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Cost-competitiveness of organic photovoltaics for electricity self-consumption at residential buildings: A comparative study of Denmark and Greece under real market conditions

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ABSTRACT

To address sustainability challenges, photovoltaics (PV) are regarded as a promising renewable energy technology. Decreasing PV module costs and increasing residential electricity prices have made self-consumption of PV-generated electricity financially more attractive than exporting to the

grid. Organic photovoltaics (OPV) are an emerging thin-film PV technology that shows promise of greatly improving the environmental and economic performances of PV technologies. Previous studies have estimated the current and future costs of OPV technologies, but the attractiveness of investing in OPV systems has not been evaluated under real market conditions, especially under PV self-consumption schemes. In this study, we investigate the self-consumption of electricity generation from conventional and organic PV systems installed at residential houses in two different countries, Denmark and Greece, under current PV regulatory frameworks. We then focus on modelling and assessing the cost-competitiveness of organic PV technologies based on cost estimations for existing pilot-scale (kW-range), and projected scale-up (100MW) and industrial-scale (100GW) manufacturing capacity levels. Our generic results applying to all PV technologies show that PV systems installed at residential houses in Greece perform economically better than those in Denmark do in terms of self-sufficiency and gross electricity bill savings (i.e. excluding PV costs). Using the two country cases, which present very different settings, we characterise and discuss the influence of three key parameters of the economic performance of PV systems, namely the PV regulatory scheme, the solar irradiation level and the temporal match between the electricity consumption and solar irradiation profiles. Focusing on organic PV systems developed in an industrial-scale cost setting (1.53 €/Wp), we find that they deliver significant electricity bill savings for residential houses in Greece (38%) under current conditions, while they may not be sufficiently attractive for residential houses in Denmark (6.5%) due to mainly the different PV regulatory schemes. Based on these findings, we therefore recommend investors interested in renewable energy technologies to pursue scaling up the manufacturing capacity of OPV technologies, as well as assess a large number of countries to identify and prioritise financially attractive settings for PV self-consumption.

Keywords: organic photovoltaics; self-consumption; net-metering; cost optimization

1. Introduction

Solar photovoltaics (PV) are seen globally as one of the most promising technologies in the race again climate change [1]. In the European context, PV systems are expected to play a key role in improving the energy performance of the building sector (Directive 2012/27/EU) despite the operation management challenges associated with large-scale penetration of renewable energy sources at residential [2] and industrial level [3], the integration of energy storage and electric vehicles [4], and load management by active end users [5].

In recent years, continuously declining PV module costs, in combination with rising residential electricity prices and fading feed-in tariffs, have made self-consumption of PV-generated electricity financially more attractive than exporting to the grid [6–8]. Nevertheless, PV-generated electricity costs are still not low enough to compete on the electricity market, but depend on state support through self-consumption and net-metering schemes [7]. If PV are to compete on the market against established electricity generation technologies, like fossils or wind power, further cost reductions are thus needed. Following these trends, a growing number of recent studies in the literature has been assessing the self-consumption of PV-generated electricity and its economics, as in PV only systems or in combination with battery storage (see review by Luthander [9]) [10–15].

Organic photovoltaics (OPV) are an emerging thin-film PV technology that shows promise of greatly improving the environmental and economic performance of PV technologies [16]. OPV utilize abundant, non-toxic organic molecules or polymer materials to absorb light and convert it to electricity [17], and are typically built in multiple layers that are deposited on plastic foil by low energy and high-throughput printing and coating techniques (see reviews by Krebs [18] and by Wang et al. [19]). Applications of OPV technologies have been demonstrated by previous studies, for example a pilot-scale OPV solar park installed in Denmark [20,21] and a portable solar charger, HeLi-

on [22]. In terms of environmental impact assessment, OPV technologies have shown the potential to lower life-cycle environmental impacts compared to conventional silicon-based PV technologies, ranging from 32% to 98% depending on the environmental impact category (e.g. climate change, acidification, toxic effects on human and environment, etc.) [23].

Until now, OPV module costs have not been able to compete at market level due to shorter lifetimes and lower power conversion efficiencies. Early studies of OPV economics have focused on preliminary cost estimates [24–26] or have calculated cost targets and financial indicators [27–29] (see summaries of findings by Mulligan et al. [30] and Gambhir et al. [31]). More recent studies have projected commercial-scale production costs based on real data from pilot-scale production [30–33]. More specifically, Machui et al. [32] have estimated that, under an industrial processing scenario, costs of OPV modules could reach 0.05-0.6 €/Wp (depending on achieved efficiency, material choice and structure), thus outperforming conventional PV technologies. Also, Gambhir et al. [31] have showed that at a conservative estimate OPV can have closely comparable levelised cost of electricity (LCOE) values to established PV technologies, while estimates at the more optimistic end showed that OPV costs can be more than 50% lower than costs of established PV technologies [31]. Although previous studies have assessed OPV costs and compared them with costs of established PV technologies, the attractiveness of investing in OPV under real market conditions has not been researched until now. Hence, do OPV technologies offer an attractive investment for households, especially in a context where government support is decreasing and PV regulatory frameworks are gradually transitioning from feed-in-tariff to self-consumption schemes?

The goal of this study is to address this question, and evaluate the competitiveness of current and potential future costs of OPV systems installed on household roofs with a 20-year investment period under the current self-consumption frameworks using Denmark and Greece as case studies. The two countries present an interesting comparison as they offer different contextual settings (e.g. PV

regulatory framework, solar energy availability, renewable energy policy, etc.) as explained later in the paper. Even though the scope of the study has a strong focus on OPV systems, the developed methodology and the detailed analysis of the regulatory and market frameworks for PV are generic and apply to all PV technologies.

