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# Non-price criteria in renewable energy auctions and consequences for the European solar PV industry

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**Abstract**

The Net Zero Industry Act (NZIA) promotes non-price criteria in renewable auctions. It aims to unlock green willingness-to-pay and scale up manufacturing capacity for net-zero technologies in the European Union (EU). This paper builds a partial equilibrium model of the European solar module sector and investigates how renewable auction design impacts solar photovoltaic (PV) manufacturing. First, a formal analysis evaluates the complementarities between the different non-price criteria. Most notably, we find that if local manufacturing development is aligned with climate goals, then non-price criteria in solar auctions do not necessarily increase costs to consumers. Then, a numerical simulation estimates solar module production in 2030 based on NZIA targets, considering various degrees of market integration within the EU. The results show that market fragmentation can inhibit economies of scale and thus increase solar PV manufacturing costs by €2 billion per year. The development of a common framework for the implementation of non-price criteria at the country level is a no-regret solution. Leveraging the common European market with an integrated policy approach represents the first-best strategy. Forming coalitions of willing Member States is a second-best strategy that can significantly reduce fragmentation costs.

*Keywords:* renewable auction, non-price criteria, market integration, photovoltaics, solar modules
JEL-Codes: L51, L52, L60, Q27, Q40

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## 1. Introduction

The Net Zero Industry Act (NZIA) is the European answer to the global competition for green technologies. The regulatory framework sets ambitious goals for the development of industries critical to decarbonise the European Union (EU). As part of this, the NZIA identifies the solar photovoltaic (PV) sector as strategic to European supply and aims to meet 40% of the demand with domestic products in 2030 (European Parliament and the Council, 2024). This strategic vision encompasses the development of 30 GW of manufacturing capacity across the solar PV supply chain (ESIA, 2022). In Europe, the production costs of solar PV modules range from 0.25 to 0.30 €/W (ETIP Photovoltaic, 2024). However, prices in the solar PV sector are at an all-time low. In 2025, modules are traded between 0.05 €/W and 0.15 €/W on European markets (PVxchange 2025). Such conditions do not provide sufficient incentives to trigger investments. Therefore, additional support is needed to meet the NZIA targets. To this effect, the NZIA set guidelines for the development of non-price criteria in renewable auctions.

Renewable auctions are currently one of the main vehicles to develop the electricity production from renewable energy sources (Anatolitis et al., 2025). The government or a public authority offers, in a competitive bidding process, a fixed quantity (e.g., in MW) of a financial derivative that ensures a stable price for renewable electricity generation over a fixed period of time. Renewable project developers then submit bids based on the minimum price at which they can supply electricity. In addition to the price, additional scoring criteria can be considered. Ultimately, bids are ranked in descending order of points awarded, and the winners secure a contract that guarantees revenue from electricity production.

Within the NZIA, non-price criteria look to favour projects with higher standards for environmental sustainability, resilience, system integration, and innovation. This framework incentivises tender selection on a basis increasingly distant from the cost minimisation principle, requiring a priori a higher budget to clear the auction. However, the impact of green criteria in public procurement on firms remains unclear. For instance, empirical evidence from green public procurements in the United States shows that they can have a positive and lasting effect on the economic performance of winning firms (Chiappinelli et al, 2025). In particular, the latter firms display increased labour productivity, which can help reduce the trade-off between environmental sustainability and costs over the long term.

In addition to unlocking green willingness-to-pay, the stated goal of the NZIA is to establish the conditions for the reshoring of the European solar PV supply chain. To this aim, the resilience criterion favour tenders whose products do not come from a dominant supply source. To secure the business case for manufacturing investments in net-zero technologies, some proposals even advocate for granting straightforward bonuses for "made-in-Europe" products in solar auctions (SPE, 2025). In any case, such measures would also impose additional financial burdens on European consumers, as global value chains enabled large cost reduction in the solar sector. From 2008 to 2020, the globalised PV module market saved the US $24 billion, Germany $7 billion and China $36 billion (Helveston et al., 2022). Additionally, empirical estimates from Indian solar auctions indicate that local content requirements have detrimental effects on competition by reducing market size, whereas their impact on learning-by-doing is limited (Münch and Scheifele, 2023). In this context, the resilience objective appears to conflict with a cost-minimisation perspective.

The NZIA takes place in a global context marked by growing trade and geopolitical fragmentation. However, the NZIA risks reinforcing this dynamic within the EU. The regulatory framework aims to develop non-price criteria in at least 30% of national renewable auctions in Europe, or alternatively 6 GW per year and per country, but does not propose a common funding strategy at the EU level (European Parliament and the Council, 2024). The actual implementation of the NZIA at the national level is the responsibility of the Member States. As public incentives only come from national State aid, this creates a risk of national demands misalignment. The fragmentation threat becomes more acute as Member States with greater fiscal space could decide to pursue their own green industrial policy (Veugelers et al., 2024). In the worst case, this could lead to auction designs implicitly favouring national champions, further widening the mismatch between national strategies and European interests. Instead of promoting healthy competition among European countries, the NZIA could cause a detrimental nurturing of national industries. Such misuse of the European scale would further undermine the EU's competitiveness and penalise consumers (European Commission, 2024).

In this context of global fragmentation, the European economic policy and the NZIA pursue three objectives: efficiency, environmental sustainability and resilience. However, the potential complementarities and contradictions between these objectives remain unclear in the economic literature. Therefore, the goal of this study is to evaluate the potential trade-offs among these three objectives when designing non-price criteria for renewable auctions and to assess how market integration can help mitigate them. This work contributes to the literature on renewable auctions and green public procurements. It provides analytical and quantitative results on the impact that auction design can have on the industrial output of net-zero technologies. These findings then lay the foundation for clear policy recommendations.

