Opportunities and challenges of photovoltaic (PV) growth with self-consumption model

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OPPORTUNITIES AND CHALLENGES OF PHOTOVOLTAIC (PV) GROWTH WITH SELF-CONSUMPTION MODEL[1]

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1. Introduction

The photovoltaic (PV) system is one of the promising technologies for power generation as it provides an abundant energy resource and lends itself well to decentralized systems. The photovoltaic (PV) market has demonstrated exponential growth over the last decades. Grid parity is achieved in many countries thanks to the reduced PV system prices. Over the decades, technological progress and industry development have helped to reduce the PV system per unit production cost. In addition, the Feed-in-Tariffs (FIT) system has played an important role in the recent PV market growth, providing incentives to investors. Policy support with a long-term vision has helped stimulate PV demand and accordingly attracted industrial investment, thus leading to more cost reductions via economies of scale in manufacturing [1]. The FIT system is an effective tool but needs a sophisticated price design mechanism to avoid any uncontrolled market development [2]. The FIT scheme is very tariff-sensitive policy instrument containing a risk factor; investors aim to maximize windfall profits from a margin of the marginal PV electricity generation cost and the fixed tariff. Under the FIT system, there are installation peaks just before the application of new reduced tariffs; this is to maximize economic gains by installing PV systems at the latest possible times to encourage price drops in module prices (see the appendix) [3].

The global PV market needs a new approach that is more stable to incite further PV growth. Since energy systems evolve with the aim of supplying energy to end-users at the lowest possible costs, energy policy should aim to minimize PV electricity costs, while minimizing grid integration costs and risks as PV penetration progresses. The PV system's integration in the current or future energy system can be justified when such efforts are based on the way of improving social welfare.

In this context, this article explores opportunities for PV electricity use under a self-consumption mechanism to find ways of PV penetration growth. The objective is to find better ways of increasing PV installations in a society with least costs. The promotion of self-consumption of PV system can be a more natural way of using PV systems. It can improve the use of PV electricity in the current and future energy system if applicable under a properly designed framework.

The study aims to look for opportunities of PV electricity use under a self-consumption mechanism following the steps below.

1. Explore new **opportunities based on a model of self-consumption**
   - Present the PV self-consumption model
   - Conduct stakeholder analysis: Identify stakeholders of PV self-consumption and understand their interests/ influences
   - Define policy risks and mitigation strategies
2. Conduct a **micro-economic case study to quantify self-consumption opportunities:** France's existing supermarkets
   - Present key data & assumptions
   - Demonstrate possible opportunities of PV electricity use in the building sector
   - Identify possible impacts on stakeholders and mitigation strategies
3. **Policy recommendations/conclusion**

2. Opportunities and challenges based on a PV self-consumption model

2.1. PV self-consumption model

PV self-consumption is a new way of using distributed PV installations in the energy system. The self-consumption of PV power refers to the use of PV electricity directly at the same site where it is produced, with a smaller amount of electricity feed into the grid [4]. The self-consumption model reduces the distance between electricity generation and consumption through onsite consumption of power.

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2.1.1. Economic incentives of the PV self-consumption model

End-users have *economic incentives* to adapt the mode of self-consumption of PV electricity when it helps them to reduce their *electricity bills* or provide them with *some financial incentives* compared with the conventional way of purchasing electricity from the grid. Furthermore, the self-consumption of PV power is interesting for countries which have *high electricity tariffs* with *less attractive feed-in-tariffs for PV* [5]. Furthermore, PV system costs are one of the most important levers when defining the initial investment needed to calculate the levelized costs of PV energy (LCOE, $/kWh). LCOE will also depend on other factors like module efficiency, capacity factor, cost of capital and lifetime. Combined with high retail rates of electricity, the reduced PV LCOE will motive end-users to install PV systems. In addition, *the ratio of self-consumption,* which defines the rate between onsite consumption and the total production of the system installed on the site, is a very important factor in terms of defining the economics of the self-consumed model of PV power. Therefore, it is necessary to choose PV installation sites where it is possible to best correlate the pattern of onsite energy use with PV system output to have an optimal adaptation of the load profile for the self-consumed model [6].

2.1.2. Applicable areas

The self-consumed model can be applicable in various sectors with different ratios of self-consumption to the output of the PV system. Possible applications for each sector are described below: [7]

1. *Industrial/commercial*: good correlation between onsite consumption & production profile with most consumption during the day
2. *Separate residential (without storage):* weak correlation between onsite consumption & production profile with impacts on the network with injected electricity
3. *Collective buildings*: better correlation between onsite consumption & production with broader geographical spread with interconnected collective buildings in a zone
4. *Non interconnected zone (with storage):* ideal to provide power in isolated areas to replace fossil fuels or to resolve interconnection problems.

The residential sector has a peak demand in the morning and in the evening; however, supermarket and office areas have a mid-day peak, which means they are more suitable for the self-consumption model because of the correlation of the mid-day PV production and consumption pattern. The good matching of PV output and onsite demand is found in commercial and office buildings rather than in the individual residential sector because self-consumers are often not home during the day. If the installed PV system cannot capture the full value of PV output, the return on investment will be significantly reduced.
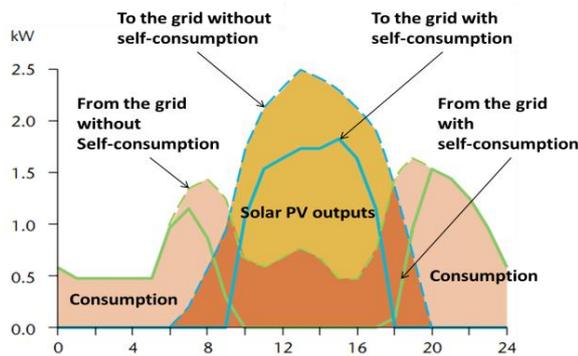

Figure 1: The self-consumed model of PV system [4][8]
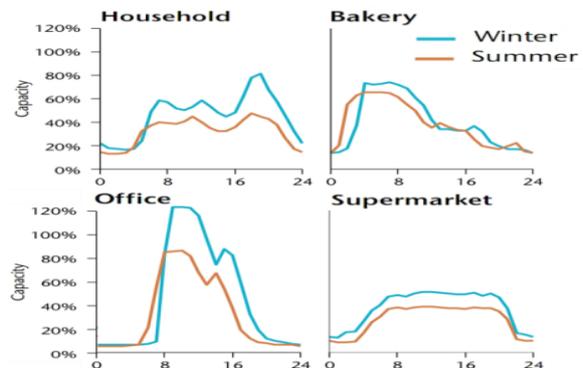
Figure 2: Daily electricity demand and PV system outputs [4]

2.1.3. Grid connection type

PV systems can be connected to the grid according to different options. Some countries allow PV systems to feed 100% of the electricity produced into the grid (in front of the meter grid connection), while others only allow the transfer of excessive PV output after onsite-consumption (behind the meter grid connection) in the grid. The first mechanism is related to *the FIT scheme* policies, whereas the latter is mostly associated with policies like *net metering* [6][9].

Figure 3: FIT scheme

Figure 4: Net metering scheme

- *FIT scheme:* PV installers are allowed to transfer all electricity produced to the grid and consume electricity from the grid. The injected electricity will be compensated on the basis of pre-defined tariffs during a fixed period, and they will pay for the electricity consumed according to the applicable electricity rates [10].

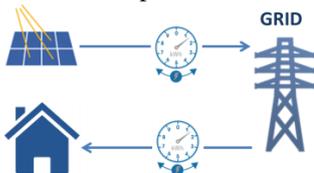- o ***Net metering system:*** End-users who produce electricity from PV systems are allowed to inject excessive electricity into the grid (the difference of PV output to onsite consumption). Billing will be calculated on the basis of the net electricity from/to the grid during the applicable period [8][11].
- o ***PV system +storage:*** PV systems can be self-consumed without connecting to the grid. In this case, a storage system is needed. This can be considered as an option to provide power to isolated areas, which mostly relies on fossil fuel generation [6].

FIT and net-metering policies differ from one country or state to the next, e.g., different rates are applicable in terms of the compensation amount or level, and often different strategies are in place with respect to the instantaneous consumption of onsite production. The self-consumption system combined with the net metering system has developed in several countries like the US, Japan, Canada and some European countries, based on different legal frameworks [12].

2.1.4. Benefits of the PV self-consumed model

The benefits of PV self-consumption are not limited to economic drivers of end-users. The PV self-consuming electricity model is a smart way of utilizing the nature of PV systems i.e. they are easily decentralized. With the widespread penetration of PV systems into the existing energy system, grid-related costs can be added in terms of grid reinforcement and extension [13][14][15]. However, the PV self-consumed system reduces network stress. In addition, when PV outputs are self-consumed during peak times, the level of avoidance is much greater by reducing power feed-in at the point of interconnection, thereby decreasing the occurrence of voltage problems [16]. Under a properly designed policy framework, the self-consumption model can provide some specific benefits by minimizing distance between production and consumption to almost zero. Some benefits are captured as below [6];

- • *Reduce power losses* during transmission and distribution (T&D)
- • *Avoid system congestion*
- • *Curtail investments for grid extension* when using the existing surfaces of buildings connected to the grid
- • *Avoid further investment for grid upgrading* when the PV system helps reduce electricity demand peaks
- • *Increase energy independence* eventually by coupling with storage systems.