2. Methods and materials

2.1. Overall methodology

Figure 1 shows the methodology and the associated steps adopted to assess the cost-competitiveness of OPV self-consumption. These steps are described in the following Sections and can be applied to any national setting. They include:

1. A comprehensive study of the Danish and Greek regulatory frameworks for residential PV installations served as a basis for identifying modelling and data requirements, e.g. PV regulations and possible installation capacity limits, technical specifications of electricity netting, electricity billing and remuneration schemes, etc. (Section 2.2);
2. The modelling of the PV system electricity flows was required to calculate electricity self-consumption, exports and imports between the PV system and the grid (Section 2.3);
3. The electricity bill savings from installing an OPV system were calculated based on current electricity bill tariffs/components and available electricity price projections (Section 2.4);
4. The OPV costs were estimated based on available literature and own assumptions (Section 2.5);
5. The profitability of investing in an OPV system was evaluated based on the Net Present Value (NPV) method and trial-and-error runs (Section 2.6).

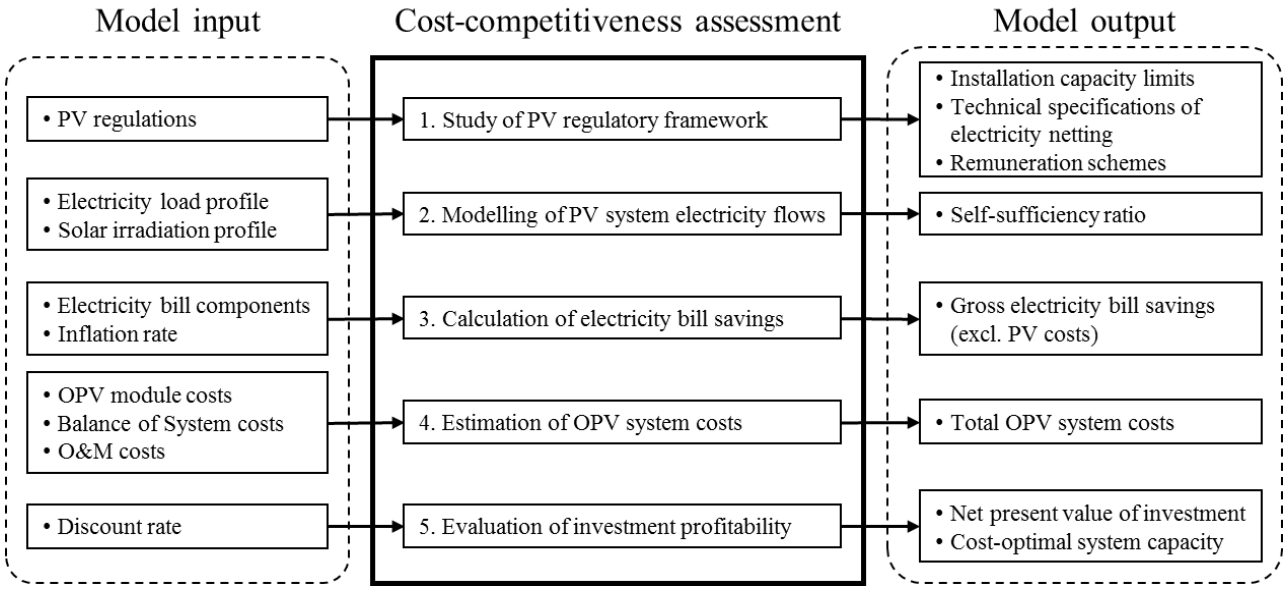

Figure 1. Steps taken and key model input and output to assess the cost-competitiveness of OPV self-consumption in this study

2.2. Danish and Greek regulatory frameworks for PV self-consumption

The two countries offer an interesting comparison due to different contextual settings (e.g. solar energy availability, renewable energy policy, PV regulatory framework, etc.). Denmark is located in northern Europe with relatively low solar energy availability (i.e. 1000 kWh/m^2), whereas Greece is part of southern Europe with abundance of solar energy resources (1700 kWh/m^2). In terms of renewable energy integration, Denmark is one of the leaders in next-generation wind and solar power as well as and energy system transformation according to the International Energy Agency [34]. However, Greece has not yet exploited its great potential for integrating wind and solar power [35].

In terms of PV regulatory framework, Denmark and Greece have relied on attractive feed-in-tariff schemes to support the adoption of PV systems in past years. At present, the focus of PV regulatory frameworks in both countries is to support the installation of PV systems for self-consumption of PV-generated electricity enabling consumers to lower their electricity bill costs. More specifically, net-

metering schemes are in place under which excess generated electricity can be exported to the grid and credited to the consumer for consumption at a different time when PV generation is not sufficient to cover electricity consumption [8]. The time period for netting PV generation and electricity consumption is one hour for Denmark [36] and one year for Greece [37]. In both countries, there is no compensation for excess exported electricity to the grid after netting. In Denmark, the transmission grid operator 'Energinet' is responsible for handling the administrative tasks of PV systems, and provides detailed information and technical guidance to consumers and potential PV owners [36]. In Greece, the distribution grid operator 'HEDNO' (Hellenic Electricity Distribution Network Operator) holds a similar administrative role [38], while the Greek PV regulatory framework has been described previously in the study by Christoforidis et al. [37].

2.3. Modelling of PV system electricity flows

A model was developed to simulate the flows of electricity at an average residential electricity consumer with an OPV installation enabling self-consumption. Time series data sets of electricity consumption and solar irradiation values were created for a typical year and were used as inputs to the model. For the modelling of the electricity flows, the same typical year was assumed and replicated during the 20-year time horizon (2017-2036) of the OPV system model.

For Denmark, the electricity consumption data were modelled based on hourly load profiles from the year 2012 developed by the Danish Energy Association [39], as in the study by Andersen et al. [40]. The solar irradiation profile (annual irradiation level at 1000kWh/m^2) was taken from the Danish Design Reference Year data set representing a typical meteorological year in Denmark and specifically developed for energy-related simulations [41].

