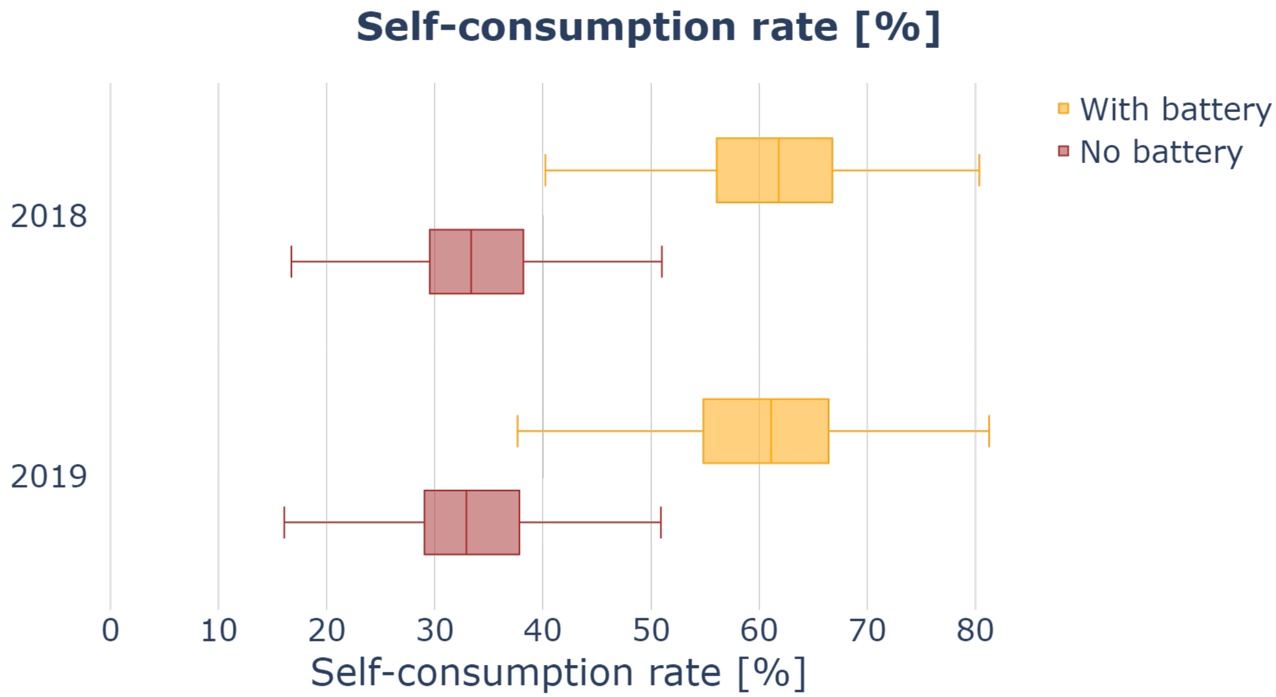

Figure 4.12: Self-consumption rate variations between the reference and modified system (PV location : Lille). The battery integration increases the self-consumption percentage by 30% (both years).

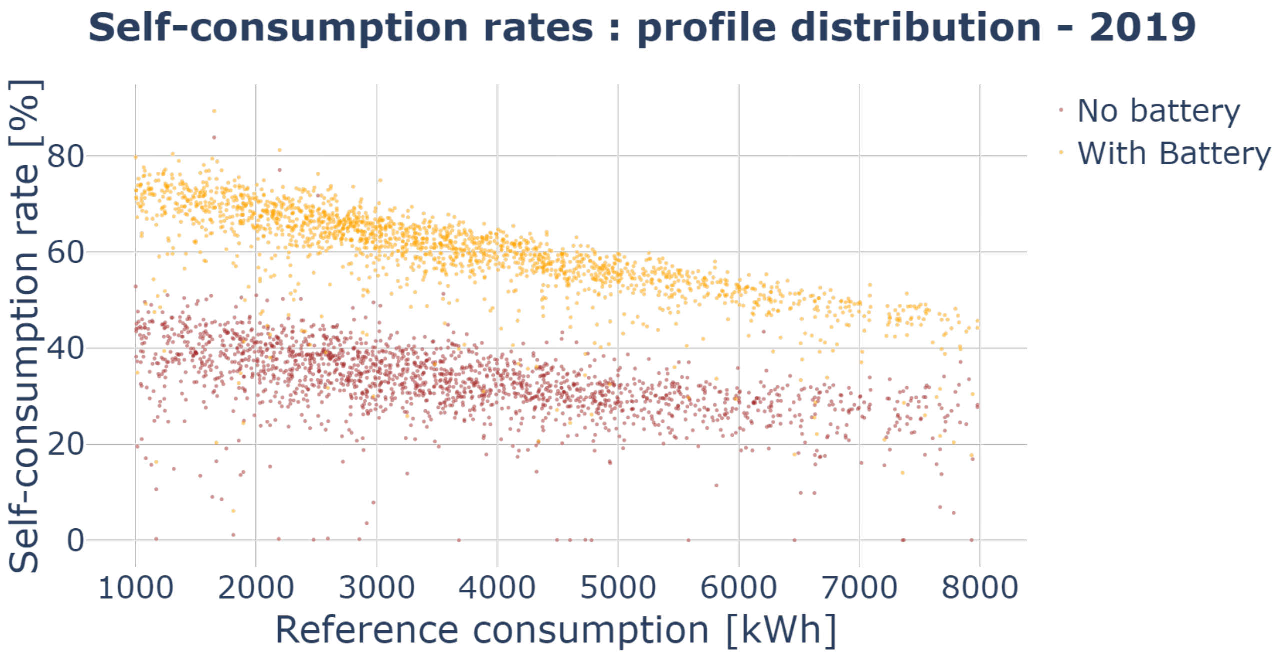

Figure 4.13: Self-consumption rates : profile distribution in 2019 (PV location : Lille). The self-consumption rate decreases as the consumption profiles get bigger.

Marginal method (Germany and France) and mean method in Germany

This shift in CO_2 content explains the significant decrease in CO_2 emissions for the marginal method (both countries) and for the mean method in Germany. Indeed, the computed marginal CO_2 contents and the German mean CO_2 content are much higher than the PV emission factors provided by the EF-assessing organizations. As a reminder, Table 4.2 shows the average CO_2 contents of both countries, methods and study years and Table 4.3 gives the rooftop PV EFs used to compute the emissions of self-consumed electricity. Figure 4.14 shows the distribution of the CO_2 reduction across the consumption profiles for the marginal method in France in 2018 (the other cases have similar distribution, see Appendix F). The CO_2 reduction decreases as the consumption profiles get bigger.

		2018	**2019**
MEAN	**FR**	46	45
	GE	467	396
MARG	**FR**	538	454
	GE	936	875

Table 4.2: Average grid electricity CO_2 contents [gCO_2,eq/kWh].

Power source	ADEME	IPCC	UNECE
PV	44	41	37
Nuclear	6	12	5

Table 4.3: PV and nuclear EFs.

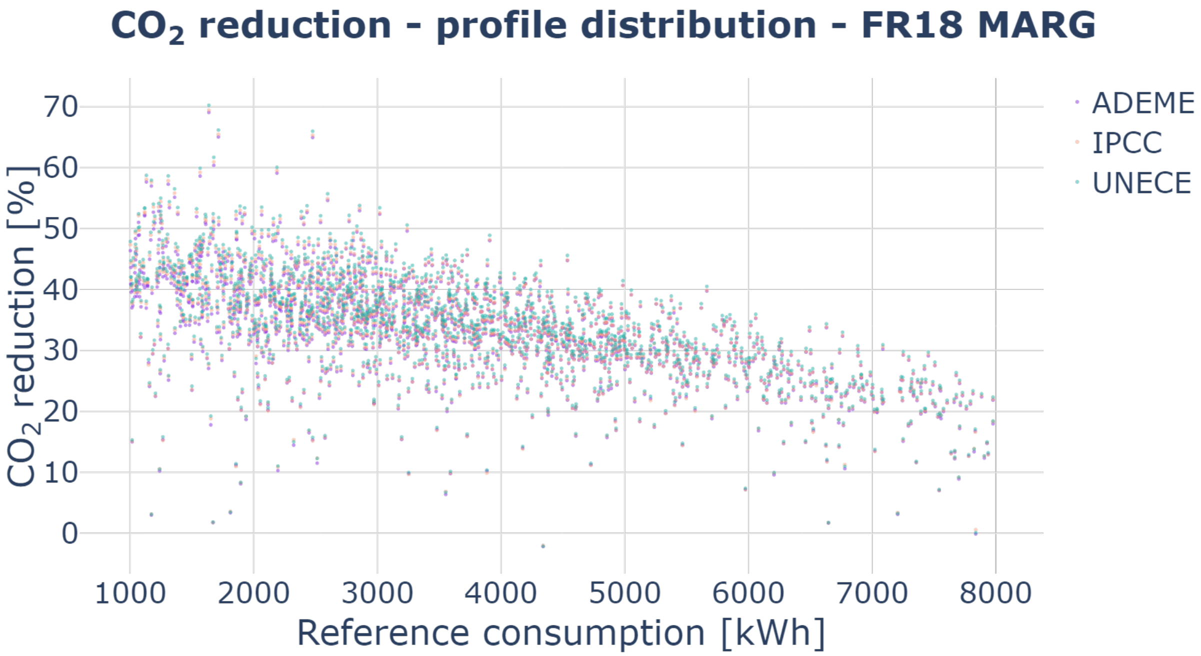

Figure 4.14: CO_2 reduction - profile distribution - marginal method in France in 2018 (PV location : Lille). The CO_2 reduction decreases as the consumption profiles get bigger

Mean method in France

For the mean method in France (Figure 4.15), the shift in carbon content is much smaller with a decrease from 45-46 to 37-44 gCO_2,eq/kWh depending on the organization). Coupled to the battery losses, this leads to a CO_2

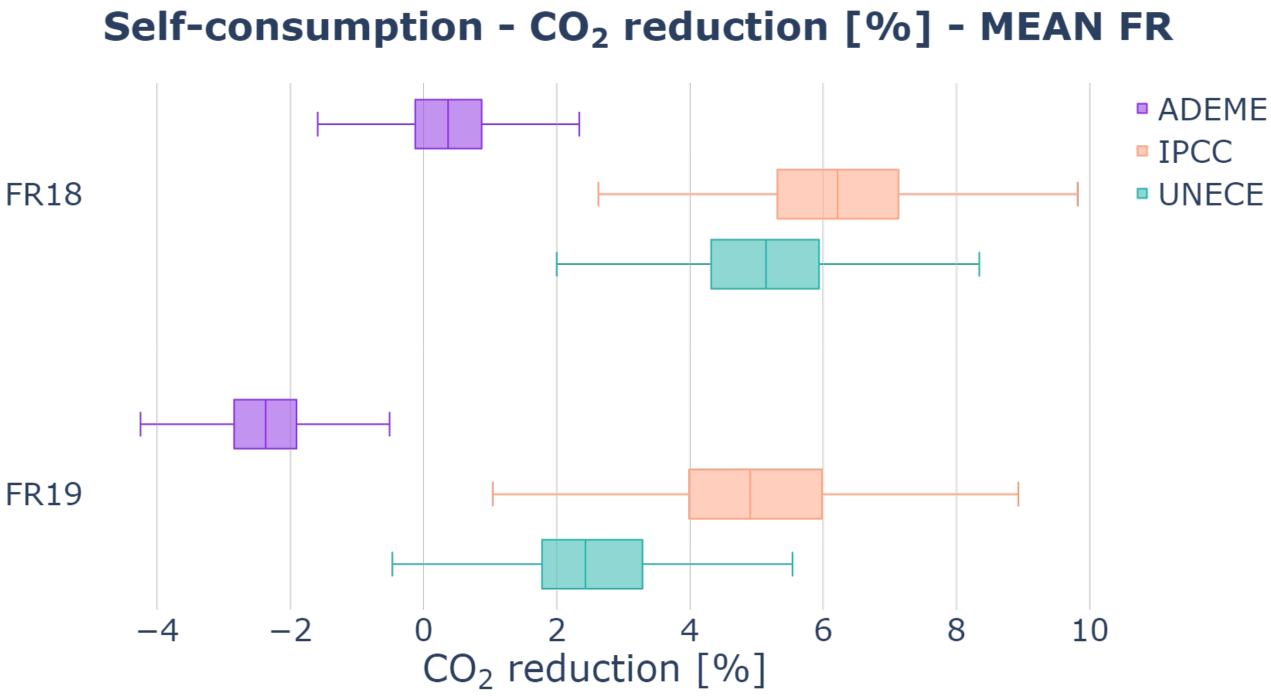

Figure 4.15: Global results (PV location : Lille) - self-consumption - mean mix method in France : the EF organization provide different results.

increase for the IPCC and only a small decrease for the ADEME and the UNECE. Only looking at the PV EFs does not explain why the IPCC EFs lead to a higher reduction than the UNECE's. In fact, one could expect the opposite as the UNECE uses a lower PV EF (37 gCO_2,eq/kWh) than the IPCC (41 gCO_2,eq/kWh). The explanation relies in the nuclear EF : as France has a large share of its production covered by nuclear power, the shift in CO_2 content from grid electricity to PV electricity has a larger impact if the nuclear EF is higher. Therefore, as the nuclear EF is doubled in the case of the IPCC (Table 4.3), a higher reduction can be observed. Combining the PV and nuclear EFs effects results in a slightly higher CO_2 reduction for the IPCC than for the UNECE.

4.2.4 Effect of different irradiation levels

Figure 4.16 and 4.17 show the mean and marginal method CO_2 variations for the various PV locations in 2019. In 2018, the difference between the PV locations is much smaller (less than 1%) because the irradiation differences across the PV locations are not as significant (Table 4.4). In 2019, Cannes allows for a higher CO_2 reduction (smaller increase in the case of the mean method for the ADEME) than Poitiers which itself allows for a higher reduction than Lille. Indeed, higher irradiation levels lead to higher self-consumption rates[6] (Figure 4.18) which allows a more important emission reduction. Locations with higher irradiation levels thus produce more PV electricity which leads to higher self-consumption rates and better CO_2 reductions.

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[6] One can also observe that the self-consumption rate increases more in Cannes than in Poitiers and Lille when the battery is added.

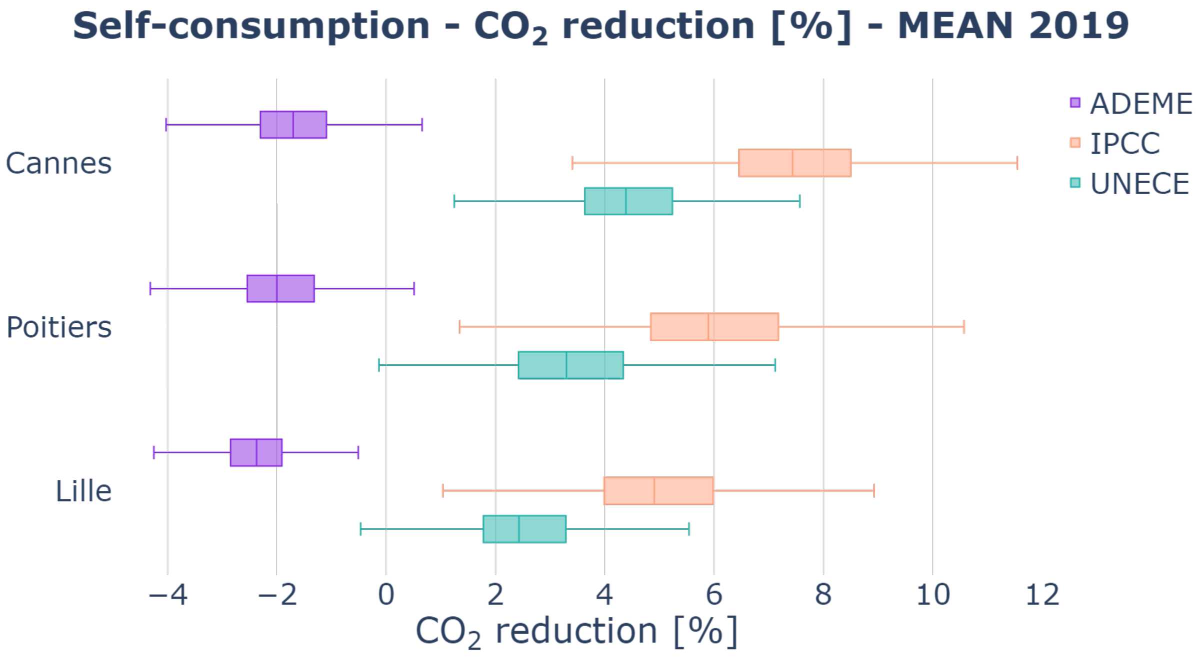

Figure 4.16: Mean method results for the various PV locations in 2019. Cannes allows for a higher CO_2 reduction than Poitiers which itself allows for a higher reduction than Lille.