In addition, one important benefit of solar PV installations is related to *land use*. PV can optimize the existing infrastructures to avoid significant impact on land use; it can be easily integrated into existing buildings or parking lots. In addition, unlike conventional energies (e.g. coal, nuclear), it does not require large spaces for waste disposal [6]. Furthermore, the development of solar energy can bring environmental benefits (e.g. reduction of greenhouse gas (GHG) emissions) and economic benefits, which *create jobs in manufacturing, installation, service industries, and associated industries for the national economy* [17][18].

2.1.5. Limits and challenges of the PV self-consumed model

Limits and challenges to develop the PV self-consumed model are related to general weak points of PV system. A large penetration of distributed PV systems in the current grid infrastructures can change energy market mechanisms. Possible challenges are explained below [4][6][8][19]:

- • *Issues in terms of grid stability (*e.g. overloading, congestion issues by excess power export, or power quality degradation). These problems are location-specific; some local areas, which have weak grid infrastructures or excess grid congestion, will encounter more problems than other regions that have solid grid systems with little grid congestion. Technological progress sometimes provides better performance levels to maintain the grid quality; e.g. advanced inverters support better network stability. The PV self-consumed model can be a good solution in congested areas within the grid.
- • *Financial impact on other stakeholders (*e.g., grid operators, other utilities, end-users of electricity, government). There are concerns around the cost recovery of fixed grid costs and reduced tax revenues.
- • *Difficulties for long-term planning and forecasting of the national electricity supply.* However, a well-designed cluster of small-decentralized PV systems can help smooth PV intermittency, thus limiting the balancing costs that can be induced by large centralized PV plants.

In addition, *new technology development* (e.g. smart grids, etc.) is very important in terms of integrating distributed PV systems into the electric mix. Furthermore, how the policy prepares the *long-term vision* with a proper institutional framework affects the success of the PV self-consumed system's development.

The exiting institutional framework should be adapted to support this development with the objective to avoid damaging the interests of stakeholders. In this regard, it is important to understand stakeholder concerns associated with the integration of the self-consumption model in energy system and its impact on their interests and benefits on a national level.

2.2. Stakeholder analysis: PV self-consumption's impacts on stakeholders and their strategies

The introduction of the PV self-consumed model in the energy system brings about changes in stakeholder interests. As impacts can be positive or negative according to the party concerned, stakeholders will take different strategies regarding the new usage mode of PV power. Political strategies on the PV self-consumption model have a great influence on stakeholder movements. When the policy decision conflicts with their interests, they sometimes generate political

pressure to affect the political decision and thereby create obstacles that hinder the use of the PV self-consumed model [6]. In this context, a deep understanding of stakeholder positions is necessary as a precedent exercise to help prepare proper steps forward to develop the PV self-consumed model. Therefore, this article conducts a ***stakeholder analysis*** to identify the key stakeholders and their interests. Based on the defined situation of each stakeholder, possible strategies to address potential policy risks related to stakeholders can be prepared.

2.2.1. Identification of key stakeholders

The current energy system is comprised of several groups of stakeholders. Any group or entity whose interests may be affected or feel they have concerns with the new policy action or organizational change, can be considered in the stakeholder analysis. The stakeholder analysis used herein is frequently used in business science, but is often applied in other fields like political or environmental sciences or game theory [20].

The stakeholder analysis should be conducted in a systemic way under the energy market mechanisms. Below Figure 5 captures the key stakeholders in a simplified value chain for the energy market with the introduction of the PV self-consumed model. End-users with the PV self-consumed model are described as *PV system owners* interacting with other stakeholders like the existing grid operation under policy and regulations. The new mode of PV power usage is associated with stakeholder interests in the value chain for the energy market.
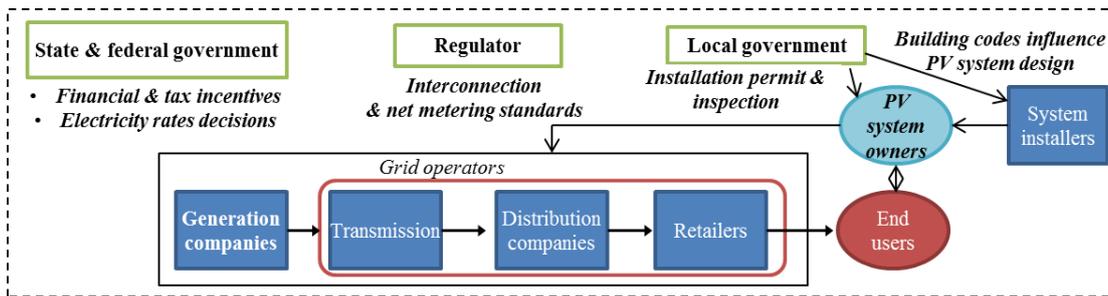

Figure 5: Stakeholders in the value chain for the energy market [21][22]

2.2.2. Understanding stakeholders interests and assessing the importance of influences

With the implementation of the new mode of PV power usage, stakeholders experience changes in their interests in the current energy market model. It is important to understand stakeholder viewpoints with potential opportunities or threats that they can create. In doing so, strategies can be better prepared to take into account negotiations with opposing groups (if any) or to mitigate policy risks.

Table I gives a general explanation of the impacts on stakeholders' interests. Self-consumers using PV systems have economic drivers to adapt the new mode with the objective of either reducing their electricity bill or gaining profits from the PV system installation. However, this movement will influence other stakeholder interests by changing the existing energy market mechanisms. First, existing power generation companies and grid operators will generate less revenue; PV self-consumers buy less electricity from the grid. End-users probably pay increased electricity bills because fewer consumers pay for the electricity from the grid. The government collects less tax faced with reduced electricity ratepayers and reduced sales of FIT electricity. In order to address such impacts, a fair cost-sharing mechanism should be considered.

Even though the large penetration of the PV self-consumed model gives rise to conflicting interests for some stakeholders, increased PV self-consumption in the energy system brings environmental (e.g. GHG emission reduction) and economic (e.g. investments in associated investments and job creation) benefits. Therefore, policy makers should conduct in-depth analysis to compare policy costs and expected benefits so as to find a balance among stakeholders with the objective of increasing social benefits prior to making policy choices for the national energy strategy.

Table I: Stakeholder analysis with penetration of the self-consumed model [4][6][8][17][23]

Stakeholders	Objectives	Impact on stakeholder interests
PV self-consumers	*Pay less for electricity* *Profit-seeking* *Energy independence* *Preference of green electricity*	*Returns (positive/negative) on investment* *Self-consumption of PV power*
Power generation companies	*Maximize profits* *Amortize existing investment*	*Reduced profits due to decreased sales of electricity* *- Lower revenue from spot-market sales* *- Less investment for long-term decisions*
Grid operators	*Stable supply of electricity*	*Grid reliability with large penetration of intermittent PV power* *Reduced revenue due to reduced electricity consumption from the grid*
End-users (electricity consumers)	*Pay less for electricity*	*Electricity rates increase with fewer ratepayers (under recovery of fixed costs)* *- Cost-shifting for surcharges to ratepayers (fair share of fixed infra costs)* *- Fair cost-sharing of energy transition and grid upgrading*

Government	Maximize social welfare	Tax revenue loss from reduced retail sales
	Tax revenue	Reduced income taxes on FIT revenues
	Energy security, Energy equity,	Increase energy diversification
	Energy transition, Green economic growth	Increase economic and environmental benefits
Investors (e.g. banks)	Maximize profits	Returns (positive/negative) on investment
Associated industries	Maximize profits	Induced investments and job creation: e.g. storage, demand response, heat pumps, electric cars, companies of components of PV value chain, and smart grid