For Greece, the electricity consumption data were modelled based on 15-minute load profiles, consisting of average consumption data from a sample of 29 residential consumers located in the Thessaloniki area referring to the year 2014 [37]. The solar irradiation profile (annual irradiation level at 1700kWh/m^2) was taken from EU's Photovoltaic Geographical Information System [42].

Electricity consumption was assumed at 4000kWh/year as representative of one-family households without electrical heating in Denmark [43] and Greece [37]. The solar irradiation data was used to calculate the electricity generation from the OPV system assuming a horizontal-plane installation, a range of installed capacity values between 1 and 10 kWp (typical of residential PV systems) and a 80% performance ratio (PR) [44], as explicated in Equation 1:

$$OPV_{generation} = solar\ irradiation * installed\ capacity * PR \quad \text{(Eq. 1)}$$

To simulate the flows of electricity, the time series data sets of OPV generation and electricity consumption were compared on a time-step basis (hourly for Denmark, 15-min for Greece). In this comparison, two simple rules were followed: (i) if OPV generation was lower than consumption, the deficit was imported by the grid; and (ii) if OPV generation was higher than consumption, the surplus was exported to the grid. Based on this comparison, the total amounts of self-consumed OPV generation as well as electricity imports and exports were calculated over one typical year (i.e. each year within the period 2017-2036).

Moreover, this enabled to calculate the self-sufficiency (SS), which is a commonly used metric to describe how PV generation can cover the electricity needs of the place where it is installed, and is defined as the ratio of the self-consumed PV generation to the electricity consumption over a year [7,9]. In our current study, the scope of self-sufficiency was broadened to offer regulatory and economic perspectives, and covered not only the physically self-consumed PV generation but the

total amount of PV generation equal to electricity consumption within the netting period over a year [8]. Therefore, in this study, self-sufficiency was calculated according to Equation 2:

$$SS = \frac{total\ PV\ generation\ equal\ to\ electricity\ consumption\ during\ the\ netting\ period}{electricity\ consumption} \quad \text{(Eq. 2)}$$

2.4. Calculation of gross electricity bill savings from PV self-consumption

In this step, gross electricity bill savings (i.e. excluding PV system costs) were calculated as the difference in the electricity bill between a household with PV for self-consumption and a household without PV installation over the 20-year investment period. This was a generic calculation and applied to all PV technologies.

The electricity bill components, tariffs and different types of charges are described in Table 1 for Denmark and Table 2 for Greece. As in most European countries, the electricity bill components are divided in:

- electricity supply charges which reflect the electricity generation cost paid to the electricity supply company under competitive market conditions,
- transmission and distribution grid charges corresponding to the cost of using the electricity grid and are paid to the transmission system and the distribution system operators,
- other charges, such as taxes to the state e.g. value added tax, financing renewable energy support schemes, etc.

More specifically, for a household with PV self-consumption in Denmark, all electricity bill components described in Table 1 (for a detailed description, see the report by Kitzing et al.[45]) were calculated based on the net electricity imports except for the feed-in charge (based on the net electricity exports), the distribution grid tariff (based on the gross electricity imports) and the reduced

Public Service Obligations (PSO) tariff (based on the self-consumption). Also, after the initial year 2017, all tariffs and charges in Denmark were assumed to increase by 1.97% annually following the inflation rate [46] unless specified otherwise (estimated inflation rate at 1.97% [47]).

For a household in Greece (for a detailed description, see study by Christoforidis et al. [37]), the 'Special Duty' was calculated based on the total charges (before VAT) excluding the 'Special Duty for Renewables', and the VAT was calculated based on the total charges excluding the 'Special Duty'. In the case of PV self-consumption, the electricity tariff was calculated based on the net electricity imports, the Services of General Interest was calculated based on the total electricity consumption (i.e. 4000kWh/year), while all other charges were calculated based on the gross electricity imports. Moreover, after the initial year 2017, all tariffs and charges in Greece were assumed to increase annually following the inflation rate (assumed inflation rate at 2%) except for the 'Other Charges', as in earlier studies [37].

Table 1. Electricity bill components, tariffs and fees for residential electricity consumers with/without PV self-consumption in Denmark over the investment period of 2017-2036 (1 DKK=0.13 EUR).

Electricity bill components	**Tariffs/fees in 2017**	**Tariff/fees between 2018-2036**
Electricity supply charges		
Subscription fee	3.02 €/month [48]	annual increase by 1.97% following inflation
Electricity spot price	0.0248 €/kWh [46]	Spot prices projection by DEA [46]
Mark-up	0.00798 €/kWh (calculated as the difference between the retail electricity price [48] and the spot price [46]	annual increase by 1.97% following inflation

Transmission and distribution grid charges		
Transmission grid tariff	0.0108 €/kWh [49]	annual increase by 1.97% following inflation
Distribution grid tariff	0.0403 €/kWh [50]	annual increase by 1.97% following inflation
Distribution grid subscription fee	4.03 €/month [50]	annual increase by 1.97% following inflation
Public Service Obligations (PSO) tariff	0.021 €/kWh [49]	annual decrease by 0.004186 €/kWh (20% of 2017 value) and phased out by Jan 1st 2022
Electricity tax	0.118 €/kWh [49]	annual increase by 1.97% following inflation
Value Added Tax (VAT)	25%	25%
Additional charges for PV self-consumption		
Feed-in charge	0.000390 €/kWh [49]	annual increase by 1.97% following inflation
Availability payment	0.728 €/month [49]	annual increase by 1.97% following inflation
Reduced PSO tariff	0.00039 €/kWh [49]	annual decrease by 0.000078 €/kWh (20% of 2017 value) and phased out by Jan 1st 2022

Table 2. Electricity bill components, tariffs and fees for residential electricity consumers with/without PV self-consumption in Greece over the investment period of 2017-2036. A typical 3-phase electricity connection was assumed with a 25kVA capacity.