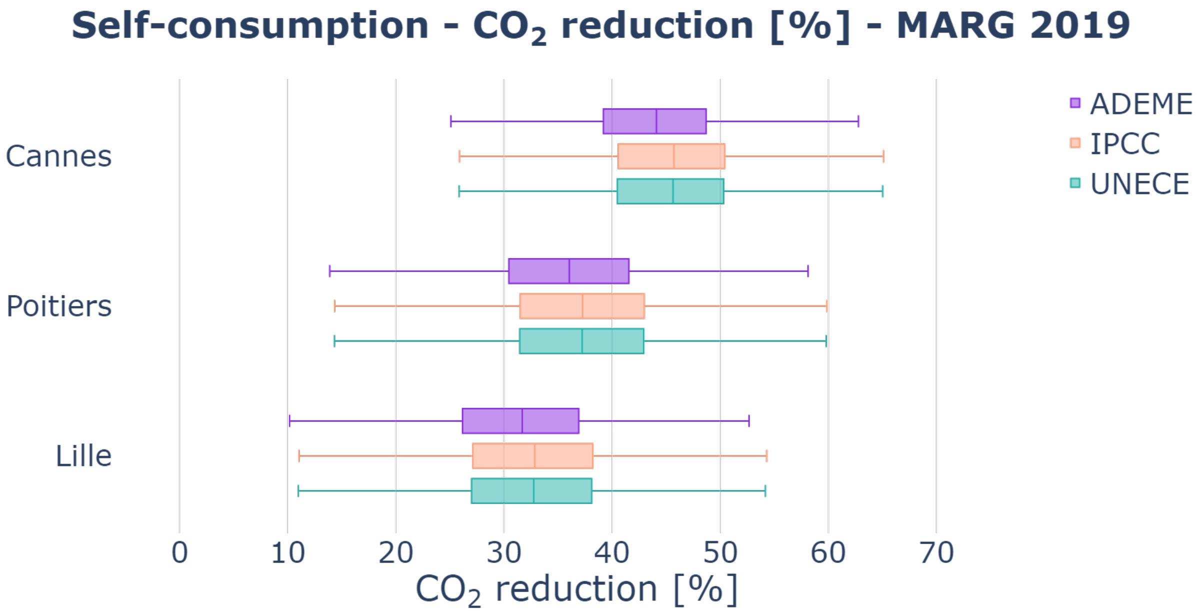

Figure 4.17: Marginal method results for the various PV locations in 2019. Again, Cannes allows for a higher CO_2 reduction than Poitiers which itself allows for a higher reduction than Lille.

	Cannes	**Poitiers**	**Lille**
2018	1813	1578	1479
2019	2004	1605	1386

Table 4.4: Total irradiation over the year [kWh/m^2]. The differences across the locations are more important in 2019 than in 2018.

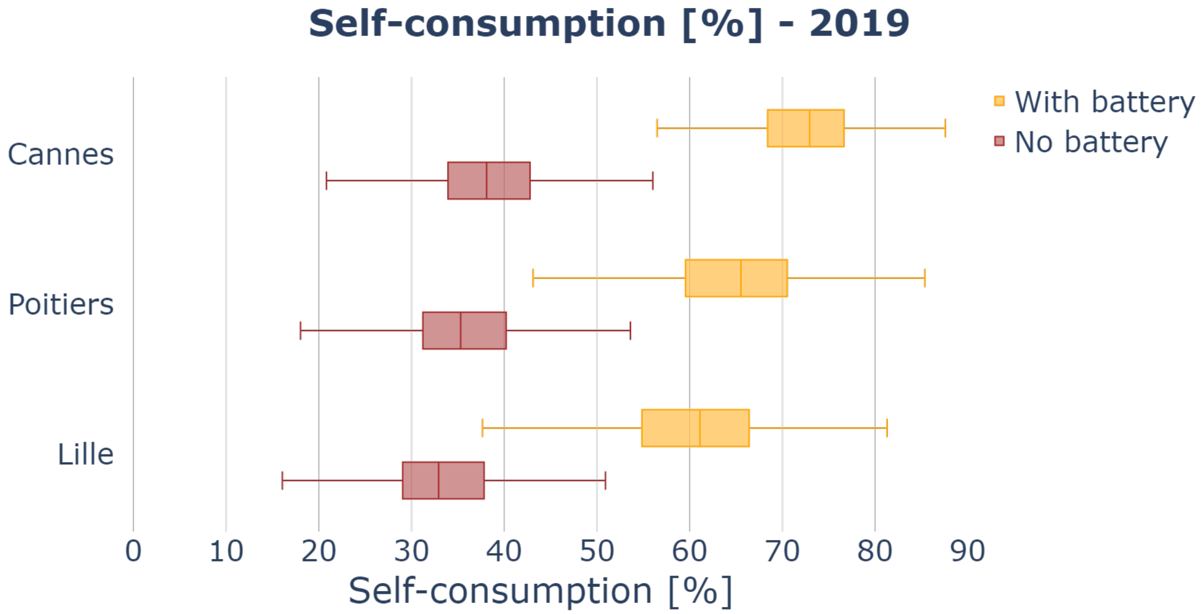

Figure 4.18: Self-consumption rates for the various PV locations in 2019. Higher irradiation levels lead to higher self-consumption rates.

4.3 Wrap-up and discussion of the results

The results presented in the previous sections show that integrating a battery to implement flexibility with dynamic pricing or PV self-consumption can lead to both reductions and increases of CO_2 emissions.

4.3.1 Dynamic pricing

In the case of dynamic pricing, the observed variations in emissions are limited and do not exceed 10% of the original emissions. The two main factors influencing the results for dynamic pricing are **the correlation between the electricity price and the instantaneous CO_2 signal** and **the efficiency of the battery**. Indeed, performing a financial optimization of the consumption only allows to reduce the emissions if their is a link between the price and the CO_2 content and if this reduction is greater than the increase due to the battery losses. In this study, reductions are only observed in France when using the mean method. The reason why it is not the case in Germany is unclear and might be linked to the CO_2 content of the over-consumed electricity. The implemented marginal method does not allow to link the electricity price and CO_2 content. This leads to an increase in emissions equal to the increase in consumption due to the battery losses (around 5% to 6% for a battery with an efficiency of 90%). It should also be noted that the smaller the consumption profile, the smaller the variation in emissions (both for a reduction and for an increase). This is due to the fact that small consumption profiles make more use of the battery, leading to more flexibility but also more battery losses. Submitting electricity production sources to different emission factors (using the EFs of the ADEME, the IPCC or the UNECE) do not provide significant variations in the case of dynamic pricing.

4.3.2 Self-consumption

Variations in emissions linked to PV self-consumption are significant : one can observe reductions in emissions ranging from 10 up to 55% for the marginal method and for the mean method in Germany. The driving factor for this mechanism is **the difference in CO_2 content between the grid and the PV system**. Indeed, the integration of the battery allows to increase the self-production rate by roughly 30%, across all consumption profiles. This leads to a large decrease of the average CO_2 content of the consumed electricity. As the gap between the grid carbon content and the PV emission factor gets smaller (using the mean method in France for instance), the potential reduction in emissions decreases and the importance of the chosen emission factors is highlighted. The higher the PV EF, the smaller the potential reduction. In the case of the mean method in France, it even leads to an increase in emissions when choosing the EF provided by the ADEME.

Though less significant, the irradiation levels of the chosen location can also have an impact on the final emission reduction. Indeed, for a fixed PV installation power, the more irradiation, the more electricity is produced. This leads to higher self-production rates which in turn lead to bigger CO_2 reductions. One can thus also say that the PV installation size is a key factor determining the self-production rate. Using the marginal method, reductions in Cannes are shown to be up to 10% higher than reductions in Lille for 2019. However, this variability depends from year-to-year as solar irradiation varies from one period to another across multiple locations. An additional comment one could make is that the selected locations in this work are chosen based upon a variation in their climate using the temperature as indicator. Though a warmer climate should mean higher irradiation levels, it would be interesting to verify this assumption. Another more straightforward possibility would be to select the locations purely based upon the irradiation they are submitted to, without taking a look at climate zones or temperature.

4.3.3 The CO_2 content of the battery

When looking at Figures 3.16 and 3.17, one can quickly realize that the physical change between the reference systems and the modified systems is the addition of the battery. Although the battery allows for potential emission reductions (in the case of PV self-consumption for instance), this study never addresses its CO_2 content. To be complete and to get a more precise estimation of the variations of emissions when flexibility is implemented, a thorough examination of the battery's carbon content should be conducted. This includes an estimation of the emissions related to its manufacturing process for instance but also of its lifetime. Assessing the carbon content of the battery is the main improvement which could be made to obtain more complete and reliable results.

4.3.4 Marginal method

In regard of the results, one could argue that the marginal method does not provide very diverse results. This is due to the way the marginal carbon content was computed in this work. A way to get more interesting results would be to investigate this matter more deeply and develop a more precise way to identify the last-called power generating unit.

Conclusion

This work tried to assess the impact that flexibility mechanisms can have on greenhouse gas emissions in the residential sector.

First, the context of global warming was introduced by addressing the greenhouse gas effect and the global warming potential of greenhouse gases. Secondly, the concepts of emission factors for power-generating sources and electricity CO_2 emission assessment methods were developed, followed by a presentation of two main flexibility mechanisms in the residential sector, namely dynamic pricing and photovoltaic self-consumption. A detailed methodology was then implemented to determine an interesting study case : study periods and countries were selected, real historical consumption profiles were retrieved, simulation parameters were set and justified and instantaneous electricity CO_2 contents were computed using the appropriate assessment methods and emission factors. Finally, variations in CO_2 emissions due to the implementation of the flexibility mechanisms were computed, presented and analyzed.

The results showed that dynamic pricing has a limited effect on CO_2 emissions : the losses in the battery limit the potential reduction because of the additional emissions of the over-consumption. Self-consumption gives more varied results and allows for high emission reductions when the grid electricity is highly carbonated. Generally speaking, smaller electricity consumers have a higher reduction potential.

Additional investigations should include the CO_2 content of the battery, as this was not taken into account in this study and the development and use of a more interesting marginal method which could provide more varied results.

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Appendix A

Lifetimes and GWPs of common greenhouse gases

Gas	**Molecular Formula**	**Lifetime [years]**	**GWP (100 years)**
Carbon Dioxide	CO_2	300-1000	1
Methane (fossil origin)	CH_{4f}	12.4	30
Methane (biogenic origin)	CH_{4b}	12.4	28
Nitrous oxide	N_2O	121	265
Sulphur hexafluoride	SF_6	3200	23500
Nitrogen trifluoride	NF_3	500	16100

Table A.1: Lifetimes and GWPs of common greenhouse gases [14]. Nitrous oxide is mainly emitted by agricultural activities (soil fertilization and animal waste management) [4]. Sulphur hexafluoride and nitrogen trifluoride are only emitted by human-related activities and both have very high GWPs. SF_6 *is primarily used as an insulating gas for electrical applications [12] while* NF_3 *is commonly used in the microelectronic manufacturing industry [13].*

Appendix B

Consumption uses electricity content comparison

B.1 Computation and analysis

In order to illustrate some of the methods described in Chapter 2, let us use some data provided by ADEME [47] to compute the emission factors of the main residential consumption uses (heating, domestic hot water production, cooking and lighting). Tables B.3 and B.4 provide the base, seasonalized and total electricity production and consumption values in France in 2019. Table B.1 shows carbon content factors for the mean yearly mix, monthly and seasonal methods. The final emission factors for each consumption use and assessment method are given in Table B.2 and are plotted next to each other in Figure B.1.

	Mean Mix $EF_{av.mix}$	Monthly Method $Q_{CO_2,i}$	Seasonal method	
			Base $Q_{base,i}$	Season $Q_{season,i}$
JAN	46.7	64.5	32.9	115.5
FEB		53.8		100.6
MAR		39.3		53.5
APR		33.7		37.0
MAY		31.2		24.7
JUN		30.7		17.1
JUL		43.2		104.4
AUG		37.4		91.6
SEP		44.5		184.6
OCT		44.7		108.1
NOV		74.2		193.7
DEC		51.9		91.1

Table B.1: CO_2 content results for the different assessment methods in [g$CO_{2,eq}$/kWh]

As expected, the heating emission factor increases the most with the seasonal method, as its consumption is function of temperature and thus very sensitive to the period of the year. Lighting increases as well but not

	Mean Yearly Mix Method	Monthly Method	Seasonal Method
Heating	46.7	54.6	102.2
Domestic Hot Water		46.6	44.8
Cooking		46.6	47.9
Lighting		49.0	66.0

Table B.2: Emission factor results for the different assessment methods in [$gCO_{2,eq}$/kWh]

as much while cooking is almost completely insensitive to a change in an assessment method. An interesting observation is the small decrease in emission factor for domestic hot water production when using the seasonal method. At first glance, this might seem odd as there is an increase in hot water demand in the winter, when the electricity has a higher CO_2 content. The lower EF is due to the low elasticity in hot water demand along the year. Indeed, the base part of hot water consumption is quite large compared to its seasonal consumption (see columns 4 and 5 of Table B.4 in Section B.2). This means that a large part of the EF of the seasonal method is determined by the base CO_2 content Q_{base} which is smaller than most of the CO_2 contents $Q_{CO_{2,i}}$ used for the monthly method, hence a slight decrease in total emission factor when using the seasonal method. One can also note the inability of the mean yearly mix method to distinguish the different consumption uses carbon contents as it is only suited to perform global GHG assessments.