2.2.3. Policy risks and mitigation strategies

As seen, the large deployment of the PV self-consumed model conflicts with some stakeholder interests. This can be threat factors when the government decides to develop the PV self-consumed model in the energy system. Therefore, possible strategies to avoid expected hindrance actions from stakeholders should be considered. Targeted strategies should be used when dealing with different stakeholders. The defined stakeholders are reorganized into *a 2x2 Interest-Influence matrix*[2]. This is based on the World Bank's approach for stakeholder mapping in terms of policy design or reform [20][24].
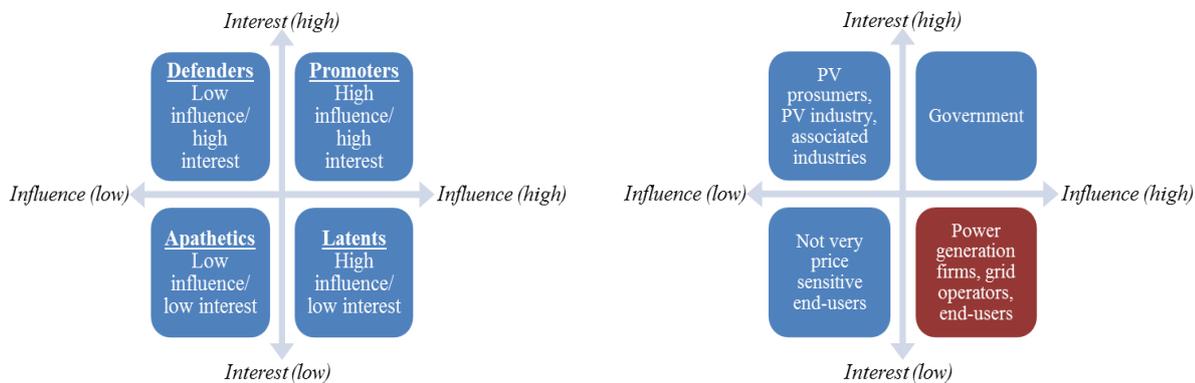

Figure 6: Interest-Influence matrix: Stakeholders with the PV self-consumed model (author's analysis)

- **Promoter***: Stakeholders who have significant interests in the policy and help to make it successful (e.g. the government, policy makers)
- **Defenders:** Stakeholders who have relative interests in the policy and make an effort to promote it in the community with the aid of media or opinion groups with little actual power (e.g. PV prosumers, PV industry, associated industries)
- **Latents:** Stakeholders who have no particular interest in the policy but have power to influence it when the policy impacts their interests (e.g. power generation companies, grid operators, end-users)
- **Apathetics***: Stakeholders who have little interest and little power; they are perhaps unaware of the policy (e.g. electricity end-users who are not very price-sensitive).

Policymakers should take into account expected change in stakeholders' interests with the new mode of energy usage. Understanding the possible influence of stakeholders on the policy decision is very important to reach the expected results. The position of promoter group is directly related to the success of the PV self-consumed model since promoter groups have great influence to develop it. Let assume a government *as promoter* who is willing to develop the PV self-consumed model. The government prepares appropriate policy support and the institutional framework to provide favorable conditions for the PV self-consumed model's development in a national energy system. On the contrary, when the government decides against being a promoter of the new mode, the PV self-consumed model faces a great obstacle. Prior to the policy decision, the government can compare expected costs and benefits on a national level to decide on their policy vision. *Defenders* are the public who want to develop the new model to gain expected interests (e.g. PV self-consumers, PV or associated industries). The *latent group* should be closely examined because they represent a large potential threat. When the policy results are expected to conflict with their interests, they will strongly oppose the policy making and disturb the development of the PV self-consumed model. In this regard, targeted strategies for defined stakeholders from the latent group are needed to address any opposing movements; e.g. power generation firms, grid operators, and end-users. This study attempts to identify the latent groups and expected changes in their interests so as to draw proper policy recommendations to address those changes.

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[2]Authors' analysis based on World Bank's definition

3. Micro-economic case study: opportunities with the self-consumption model in French supermarkets

3.1. PV self-consumption modeling methodology

A micro-economic case study has been conducted to review opportunities for the PV self-consumed model by using the existing surface area of supermarkets in France. The supermarket sector theoretically shows the best correspondence between onsite consumption and PV outputs, while providing large unoccupied surface areas to install PV systems. This section describes a simulated model to give a quick yet precise idea of the opportunities of PV self-consumption. Possible challenges and risks under this model are also considered so as to better prepare future strategies. Policy strategies to support the model are discussed at the end of this article. The modelling methodology has the following steps.

Firstly, the key drivers of the PV self-consumed model were studied to define the key input data; these data are related to the economics of the self-consumed system. For example, electricity prices for supermarkets, LCOE, surface area available, and the ratio of correspondence between onsite consumption and PV output. Secondly, the production and consumption curves in supermarkets were modeled according to the input data defined in the above step. Thirdly, the collective outcomes were calculated; ***expected installed capacity***, ***PV electric output***, ***impacts on the grid*** (avoided system congestion, contribution to lowering the electricity peak) and the ***increased energy independence***. Lastly, based on the results, we aim to review ***costs/benefits for key stakeholders with a focus on the latent group*** (utility power plants, grid operators, and the government). It is because they represent a potential threat if the PV self-consumed model conflicts with their interests. The key findings may prove useful when make policy recommendations related to the PV self-consumed model.

3.2. Key input data & assumptions

We have identified key economic drivers, which define the economics of the PV self-consumption system. Key data and assumptions are presented here below.

3.2.1. Electricity price

Higher retail electricity prices lead to economic incentives for using a PV self-consumed system or vice-versa. In most countries, retail rates of electricity include electricity generation costs, T&D costs, profit margins and additional surcharges or taxes [6]. Table II indicates France's electricity tariff changes in residential and small industrial areas over time. France has relatively low electricity rates compared with other neighboring or European countries. However, tax represents a large fraction in the electricity tariff in France, having increasing from 25% in 2008 to 33% in 2014. Since 2009, there is a rising trend in electricity prices in both residential and industrial sectors in France. A similar trend also exists in the German electricity rates over the last years; as Table II shows, Germany's electricity rates have risen by 53% from 19.49 c€/kWh in 2007 to 29.81 c€/kWh in 2014. This is mainly due to the increased EEG (renewable energy sources act) to finance the national energy transition.

Table II: Electricity Prices in France and Germany [25][26][27]

France

Household

Year	Electricity price (c€/kWh)	CSPE (c€/kWh)
2000	11.79	0
2007	12.11	0.45
2014	15.85	1.65

Industry < 2000MWh

Year	Electricity price (c€/kWh)	CSPE (c€/kWh)
2000	6.59	0
2007	7.01	0.45
2014	11.57	1.65

Germany

Household

Year	Electricity price (c€/kWh)	EEG (c€/kWh)
2000	15.26	0.2
2007	19.49	1.02
2014	29.81	6.24

Industry < 2000MWh

Year	Electricity price (c€/kWh)	EEG (c€/kWh)
2000	7.98	0.2
2007	12.72	1.02
2014	20.71	6.24

In the French electricity system, customers pay a fixed charge for grid connection which is set by the government (subscription fees [28]) depending on the subscribed power. In France, a time-of-use tariff option is currently applied for peak shaving; this is focused on smoothing the seasonal peak rather than the hourly variation (higher tariffs applicable from November to March). There are no taxes on self-consumed electricity in France [6].

The government has an important role in setting electricity rates. France has regulated electricity tariffs; *blue tariffs* for residential & professional segments (less than 36 kWh of electricity use), *yellow tariffs* for SMEs consumers (36-240 kWh [29]) and *green tariff* (more than 240 kWh) for large industrial consumers. Most supermarkets have been offered yellow tariffs by EDF. However, yellow and green tariffs will be abolished at the end of 2015 and blue tariffs will remain until 2025 [30].

These electricity tariffs include energy costs (electricity) and the grid cost for electricity delivery (user fee for the electrical public network known as TURPE[3]). TURPE represents 90% of ERDF's revenue [31]. TURPE is calculated

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[3] French abbreviation for *Tarif d'Utilisation des Réseaux Publics d'Electricité*

taking into account both fixed and variable costs which depend on the subscription type, the options taken, and the consumption profile. On average, yellow-tariff consumers pay a similar amount of TURPE as they do energy costs. There are other segments in the retail electricity rates; different taxes and fees are added to these tariffs [32][33][34][35]:

- **Contribution to Electricity Public Services (CSPE[4])** used to offset the charges related to public services such as renewable energy generation, social tariffs and nationwide equalization electricity tariffs. The CSPE for 2015 is set at 0.195€/kWh. In 2013, solar support represented 41% of the CSPE [36].
- **Tax on Final Electricity Consumption (TCFE[5])** is a local tax varying on the local policy. The average tax is 2.1% of the total electricity price.
- **Transmission Tariff Contribution (CTA[6])** goes towards the national electricity and gas industries fund (CNIEG). The CTA represent 21% of the transmission part of any fixed electricity subscription. The average CTA represents 3.1% of the electricity price.
- **Value Added Tax (VAT)** is set at 20% of the electricity price. In general, yellow-tariff users are free from VAT. This tax is not considered in the study.