Electricity bill components	**Tariffs/fees in 2017**	**Tariff/fees between 2018-2036**
Electricity supply charges		
Subscription fee	4.80 €/quarter [51]	annual increase by 2% following inflation
Electricity tariff	0.0946 €/kWh [51]	annual increase by 2% following inflation
Regulated charges		
Transmission grid fee	0.13 €/kVA/year [51]	annual increase by 2% following inflation

Transmission grid tariff	0.00527 €/kWh [51]	annual increase by 2% following inflation
Distribution grid fee	0.54 €/kVA/year [51]	annual increase by 2% following inflation
Distribution grid tariff	0.0213 €/kWh [51]	annual increase by 2% following inflation
Services of General Interest	0.00699 €/kWh [51]	annual increase by 2% following inflation
Special Duty for Renewables	0.02477 €/kWh [51]	annual increase by 2% following inflation
Other Charges	0.00007 €/kWh [51]	0.00007 €/kWh [37]
Duties and Taxes		
Special Consumer Tax	0.0022 €/kWh [51]	annual increase by 2% following inflation
Special Duty	0.5% [51]	0.5%
Value added tax	13%	13%

2.5. OPV system cost scenarios

The lifetime costs of the OPV systems were calculated based on the cost analyses by Machui et al. [32] and Gambhir et al. [31] and complemented by additional assumptions – see Table 3. Following the approach by Machui et al. [32], three manufacturing capacity levels were considered for estimating OPV module costs: (i) a pilot-scale cost analysis with actual process data based on a kW-range OPV manufacturing capacity level; (ii) a scale-up cost projection estimating module costs based on a 100 MW OPV manufacturing capacity level; and (iii) an industrial-scale cost projection estimating module costs based on a 100 GW OPV manufacturing capacity level. In terms of OPV module types, single devices based on P3HT:PCBM active layer materials were considered for the pilot-scale scenario [32] and MH301:PCBM with carbon electrodes for the scale-up scenario and industrial-scale scenarios [32]. The values for the OPV cell efficiency and module lifetime were based on own assumptions albeit within the ranges of Machui et al. [32]: 3.5% and 5 years (pilot-scale), 5%

and 5 years (scale-up), and 10% and 10 years (industrial-scale). Since the assumed OPV module lifetimes were actually shorter (5/10 years) than the system lifetime (20 years), re-installations were considered as follows: three re-installations for the pilot-scale and scale-up production levels and one re-installation for the industrial production level. For the re-installations, the same module costs were considered taking a conservative approach and assuming no learning curve. In these settings, total OPV costs over the lifetime of the systems were calculated as the sum of (i) module costs, (ii) balance of system costs, (iii) installation/re-installation costs and (iv) operation and maintenance costs: 13.42 €/Wp, 2.72 €/Wp and 1.53 €/Wp for the pilot-scale, the scale-up and the industrial-scale production levels respectively.

Table 3. OPV cost projections based on manufacturing capacity levels: pilot-scale (current state at kW-range capacity), scale-up (at 100 MW capacity), and industrial-scale (at 100 GW capacity). Cell efficiency and module lifetime values were based on own assumptions.

Costs and parameters	**Pilot-scale production**	**Scale-up production**	**Industrial-scale production**
Module cost	33.74 €/m^2 [32]	6.52 €/m^2 [32]	5.16 €/m^2 [32]
Device architecture (active layer materials)	Single device (P3HT:PCBM) [32]	Single device with carbon electrodes (MH301:PCBM) [32]	Single device with carbon electrodes (MH301:PCBM) [32]
Cell efficiency	3.5%	5%	10%
Fill factor (FF)	37% [32]	75% [32]	98% [32]
Module lifetime	5 years	5 years	10 years
Module cost	2.61 €/Wp [32]	0.17 €/Wp [32]	0.05 €/Wp [32]

Balance of system cost	0.6 $/Wp [31]		
Balance of System (BoS) lifetime	20 years [31]		
Installation/re-installation cost	0.51/0.26 $/Wp [31]		
Operation & maintenance service	0.5% of modules and BoS costs per year [31]		
System lifetime	20 years		
Total OPV system costs	13.42 €/Wp	2.72 €/Wp	1.53 €/Wp

2.6. Investment profitability of OPV self-consumption

To assess the cost-competitiveness of OPV, the Net Present Value (NPV) method was used [52]. In finance, the NPV is a method for evaluating the profitability of an investment by netting the present value of future cash inflows (revenues) and cash outflows (costs) over the period of the investment [52]. In this study, the NPV of investing in an OPV system was calculated based on the initial capital cost of acquiring and installing the OPV system, and the cash inflows achieved by the annual electricity bill savings during the 20-year lifetime of the OPV system, given by Eq. (3).

$$Net\ Present\ Value = \sum_{year=1}^{20} \frac{electricity\ bill\ savings_{year}}{1-real\ discount\ rate^{year}} - OPV\ system\ costs \quad \text{(Eq. 3)}$$

The real discount rate was calculated based on Eq. (4) assuming a 5% nominal discount rate and the estimated inflation rate over the period of the investment. The inflation rate was taken at 1.97% for Denmark [47] and assumed to be similar and equal to 2% for Greece [37].

$$real\ discount\ rate = \frac{nominal\ discount\ rate - inflation\ rate}{1+inflation\ rate} \quad \text{(Eq. 4)}$$

If the NPV result was positive, the investment would be profitable, and if otherwise, it would result in a loss. After calculating the NPV of OPV systems for a range of 1-10kWp capacities, the optimal investment solution was given by the highest (positive) NPV result.