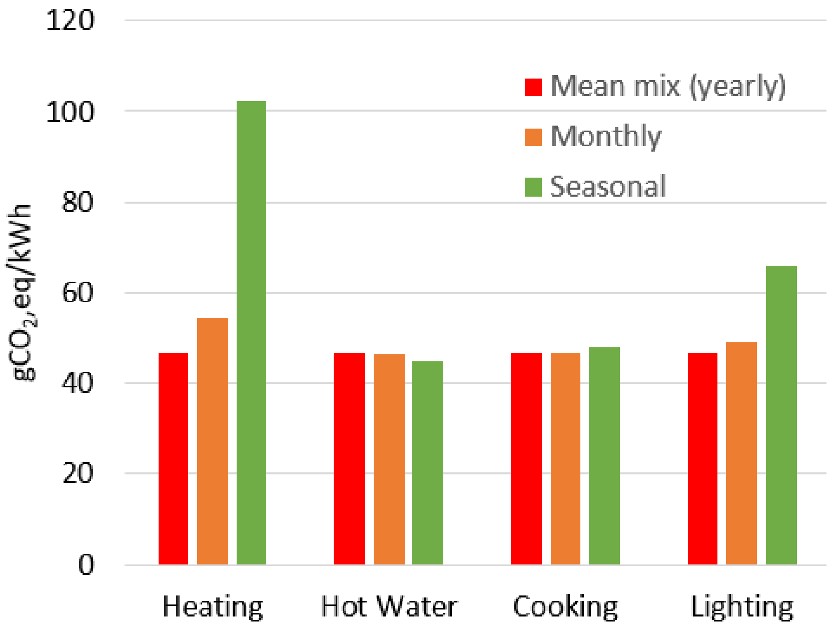


Figure B.1: Emission factor comparison for the different assessment methods and uses. Heating and lighting get higher results when using the seasonal method due to their intensive use in the winter. Cooking and hot water production have a much more constant consumption along the year and thus get similar results across the different methods.

B.2 Data

	Nuclear	Hydro	Wind	Solar	Thermal Renewables	Coal	Oil	Natural Gas	Imports	Total
Base	27533	2576	1636	417	741	7	60	1655	0	**34625**
Seasonalized : JAN	12625	2396	1402	0	105	405	62	4136	387	**21518**
FEB	8556	2428	993	363	35	214	46	2839	10	**15484**
MAR	7964	2589	2790	691	124	9	39	1523	2	**15731**
APR	4223	1930	685	704	15	22	33	365	21	**7998**
MAY	4135	2951	573	955	87	0	12	214	0	**8927**
JUN	1027	3204	235	1031	0	8	0	0	2	**5507**
JUL	1662	1821	66	1133	59	67	15	1004	32	**5859**
AUG	188	1169	0	1017	139	23	8	327	0	**2871**
SEP	0	0	982	786	33	24	6	1048	0	**2879**
OCT	1629	1225	1732	363	31	27	3	1414	21	**6445**
NOV	1600	3834	1712	40	66	446	46	3417	806	**11967**
DEC	5452	5202	3023	10	105	233	48	2379	322	**16774**
Total	379457	59661	33825	12097	9691	1562	1038	38526	1603	**537460**

Table B.3: Electricity production mix [GWh] - France - 2019 - [47]

	Heating			Domestic Water Production			Cooking			Lighting		
	Base	**Season**	**Total**	**Base**	**Season**	**Total**	**Base**	**Season**	**Total**	**Base**	**Season**	**Total**
JAN	0	15627	15627	1503	750	2253	805	370	1175	345	587	932
FEB	0	10161	10161	1503	514	2017	805	218	1023	345	403	748
MAR	0	7190	7190	1503	620	2123	805	339	1145	345	358	703
APR	0	4968	4968	1503	416	1919	805	264	1070	345	220	565
MAY	0	2606	2606	1503	380	1883	805	235	1041	345	92	437
JUN	0	183	183	1503	162	1665	805	133	939	345	28	373
JUL	0	0	0	1503	32	1535	805	64	870	345	9	354
AUG	0	2	2	1503	0	1503	805	0	805	345	0	345
SEP	0	76	76	1503	107	1610	805	156	962	345	159	504
OCT	0	1328	1328	1503	356	1859	805	347	1152	345	344	689
NOV	0	8823	8823	1503	475	1978	805	396	1201	345	475	820
DEC	0	10527	10527	1503	696	2199	805	377	1182	345	616	961

Table B.4: Electricity consumption in the residential segment [GWh] - France - 2019 - [47]

Appendix C

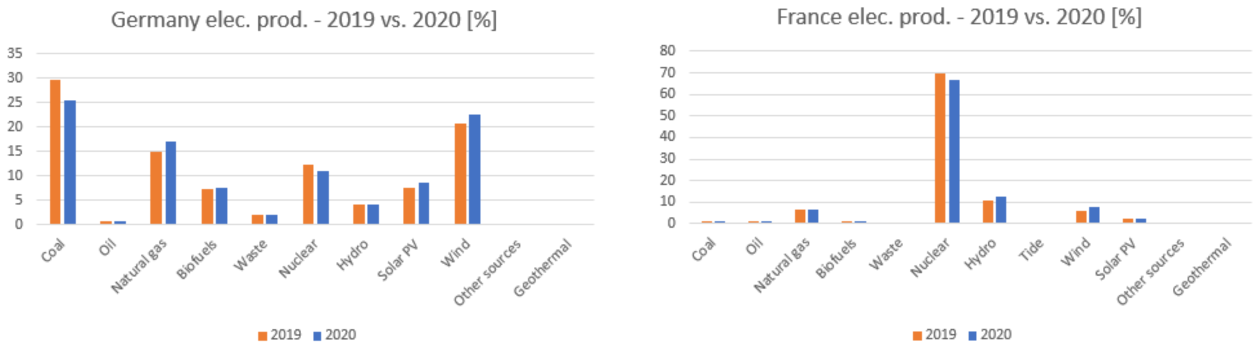
Electrical mixes comparison : 2019 vs. 2020

C.1 Data table

	Coal	**Oil**	**Natural Gas**	**Biofuels**	**Waste**	**Nuclear**	**Hydro**	**Tide**	**Wind**	**Solar PV**	**Geothermal**	**Other sources**	**Total**
Germany	148 164 (25.5)	4907 (0.8)	99 564 (17.1)	44 751 (7.7)	12 394 (2.1)	64 382 (11.1)	24 877 (4.3)	0 (0)	130 965 (22.5)	50 600 (8.7)	217 (<0.1)	1174 (0.2)	581 995
France	5067 (1.0)	5266 (1.0)	35 203 (6.6)	6496 (1.2)	4461 (0.8)	353 833 (66.5)	66 708 (12.6)	482 (<0.1)	40 704 (7.6)	13 579 (2.6)	128 (<0.1)	508 (<0.1)	532 435
United Kingdom	6201 (2.0)	887 (0.3)	114 128 (36.5)	35 094 (11.2)	9855 (3.2)	50 278 (16.1)	7894 (2.5)	11 (<0.1)	75 610 (24.2)	12 801 (4.1)	0 (0)	0 (0)	312 579
Italy	13 064 (4.6)	9771 (3.5)	137 649 (48.9)	17 330 (6.2)	4838 (1.7)	0 (0)	48 558 (17.3)	0 (0)	18 702 (6.6)	24 942 (8.9)	6029 (2.1)	604 (0.2)	281 487
Australia	145 522 (54.9)	4509 (1.7)	55 216 (20.8)	3352 (1.3)	0 (0)	0 (0)	15 150 (5.7)	0 (0)	20 396 (7.7)	21 029 (7.9)	0 (0)	0 (0)	265 178
Spain	5980 (2.3)	11 136 (4.2)	69 388 (26.5)	4958 (1.9)	1716 (0.7)	58 279 (22.2)	33 888 (12.9)	0 (0)	56 273 (21.5)	15 552 (5.93)	0 (0)	5126 1.9	262 296
Belgium	1834 (2.1)	88 (<0.1)	26 521 (29.8)	4324 (4.9)	2229 (2.5)	34 435 (38.7)	1319 (1.5)	0 (0)	12 871 (14.5)	4972 (5.6)	0 (0)	321 (0.4)	88 914
Romania	9581 (17.1)	174 (0.3)	10 046 (17.9)	444 (0.8)	0 (0)	11 466 (20.4)	15 701 (28.0)	0 (0)	6945 (12.4)	1733 (3.1)	0 (0)	0 (0)	56 090

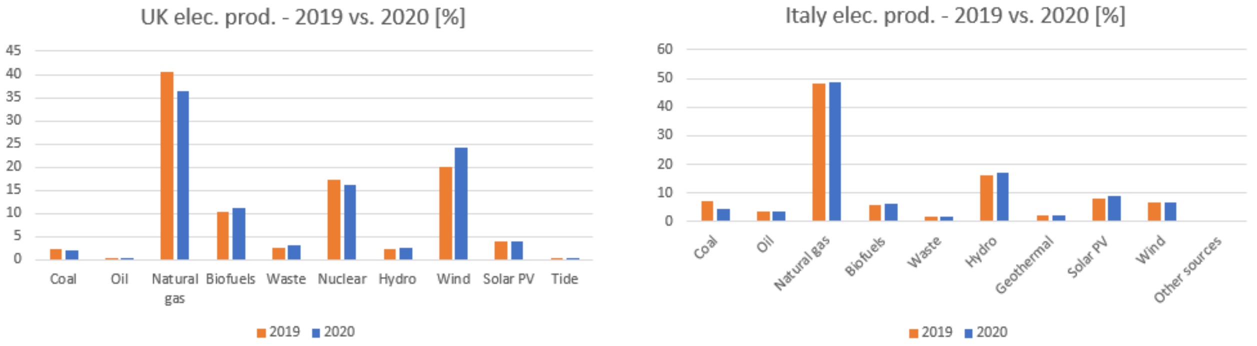
Table C.1: Detailed electrical generation data in 2020, expressed in [GWh] [33]. Numbers in parentheses are the percentages of the total national production covered by the production type.

C.2 Figures



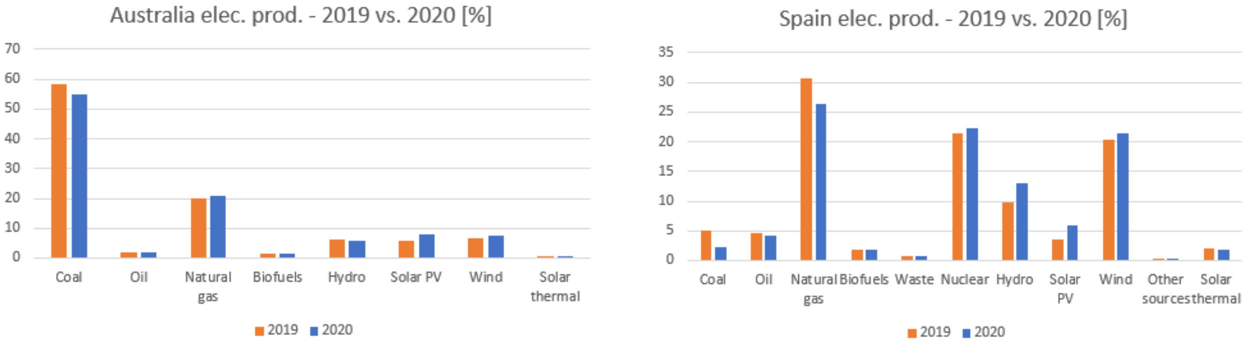
(a) Germany

(b) France



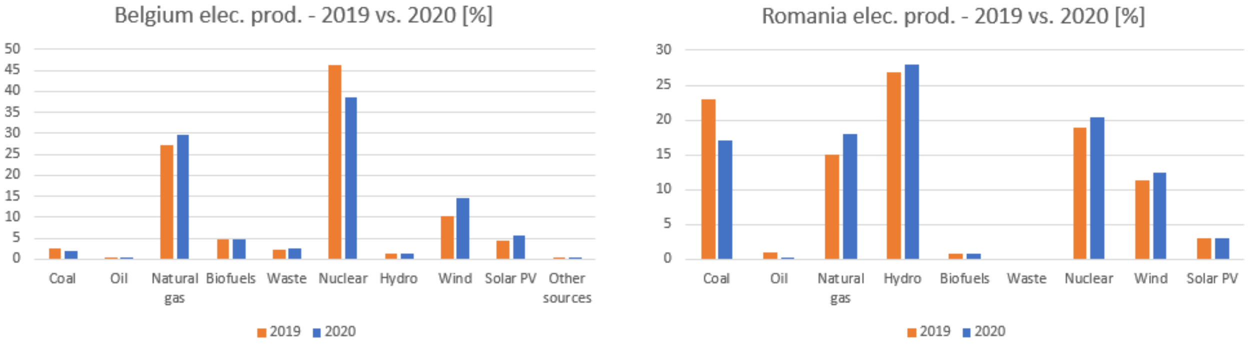
(c) United Kingdom

(d) Italy



(e) Australia

(f) Spain



(g) Belgium

(h) Romania

Figure C.1: Electrical mix comparison 2019 vs. 2020

Appendix D

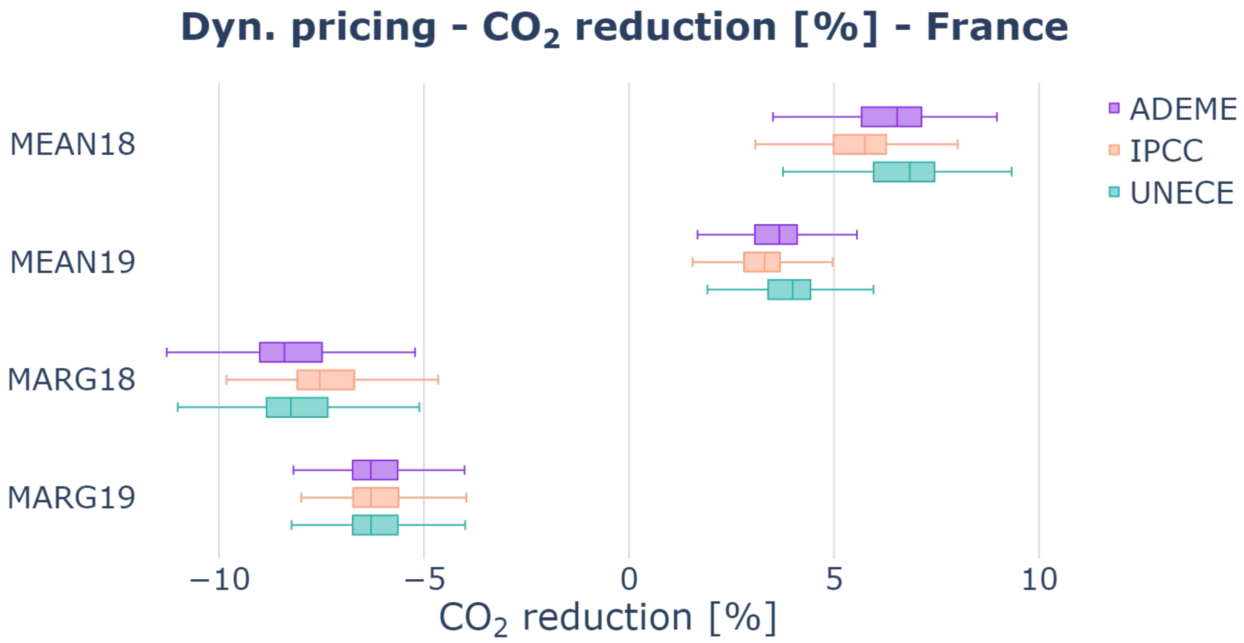
Commercial batteries

Commercial Battery Name	Useable capacity [kWh]	Peak power [kW]	Round-trip efficiency [%]	Depth of discharge [%]
Tesla Powerwall	13.5	5	90	(not provided)
Sonnen ECO 12.5	12.5	7.5	(not provided)	90
Delta BX 12.6	12.6	4.5	(not provided)	(not provided)
LG Resu 10	8.8	5	>95% (under specific conditions)	(not provided)