The diagrams in Figure 7 show different price breakdowns of the average residential, commercial and industrial electricity rates in France in 2014.
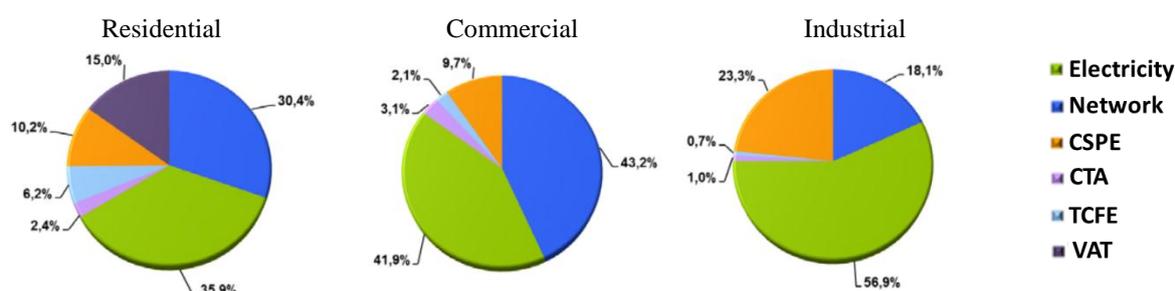

Figure 7: Price breakdowns of the average residential, commercial and industrial electricity rates in France (2014) [35]

In the simulation, we assumed that yellow tariffs were applicable for all the supermarkets and hypermarkets in question. In the supermarket segment, the electricity consumption per square meter (m^2) stays relatively constant regardless of the supermarket size. A study gives a mean consumption of around ***650 kWh/m²/year*** for large supermarkets (> 1000m2) and hypermarkets (> 5000m2) [37]. We assumed that the consumption profile was proportional to the surface area.

There are four different prices in the yellow tariff category: winter (November to March), summer (April to October), off-peak hours (lower price) and peak hours (higher price) for each season. Off-peak hours and peak hours vary depending on the local government policy but peak hours are usually during the day while off-peak hours are during the night (the local differences in terms of peak periods are neglected in this study). The day tariff is applicable from 6 am to 10 pm and supermarkets mainly use the day tariff. The day price during the winter is 0.09522 €/kWh and 0.04990 €/kWh in the summer [38].Therefore, the electricity prices paid by yellow-tariff consumers are shown in Table III (tariffs used for our simulation).

Table III: Electricity tariff paid by yellow-tariff consumers

€/kWh	November to March	April to October
Electricity Tariff	**0.0952**	**0.0499**
Electricity production	0.0476	0.02495
TURPE (Network)	0.0476	0.02495
CSPE	0.0195	0.0195
CTA	0.0038	0.0023
TCFE	0.0025	0.0015
Total	**0.1210**	**0.0732**

The use of the PV self-consumption model will bring about some changes in electricity tariffs. The changed tariff of each segment is related to stakeholder interests. The Table IV explains the possible impacts on stakeholders. The possible impacts will be further examined later in this article.

Table IV: Possible impacts on stakeholders

Electricity production	Impact on the electricity market and revenues of the ***electricity producers***
TURPE (Network)	Reduced revenues of ***grid operators*** (transportation and distribution)
CSPE	With less consumed electricity from the grid, the CSPE paid by ***end-users*** will increase to maintain the same level. Moreover, the support of PV installation can increase the CSPE.
CTA	***Electricity industry employees, government***

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[4] French abbreviation for *Contribution au Service Public de l'Electricité*
[5] French abbreviation for *Taxe sur la Consommation Finale d'Electricité*
[6] French abbreviation for *Contribution Tarifaire d'Acheminement*

TCFE	Reduced tax revenues of *local government*
VAT	Reduced tax revenues of *government*

3.2.2. PV electricity production costs

PV power is commonly priced as levelized costs of electricity (LCOE, \$/kWh). Solar PV system costs are an important lever when defining the initial investment needed to calculate the levelized costs of PV energy. LCOE will also depend on other factors like module efficiency, capacity factor, cost of capital and lifetime [39]. In order to calculate the LCOE[7] of the PV self-consumed model in France, we referred to the following data and assumptions.

o PV system price: 1.9€/W in 2013 using c-Si PV technology[8] for large commercial roofs with simplified integration (ISB), which is > 100kWc [40]
o Insolation: Average global standards from 3.12 kWh/m^2/day to 4.27kWh/m^2/day [6]. Insolation is higher in the southern regions of France. Insolation in Paris (3.32 kWh/m^2/day [41]) was used for modeling in this study, while the location difference was ignored to simplify the simulation. If we had conducted the same study using data from the southern regions, e.g. Nice, the results would have been quite different.
o O&M: 1% of PV system price [42].
o A discount rate of 5% is used to consider the weighted average costs of capital (WACC) for the respective investment [43][44].
o Module efficiency: We assumed 16% of module efficiency using the monocrystalline technology [4].
o 77% of PV system efficiency using electrical conversion hardware [45]
o 20 years of lifetime.

3.2.3. Available surface areas

The data on French supermarket surface areas was taken from the website *www.distripedie.com.* The total sum of nation-wide supermarkets & hypermarkets were used; as of 2009, France had a total of about *16 million m^2* of supermarket (Table V). We assumed that every supermarket was a 1-floor independent building with a flat roof usable for PV installation.

Table V: Data on French supermarket surface areas [46][47]

Total surface area of French hypermarkets
(nation-wide)

Hypermarket (2009)	Number	Average area (m2)	Total area (m2)
E. Leclerc	467	5100	2381700
Carrefour	231	9100	2102100
Auchan	134	10500	1407000
Géant-Casino	120	7400	888000
Hyper-U	61	4900	298900
Cora	59	9600	566400
TOTAL			**7644100**

Total surface area of French supermarkets
(nation-wide)

Big supermarket (2009)	Number	Average area (m2)	Total area (m2)
Intermarché	1494	1900	2838600
Champion-Carrefour market	987	1830	1806210
U	718	2100	1507800
Atac – Simply	414	1500	621000
Casino	380	1470	558600
Monoprix	276	1800	496800
Match	149	1550	230950
E. Leclerc	115	1800	207000
TOTAL			**8266960**

3.2.4. Ratio of matching between onsite consumption and PV output

Literatures explain that the ratio of correspondence between onsite consumption and PV output is an important variable in defining the economics of the self-consumption model [4][6][8]. As explained, the residential sector shows a weak correlation between PV output and onsite consumption and only a small share of generated PV power is self-consumed without a storage system (between 30% and 40% [48]). Moreover, the peak demand time for the residential sector is winter in the evening; this gives the worst correlation between PV output and onsite consumption. It does not reduce congestion levels because the generated PV electricity during peak times is often higher than the onsite consumption. This may require further investment on grid reinforcement when aggregated surplus of electricity exceeds the current capacity of the grid infrastructure. On the contrary, the application in supermarkets shaves the peak demand during summer at midday thanks to the possibility of full self-consumption.

Here below, we have attempted to justify the correspondence ratio between electricity consumption and PV output in supermarkets using 2010 data [49]. The simulation attempts to give an approximation of opportunities for PV self-

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[7]LCOE $= \dfrac{\sum_{t=1}^{n} \frac{\text{Investment}_t + \text{O\&M}_t + \text{Fuel}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\text{Electricity generation}_t}{(1+r)^t}}$

[8]*PV technology:* In this study, we considered the *c-si technology*. We assumed that PV modules were installed using horizontal placement and covered the entire surface available. This is an approximation because space between modules is needed in terms of installation and maintenance. In addition, other installations can exist on roofs. Technological constraints (weights, temperature sensiveness) were neglected. If weight matters, c-Si modules can be replaced by a thin-film solution with less efficiency (8%-10% efficiency) but cheaper selling price. This solution can be supported by a national innovation policy. The module orientation can be optimized according to the local or seasonal conditions.

consumption. Figure 8 demonstrates the supermarket model containing the consumption profile (winter, summer) and the maximum production curve of PV electricity.
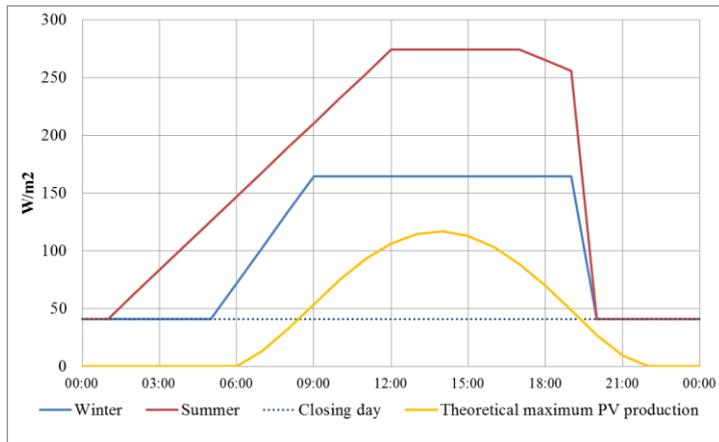

Figure 8: Consumption profile and maximum production curve of PV electricity

- *Supermarket consumption profile (winter, summer and closing day)*

The supermarket consumption profile is based on a study, which shows an analysis of the real consumption profile (every 15 minutes) of a medium-sized supermarket [49]. Data on real consumption profiles in winter and in summer were taken to develop the demand curve. The main sources of energy use in the supermarket sector can be divided as follows:

- Cold storage (negative cold for frozen goods and positive cold for perishable goods)
- Lighting (indoor for a large majority)
- Heating in the winter and air-conditioning in the summer.