In particular, this study develops a partial equilibrium model of the solar PV module manufacturing sector. The model emulates the demand for solar PV modules stemming from renewable auctions and evaluates the impact of auction design on industrial output. First, a formal analysis evaluates the complementarity between price and carbon content criteria. It shows that accounting for carbon emissions does not necessarily induce higher costs. Firms that lag behind on the carbon score must reduce their price bids to stay competitive, thereby lowering the average price consumers ultimately pay. This analysis also demonstrates how national preference divergence, for instance, exacerbated by local content requirements, can impact global supply cost. From a policy perspective, these results indicate that the development of local content criteria and domestic manufacturing must align with a broader climate strategy to avoid additional losses. Then, a numerical simulation estimates European solar PV production in 2030 based on NZIA targets, considering various degrees of market integration. The results show that market fragmentation can increase manufacturing costs by €2 billion per year. Moreover, heterogeneous demand incentivises solar module production to conform to the preferences of countries with large domestic markets, raising both fairness and competition concerns. Such concerns only worsen with lower ambition for the European solar PV sector, as the potential gains from economies of scale become more critical. Considering groups of countries with homogeneous auction designs, limits fragmentation costs to €370 million when coalition sizes amount to 5 GW. These results highlight the benefits of developing a common framework that aligns national demands and coordinates the implementation, at the country level, of the non-price criteria promoted by the NZIA. Cooperation at the EU-level yields the most benefits. However, reduced coordination among willing Member States provides a pragmatic second-best solution that significantly decreases market fragmentation costs.

The remainder of this paper is organised as follows. Section 2 provides an overview of the literature related to renewable auctions and green public procurements. Section 3 describes the analytical model and draws preliminary formal results. Section 4 presents and discusses the numerical results. Finally, section 5 concludes with policy recommendations.

## 2. Litterature review

This paper builds on two areas of economic research. First, it complements the literature on renewable auction design and its impact on net-zero industries. Then, on a broader level, it also engages with research on green public procurement. Each of these areas will be reviewed successively in the present section to highlight the paper´s contribution.

The literature on renewable auctions can be divided into two parts. The first part excludes the manufacturing sector from the scope of the analysis. Topics of interest in this branch of the literature encompass the optimal geographical scope of renewable auctions (Bichler et al., 2020; Kröger et al., 2022; Thomaßen and Fuhrmanek, 2025), the impact of auction design on financing conditions (Anatolitis et al., 2022; Alexander-Haw and Breitschopf, 2024), and multi-technology auctions (Diallo and Kitzing, 2024; Bindal and Abhyankar, 2026).

The second part of the literature includes the manufacturing sector in the scope of analysis. Reviewing renewable auction schemes in different countries, del Rio and Linares (2014) find that historically, auctions showed limited ability to support the manufacturing sector, especially for less mature technologies. The focus on cost-efficiency often discouraged investments in innovation or local manufacturing. Based on a systematic literature review of renewable auctions, del Rio and Kiefer (2023) find similar results, reflecting a clear trade-off between cost-efficiency and the development of local manufacturing. The development of local content criteria helps local manufacturers, but also reduces competition and increases bid prices. Anatolitis et al. (2025) evaluate the influence of auction design on the number and diversity of component manufacturers. The results show that while a higher frequency of auction rounds encourages participation, stringent prequalification requirements may deter smaller manufacturers. Also, multi-technology auctions may favour established technologies, reducing opportunities for newer manufacturers. Alternatively, Münch and Scheifele (2023) conduct an empirical analysis on local content requirements in India and find similar negative effects on innovation and competition. However, the incremental cost is relatively small. Additionally, market size and stability appear to be key components of a successful implementation of local content criteria (Hansen et al., 2020; Eicke, 2025). Finally, Tsany et al. (2024) carry out a systematic literature review of local content policies and find that most studies focus on traditional economic goals (job creation, supply chain development, etc.) but neglect links to sustainability.

However, environmental and economic goals entail interdependencies. On the one hand, environmental regulations have long been associated with higher production costs and lower competitiveness in the manufacturing sector because they introduce additional compliance costs (Palmer et al., 1995; Chan et al., 2013; Dechezleprêtre and Sato, 2017). On the other hand, the Porter hypothesis suggests that environmental regulations can stimulate innovation and improve industry competitiveness, due to efficiency gains, technological advancements, and new market opportunities (Porter and van der Linde, 1995). Although green public procurements fit within the environmental regulatory toolbox, they possess unique and distinctive features. In particular, firms can self-select their participation in the process and can choose not to engage with it. The potential negative impact of green public procurement on firms is therefore limited. Liu et al. (2025) show that firms receiving Chinese public procurement contracts reduce their carbon intensity without affecting firm value. Such an effect occurs in the absence of explicit scoring for green criteria. Testa et al. (2011) show that green public procurement has a positive effect on firms' investment in innovative solutions. Krieger and Zipperer (2022) also found empirical evidence that green public procurement triggers innovation, as firms exhibit a higher probability of introducing new environmentally friendly products. Finally, Chiappinelli et al. (2025) show, using data from the United States, that green public procurement can have a positive effect on both the environmental and economic performance of firms. By fostering competition for green performance among firms, green public procurement incentivises the best-performing firms to push the frontier further, while other companies are encouraged to catch up. Moreover, winning firms exhibit better economic performance, leveraging reduced budgetary constraint, learning-by-doing effects and increased market penetration.

This review identifies gaps in the literature on renewable auctions and green public procurements. The long-term effects of green and local content criteria on manufacturing costs remain unclear in terms of direction and size. Also, while local content criteria in renewable auctions have faced significant scrutiny, their interactions with green criteria have received comparatively little attention. This paper contributes to these two strands of literature by investigating how the non-price criteria proposed by the NZIA can interact to impact cost and competition in the European market.

## 3. Analytical framework

### *3.1. Background*

#### *3.1.1. Preliminary framework for solar PV auction: Project selection*

The analytical framework developed in this study directly builds on the specifications of the French auctions for solar PV facilities and the NZIA (CRE, 2025; European Parliament and the Council, 2024; European Commission, 2025). A detailed decomposition of the scoring system in French solar PV auctions, along with the non-price criteria proposed by the NZIA, can be found in Appendix A.