2.7. Further analysis

An additional prospective analysis was conducted to investigate the extent to which current trends in electricity prices will affect the cost-competitiveness of OPV in the following five years. In this prospective analysis that applies to all PV technologies, gross electricity bill savings (i.e. excluding PV system costs) for a 1kW PV system for self-consumption were calculated assuming the installation takes place in 2022 (instead of 2017) with a 20-year investment period up to 2041, under the existing regulatory frameworks in Denmark and Greece. The electricity tariff/fee trends described in Tables 1 and 2 for the period up to 2036 were extended to 2041.

3. Results and discussion

3.1. Self-sufficiency of residential PV systems installed in Denmark and Greece

Figure 2 shows the self-sufficiency ratios obtained for a residential PV system operating under the existing regulatory frameworks and installed either in Denmark (i.e. termed scenario DK1) or in Greece (i.e. scenario GR1). Depending on PV capacity, the self-sufficiency ratios range from 19% to 44% for Denmark, and from 34% to 100% for Greece. The large differences in shape and magnitude of the two self-sufficiency curves in Figure 2 mainly reflect the different PV regulatory frameworks of the two countries and more specifically the different period for netting PV generation and

electricity consumption, i.e. hourly netting in Denmark compared to annual netting in Greece. To investigate the impact of the different netting periods, we calculated the self-sufficiency curve by simulating a hypothetical setting of a 15-min netting period in Greece (i.e. scenario GR2) – see Figure 2). In this hypothetical situation, the self-sufficiency curve for GR2 ranges from 27% to 50%, showing a trend similar to the curve for DK1, and significantly lower compared to the curve for the GR1 existing annual net-metering, thus confirming the significant influence of the net-metering framework.

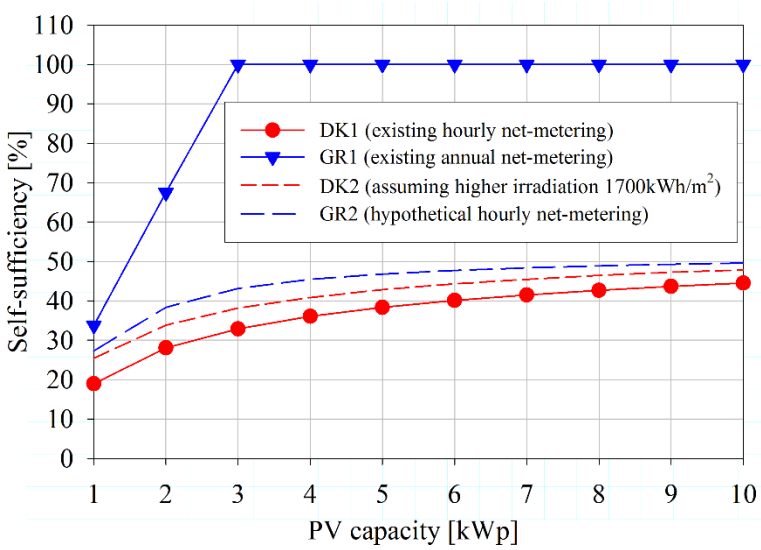

Figure 2. Self-sufficiency potential of residential PV systems with a 4,000kWh/y electricity consumption in Denmark and Greece.

Similar results have been found in the literature. For example, Quoilin et al. [12] calculated the self-sufficiency of residential PV systems installed at several European countries with a 15-min netting period, and reported average self-sufficiency ratios of about 32% for Denmark, 35% for Greece, and ranging between 30% and 37 for all six countries (including Romania, Italy, Portugal and France) considered in their study. However, Quoilin et al. only considered systems with a ratio

of annual PV generation to annual consumption of 1:1, instead of calculating the self-sufficiency of residential consumers for a range of PV capacities as conducted in this analysis. To offer comparison with this study, such PV systems (i.e. with an annual PV generation to annual consumption ratio at 1:1) correspond to a self-sufficiency value of 39% at a 4.8 kWp capacity for DK1 and 43% at a 3kWp capacity for GR2 (a direct comparison with the self-sufficiency performance of a PV system calculated based on the existing annual netting period in Greece would be unfit as explained above). Therefore, there is a relatively good agreement between our results and those previously found by Quoilin et al., albeit with a narrower scope.

3.2. Key influential factors of PV self-sufficiency performance

Self-sufficiency performances of PV systems can vary significantly depending on the geographical location because of differences in solar irradiation levels and electricity consumption behaviours/patterns [9,12,13]. Previous studies have recommended that more comparable studies are needed to identify similarities and differences and allow application of results to other situations than the studied ones [9,12,13]. In our study, three key influential factors were identified: (i) the PV regulatory framework, (ii) the solar irradiation level, and (iii) the electricity consumption profile. We recommend that these factors be systematically characterised and reported along with self-sufficiency results to allow for comparability and further application of the self-sufficiency results (see examples of Greece and Denmark in Table 4).

As described in Section 3.1, the PV regulatory framework can significantly alter the self-sufficiency curves (e.g. see scenarios GR1 and GR2 in Figure 2). To explore the influence of solar irradiation, on PV self-sufficiency results, the self-sufficiency curve for Denmark (i.e. scenario DK1) was recalculated with the assumption that Denmark's solar irradiation was similar to that of Greece

(i.e. 1700kWh/m^2 instead of 1000kWh/m^2; scenario DK2 in Figure 2). This simulation showed that self-sufficiency results for DK2 would be higher than those for DK1 by 3.3 to 6.5 percentage points (Figure 2), thus indicating a relatively low influence. Finally, the influence of the electricity consumption profiles can be observed in Figure 2 by comparing the self-sufficiency curves of DK2 and GR2 (same solar irradiation at 1700 kWh/m^2 and comparable net-metering). The comparison shows that the curve for GR2 demonstrates higher self-sufficiency results than DK2 by about 2 to 5 percentage points, indicating a better match between solar irradiation and the residential electricity consumption in Greece than in Denmark. This is similar to the findings obtained in Denmark when assessing the influence of the electricity consumption profiles on self-sufficiency results of residential, commercial and industrial consumers [53].