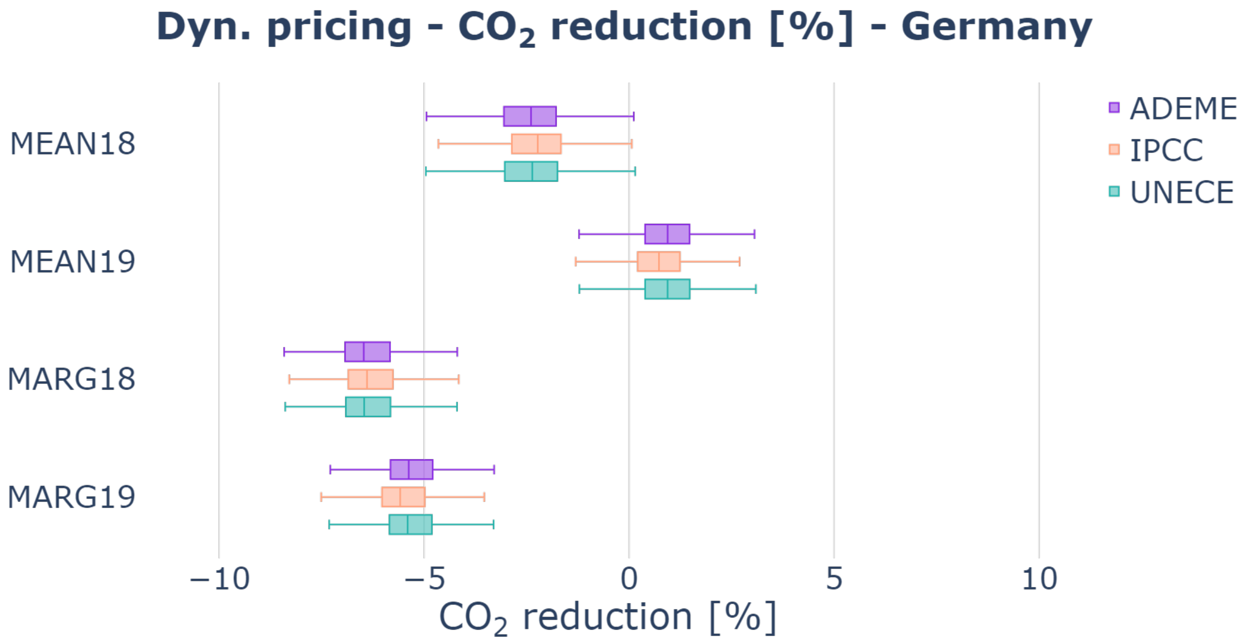
Table D.1: Overview of commercial stationary batteries. [48] [49] [50] [51]

Appendix E

Additional results : dynamic pricing

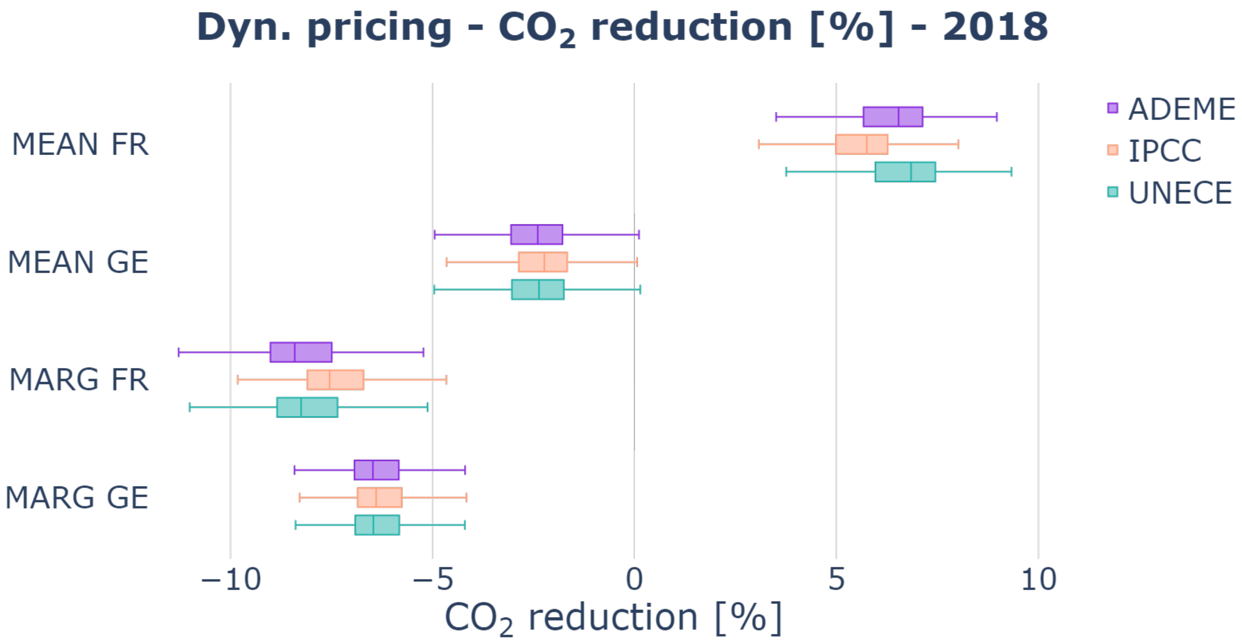


(a) Global results - dynamic pricing - France.

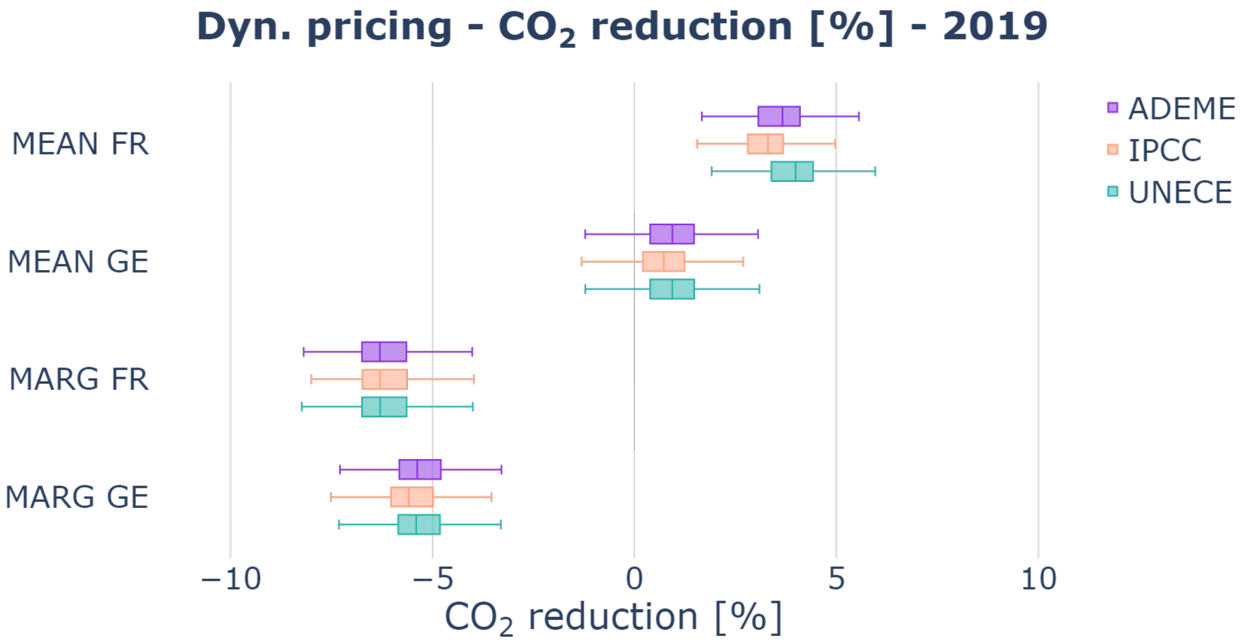


(b) Global results - dynamic pricing - Germany.

Figure E.1: Global results - dynamic pricing - separated by country

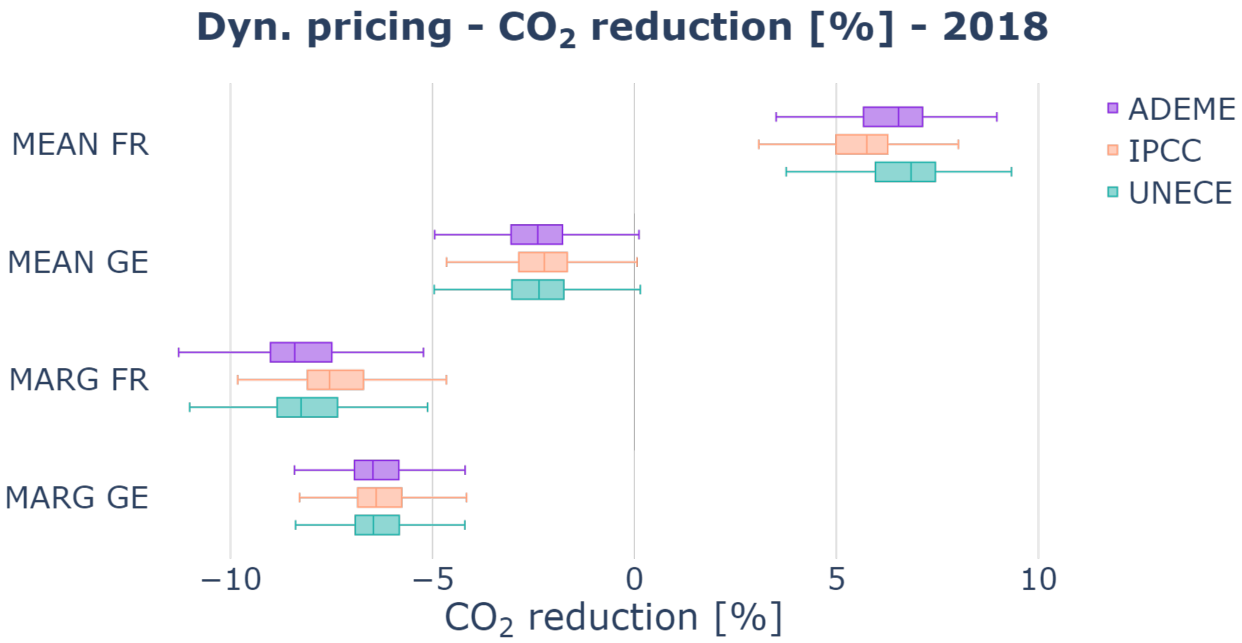


(a) Global results - dynamic pricing - 2018.

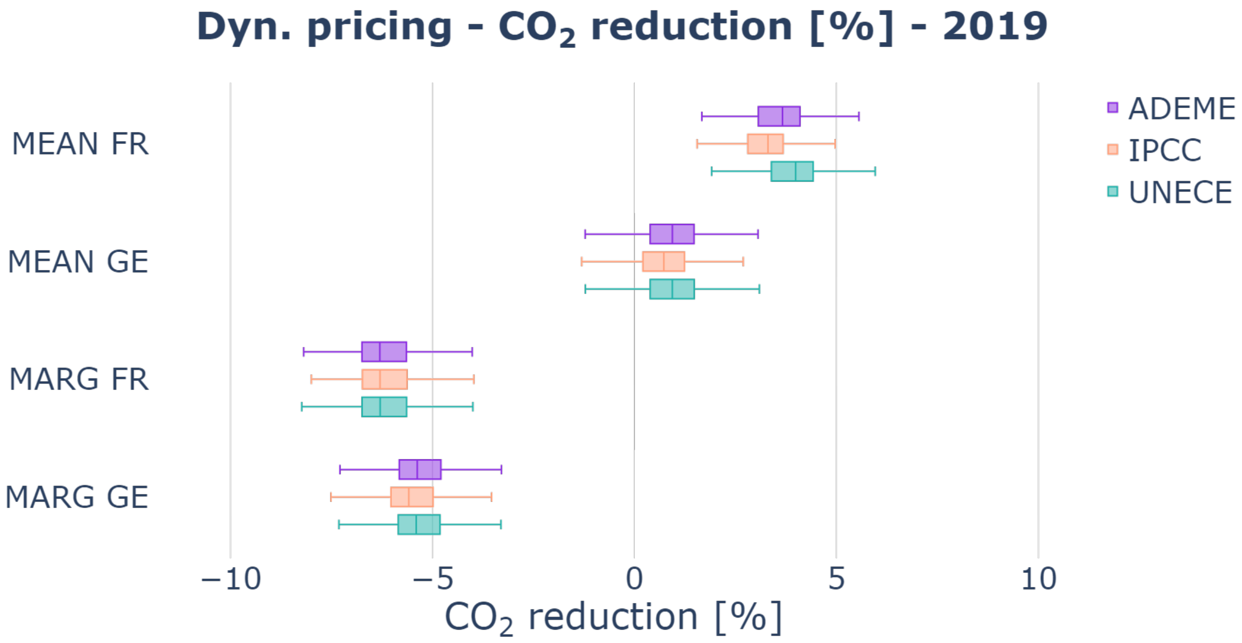


(b) Global results - dynamic pricing - 2019.

Figure E.2: Global results - dynamic pricing - separated by study year.

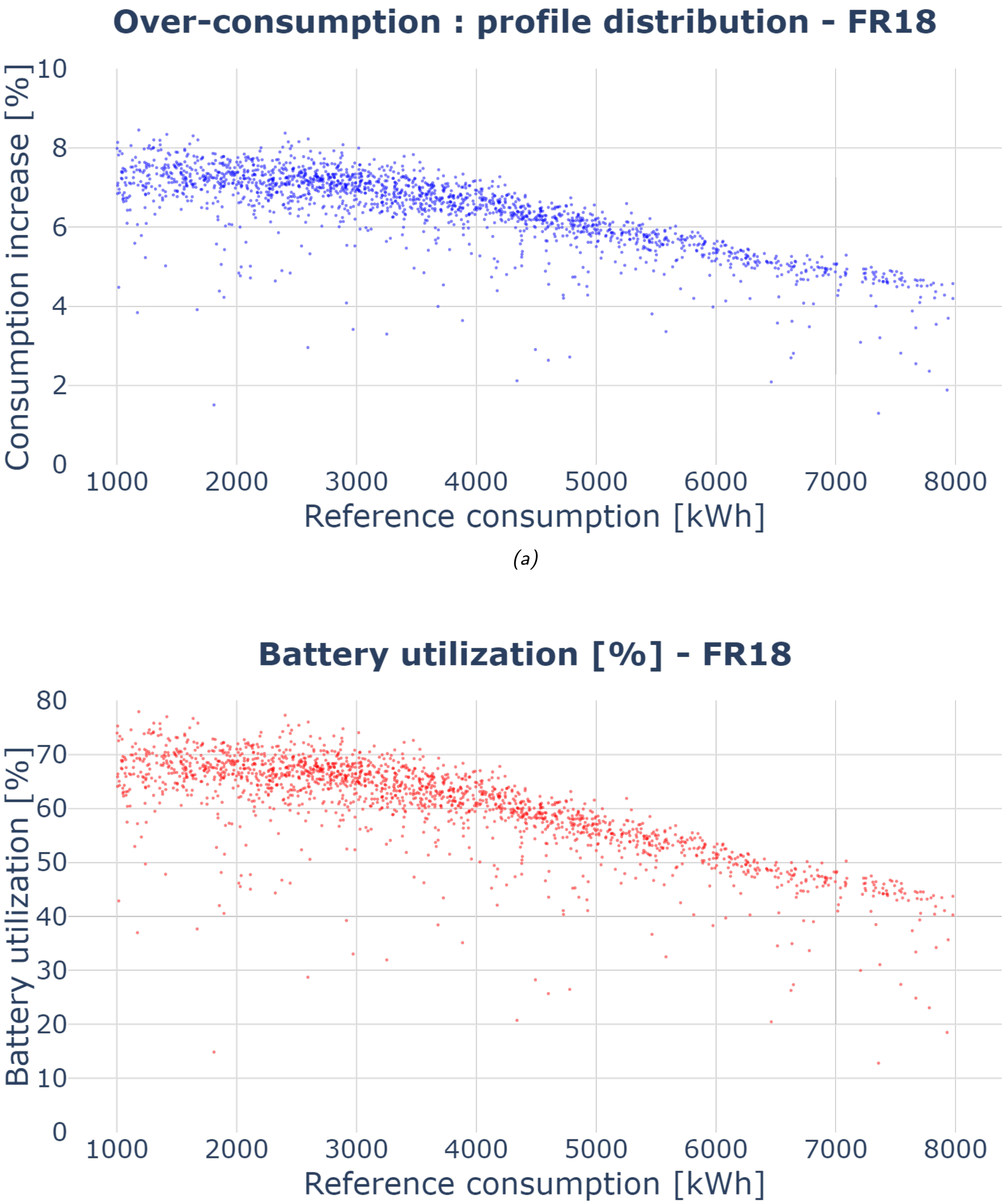


(a) Global results - dynamic pricing - 2018.