In particular, bids are selected in decreasing order of their scores. Therefore, the average score per project of the set of winning bids is superior to the average score per project of any selection of bids that respects the constraint defined by the volume of the tender. Let P be the set of bidding projects $\rho$, and $\Pi$ a subset of P. The subset of winning projects of the renewable auction occurring in country $j$ is a solution of the following problem:

$$\max_{\Pi \subset P} \frac{1}{card(\Pi)} \sum_{\rho \in \Pi} \left[ NP_j \frac{p^{sup} - p(\rho)}{p^{sup} - p^{inf}} + NC_j \frac{C^{sup} - C(\rho)}{C^{sup} - C^{inf}} + \sum_{\gamma \in \Gamma} K_j^{\gamma}(\rho) \right] \quad (1)$$

$$s.t. \sum_{\rho \in \Pi} x_\rho = A_j \quad (2)$$

where $x_\rho$ (in MW) is the quantity of solar modules consumed by project $\rho$. $A_j$ (in MW) represents the fixed volume of capacity called in the tender. $p(\rho)$ (in €/MW) and $C(\rho)$ (in $kgCO_2$/MW) reflect respectively the electricity price and carbon footprint of the project $\rho$. $NP_j$ and $NC_j$ denote the maximum score for price and carbon footprint in country $j$. $p^{sup}, p^{inf}, C^{sup}, C^{inf}$ indicate ceiling and floor for, respectively, price and carbon footprint. $\Gamma$ denotes the set of remaining scoring criteria $\gamma$ (e.g., environmental pertinence, governance, etc.). $K_j^{\gamma}(\rho)$ is the score of the project $\rho$ for the criterion $\gamma$ in auction $j$. Finally, card($\Pi$) indicates the number of projects in $\Pi$. Dividing by card(Π) ensures that the choice of winning bids is indifferent to the formal division of a project into smaller but similar subprojects (e.g. in terms of price and carbon footprint).

*3.1.2. Preliminary framework for solar PV auction: Scoring decomposition*

Let us express the electricity prices of a project $p(\rho)$ as the sum of the cost that can be attributed to solar modules $m(\rho)$ and of the cost that can be attributed to the rest of the project $r(\rho)$. Similarly, we can decompose $p^{sup}$ into $m^{sup}$ and $r^{sup}$. We have:

$$p(\rho) = m(\rho) + r(\rho) \tag{3}$$

$$p^{sup} = m^{sup} + r^{sup} \tag{4}$$

Let us partition the set of remaining criteria $\Gamma$ into two sets: one that can be attributed to modules $\Gamma m$ (local content, recyclability, efficiency, etc.) and one that can be attributed to other characteristics of the project $\Gamma r$ (governance, site location, etc.).

$$\Gamma = \Gamma m \cup \Gamma r \tag{5}$$

Also, let us notice that such a decomposition is not necessary for the scoring of the carbon footprint, as this scoring criterion is already limited to solar modules.

In this context, the objective function defined in eq.1 can be expressed as the sum of two components (I) and (II):

$$(I) = \frac{1}{card(\Pi)} \sum_{\rho \in \Pi} \left[ NP_j \frac{m^{sup} - m(\rho)}{p^{sup} - p^{inf}} + NC_j \frac{C^{sup} - C(\rho)}{C^{sup} - C^{inf}} + \sum_{\gamma \in \Gamma m} K_j^{\gamma}(\rho) \right]$$

$$(II) = \frac{1}{card(\Pi)} \sum_{\rho \in \Pi} \left[ NP_j \frac{r^{sup} - r(\rho)}{p^{sup} - p^{inf}} + \sum_{\gamma \in \Gamma r} K_j^{\gamma}(\rho) \right]$$

Component (I) reflects the points of the project associated with solar modules. Component (II) encompasses the points that can be attributed to the remaining features of the project.

*3.2. The model: analytical framework for the demand of solar PV module*

In this context, we assume that the choice of solar modules maximizes component (I). The average score attributed to the solar modules of winning projects is superior to the average score of solar modules across any selection of projects that respects the constraint defined by the volume of the tender.

Because the selection process is indifferent to the number of projects, for the points related to solar modules, it is possible to formally split each bid into a number of projects equal to the capacity of the initial bid without affecting the rankings. Then, regrouping per type of modules, component (I) can be adapted to represent solar module demand per type of product. The quantities $x_{ij}$ (in MW) of solar modules of type $i$ consumed by the winning projects of solar PV auction in country $j$ are the solutions of the following program:

$$\max_{x_{ij}} \frac{1}{A_j} \sum_i x_{ij} \left[ NM_j \frac{m^{sup} - m(i)}{m^{sup} - m^{inf}} + NC_j \frac{C^{sup} - C(i)}{C^{sup} - C^{inf}} + \sum_{\gamma \in \Gamma m} K_j^{\gamma}(i) \right] \quad (6)$$

$$\sum_i x_{ij} = A_j \quad (7)$$

$$x_{ij} \geq 0 \quad (8)$$

where $m(i)$ (in €/MW) and $C(i)$ (in $kgCO_2$/MW) reflect respectively the price and carbon footprint of module $i$. $m^{sup}$ (in €/MW) and $m^{inf}$ (in €/MW) reflect the price ceiling and price floor of solar modules, respectively. $NM_j$ is a scaling factor satisfying the following equation:

$$\frac{NM_j}{m^{sup} - m^{inf}} = \frac{NP_j}{p^{sup} - p^{inf}} \quad (9)$$

Let us notice that $NM$ is lower than $NP$ as solar module cost variation cannot exceed project cost variation. Solar modules generally make up approximately 30% of the project cost (IRENA, 2024). Assuming that module cost variation explains project cost variation in the same proportion, eq. 9 show that $NM$ should represent 30% of $NP$. Currently, prices account for 70 points over the full project (see Appendix A). In that case, $NM$ would be defined around 20 points.

*3.3. First-order condition analysis*

In the rest of this section, we will assume that solar module manufacturing is subject to linear economies of scale described by a cost reduction coefficient $m$ (in €.$MW^{-2}$). Prices can be describe as a decreasing function of the total quantity produced:

$$m(i) = m^{sup} - m \sum_j x_{ij} \qquad \text{with } m > 0 \tag{10}$$

Let us consider the demand model described by eqs. 6, 7, 8 and 10. Evaluating the first-order conditions of the problem, we can find analytical expressions for the quantity of module consumed at equilibrium and the associated budget.