Table 4. Characterisation of the base scenarios in Denmark and Greece (DK1 and GR1) with respect to the identified key factors influencing PV self-sufficiency.

Self-sufficiency and key influential factors		DK1	GR1
Regulatory framework		Net-metering (hourly)	Net-metering (annual)
Solar irradiation level [kWh/m2/y]		1000	1700
Electricity consumption profile		Residential 4,000kWh/y	Residential 4,000kWh/y
Self-sufficiency [%]	1kWp	19	34
	2kWp	28	67
	3kWp	33	100
	4kWp	36	100
	5kWp	38	100
	6kWp	40	100
	7kWp	41	100

8kWp	43	100
9kWp	44	100
10kWp	44	100

3.3. Gross electricity bill savings from PV self-consumption

This section presents gross electricity bill savings (i.e. excluding PV system costs) from PV self-consumption in Denmark and Greece thus offering a technology-neutral perspective. Figure 3 shows the results calculated as the ratio of the NPV of electricity bill savings excluding PV system costs to the NPV of the electricity bill costs over the period 2017-2036 (see Figure A1 in Appendix for absolute values of NPV of electricity bill savings in euros). As illustrated in Figure 3, gross electricity bill savings from residential PV systems reach 75% in Greece and 32% in Denmark for a 10kWp PV system. The differences in shape and magnitude of the bill savings curves in Figure 3 can mainly be attributed to the different PV regulatory frameworks of the two countries along with different solar irradiation levels and electricity consumption profiles (see Section 3.2). The comparative analysis of the two countries suggests that Greece offers a financially more attractive market for both residential PV owners and PV manufactures/suppliers than Denmark. Therefore, for emerging PV technologies such as OPV, Greece seems to offer an easier market to enter than Denmark.

Our results can be compared to previous findings from the literature. Figure 3 shows adapted results of PV revenues for Belgium, Germany, Italy, Spain and France retrieved from De Boeck et al. [15], with 2014 as the base year of the investment. To allow comparability with the results in our study, the NPVs of PV revenues for those five countries were calculated based on the original data in De Boeck et al. [15] with the assumptions of a 3% inflation rate and a 2% real discount rate. The results obtained for Denmark and Greece are in the same level as the adapted results from De Boeck

[15] for Spain and Germany, but much lower than results for Belgium, Italy and France. This is because all countries but Spain in De Boeck et al. [15] had PV regulatory schemes with subsidies and/or net-metering allowing for remuneration of excess exported electricity, thus bill savings higher than 100% could be achieved.

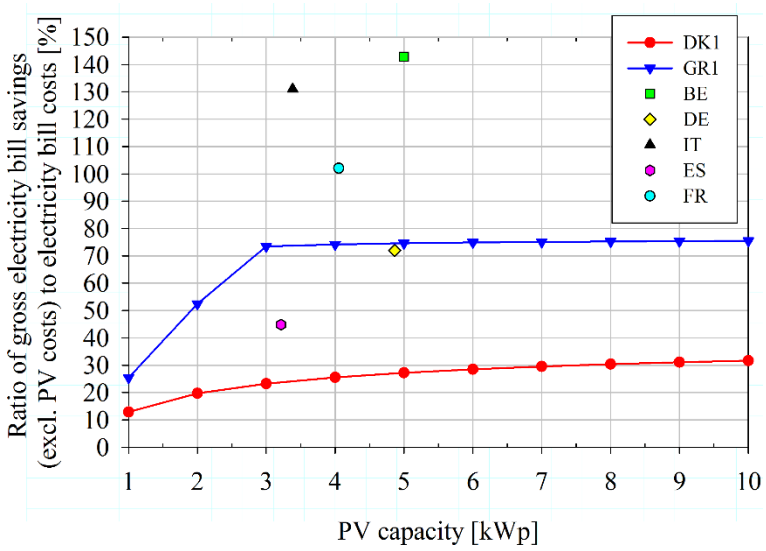

Figure 3. Ratio of gross electricity bill savings (i.e. excluding PV investment costs) to electricity bill costs over the investment period 2017-2036. DK1 and GR1 curves refer to Denmark and Greece investigated in our study; comparative results for BE (Belgium), DE (Germany), IT (Italy), ES (Spain), and FR (France) are adapted from De Boeck et al. [15].

3.4. Cost-competitiveness of OPV systems for self-consumption

Figure 4 plots the calculated profitability of investing in an OPV system in Denmark and Greece for residential consumers with annual electricity consumption of 4,000kWh based for each of the three OPV cost levels (see definitions in Section 2.5). As illustrated in Figure 4a, the NPV results based on the pilot-scale OPV cost level show negative values for both Greece and Denmark regardless

of the OPV capacity, thus indicating that an OPV total system cost of 13.42 €/Wp would be economically unviable to invest in OPV in Denmark or Greece.

In contrast, Figure 4b shows some sensibly positive results for both Greece and Denmark. The highest NPV result point of each curve indicates the optimal investment solution for that case. For Denmark, the optimal investment solution was achieved by a 1kWp OPV system with a 120€ NPV achieving a 0.55% electricity bill reduction. For Greece, the optimal investment solution was achieved by a 2.5kWp OPV system with a 1504€ NPV achieving a 12% electricity bill reduction. These results suggest that investing in OPV with a total system cost of 2.72 €/Wp, would offer marginal benefits in Denmark but significantly higher gains in Greece.

The industrial-scale setting, as described in Figure 4c, increases the benefits for both countries. For Denmark, the optimal investment solution is achieved by a 1.5kWp OPV system with a 1432€ NPV, now reaching a 6.5% electricity bill reduction. For Greece, the optimal investment solution is achieved by a 3kWp OPV system with a 5014€ NPV reaching a 38% electricity bill reduction. Therefore, the above results indicate that installing an OPV system with a total system cost of 1.53 €/Wp could offer an attractive investment for residential buildings in Greece achieving a electricity bill reduction of over 35%, but not in Denmark where an electricity bill reduction of about 7% might not be considered sufficiently attractive.