In winter, the power demand has a linear growth from 5 am to the opening hour (9 am), it stays constant during the opening hours (~160 W/m^2) and comes back to the night demand at closure (7 pm). In summer, the power demand has a linear growth from 1 am to midday. The peak demand period is constant between midday and 5 pm[9]. Then, the demand reduces steadily until the closing hour and comes back to the level of night demand after closure. During days-off and nights, the constant power demand is about 40 W/m^2. It is used for negative and positive cold storage [37] which must operate all day constantly without interruption. The level stays constant in both winter and summer.

- *Theoretical maximum PV production*

The theoretical maximum PV production was determined for comparison with the above supermarket consumption (demand) curves. This curve was developed using the European Commission's Photovoltaic Geographical Information System (PVGIS) [50], based on the assumption of average solar irradiation in June under a clear sky in Paris, weighted by the module's efficiency (16%) and the system's efficiency (77% [45]). We assumed that PV modules were installed using horizontal placement and covered the entire surface area available.

From the PV self-consumption model developed, we have found that:

- All the PV production can be self-consumed during the opening days
- The PV production peak never exceeds the demand peak and there is no need for grid reinforcement.

Therefore, in this study we assumed *100% of the PV production was self-consumed in supermarket sectors* without further investment due to grid reinforcement.

3.3. Results: Opportunities with a PV self-consumption model

Opportunities for the PV self-consumed model using supermarket surface areas will be defined in this part. We attempt to calculate the expected *installed capacity, PV electric output, impact on the grid* (avoided system congestion, contribution to lowering electricity demand peak), and the increased *energy independence.* In addition, the reduced GHG emissions and economic benefits (job creation, sales, and avoided fossil fuel imports) can be included to define benefits of the PV self-consumed model. However, these results are not quantified in this study even though there are obvious consequences. The profitability of the self-consumed model is compared under scenarios without any support and with the current FIT scheme to define policy support needed to make the model profitable. Possible quantified impacts on stakeholders are then presented with the objective of preparing strategies to mitigate policy risks in search of PV self-consumption growth.

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[9] The solar midday in summer is at about 2 pm GMT in Paris

3.3.1. Opportunities of supermarkets/ hypermarket surface areas

The *real maximum PV productions* in summer and winter, which reflect the real production condition, are modeled as below. We drew the real maximum PV output curve, which produces less electricity than the theoretical curve. When PV power is self-consumed onsite, supermarkets use less electricity from the grid which moves the demand curve down. A new shaped demand curve is expected (see Figure 9) with the following aspects:

- PV production reduces the electricity consumption from the grid, thereby reducing the electricity demand peak
- The midday electricity demand peak in supermarkets is shifted to the end of the day (~ 6 pm). The impact is greater during the summer than in winter and depends on the local configuration; *the demand peak is reduced by around 55 W/m^2 in Paris during the summer*, therefore putting less pressure on the grid. The peak shaving result will produce larger positive results in regions or countries with a midday peak in summer (e.g. the US).
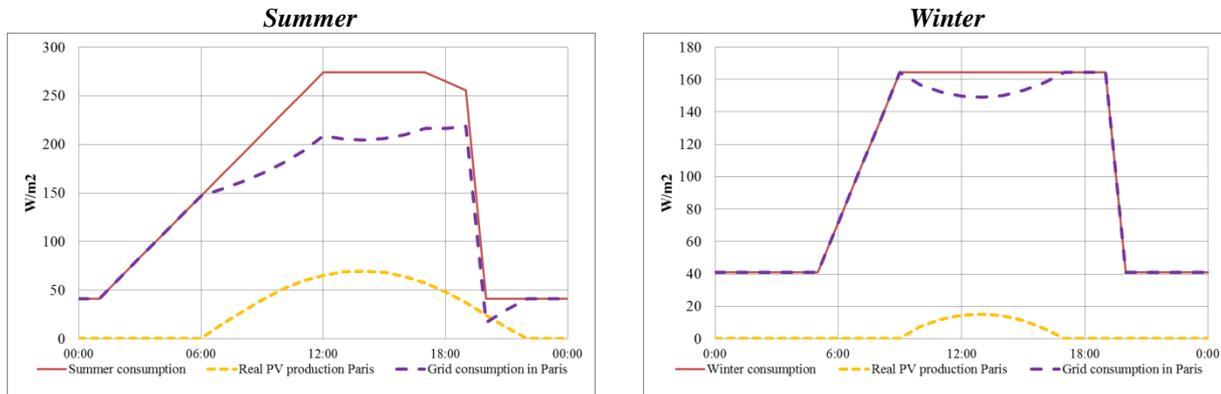

Figure 9: Demand from the grid with and without self-consumption

From this simulation, we were therefore able to conclude that the supermarket sector fits well with PV self-consumed usage model for PV power for the following reasons:

1. Opportunities to utilize the existing large surface areas to install PV modules on the roof.
2. Good correspondence between onsite consumption and produced PV power: almost all power generated can be self-consumed (assumption: when the entire available surface area is used to produce electricity).
3. The new mode will reduce electricity peak demand purchased from the grid with self-consumption of PV power, thereby reducing pressure on the grid.
4. Grid reinforcement is not needed: PV electricity production never exceeds the electricity demand level of supermarkets.

▪ *PV installations*

We have also found that **possible nation-wide PV installations in France could represent 2.56 GWp[10]** on the condition that all the existing supermarkets in question install the PV systems on their roofs. This accounts for **47% of the total French PV installation of 2015** [51].

▪ *Electricity produced & increased energy independence*

The PV production per square meter (m^2) in Paris is given in Table VI.

Table VI: PV production in Paris [50]

Paris	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly irradiation kWh/m^2	27.3	45.1	96.7	137.4	160.9	173.4	176.7	149.1	110.1	65.7	32.4	24.1	
PV production kWh/m^2	3.4	5.6	11.9	16.9	19.8	21.4	21.8	18.4	13.6	8.1	4.0	3.0	148

The total annual PV production in Paris is 148 kWh/m^2, which is around 23% of supermarket consumption (~650 kWh/m2/year). This means the model contributed to increase the energy independence of supermarkets to 23%. If we consider that production in Paris is representative of the French average production, the total possible production could reach **2.36TWh[11] (0.5% of the total French electricity consumption,** 447 TWh [52]).

3.3.2. Profitability of the PV self-consumed model: viewpoint of PV system users

In this paper, we aim to define the economic incentives of end-users to adapt the PV self-consumed model. The profitability of the PV self-consumed model is country-specific depending on various factors such as the economics of PV power, electricity tariffs and political decisions. If the PV LCOE is much higher than the electricity price paid by the commercial consumers, there are insufficient economic incentives to install PV self-consumed systems in supermarkets

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[10]16 million m^2 x 160 Wp/m^2 = **2.56 GWp** (47% of the current installations)
[11]16 million m^2 x 148 kWh/m2/year = **2.36 TWh/year** (0.5% of the total electricity consumption of 447 TWh (Eurostat))

unless they generate interesting financial returns on the initial investment through policy support or other revenue creation. It is therefore important to define the break-even point of the proposed model. If it is not economically competitive on its own, policy support can lead PV installation growth using the defined self-consume model.

- *PV end-user investment and expected revenue*

Electricity end-users have economic incentives to install PV systems on the roof when it gives them a sufficient rate of return on their investment. In order to define profitability, it is necessary to know the investment required and the expected revenue stream under the PV self-consumed model.

> ***Investment to install PV systems with operation and maintenance (O&M)***

Investment refers to the total costs in terms of PV system installation with operation and maintenance (O&M) during the lifetime of the PV system. The PV initial investment was estimated at 1.9 €/Wp in 2013 [40] using monocrystalline PV modules with an efficiency of 16%. Based on the standard test conditions to define watt peak[12] [53] of 1 kW/m^2 of solar irradiance, we concluded that 160Wp was produced by m^2 based on a monocrystalline module efficiency of 16%; this means that 6.25 m^2 is needed to produce 1 kWp.

Therefore, the initial investment per square meter (m^2) is $I_{PV=}$ **1.9 €/Wp x 160 Wp/m^2 = 304 €/m^2.**

The O&M costs, which are usually set at 1% of the investment, should be included. The total cost is discounted during the lifetime of PV system (20 years). The discounted cost of the System C_{PV} is;

$$C_{PV} = I_{PV} + \sum_{N=1\ to\ 20} \frac{I_{PV} \times 1\%}{(1+r)^N} = \mathbf{342}\ €/m^2\ , with\ r=5\%$$

For example, for a medium-sized supermarket with 2000 m^2, the total investment amounts to €684,000.