(b) Global results - dynamic pricing - 2019.

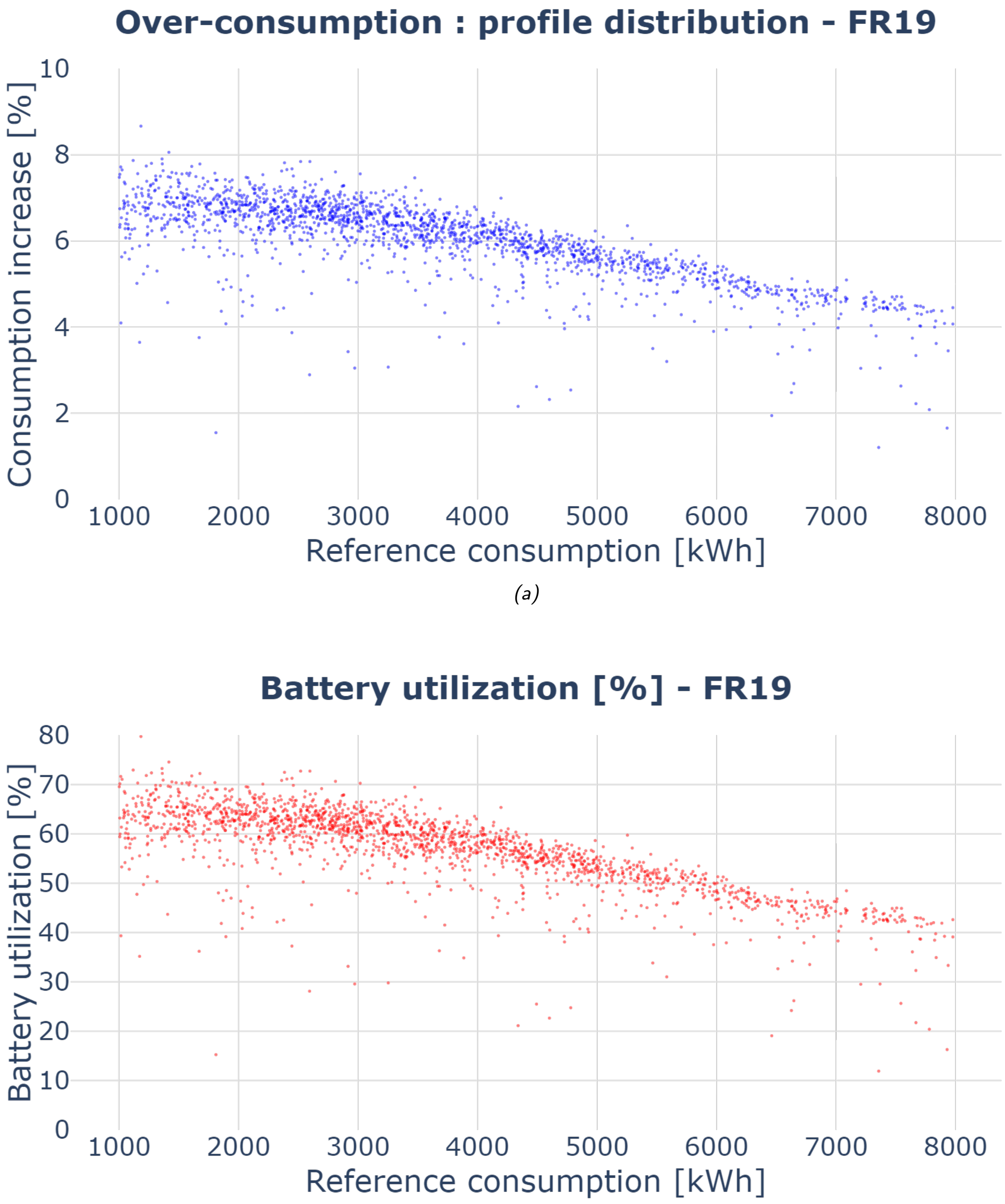
Figure E.3: Global results - dynamic pricing - separated by study year.



(a)

(b)

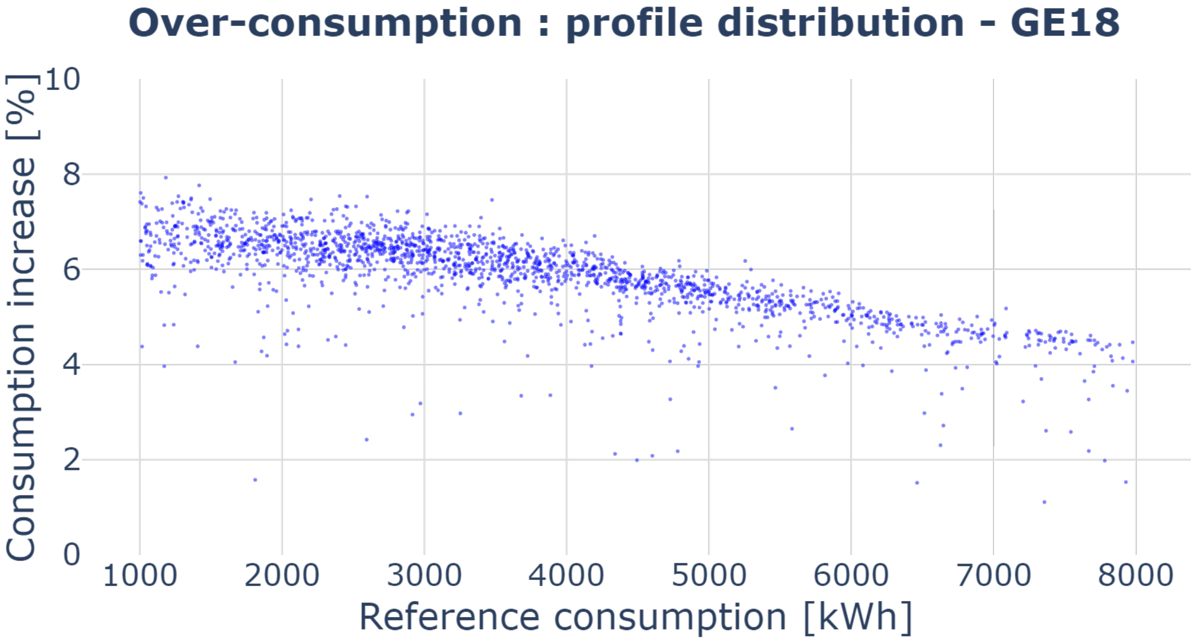
Figure E.4: Over-consumption and battery utilization in France in 2018.



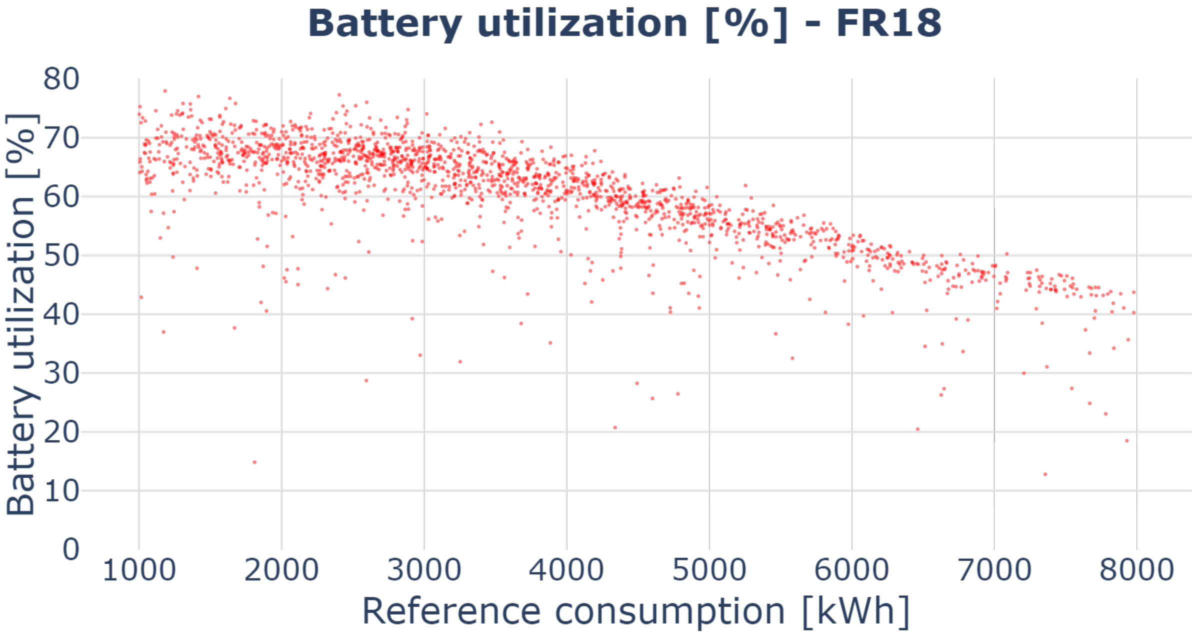
(a)

(b)

Figure E.5: Over-consumption and battery utilization in France in 2019.

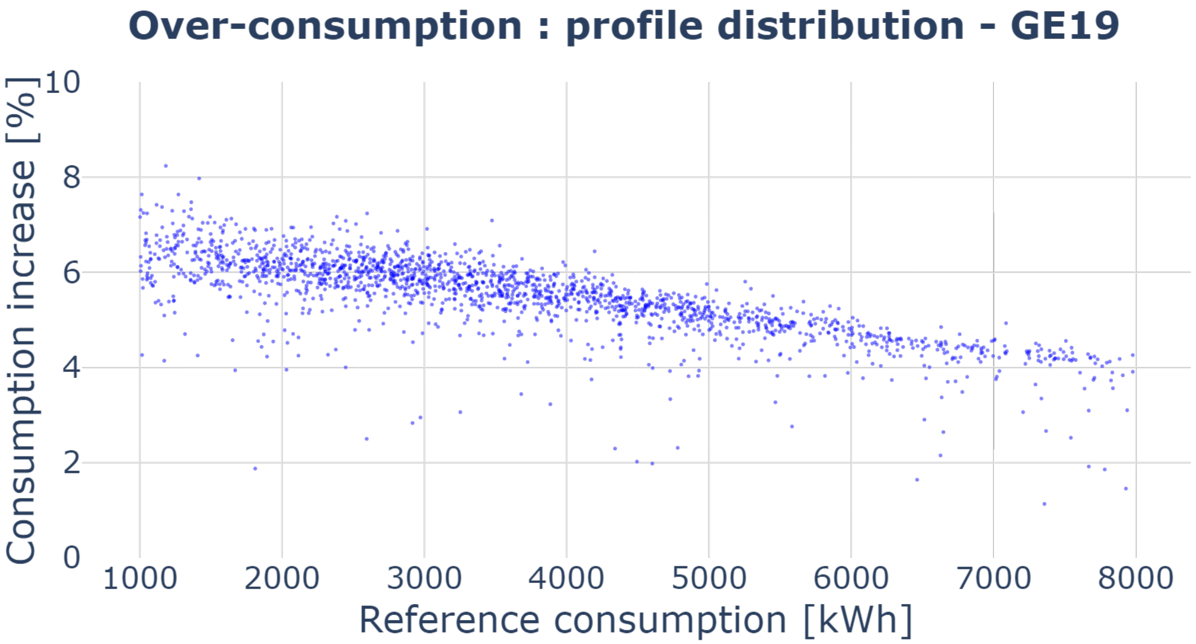


(a)

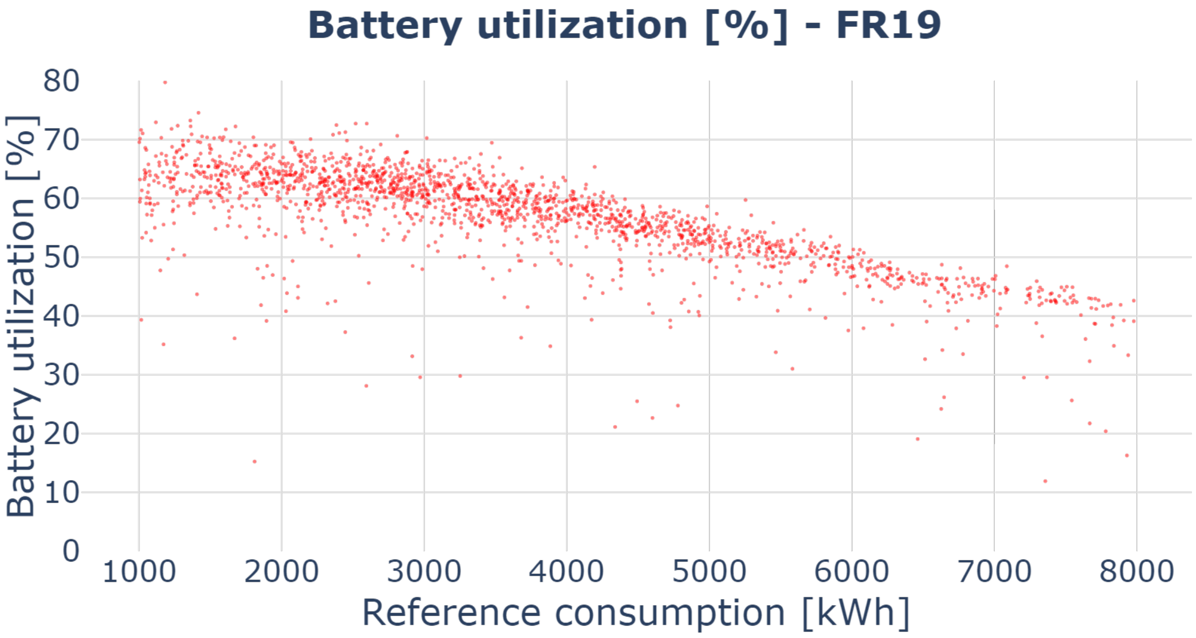


(b)

Figure E.6: Over-consumption and battery utilization in Germany in 2018.