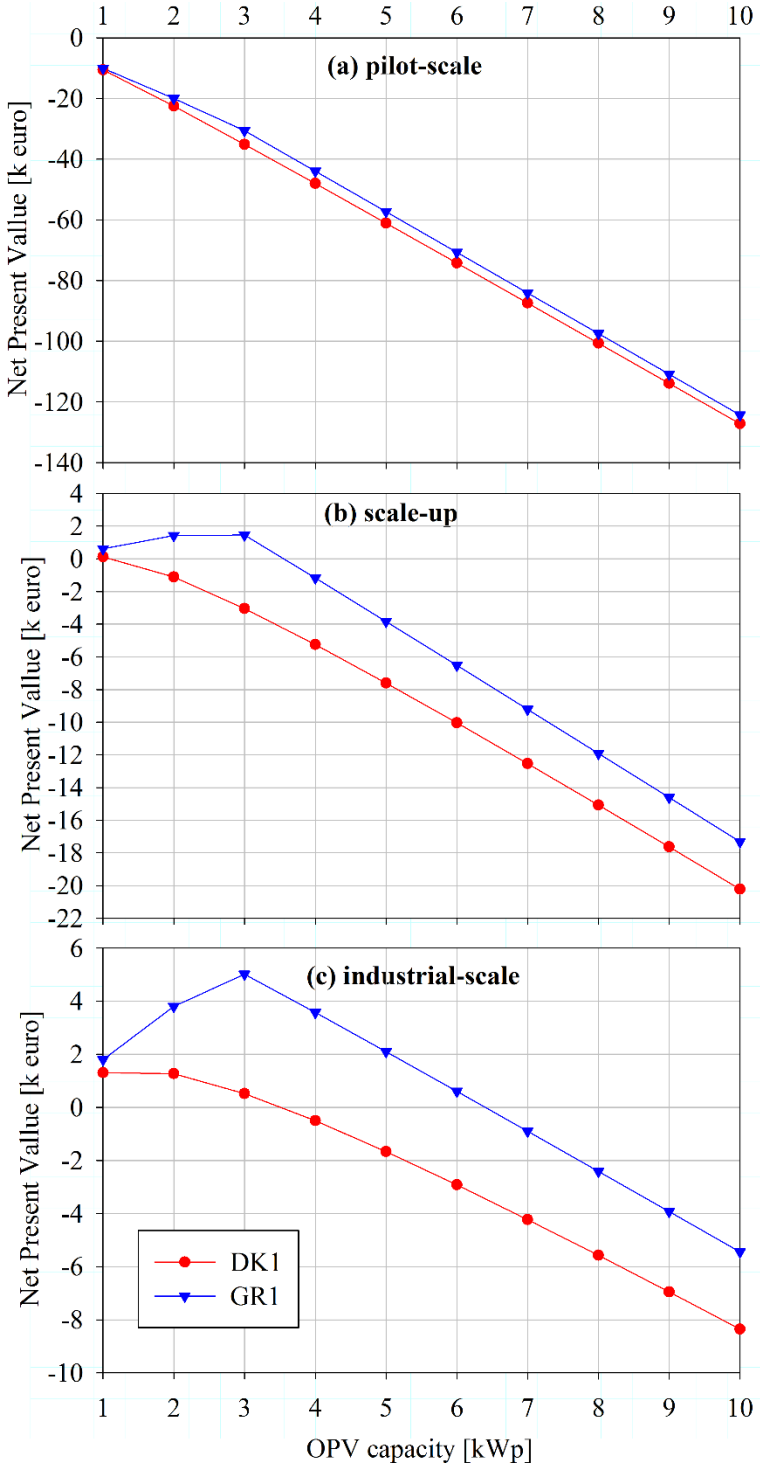

Figure 4. Net present value of OPV self-consumption in Denmark (DK1) and Greece for (GR1) according to the (a) the pilot-scale, (b) the scale-up, and (c) the industrial cost projections (see definitions in Section 2.5 and Table 3).

3.5. Target costing for PV

Our methodology was further used from a target costing perspective to determine the required total PV system costs, for which the installed system would achieve a range of electricity bill reductions under current market conditions (e.g. in Denmark or Greece). The results of this target costing approach are relevant to all PV technologies, and not only to OPV.

Figure 5 shows applications of such target costing to Greece and Denmark: DK1 and GR1 curves show the total system costs (left axis) that PV technologies need to reach as a function of the desired electricity bill reduction (horizontal axis). Greece can be observed to offer a more attractive investment environment for residential PV self-consumption than Denmark. For example, the break-even costs (i.e. at 0% electricity bill reduction in Figure 5) for PV systems installed in Denmark and Greece were found at 2.83 €/kWp and 3.57 €/kWp respectively. Overall, PV costs for systems installed in Denmark would thus need to be 80% lower on average than systems installed in Greece to achieve the same level of electricity bill reduction.

Specifically to OPV technologies, the three OPV cost levels of the pilot-scale (13.42 €/kWp), the scale-up (2.72 €/kWp) and the industrial-scale (1.53 €/kWp) scenarios are included in Figure 5 to allow comparison with the DK1 and GR1 curves. By comparing the pilot-scale OPV cost level (assuming it reflects the current status of the technology) with the DK1 and GR1 curves at a desired electricity bill reduction value, the required cost improvements can be identified. Moreover, the intersection points between the up-scale and industrial-scale OPV cost levels and the DK1 and GR1 curves correspond to the optimal investment solutions found in Section 3.4.