> ***Expected revenue streams***

Revenue concerns avoided electricity bills in the case of self-consumption, sales of PV electricity surplus, sales of green certificates (if applicable), and potentially, government support.

A. PV electricity production for self-consumption without any policy support

Here we assumed that there was no policy support for the PV self-consumed model; e.g. no installation subsidies, no FIT, no permission for feed-in electricity to the grid. When the entire PV production is self-consumed without such supports, the expected revenue is equal to the retail electricity price avoided based on **the PV electricity produced (E_{PV}).** The discounted revenue depends on the **retail electricity price (P_E)** change with time. The electricity price is related to profitability. Since 2008, the average electricity price excluding taxes has increased by **3.5%** every year in France [25]. Assuming the constant E_{PV} every year[13], the expected revenue (=E_{PV} x P_E) is given in the Table VII.

Table VII: Expected revenue with self-consumption in Paris

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
E_{PV} (kWh/m^2)	3.4	5.6	11.9	16.9	19.8	21.4	21.8	18.4	13.6	8.1	4.0	3.0	**148**
P_E (€/kWh)	0.1210	0.1210	0.1210	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.1210	0.1210	-
Revenue (€/m2)	0.407	0.672	1.442	1.239	1.451	1.564	1.594	1.345	0.993	0.593	0.483	0.359	12.1

For example, a 2000 m^2 supermarket can save 24,200€ of annual electricity fees by avoiding power purchase from the grid.

With a discount rate of 5% [44], the discounted revenue (R_{SC}) over 20 years was calculated according to the annual increase in the retail electricity price (*a)*;

$$R_{SC} = \sum_{N=1\ to\ 20} \frac{E_{PV} \times P_{E\ retail} \times (1+a)^N}{(1+r)^N}$$

By comparing the investment required (C_{PV}) and the expected revenue (R_{SC}), we came to the conclusion that the PV self-consumed model was not economically attractive without policy support (see Table VIII).

Table VIII: Comparison between the investment required and the expected revenue from self-consumption

Segment	Investment (€/m^2)	Revenue (expected) (€/m^2)	Payback period	Investment gains/ losses over 20 years (€/m^2)
Self-consumption: a=0%	342	151	> 30 years	191

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[12]Watt peak (Wp) refers to the peak power of a PV module or system under standard test conditions (light intensity: 1000 W/m^2, temperature: 25 ºC, and air mass: 1.5)
[13] The degradation of module efficiency with time is neglected

| Self-consumption: a=2% | 342 | 177 | > 30 years | **165** |
| Self-consumption: a=5% | 342 | 230 | > 30 years | 112 |

a: annual increase in retail electricity prices

B. PV electricity production under the current FIT scheme

In this case, 100% of PV electricity produced is fed into the grid with a financial compensation based on the current FIT system. The fixed tariff was set at the beginning of the 20-year long-term contract. The annual constant E_{PV} (=148 kWh/m^2) was also considered to calculate the expected revenue (R_{FIT}). The FIT was **0.1727 €/kWh** during the first quarter of 2013 [54] for commercial-sized systems above 36 kWp[14]. The discounted revenue (R_{FIT}) over 20 years was calculated with a discount rate of 5% [44].

$$R_{FIT} = \sum_{N=1\ to\ 20} \frac{E_{PV} \times FIT}{(1+r)^N}$$

$$R_{FIT} = 319\ €/m^2$$

The discounted revenue (R_{FIT}) over 20 years proves to be smaller than the required investment (C_{PV}) of €342 per m2. In this calculation, we used the mean PV system price with uncertainties on the discount rate (r) and the differences in solar irradiance according to the location (see Table IX). The calculation can be considered concise and the results will be different depending on the assumptions and data used. The tariff is not attractive in Paris but is sufficient in the sunniest regions located in the south of France. To make the PV system profitable, the discounted revenue (R_{FIT}) should be at least equal to the discounted investment required (C_{PV}). The general equation is:

$$C_{PV} = R_{FIT}$$

$$I_{PV} + \sum_{N=1\ to\ 20} \frac{I_{PV} \times 1\%}{(1+r)^N} = \sum_{N=1\ to\ 20} \frac{E_{PV} \times FIT}{(1+r)^N}$$

To make the PV system profitable in Paris, the FIT should be at least equal to the LCOE. The investment (C_{PV}) of €342 per m^2 with a 5% discount rate needs a minimum support of 0.186 €/kWh[15].

Table IX: Impact of the location in France on the profitability of the FIT

Segment	Investment (€/m^2)	Revenue (expected) (€/m^2)	Payback period	Investment gains/losses during 20 year (€/m^2)
Paris with FIT	342	319	23 years	-23
Nice with FIT	342	428	15 years	+86

3.3.3. PV supports and results: viewpoint of policy makers

Policy support (S) is needed to make the proposed model profitable. Otherwise, there are no economic incentives to install PV systems for end-users. Here below, we have attempted to formularize the financial support to give economic incentives to end-users to install PV system on their roof for the purpose of self-consumption. This support is decided by the country and can be conducted via different policy instruments, e.g. direct installation subsidies or a long-term contract.

$$S = I_{PV} + \sum_{N=1\ to\ 20} \frac{I_{PV} \times 1\%}{(1+r)^N} - \sum_{N=1\ to\ 20} \frac{E_{PV} \times P_{E\ retail}}{(1+r)^N}$$

Necessary financial support for PV self-consumption

Policies to promote PV systems should be interpreted in a global perspective. Policymakers have the global targets in terms of PV installation, PV electricity production, the share of renewable energies in the electricity production mix, GHG emission reduction, and related economics objectives like job creation.

France has the PV installation target of 5400 GWp by 2020; this target was actually reached at the end of 2014 [51]. However, the new law on the energy transition is currently under discussion; this new law aims to increase the part of renewable energies in the final gross energy consumption to 23% by 2020 and 32% by 2030 (cf. 14% in 2013 [55]) and in the electricity production to 40% by 2030 [56] (cf. 19% in 2014). The objective of this new law is to improve financing for renewable energies and to create jobs. PV power can be an interesting levier to reach these objectives because the PV sector becomes more competitive and has potential to improve its economic competitiveness. In addition, PV has better social feasibility compared with wind power [57]. In this context, it is interesting for the government to review the opportunities offered by the PV self-consumed model to meet the target of increasing renewable energies in the electricity system.

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[14] The support is limited to the installation lower than 100kWc. In this study, we ignore this limitation and apply the given tariff of *0.1727€/kWh* for all the size.
[15] Authors' calculation

The Table X explains possible benefits and the minimum financial support needed to apply the proposed model. Supermarket surface areas in France represent significant opportunities for PV installation, as well as PV power production. If France were to use all its supermarket surface areas (16 million m²)[16], it could add an extra PV installed capacity of 2.56 GWp, which accounts for around 47% of the current cumulative installation in France. This provides an annual electricity production of 2.36 TWh. Furthermore, the produced PV power in supermarkets could be consumed 100% onsite thanks to the good correspondence between PV output and the power consumption profile. Consequently, the self-PV consumed model could help reduce the midday peak of supermarkets using self-consumption.

Table X: Expected benefits of the PV self-consumed model and policy support [39]

Energy transition	**Possible installations**: 16 million m² x 160 Wp/m² = **2.56 GWp** (47% of the current installations)	
	Electricity production: 16 million m² x 148 kWh/m2/year = **2.36 TWh/year** (0.5% of the total electricity consumption of 447 TWh (Eurostat))	
Land usage	16 million m² available **without new land use**	
Local grid pressure reduction	no **grid reinforcement** needed and **T&D losses** avoided Depends on local configuration, the summer peak is reduced by about 55 W multiplied by the supermarket surface area	
Economic Benefits	Job creation, exports, domestic sales Reduced fuel costs (e.g. imported oil or coal)	
CO2 emission avoided	GHG emission reduction: little impact with the large part of nuclear power in France	

	Policy costs under self-consumption	Policy costs under FIT scheme
Annual policy costs of the support	€ 215 million[17]	2.36 TWh x 0.1727 €/kWh = €408 million
Discounted policy costs of the support over 20 years	16 million m² x 165 €/ m² = €2.6 billion (a=2%)	16 million m2 x 319 €/m2 = €5.1 billion

We have found that PV electricity production using the self-consumption model seems more interesting compared with the FIT system. Under these two different configurations, PV electricity under the self-consumed model offers more benefits in terms of reducing the summer demand peak. In addition, it generates fewer policy costs.