*3.3.1. Quantity*

Considering $M$ countries and that $N$ types of solar module have non-zero production at equilibrium, the production of solar module $i$ is the sum of two components: the first component (I) is driven by total demand, price and carbon content, while the second component (II) expresses the impact of other non-price criteria. The full demonstration of this formula can be found in Appendix B. We have:

$$\sum_{j=1}^{M} x_{ij} = (I) + (II) \tag{11}$$

with

$$(I) = \frac{1}{N}\sum_{j=1}^{M} A_j - \frac{m^{\text{sup}} - m^{\text{inf}}}{m} \cdot \frac{1}{M+1} \cdot \frac{1}{N} \cdot \left[\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}\right] \left[\sum_{k=1}^{M} \frac{\text{NC}_k}{\text{NM}_k}\right]$$

$$(II) = -\frac{m^{sup} - m^{inf}}{m} \cdot \frac{1}{M+1} \cdot \frac{1}{N} \cdot \left[\sum_{k=1}^{M}\sum_{l=1}^{N} \left(\frac{K_k(i)}{NM_k} - \frac{K_k(l)}{NM_k}\right)\right]$$

Here, $K_j(i)$ are coefficients that aggregate the score of non-price criteria such that:

$$K_j(i) = \sum_{\gamma \in \Gamma m} K_j^{\gamma}(i) \tag{12}$$

This equation presents the quantities of solar modules $i$ produced at equilibrium. In particular, each technology provides the same value, based on cost reduction, carbon emissions, and the remaining criteria. Because module price heterogeneity is driven here by economies of scale, it indicates the minimum market share a technology should achieve to become competitive.

Component (I) shows first that module consumption grows with the total volume auctioned across countries. It also shows that increasing the score related to carbon emission reduces the competitiveness threshold for above-average climate-friendly products. Component (II) expresses how national preferences divergence impacts the competitiveness threshold. When preferences are aligned, and component (II) is null, the demand model is fully driven by the price and carbon content criteria expressed in component (I). Depending on the overall differences between the remaining criteria and their directions, they can mitigate or exacerbate the complementarity between price and carbon reduction expressed in component (I) for quantity at equilibrium.

*3.3.2. Budget*

We can define the budget $B_i$ (in €) necessary for solar modules $i$ as follows:

$$B_i = m(i) * \sum_{j=1}^{M} x_{ij} \tag{13}$$

Summing over all the types of solar modules, we get:

$$\sum_{i=1}^{N} B_i = \sum_{i=1}^{N} \left[ m(i) * \sum_{j=1}^{M} x_{ij} \right] = m^{sup} \sum_{j=1}^{M} A_j - m \sum_{i=1}^{N} \left[ \sum_{j=1}^{M} x_{ij} \right]^2 \tag{14}$$

Total spending variations can now be expressed as a function of carbon content scoring. The full demonstration is provided in Appendix C. We have:

$$\frac{d(\sum_i B_i)}{dNC_h} = -\,(\frac{2m \cdot R^2}{NM_h}) \cdot (\sum_{j=1}^{M} \frac{1}{NM_j}) \cdot \sum_{i=1}^{N} \left[ (\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}) \cdot (\sum_{j=1}^{M} N \cdot K_j(i)) \right]$$
$$-\,(\frac{2m \cdot R^2}{NM_h}) \cdot (\sum_{j=1}^{M} \frac{\text{NC}_j}{\text{NM}_j}) \cdot \sum_{i=1}^{N} \left[ \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right]^2$$

When $K_j(i)$ are homogeneous across technologies and independent of $i$, budget variation depends only on price and carbon reduction. In this context, total spending decreases with a stringent scoring for carbon content. In a context where firms can compete and adjust efficiency over production size and economies of scale, this result highlights a channel through which environmental standards impact firm performance. To stay in the market and maintain competitiveness against firms with better environmental performance, laggers must increase cost-efficiency, reducing the overall cost of the renewable auction. This result aligns with the findings of Chiappinelli et al. (2025), highlighting how the complementarity between price and carbon content criteria can impact firm efficiency. Let us notice that this result holds under the assumption that carbon reduction does not induce additional costs. This hypothesis is not necessarily discarded for solar PV, as electricity accounts for 80% of the energy needed for the manufacturing process (IEA, 2022). However, countries with lower carbon intensity can also display lower electricity prices (IEA, 2025).

When the $K_j(i)$ are heterogeneous across technologies, but favour overall modules with the lowest carbon footprint, increasing the number of points for carbon footprint reduction reduces the total budget. However, when the $K_j(i)$ favour the least performing modules in terms of carbon footprint, increasing the score for carbon reduction has a negative impact on the total budget. Interpreting the $K_j(i)$ as local content criteria, this highlights the benefits of aligning industrial development targets for the domestic industry with a broader climate strategy to reduce costs.

The budgetary impact of the remaining non-price criteria $K_j(i)$ and their divergence is demonstrated in Appendix C. Similarly, its direction is dictated by the importance of the carbon score relative to other criteria and their heterogeneity:

$$\frac{d(\sum_i B_i)}{dK_k(h)} \leq 0$$
$$\Leftrightarrow \left( \left[ \sum_{k=1}^{N} \frac{C(k) - C(h)}{C^{\text{sup}} - C^{\text{inf}}} \right] \left[ \sum_{k=1}^{M} \frac{\text{NC}_k}{\text{NM}_k} \right] + \left[ \sum_{k=1}^{M} \sum_{l=1}^{N} \left( \frac{K_k(h)}{NM_k} - \frac{K_k(l)}{NM_k} \right) \right] \right) \geq 0$$

Interpreting $K_j(i)$ directly as a local content criterion, this result indicates that the development of a local industry producing solar modules with low carbon footprints minimises costs. To reduce the production cost of solar modules, ambitions for domestic manufacturing should align with a broader strategy for climate leadership.

## 4. Numerical simulation

This numerical simulation aims to evaluate how the implementation of non-price criteria in renewable auctions can affect solar module manufacturing in a prospective model of the European sector in 2030. In particular, various degrees of auction design heterogeneity are tested, simulating how divergent scoring systems at the national level impact industrial output and competition incentives.

This application of the framework assumes that resilience criteria are effective in safeguarding a market segment for European modules. In this greenfield approach, the modelled demand for solar modules stemming from renewable auctions with non-price criteria is met by newly built manufacturing capacity.