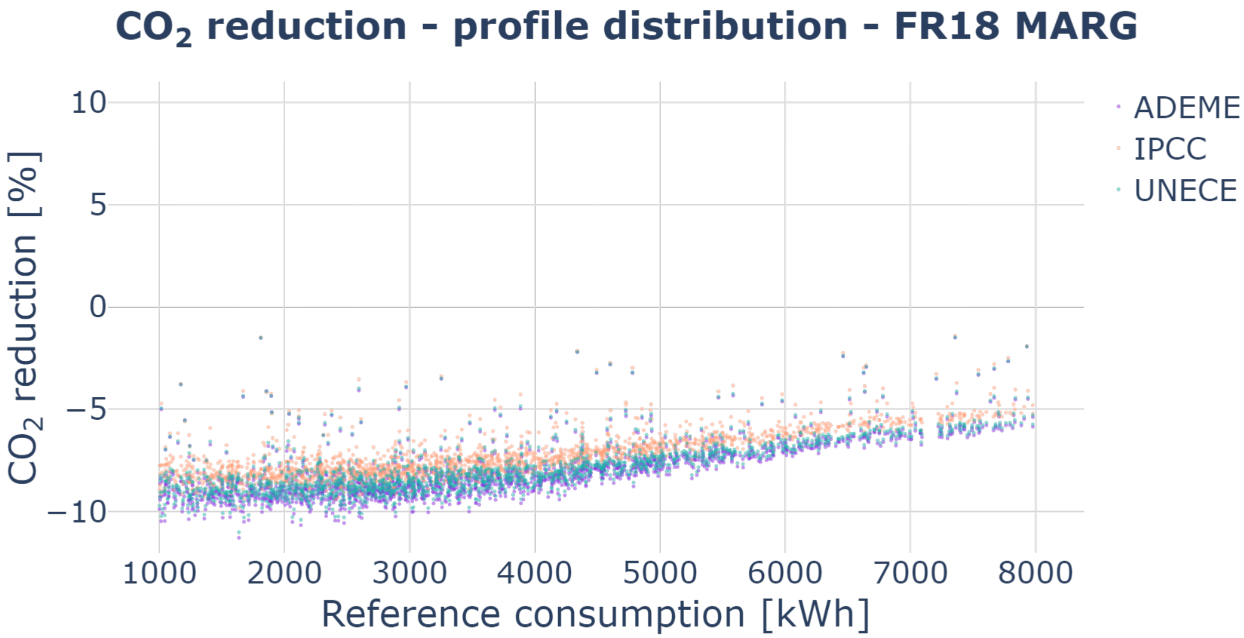


(a)

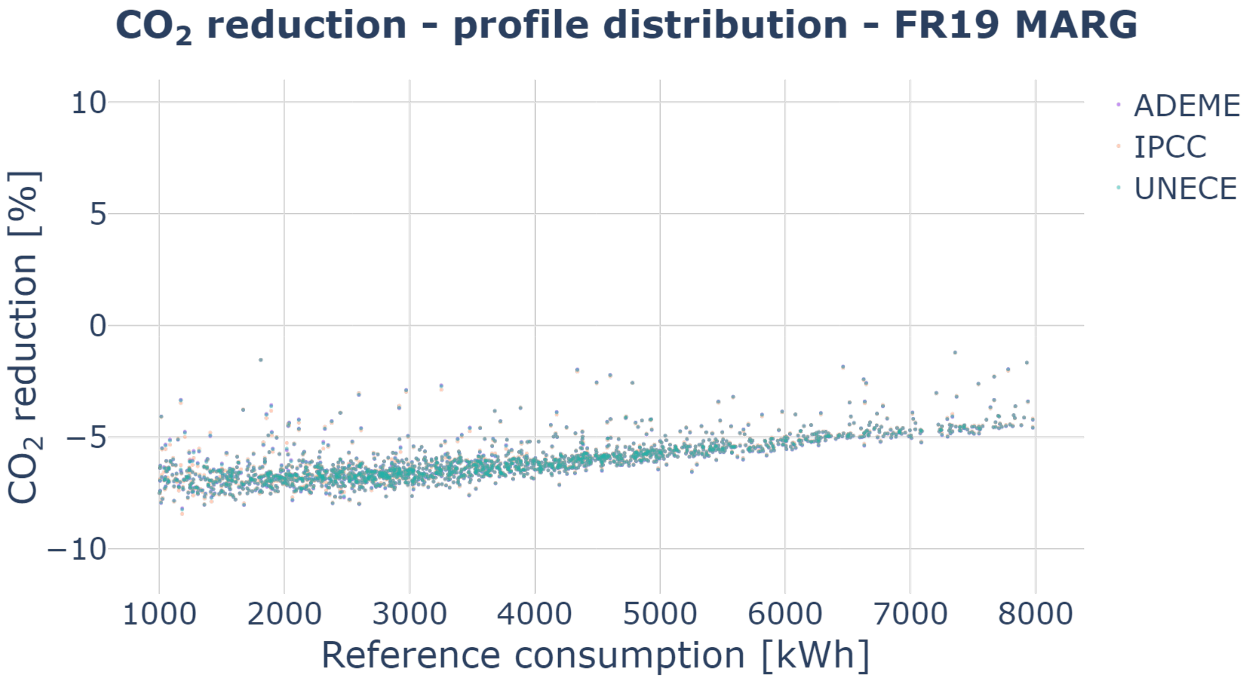


(b)

Figure E.7: Over-consumption and battery utilization in Germany in 2019.

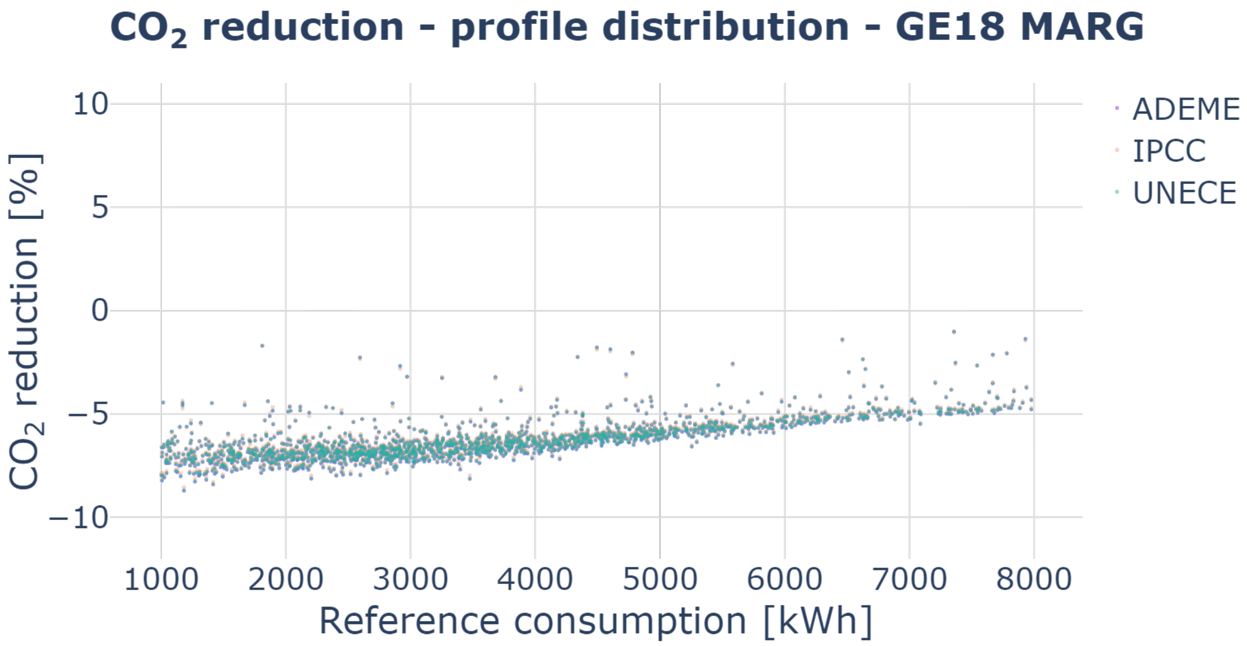


(a) 2018

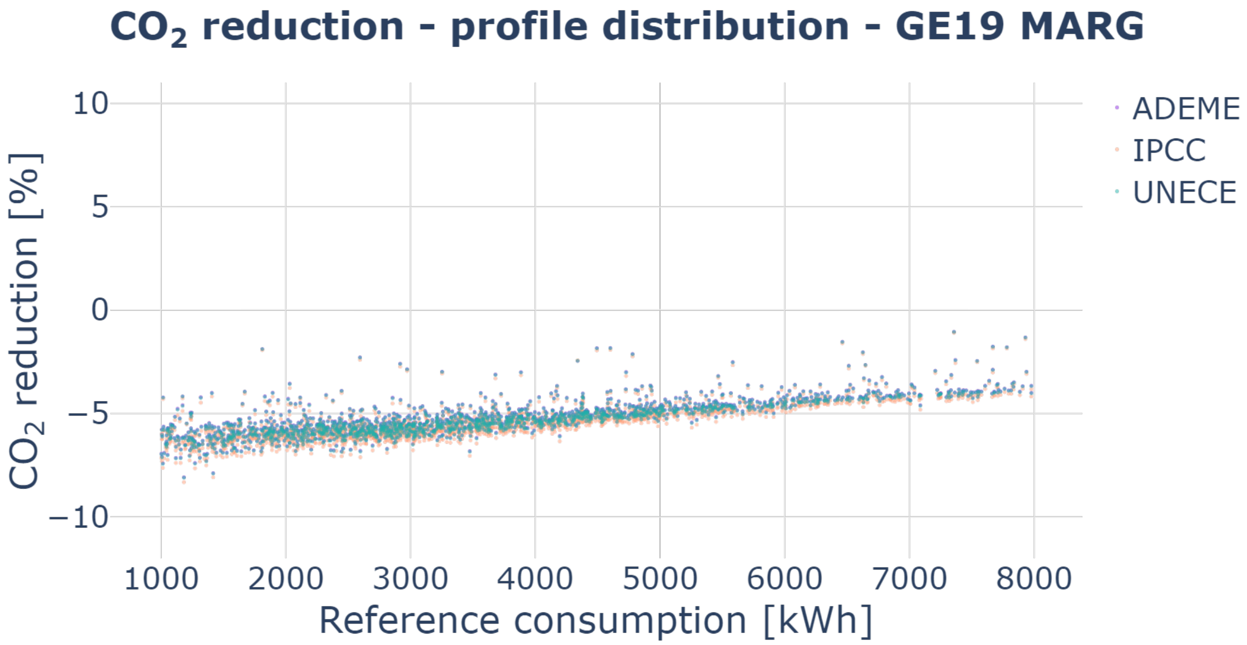


(b) 2019

Figure E.8: Marginal method profile distribution in France.



(a) 2018

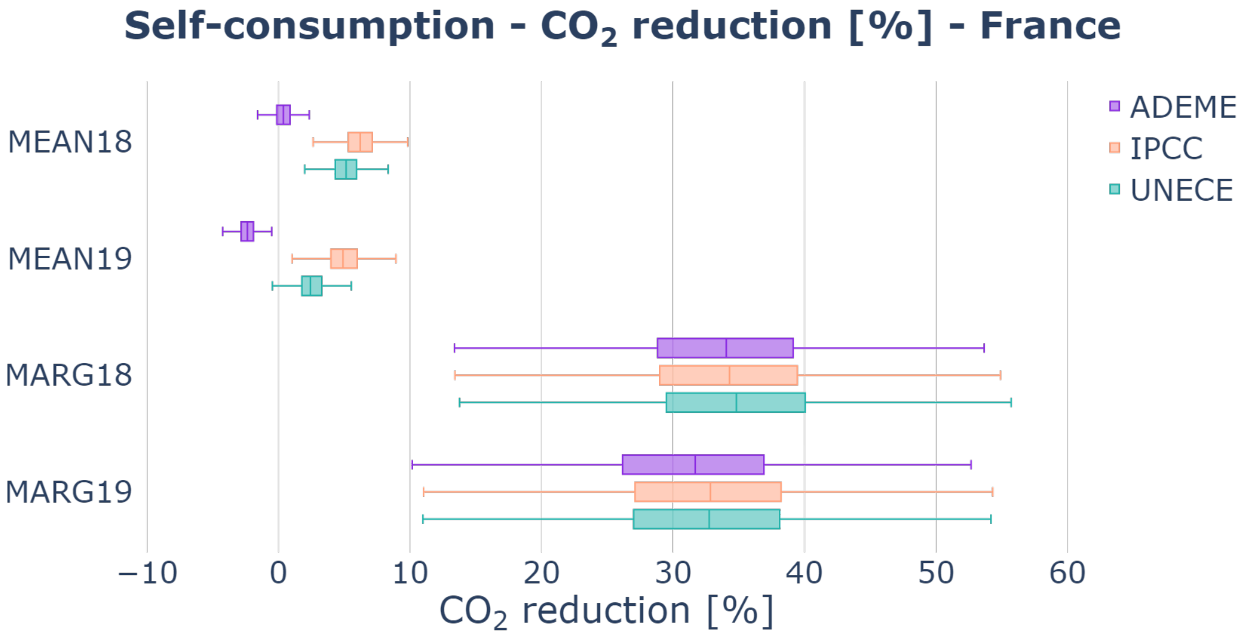


(b) 2019

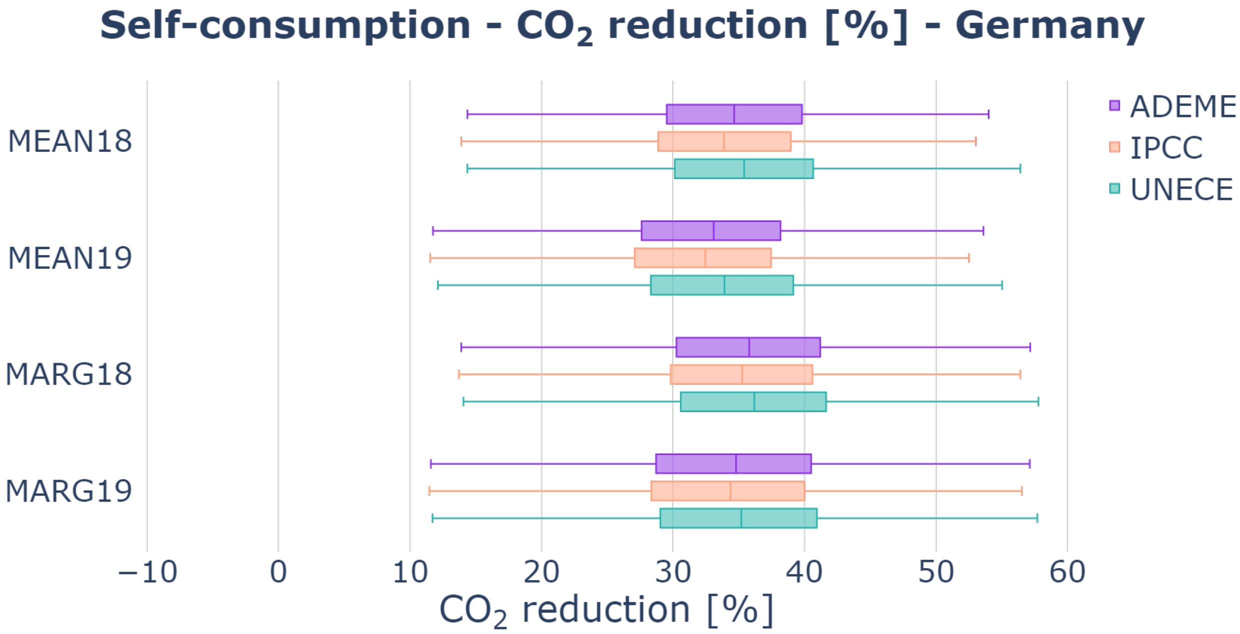
Figure E.9: Marginal method profile distribution in Germany.