3.3.4. Impact on other stakeholders

The government's policy strategy is directly related to the success of the PV self-consumed model. Other stakeholders, particularly the latent group, can threaten the policy decision on the PV self-consumed model if the new usage mode of PV electricity conflicts with their interests. The proposed model reduces the purchased electricity from the grid, influencing the profits of energy market players, e.g. utility generators and grid operators. In addition, as more people install PV systems for self-consumption to pay lower electricity bills, other end-users who continue to use electricity from the grid will pay increased electricity rates to cover CSPE and the fixed costs of grid investment [4][6][8]. If the government aims to promote the PV self-consumed model to take advantages of the model, the preparation of policy threats from stakeholders is an essential step. Therefore, policy makers should examine the expected impact on other stakeholders' interests to mitigate policy risk and to avoid any interruption. Below, the possible impacts are quantified to capture policy risks.

▪ *Impact on stakeholders' interests under the FIT scheme*
By using *the FIT scheme*, PV producers continue to pay all taxes and fees. However, with the penetration of PV electricity production, the existing power generators will sell less electricity in the market (the average wholesale market price was 0.0443 €/kWh in 2014), thus leading to reduced sales revenue for other power generators. Moreover, the financing of the FIT is supported by the CSPE from the electricity rates. Possible impacts on stakeholder interests are calculated Table XI. This means €408 million is paid to support the PV installation of 2.56 GW.

Table XI: Impact on stakeholder interests of the FIT scheme

FIT policy	Stakeholder	Amounts by m² of installation (annual)	Nation-wide amount (annual)
Conventional electricity production decrease	**Utility generators**	€6.55/m²	€105 million
Sub-total		**6.55 €/m²**	**€105 million**
FIT financing (CSPE)	**End-users** of electricity	€25.56/m²	€408 million
Total		**32 €/m²**	**€512 million**

▪ *Impact on stakeholder interests under the self-consumption model*
In case of self-consumption, the produced PV power is consumed onsite and the surplus can be fed into the grid. The impact on stakeholder interests can be roughly calculated by reviewing changes in electricity bills with the penetration of

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[16] The solar irradiation in Paris has been used to represent the average solar irradiation conditions in France.
[17] Assumption: LCOE= 0.1727€/kWh

the self-consumption model. The losses can be calculated by multiplying the electricity tariff for each segment by the electricity avoided from the grid:

$$E_{PV} \text{ (kWh/m}^2) \times \text{the part of electricity tariff (P}_{\text{stakeholder}}) \text{ (€/kWh)} = \text{Revenue losses}_{\text{stakeholder}} \text{ (€/m}^2)$$

The Table XII captures the expected impact on each stakeholder. Due to reduced purchasing from the grid, end-users who own PV systems use less electricity from the grid. The existing power plants and grid operators will earn less revenue. In addition, end-users will pay more for the CSPE. The government will have less tax revenue. In this study, the government's reduced tax revenue from VAT is excluded: French supermarkets do not pay VAT. However, this impact is notable in the residential sector with 20% of VAT. Further financial support is needed to achieve the PV self-consumed model.

Table XII: Impact on stakeholder interests of the self-consumption scheme

Self-consumption	Stakeholder	Amounts by m² of installation (annual)	Nation-wide amount (annual)
Conventional electricity production decrease	**Utility generators**	4.31 €/m²	€69 million
TURPE (network)	**Distribution**	4.31 €/m²	€69 million
CSPE	**End-users** of electricity	2.88 €/m²	€46 million
CTA	Retired electricity employees / **Government**	0.38 €/m²	€6.0 million
TCFE	Local **government**	0.26 €/m²	€4.1 million
Sub-total		**12.14 €/m²**	**€194 million**
Self-consumption support		13.4 €/m²	€214 million
Total		**25.54 €/m²**	**€408 million**

Based on the above calculations, we have found that the same level of cost exists under the FIT system and the self-consumption model to make the PV system profitable. However, there are important differences.

Firstly, under the FIT system, PV electricity is supported by fixed tariffs based on long-term contracts and this is directly financed by CSPE, placing the burden mainly on end-users. We have seen the rapid increase in electricity retail tariffs in France and Germany mostly due to the contribution of CSPE and EEG respectively. The financial support to the energy transition has increased retail prices and there are now issues about energy poverty and industrial competitiveness. However, the PV self-consumption model with its good correspondence ratio requires less direct financial support and electricity bill savings make up the profitability of the model.

Secondly, the FIT scheme has larger potential losses than the PV self-consumption model; the total sum adds the policy supports for purchased PV electricity and potential revenue losses of exiting utility generators with the increase of PV power production in the energy market. In the second calculation, we can find that the potential revenue losses are widespread among stakeholders as more PV power is consumed onsite. An interesting point is that such impacts on stakeholders are quite similar to the results of reduced electricity loads from an energy efficiency policy, which has priority in the EU energy policy [6].

In addition, under the FIT system, PV system installers do not have economic incentives that match their real consumption profile; instead, there can be a windfall effect for profit-seeking. Uncontrolled installations require further policy support, leading to an increase in the CSPE. However, a well-designed policy framework can incite people to maximize onsite self-consumption, thus avoiding such windfall effects. This will lessen the burden of the CSPE.

Lastly, under the self-consumption model, we gain a clearer overview of the impact on stakeholders with the penetration of PV electricity. This clear overview allows the government to approach policy design and implementation in a shrewd manner to address potential policy risks factors.

A possible negative impact on the revenue stream of other stakeholders could be counterbalanced by the benefits that the PV self-consumed model creates. As said, good utilization of the self-consumption solution reduces the burden on end-users with a lower CSPE increase. In addition, the PV self-consumed model cuts the peak demand level; the midday peak shifts to an end-day peak around 55 W/m² lower, thereby reducing grid pressure. A lower participation in the grid infrastructure (TURPE) is somehow partially justified. Furthermore, even though the PV self-consumed model affects the interests of stakeholders, it also brings about a positive impact for society. The PV self-consumed model can bring environmental, economic and energy mix benefits. PV is worth investigating to meet the national target of renewable energy growth in the future energy mix. All populations - including stakeholders - will benefit. For example, more eco-friendly living conditions will be available to populations through the large penetration of PV installation in the energy mix. In addition, the PV self-consumed model stimulates economic growth in terms of job creation, development of the PV industry and associated industries. Increasing energy diversification and independence improves the national energy security.

4. Policy recommendation

This paper analyzes the benefits and issues of the PV self-consumed model. The new mode of power consumption requires additional costs 1) to change the general organization needed to penetrate the energy mix, and 2) to avoid

provoking impacts on other stakeholders. It is important to define strategies to stimulate the PV self-consumed model. In addition, such strategies should help drum up the participation of other stakeholders. Here, we have attempted to define possible strategies to help develop the proposed PV self-consumed model. Figure 10 explains possible *promotional policies with different strategy directions.*
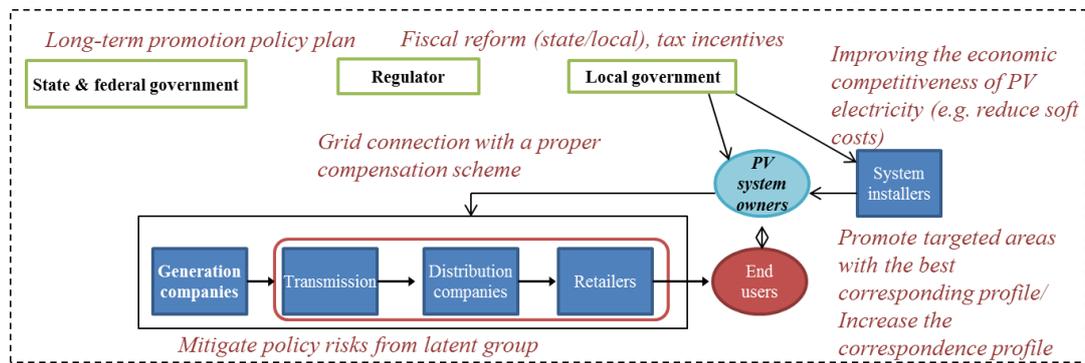

Figure 10: Possible promotional policies with different strategy directions

1. *Establishing long-term policy vision of PV self-consumption (long-term promotion policy plan)*
The national policy strategy - whether to encourage or prevent the use of such a model - will determine the level of promotion of the PV self-consumed model in the energy mix. The organizational changes are taking place under the new regulatory system to introduce new business practices and grid models. When the political strategy aims to promote self-consumption of PV power putting stress on benefits, policy support should be deployed to give incentives to install PV systems for self-consumption. This policy support should present *a long-term vision* to secure stable growth. *Appropriate remuneration schemes* should be prepared to encourage the self-consumption of decentralized PV electricity generation when the self-consumed model is not yet competitive on its own [8]. The proposed opportunities of PV growth using the existing supermarket surface areas can be gained via long-term policy support: e.g., *solar commercial building mandates* can be one solution with proper compensation that covers PV installation investment.