### *4.1. Simulation set-up*

#### *4.1.1. Data*

Table 1 presents the main data sources for the numerical simulation.

The volume auctioned at the national level is computed as a share of Member States' renewable targets. First, we suppose a linear trajectory for the development of solar PV between 2023 and 2030. This yields the annual increase in capacity assumed in this study, which is displayed for each country in Appendix D. Then, we assume that a third of new solar PV capacity is funded through renewable auctions. Summing over European countries,

| Parameter | Name | Unit | Value | Source |
|---|---|---|---|---|
| Volume auctioned at the national level | $A_j$ | GW | (national PV target)/3 | SPE (2024) |
| Volume auctioned at the EU level | $\sum_j A_j$ | GW | 30 | ESIA (2022) |
| Scale economies | $S$ | GW | 1.8 | Dehghanimadvar et al. (2022) |
| Maximum production cost | $m_{\max}$ | €/W | 0.4 | Dehghanimadvar et al. (2022) |
| Minimum production cost | $m_{\min}$ | €/W | 0.2 | Dehghanimadvar et al. (2022) |

Table 1: Numerical simulation - data

this yields the targeted 30 GW of manufacturing capacity necessary to meet the NZIA objectives. Because of scale economies, production costs are a decreasing function of total consumption. Based on the results of Dehghanimadvar et al. (2022), they are simulated using a decreasing exponential function. A graph presenting the calibration of production costs is displayed in Appendix E.

$$m(i) = (m_{\max} - m_{\min})e^{-\frac{\sum_j x_{ij}}{S}} + m_{\min} \tag{15}$$

*4.1.2. Simulation process*

The equilibrium problem described by eqs. 6, 7, 8 and 10 is considered for the 27 EU Member States. The $NM_j$ are assumed uniform across countries. The $K_j(i)$ expresses increasingly divergent non-price criteria through a constant $K$. The $NC_j$ are not directly represented, as carbon scoring heterogeneity is aggregated under $K$. We have:

$$\begin{aligned} \text{For all } j : NM_j &= NM \\ \text{When } j \neq i : K_j(i) &= 0 \\ \text{When } j = i : K_j(i) &= K \end{aligned}$$

In this numerical simulation, $NM$ is set to 20. This assumes that 70 points are dedicated to project price, and that module cost accounts for 30% of the total cost variation.

For each country, the objective function is evaluated in two cases. First, the solar module produced with the lowest cost is selected, and the associated points are computed. Because of economies of scale, it is the type of module produced in the largest quantities. It is also the module that yields the most points with respect to the price criterion. Second, the type of solar module that fits national preferences earns the points associated with K, and its total score is computed. Comparing the two scores indicates when a country stops selecting the least-cost solution. When a country stops sourcing from the largest market, the size of that market decreases, affecting the choices of the remaining participants. An equilibrium is found when no country has an incentive to unilaterally deviate from its position.

*4.2. Simulation results*

*4.2.1. Efficiency analysis*

Figure 1 shows the evolution of the total budget required to clear the solar PV auctions as a function of $K$.

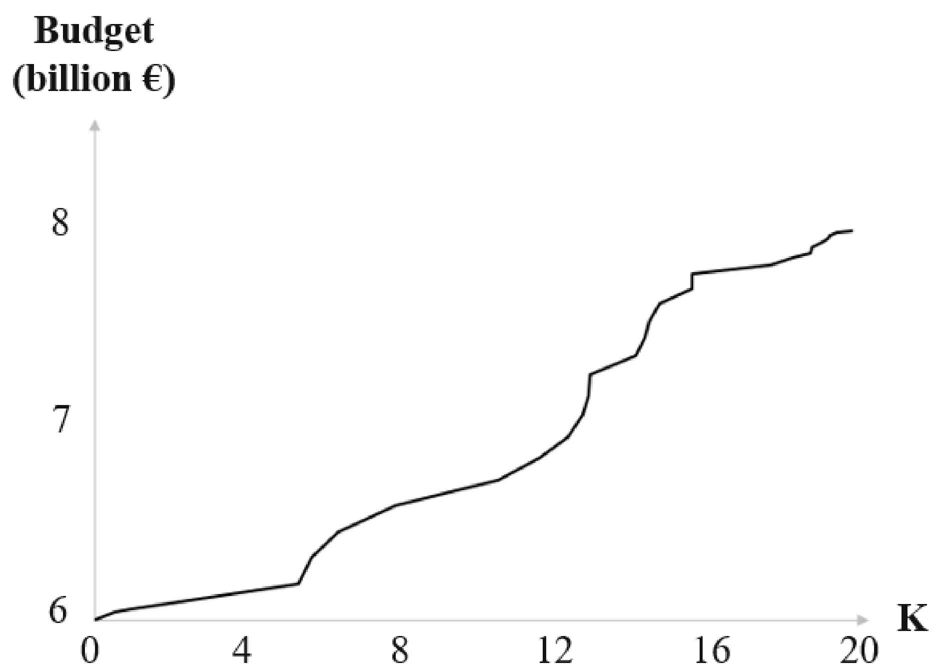


Figure 1: Cost of European solar modules

When price reduction accounts for all the points dedicated to solar modules ($K = 0$), the budget necessary to clear the auction is minimal, at €6 billion. Divergent non-price criteria across Member States then impact industrial outcome and increase solar module prices. When $K$ increases from 0 to 20, the budget increases by €100 million per point on average. This reflects the growing fragmentation of the European space. The emergence of reduced and isolated markets limits the potential for economies of scale. The cost of European production reached its highest point at €8 billion when $K$ equals $NM$. National preferences divergence can yield a 30% increase in the cost of European manufacturing.

*4.2.2. Equilibrium analysis*

Figure 2 displays how national preferences drive production as a function of $K$. In particular, it shows the set of countries in which the product favoured by non-price criteria can be manufactured, and the number of products actually manufactured at equilibrium.