Appendix F

Additional results : self-consumption

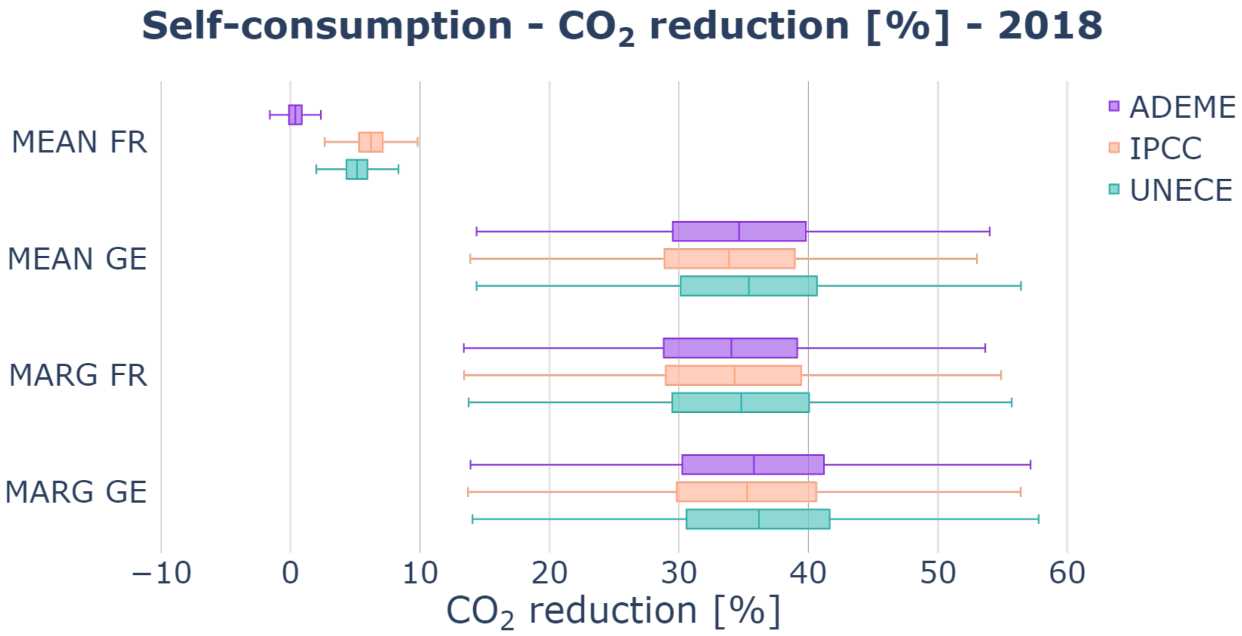


(a) Global results - self-consumption - France.

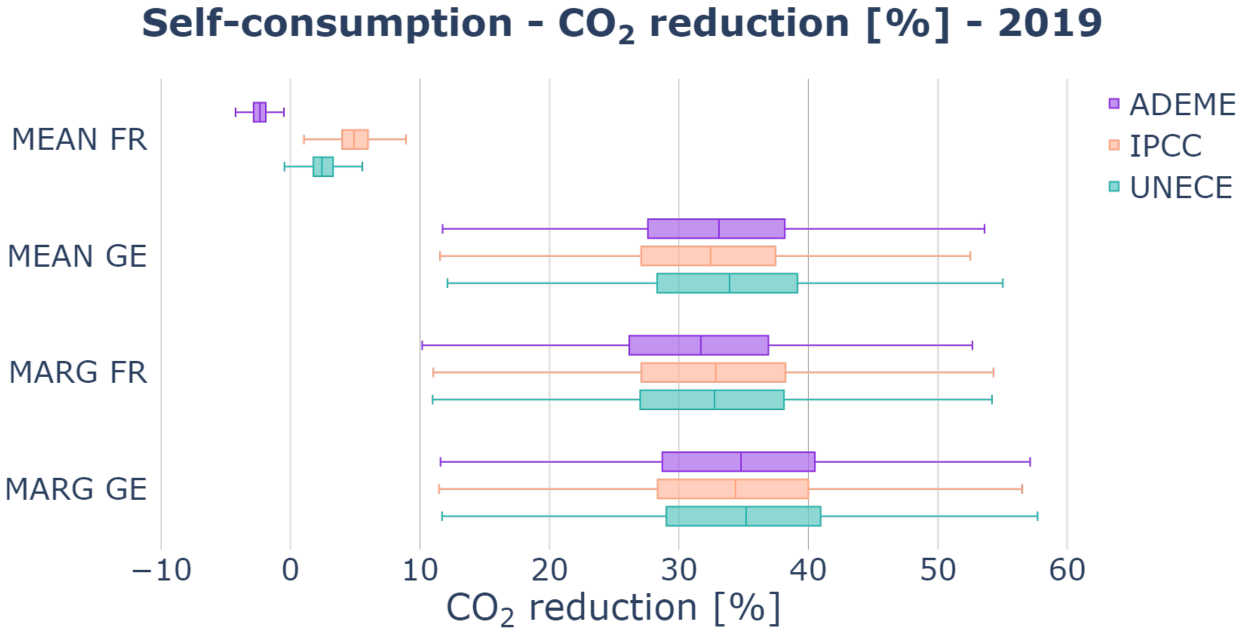


(b) Global results - self-consumption - Germany.

Figure F.1: Global results - self-consumption - separated by country.

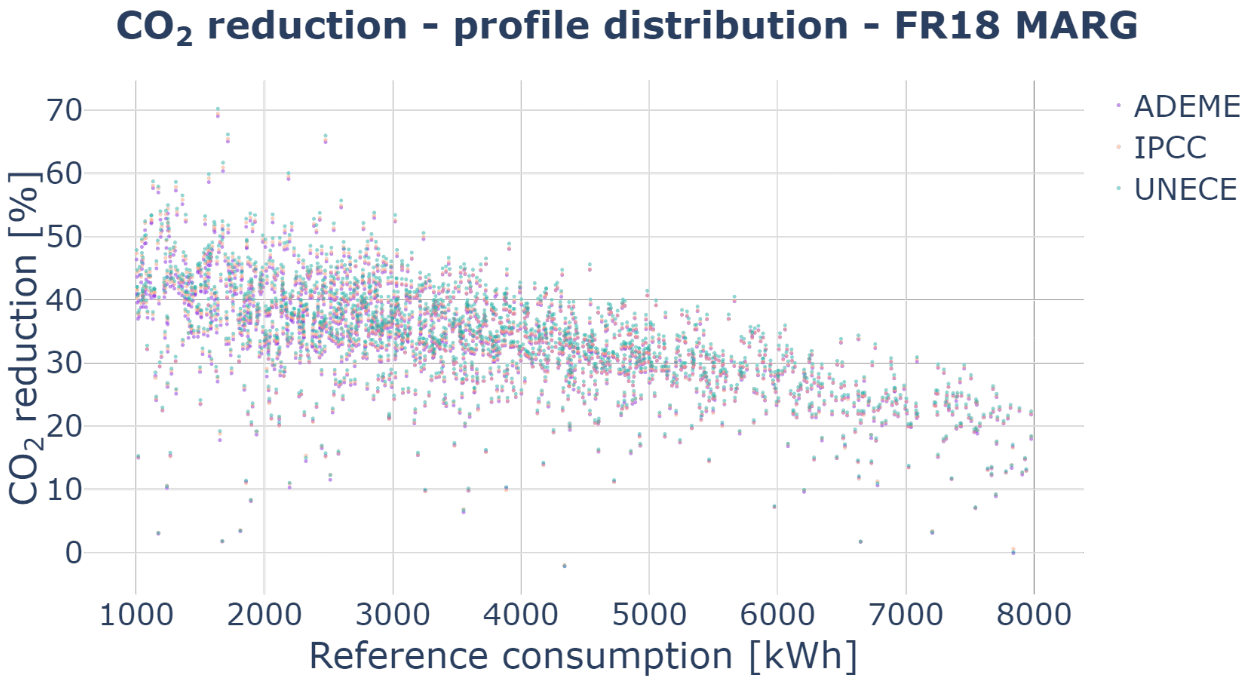


(a) Global results - self-consumption - 2018.

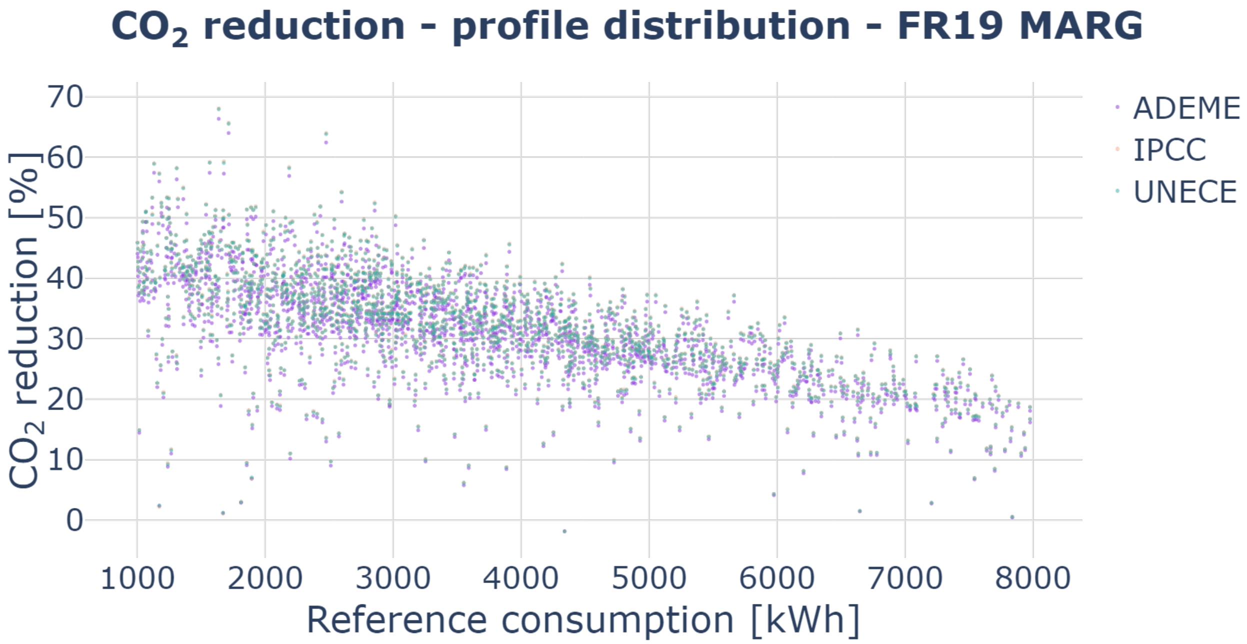


(b) Global results - self-consumption - 2019.

Figure F.2: Global results - self-consumption - separated by study year.

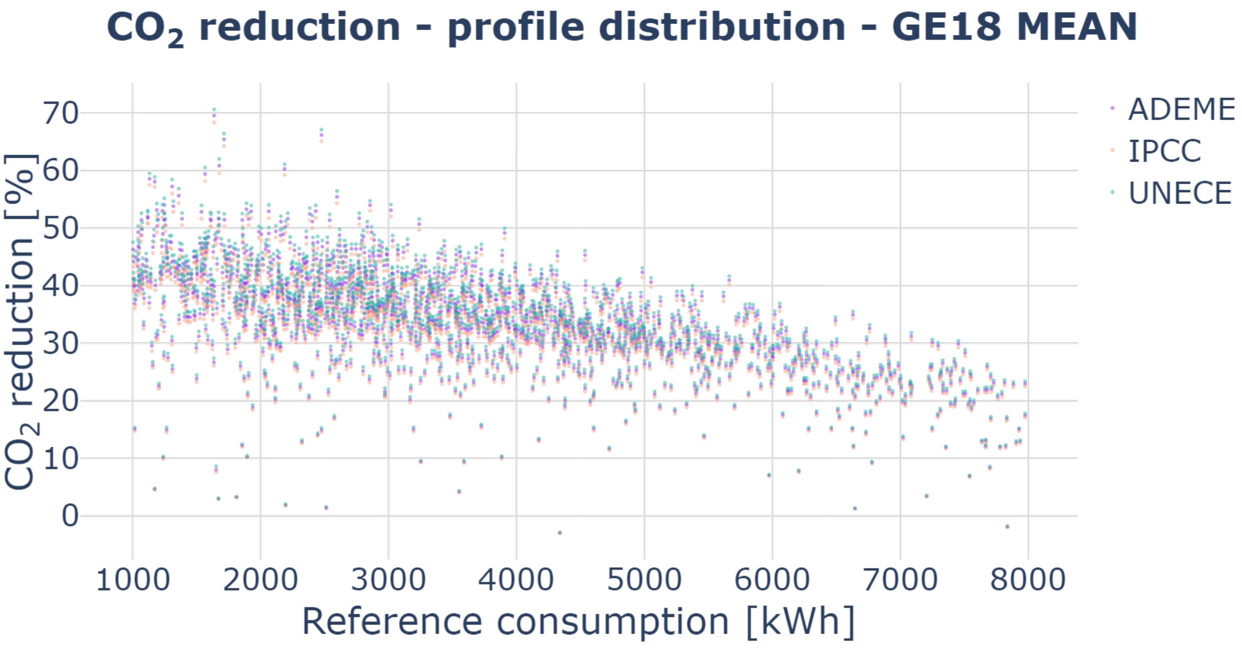


(a) 2018

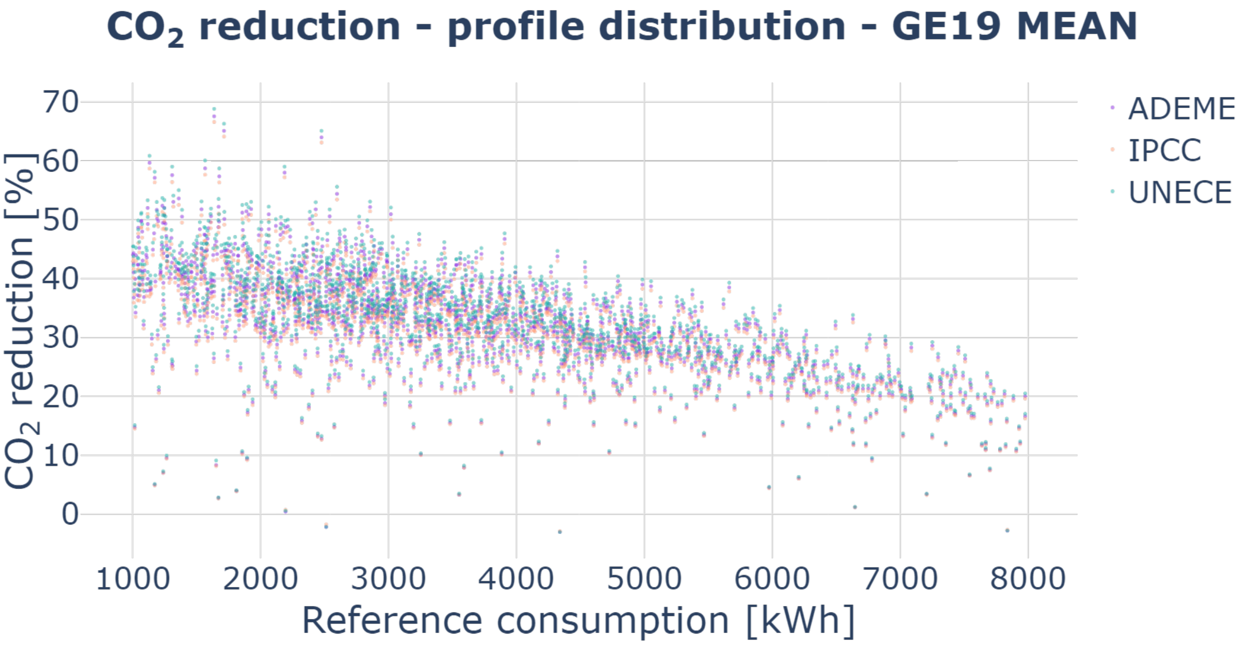


(b) 2019

Figure F.3: Self-consumption CO$_2$ reduction - profile distribution - marginal method in France