2. *Giving priority to PV installation with the best corresponding profile between onsite demand and production*
We have seen that the self-consumed PV system can maximize benefits with the best correspondence between onsite demand and production, encouraging better returns on investment than in poorly corresponding areas.
First, policy should *promote targeted areas with the best correlation* between onsite consumption and PV production peak like supermarkets. In addition, *local PV production should be consumed locally* to increase the self-consumption ratio on a local level. The PV self-consumed model may provide a good solution for congested regions or areas with grid problems.

3. *Increasing the correspondence profile between onsite demand patterns and production*
Sectors with poorer correlation can be promoted in line with the *demand-side policy* to obtain optimal correspondence between PV power production and PV self-consumption [8]. The results will smooth the PV injection peak during the PV generation peak, thereby reducing the impact on the exiting power grid system. A *smart grid* may provide a dynamic policy instrument to improve correspondence between PV prosumer demand profiles and the production pattern, based on a more responsive grid system. *Smart grids* are designed to better control load managements by improving the transparency of the electricity market. Improving the *storage solution* is a good way to improving the correspondence of the supply-demand balance for the PV self-consumed model. PV self-consumption with storage increases the flexibility of PV systems by shifting the electricity demand load to non-peak times of PV production. However, the issue is to improve the economic competitiveness of such storage systems.

4. *Allowing connection to the grid with a proper compensation scheme*
The permission to connect to the electricity network is needed to secure the reliability of PV systems. The rules and regulations regarding grid connection will play a key variable in the economics of the model affecting prosumer decisions for usage [6]. In the long term, the PV self-consumed model can be developed by disconnecting from the grid when the storage system becomes economically viable for users. However, before this happens, the PV self-consumed model needs policy support which allows for grid connection with proper economic compensation. The compensation level, type and amount will vary according to the country's policy decisions.
Historically, the FIT system allows PV power generators to feed all electricity generated into the grid by providing long-term fixed-tariff compensation, which is usually set at higher level than the retail rate. However, the compensation level of the current FIT system differs from country to country; for example, the German FIT rate for residential producers (EUR 0.131/kWh in May 2014) is lower than average retail rate of electricity (~0.29 €/kWh in 2014) [6].
Countries compensate for excessive generation depending on the country's position of instantaneous self-consumption. *Net metering* allows PV generators to feed the excessive electricity produced into the grid. Countries have different

carryover provisions based on different time limits (within a year, months, and sometime in an hour). This restricted carryforward incites PV installers to reduce the PV system size to optimize the economic gains [6][17]. This also helps avoid the windfall effects created by the FIT, reducing policy costs.

5. *Preparing strategies to minimize the economic losses of key stakeholders (latent group)*
We have analyzed gains and losses for each stakeholder with the penetration of the PV self-consumed model. In order to reduce the potential risks of policy disturbance, policy makers should prepare some proper policy actions to minimize their losses.

- ▪ *Utility generators*

With the penetration of intermittent energies with low marginal production costs, the recovery of fixed investment costs for power generators becomes a concern. In order to maintain a certain level of dispatchable generation capacity in the energy mix, it is important to make conventional power plants economically viable though policy support like *capacity payment* [8]. The separated revenue creation mechanism will help recover the investment of existing power capacity generators. However, when the policy presents a long-term vision, utility generators can explore *new business opportunities* with the PV self-consumption model by diversifying their business areas.

- ▪ *Grid operators*

The impact on the network cannot be ignored. From the study, we have found that electricity retail prices can be used to prepare an economic instrument to promote PV self-consumption. Preparing a fair scheme for grid cost recovery in terms of electricity transmission and distribution is necessary to justify the development of the self-consumed model [4][6][8]. The fixed cost recovery of grid investment should be addressed via a fair allocation scheme among users. The *increased fixed tariff* in electricity tariffs or *resigned electricity tariffs* (e.g. demand-based charges, time-based pricing) can be considered [4][8]. Further costs can arise in terms of grid extension and upgrading. However, as said, the self-consumption in areas with the best correspondence will reduce pressure on the grid with little additional investment for grid extension or upgrading. Therefore, it may provide an interesting method for priority sectors like supermarkets to avoid additional grid costs. In addition, in-depth discussions on France's high grid-interconnection costs are needed; this should provide opportunities for new financing of grid operator losses [58].

- ▪ *End-users*

Government policy decisions concerning the energy transition are mainly supported by end-users via CSPE or EEG. However, as we have seen from calculations, the financial support for the self-consumed model in supermarkets distributes the financial burden among stakeholders. It should also be easier to control the increase in electricity rates. Otherwise, additional revenue creation can be considered to finance the PV self-consumed model: e.g. renewable energy certificates (RECs) or carbon tax.

6. *Reducing investment by improving the economic competitiveness of PV electricity*
We have demonstrated that the PV self-consumed model is not economically feasible. Improving the economics of PV systems is one way to reduce necessary policy support of the PV self-consumed model. Without policy support, Germany has better economic incentives to install PV systems for self-consumption than France does. Since the global module prices have fallen below US1$, the non-module sector has become important in determining the initial investment, even though there are other factors which carry weight in the economics of PV systems. Targeted policies will reduce soft costs (see below in terms of possible policy instruments) [58].
- o *Standardization of PV installation:* e.g. hardware, engineering, PII (Permission, Inspection, and Interconnection) process, customer acquisition and installations
- o *Increase transparency of grid connection data: e.g. grid-connected map[18]*
- o *Simplified process* from project design to grid connection
- o *Training installers/ customers* to reduce additional time and costs of PV installations

In addition, the preparation of favorable conditions to provide economic incentives plays a key role in encouraging people to install PV systems for self-consumption. *Tax incentives* like exempted VAT for PV components or no VAT on self-consumed electricity are possible.

5. Conclusion
Self-consumption using a proper mechanism can provide a way to improve the existing model of decentralized PV systems with better cost sharing as the energy transition takes place. The utilization of self-consumption for PV decentralized electricity can minimize distance between production and consumption sites, feeding small amounts of electricity into the grid. This reduces electricity losses during transmission and distribution, and helps avoid system congestion. Consequently, the model is more suitable for sectors that have midday peaks such as supermarkets and

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[18] *Publishing more grid connection information is one idea to increase grid connection transparency; grid connected maps (good for finding ideal areas for PV system installation): e.g. South Korea (KEPCO site)*

commercial buildings. The impact will be more visible in countries with summer day demand peaks. To provide a precise idea of the potential outputs and benefits, we performed an economic calculation using the existing surface areas provided by French supermarkets. This calculation revealed possible issues and risks under this model. The growing interest in the PV self-consumed model requires new business models which provide enough economic incentives to create a new mode of PV electricity consumption, while avoiding social losses particularly in terms of negative impacts on grid issues. To do so, well-designed policy support with a long-term vision is first needed to create the opportunities defined in this article. We also found that the stakeholder groups represent a threat to PV self-consumed policy when the new model conflicts with their interests. Therefore, it is necessary to prepare future strategies to mitigate the expected financial damage to other key stakeholders in order to alleviate such policy risks.

With appropriate political support, the deployment model can also provide PV growth opportunities. The model proposed in this study provides us with the basic information need to further analyze and define the global PV market for the future. From a strategic perspective, the PV self-consumed model should be applied in sectors with the best correlation between the load profile of electric consumption and PV production, so as to gain the best results. In the future, as electricity prices continue to rise while PV system prices goes down, the PV self-consumed model will benefit from better conditions for its application. The economics of the PV self-consumed model will greatly improve, making the model profitable for other sectors whose correspondence ratios are poorer, e.g. residential. Before achieving the ideal level, current policy should aim to prepare targeted strategies for each sector, e.g. residential, commercial and industry, so as to achieve the best results.
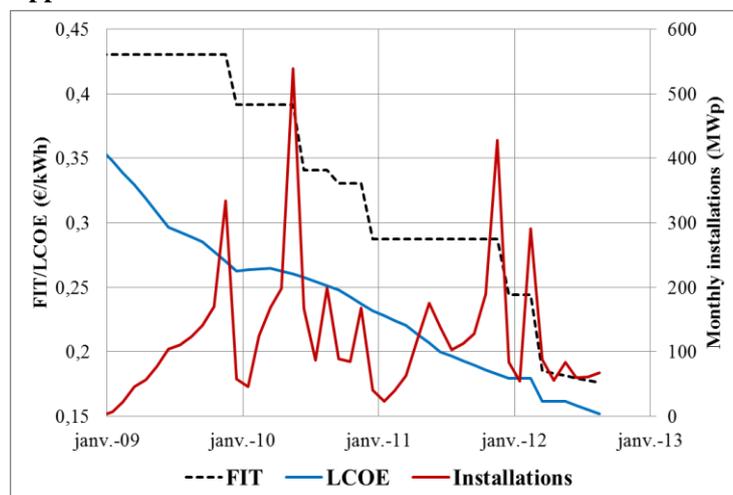
Appendix

Figure 2: Installation peaks under the FIT system

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