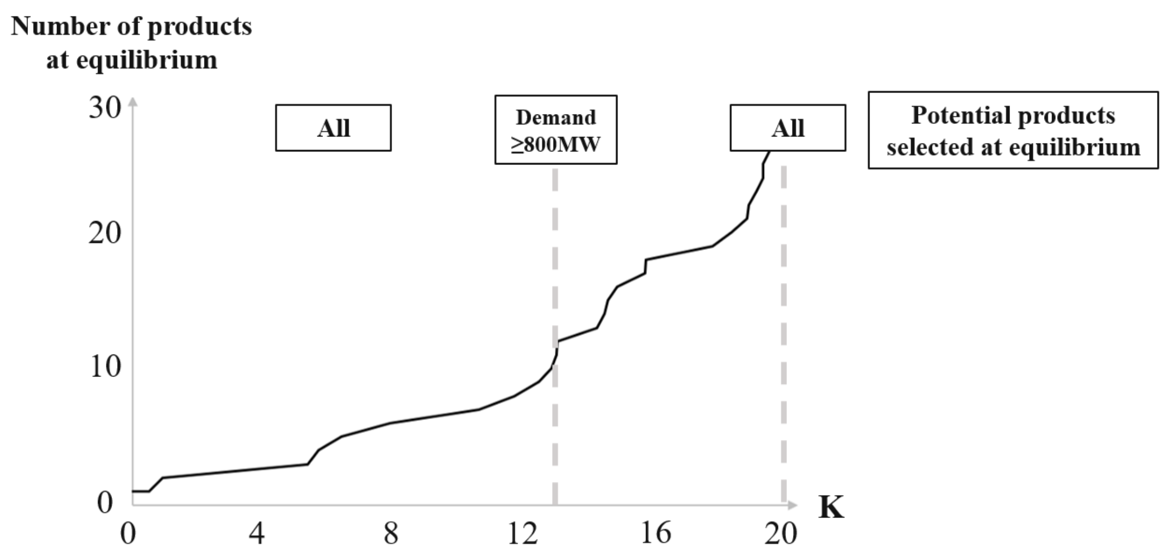


Figure 2: Production at equilibrium

When $K = 0$ and European demand is fully driven by price reduction, every type of solar module $i$ can be produced at equilibrium. The market size is also optimally framed at the EU level. However, because production costs are decreasing with economies of scale, competition in the market is limited: ultimately, only one product dominates the market at equilibrium.

With $K$ between 0 and 13, non-price criteria start diverging. Countries with the largest national markets have sufficient size, and the product they favour is selected at equilibrium. The remaining countries form a market in which one product is produced at equilibrium. Overall, this market configuration still allows any product to be selected at equilibrium. Also, the number of products actually selected at equilibrium is increasing. However, the number of markets also grows in the same proportion. Therefore, competition in the market is not improved as the European market gets further fragmented. Products are only competitive in the country where they are favoured, and face reduced market sizes.

When $K = 13$, fragmentation reaches a particular threshold at which products favoured by countries with demand below 800 MW are excluded from the set of potential equilibria. Those countries cannot form a market large enough to harness sufficient economies of scale and render production competitive. In this context, actual production at equilibrium is dictated by the preferences of the largest consumers. The set of potential equilibria is reduced accordingly for $K$ between 13 and 20. However, $K$ also lowers competitiveness requirements and diminishes the threshold for standalone production. As a result, the set of products produced at equilibrium is growing, in descending order of market size.

Finally, when $K$ is equal to $NM$ at 20, any product favoured by one Member State can once again be selected for production at equilibrium. However, this reflects a fully fragmented market.

*4.2.3. Alternative scenario I: Low demand (10 GW)*

Figure 3 shows the evolution of the budget in a scenario with a reduced demand of 10 GW for European solar panels.

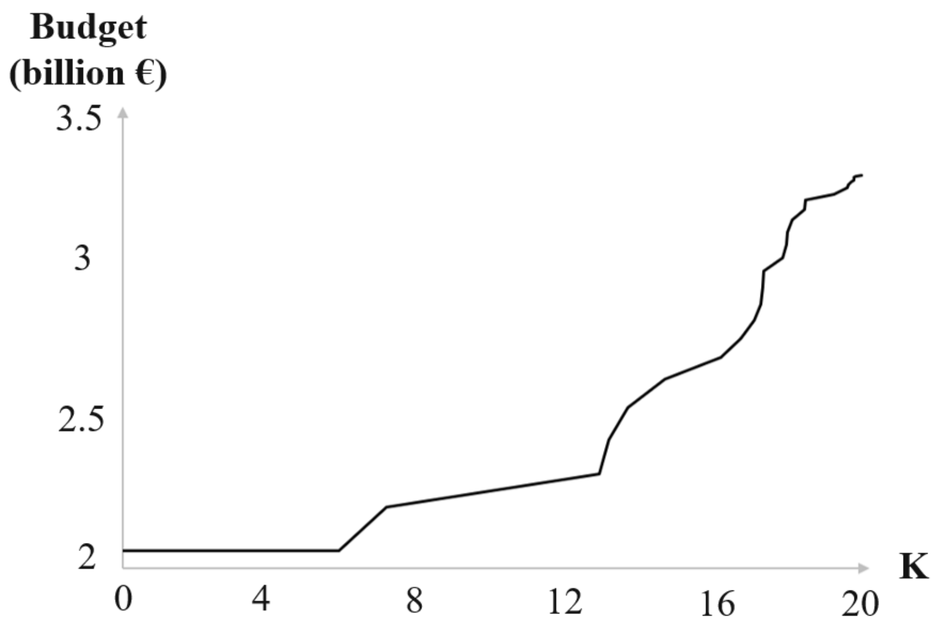


Figure 3: Cost of European solar modules - Low demand scenario

When scoring divergence across countries is limited to six points ($K = 6$), the budget necessary to clear the auction is minimal, at €2 billion. With lower demand, the divergence between non-price criteria needs to be higher to induce market fragmentation. For $K > 6$, fragmentation occurs with similar intensity as the previous case. Each point difference results in a loss of €100 million. Full market fragmentation raises costs by €1.3 billion and increases the auction budget by more than 50%. Overall, lower demand reduces fragmentation costs in absolute terms but increases them in relative terms, as the marginal benefits from economies of scale are more acute. Reduced demand does not solve market fragmentation issues but displaces them.