In addition to the PV costs, Figure 5 presents the PV system capacities (right axis) that correspond to the specific electricity bill reductions to enable consideration of installation area requirements, which are more relevant to PV technologies with lower power conversion efficiencies such as OPV.

For example, for Denmark, a 30% electricity bill reduction could be achieved by a 16.5kWp PV system, which would however require a roof space as large as 168m^2 assuming a 9.8% OPV module efficiency (e.g. calculated based on cell efficiency at 10% and fill factor at 98%). However, in the case of Greece, electricity bill reductions of up to 50% could be achieved by up to 3kWp PV systems, equivalent to a roof space requirement of 36m^2, thus indicating no serious constraints for OPV systems with an indicative 9.8% module efficiency.

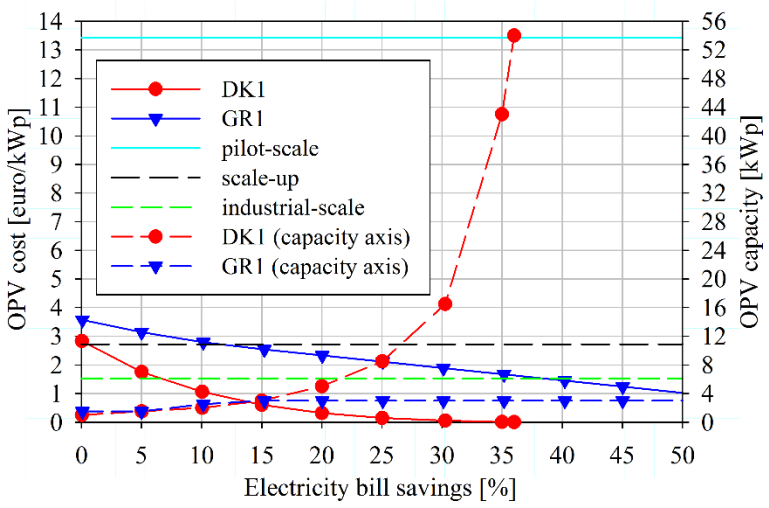

Figure 5. Total PV system costs for which a range of electricity bill savings could be achieved under current market conditions in Denmark (DK1) and Greece (GR1). The pilot-scale, scale-up and industrial-scale OPV cost levels are included for benchmarking.

3.6. Prospective analysis

The extent to which current trends in electricity prices will affect the cost-competitiveness of OPV in the following five years were assessed. The evaluation beyond this 5-year period was deemed too uncertain. The period 2017-2022 was investigated assuming no change in the current Danish and

Greek regulatory frameworks for PV. Using the electricity price projections and assumptions (see Table 1 and 2), gross electricity bill savings for a 1kW PV system for self-consumption were calculated assuming the installation takes place in 2022 instead of 2017. For Denmark, in 2022, gross electricity bill savings based on a 1kW PV system for self-consumption were found to vary less than 0.5% compared to savings in 2017; for Greece, savings vary less than 1.5% compared to savings in 2017. These results demonstrate that, under the current regulatory frameworks, the profit margins and, consequently, the break-even costs, of residential OPV systems for self-consumption are expected to vary marginally until 2022 based on current price projections.

4. Conclusions and recommendations

This study assesses the self-consumption of electricity generation from conventional and organic PV systems installed at residential houses in two European countries as indicative case studies, Denmark and Greece. The results show that Greece performs better than Denmark in terms of the self-sufficiency ratio, primarily due to a more favourable PV regulatory scheme, and secondarily due to different solar irradiation levels and the temporal match between the electricity consumption and solar irradiation. Our analysis indicates that the PV self-consumption performance of a given country can vary significantly depending on these three key influential factors: PV regulatory framework, solar irradiation, and, electricity consumption profile. Therefore, when investigating PV self-consumption, researchers are encouraged to produce new studies with location-specific data rather than rely on already existing studies with assumed similar geographical and policy contexts. Our developed methodology, fully described in Section 2, should be used in this effort, and be applied to other countries by adapting the country- and policy-specific input data.

The economic analysis of PV self-consumption at residential houses, using the current Danish and Greek PV regulatory schemes as examples, shows that Greece offers a significantly higher profit margin than Denmark, calculated as gross electricity bill savings (i.e. excluding PV costs). This demonstrates that PV technology developers should carefully assess a wide range of countries to identify and prioritise financially attractive environments.

Specifically to OPV technologies, our study evaluates whether OPV systems can offer a profitable investment for households based on electricity self-consumption. The results show that OPV systems developed under an industrial-scale cost setting (1.53 €/kWp) deliver significant electricity bill savings for residential houses in Greece (38%), whereas these were relatively limited for Danish households (6.5%), hence likely rendering OPV systems insufficiently attractive for residential houses in Denmark. Therefore, OPV technologies can offer a profitable business opportunity in specific locations, and investors in the renewable energy sector are thus encouraged to pursue scaling up the manufacturing capacity of OPV technologies.

Although not addressed in this work, future similar studies on residential PV systems should further explore how the combination of the PV system with other systems and add-on components, such as battery storage, electric vehicles and heat pumps, may influence the economic profile of the overall energy system of the household. Moreover, moving towards sustainable energy systems, studies should assess the environmental impacts of electricity self-consumption from residential PV systems with battery storage capacity. Most importantly, studies should evaluate whether the addition of battery storage, while necessary to increase utilisation of renewable energy, may contribute to reduction of environmental impacts or not.

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Appendix

Table A1. NPV of gross electricity bill savings (i.e. excluding PV costs) from PV self-consumption in Denmark and Greece for the period 2017-2036.

PV capacity [kWp]	**NPV of gross savings in DK [euro]**	**NPV of gross savings in GR [euro]**
1	2840	3331
2	4332	6864
3	5114	9611

4	5627	9707
5	5993	9762
6	6275	9799
7	6499	9826
8	6685	9848
9	6838	9864
10	6970	9877