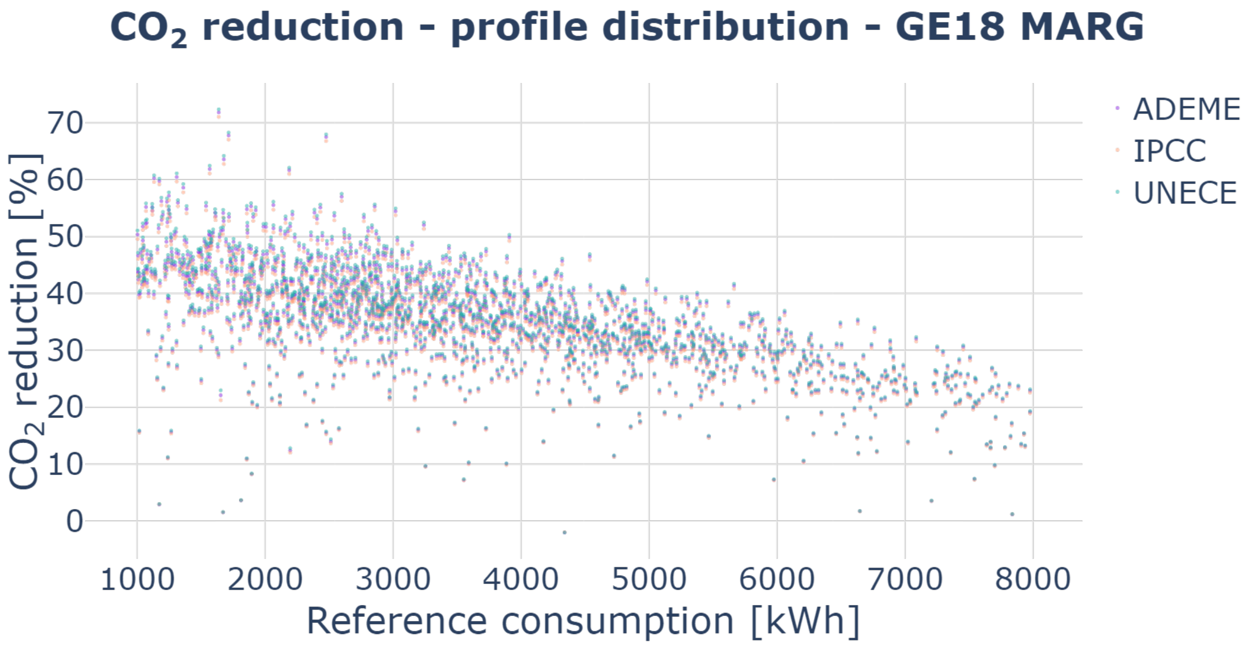


(a) 2018

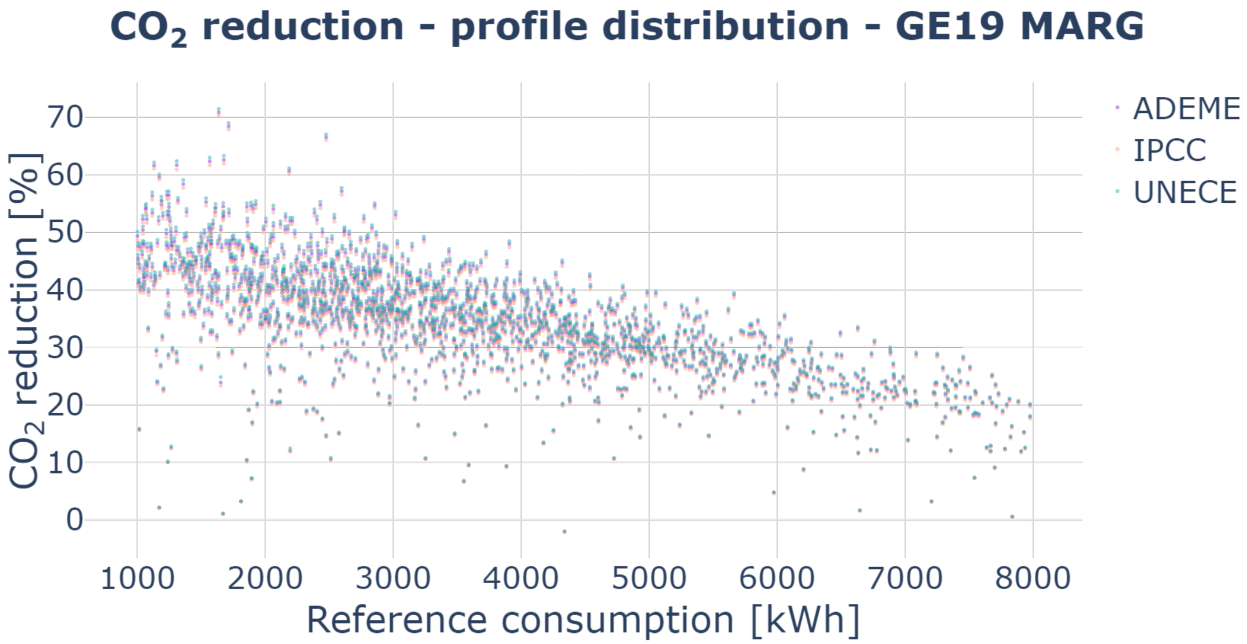


(b) 2019

Figure F.4: Self-consumption CO_2 reduction - profile distribution - mean method in Germany



(a) 2018



(b) 2019

Figure F.5: Self-consumption CO_2 reduction - profile distribution - marginal method in Germany

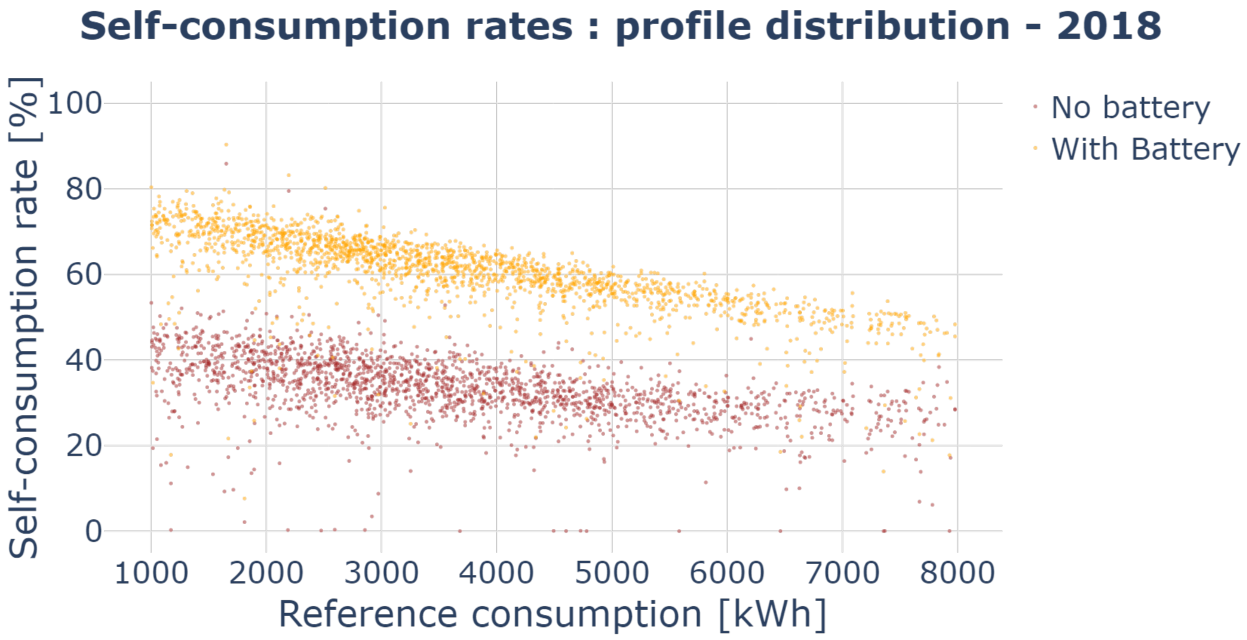
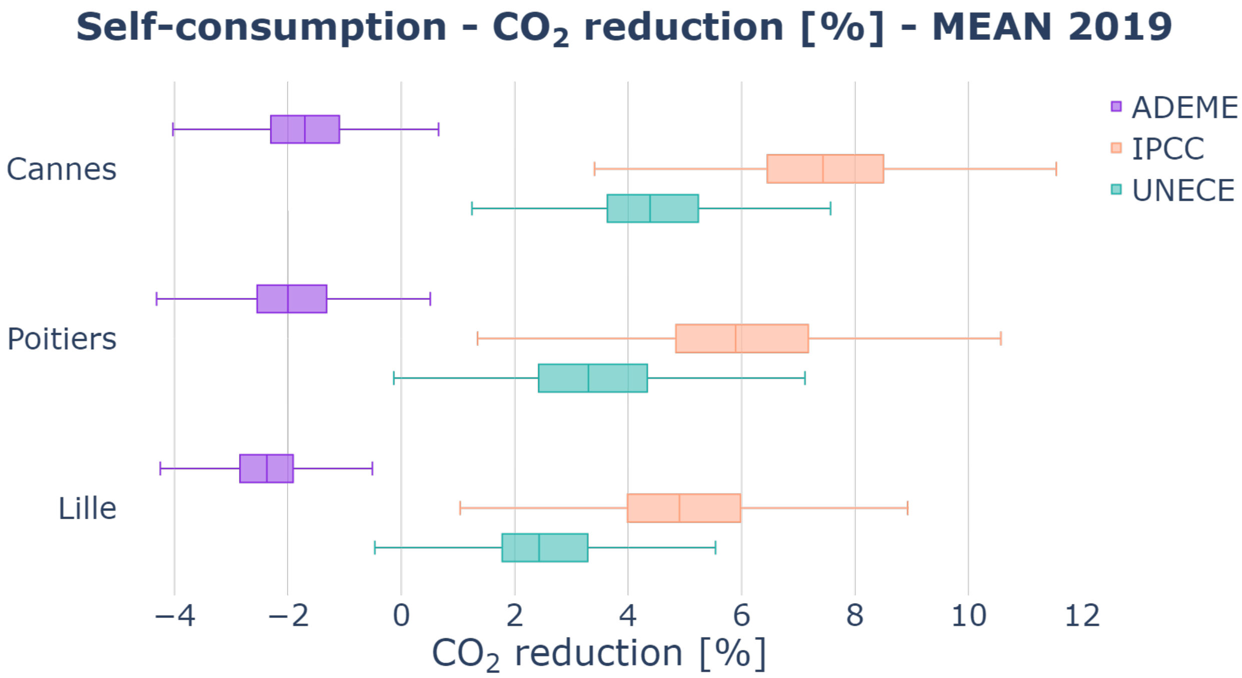
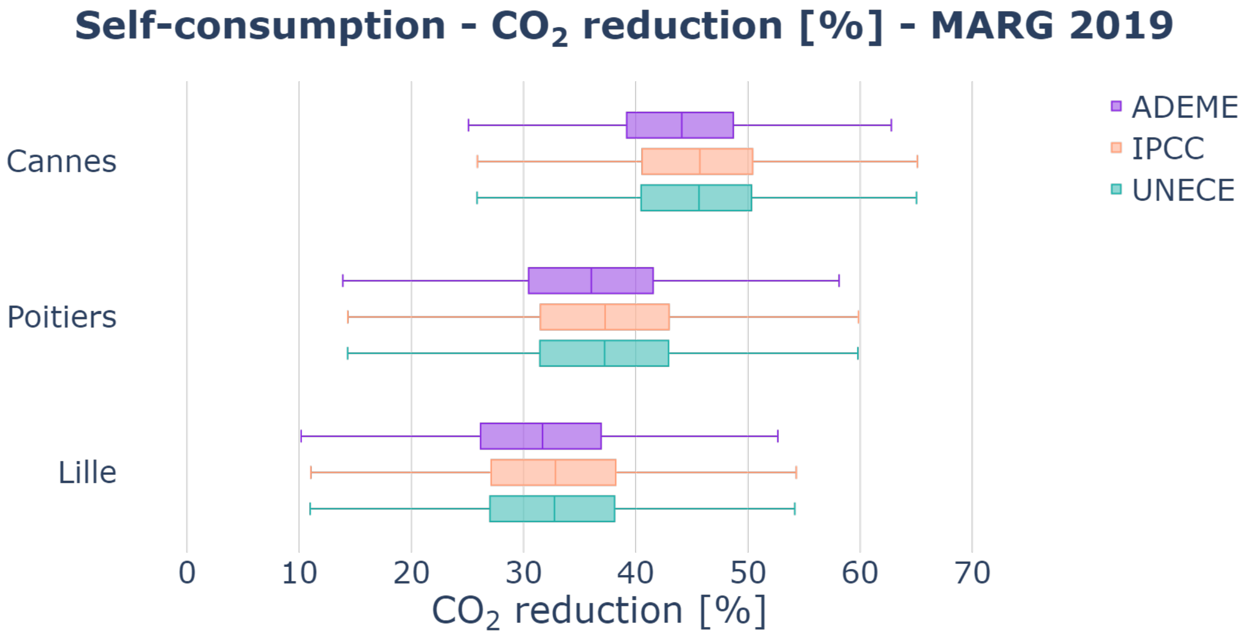


Figure F.6: Self-consumption rates distribution in 2018 (PV location : Lille)



(a) Mean method results for the various PV locations in 2019.



(b) Global results - self-consumption - 2019.

Figure F.7: Marginal method results for the various PV locations in 2019.

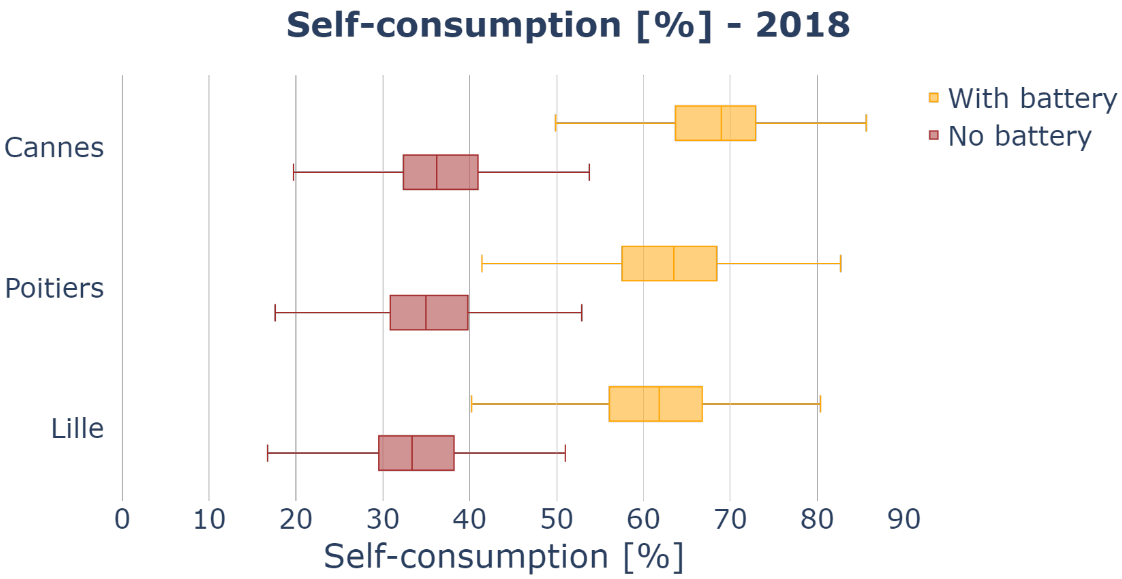


Figure F.8: Self-consumption rates for the various PV locations in 2018.

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