*4.2.4. Alternative scenario II: Demand clusters (5 GW)*

Figure 4 shows the evolution of the budget in a scenario where national demands are grouped in six clusters of 5 GW. For these six clusters, preferences for solar modules are similar. In this case, $K$ expresses divergences across clusters.

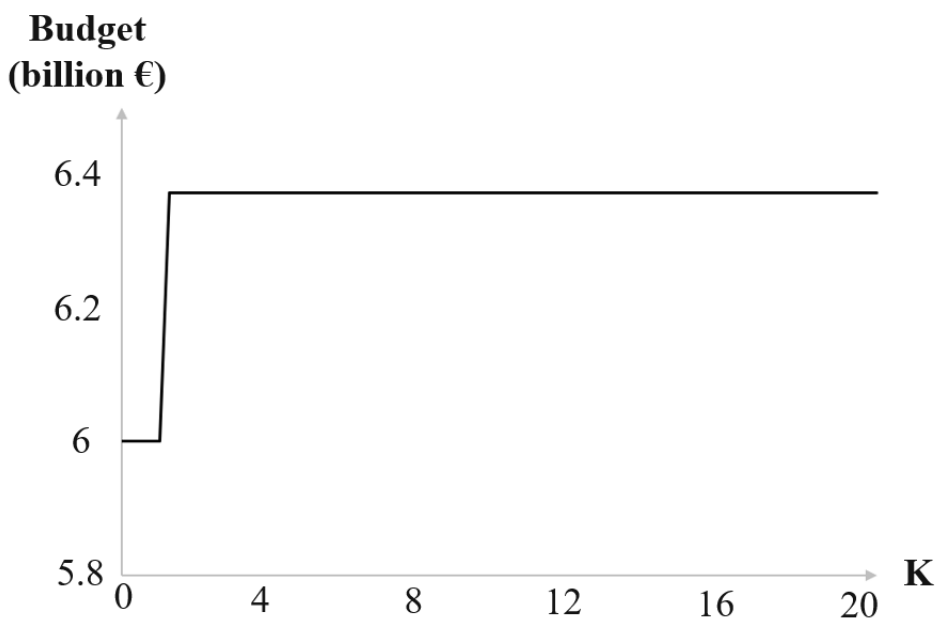


Figure 4: Cost of European solar modules - Demand clusters scenario

In this scenario, any scoring divergence exceeding 2 points ($K = 2$) induces maximal disaggregation between clusters. Fragmentation between clusters is highly sensitive to preference heterogeneity. However, the worst outcome is mitigated. Indeed, market fragmentation results in additional costs limited to €370 million. Compared with the €6 billion budget required under market integration, this represents a 6% cost increase. If demand alignment is impossible at the EU level, the formation of demand clusters between willing countries is a second-best solution that substantially reduces the cost of market fragmentation.

### *4.3. Discussion*

#### *4.3.1. Market size, equilibrium selection and competition*

This numerical simulation shows that countries with the largest markets can dictate the type of product produced at equilibrium, when smaller countries cannot. This demand asymmetry can be leveraged to indirectly favour specific products. In this context, the coefficients $K$ can be interpreted as indirect preferences for domestic firms with two consequences. First, only national champions from the largest countries would benefit from sufficient domestic support to become competitive, substantially reducing competition for the market. Second, in a context in which the NZIA imposes the development of non-price criteria in renewable auctions, small countries have little incentive to contribute to the common effort. The policy can undermine their budgetary and trade balance, while they derive no benefit in terms of jobs, external economies of scale, etc. Without coordination, this policy risks favouring bigger players, raising both competition and fairness concerns.

*4.3.2. Implications for renewable auction design*

This study stresses the importance of market integration for the reshoring of the European solar PV industry envisioned by the NZIA. Even with reduced objectives for the sector, policy coordination can foster significant efficiency gains, competition incentives and fairness improvement. However, while European institutions can promote a common energy policy agenda, the current treaty guarantees a degree of autonomy for Member States regarding their energy mix and supply strategy. In this context, the NZIA supervises the development of non-price criteria in renewable auctions but allows for a high degree of liberty. This can lead to very different outcomes depending on the precise implementation at the country level.

These numerical results advocate for the design of a shared framework between Member States that homogenises non-price criteria across countries and aligns national demands. This way, the European market selects the most efficient equilibrium and provides equal opportunity to Member States. Coordination ensures efficient budget management at the EU level and that NZIA targets are met with minimal public spending. Also, it prevents countries with greater fiscal space from pursuing their own industrial policy. It would create a level playing field that protects European manufacturers while maintaining a healthy level of fair competition. Such a policy would avoid winner-picking initiatives from Member States and the detrimental nurturing of national champions. This policy would fully harness the European scale and its internal market. This resonates with the results of Münch and Scheifele (2023), who demonstrated how market size and competition are decisive factors in solar auctions to stimulate innovations.

The numerical results also show that the building of homogeneous demand clusters is an efficient second-best strategy for mitigating market fragmentation risks. If full market integration is not possible at the EU level, this study advocates for the formation of coalitions between willing countries with shared interests. A smaller number of stakeholders facilitates consensus and improves political feasibility, with minimal trade-offs in efficiency.

In addition to renewable auctions, the European solar PV market is also driven by household and private demand. In that regard, even if non-price criteria do not create additional distortion in favor of domestic producers, household demand can. Indeed, households can have a higher willingness to pay for domestic panels than imported ones (Kim et al., 2021). Complete market integration is conditional to broader European integration. However, aligning non-price criteria in renewable auctions is still beneficial despite this context.

### *4.4. Limits*

This study entails several limitations. First, the numerical simulation proposes a greenfield approach that focuses on the reshoring of the European industry. Resilience criteria are considered efficient in providing a sufficient competitive advantage to European products against cheaper imports. This assumption can be challenged. Explicit representation of resilience criteria and products from existing extra-European manufacturing plants would complete the results. However, to reach 30 GW of European manufacturing capacity, European modules should ultimately be called in the renewable auctions at the scale of the NZIA target. Competition for this market segment is adequately represented in this study.

Second, no heterogeneity is considered to differentiate countries. In reality, they have different labour and energy costs. Also, they can choose to support the national or European industry with various intensities. Differences in competitiveness, preferences and strategic behaviour can significantly impact the simulation outcome.

Finally, economies of scale are limited to the plant level. Also, a single time period and a single stage of the supply chain are considered. Expanding the model along those dimensions may lead to the emergence of other configurations for the European solar PV sector. In particular, smaller countries might look to compete for limited market segments where they can develop a comparative advantage.

## 5. Conclusion and policy implications

This study develops a demand model for solar PV modules, rooted in the specifications of renewable auctions, to analyse the interplay between industrial and environmental policies embedded in the NZIA. Leveraging analytical and numerical insights, this analysis highlights complementarities among policy objectives and identifies the underlying economic channels and mechanisms at play. It provides actionable guidelines for the effective implementation of the regulatory framework at the European level.

The analytical results evaluate the complementarity between price and non-price criteria, in an international context where local content requirements have gained political traction. They show that carbon scoring can reduce auction budgets by incentivising higher-emitting firms to improve their economic performance in order to remain competitive with lower-emitting firms. Price and carbon scoring do not necessarily conflict if firms have room to adapt. When considering local content criteria, this complementarity holds if manufacturing development targets align with climate objectives. The reshoring of high-emitting production would further increase costs. This result highlights the need for a comprehensive policy approach: non-price criteria must be designed to ensure that industrial development supports climate leadership.

The numerical results analyse the complementarity between price and non-price criteria divergence. It shows how the flexibility of renewable auction design enabled by the NZIA impacts industrial outcomes, and evaluates the benefits of broader market integration at the EU level. In particular, the numerical simulation of European solar PV auctions in 2030 reveals that divergent designs can increase manufacturing costs by up to €2 billion annually due to reduced market size and economies of scale. Besides, market fragmentation provides opportunities for the largest countries to leverage their size and influence the resulting equilibrium. This possibility raises fairness concerns as such an effect is impossible for smaller countries. If the NZIA proposes ambitious goals for the reshoring of the solar PV industry in Europe, the sensitivity analysis conducted in this study shows that similar effects hold even with partial achievement of the targets.

A unified European framework for renewable auction design is critical to harmonise national demands, prevent market distortions, and ensure fairness and budget efficiency. Because non-price criteria depend on public spending, they are subject to unequal implementation due to disparities in fiscal space across Member States. However, a uniform implementation at the national level is a no-regret solution for Europe that minimises cost at the EU level. Forming coalitions of aligned countries emerges as a pragmatic second-best strategy. Considering 5 GW clusters with homogeneous auction designs limits fragmentation costs to €370 million. This result calls for European countries with similar interests to collaborate and jointly design renewable auctions beyond the guidelines provided by the NZIA.

## Appendix A. Background

*Appendix A.1. Renewable auction: current design*

The analytical framework developed in this study directly builds on the specifications of the French auctions for solar PV facilities (CRE, 2025). In particular, a fixed volume of capacity is auctioned at each period. Then, the scoring system evaluates each bid based on four primary criteria.

- Price (NP) accounts for 70 out of 100 points. The score is calculated relative to the reference price at which the bidder is willing to sell the electricity. The final score for price $NP$ is determined using the following formula:

$$NP = NP_0 * \frac{p^{sup} - p}{p^{sup} - p^{inf}}$$

  where $p$ is the proposed price by the bidder, $p^{sup}$ is the price ceiling, $p^{inf}$ is the price floor, and $NP_0$ is the maximum score for price (70 points).

- Carbon Footprint (NC): This criterion accounts for 16 out of 100 points and evaluates the carbon emissions associated with the production of the solar modules. The carbon score $NC$ is evaluated as follows:

$$NC = NC_0 * \frac{C^{sup} - C}{C^{sup} - C^{inf}}$$

  where $C$ is the carbon footprint declared by the bidder, $C^{sup}$ is the carbon ceiling, $C^{inf}$ is the carbon floor, and $NC_0$ is the maximum score for carbon (16 points).

- Environmental pertinence (NE): This criterion is worth 9 points and assesses the environmental suitability of the project site.

- Financing and governance (FC): This criterion accounts for 5 points and rewards the project if funding comes from local stakeholders, or if the project´s equity or voting rights are held by local stakeholders or public entities.

The total score (N) for each bid is the sum of the points awarded for each criterion:

$$N = NP + NC + NE + FC$$

The selection process follows these steps. First, bids that fail to meet the minimum requirements (e.g., exceeding the price ceiling or carbon threshold) are disqualified. Then, the remaining bids are ranked by their total score and the highest-scoring bids are selected until the total auctioned volume is reached. This way, the auction selects bids that maximise the number of points for a fixed capacity.

*Appendix A.2. Renewable auction: NZIA and non-price criteria*

Against this background, the NZIA imposes the development of additional non-price criteria in at least 30% of the volume auctioned per year and per Member States, or at least 6 GW per year and per Member States (European Parliament and the Council, 2024; European Commission, 2025). Mandatory pre-qualification criteria encompass responsible business conduct, cybersecurity and the ability to deliver the full project on time. Other criteria defined in the NZIA are optional, providing flexibility to Member States in their application. In particular, the NZIA emphasises four categories of non-price criteria related to environmental sustainability, contribution to economic resilience, energy system integration and innovation.

- Environmental sustainability criteria increase the scoring of projects with a lower carbon footprint, better characteristics regarding circular economy standards (recyclability, use of recycled materials), higher energy efficiency and reduced impact on biodiversity, water use and pollution.

- Resilience criteria provide additional points for projects contributing to the diversification of supply chains. For technologies where 50% of supply comes from a single third country, auctions must limit participation or award points to bids that rely on different sources.

- Innovation criteria favour projects that demonstrate improvement beyond state-of-the-art in key performance indicators. The choice of such an indicator depends on the policy objective pursued by the Member State, but it can include, for example, energy generation efficiency, recyclability, raw material consumption, and longevity.

- Energy system integration criteria allow authority to evaluate bidding projects based on their alignment with system needs, regarding temporal, locational and cross-carrier connectivity. These dimensions ensure that projects address energy system demand and production variability in a coherent manner with other technologies.

Besides these four categories, the NZIA does not preclude Member States from considering additional criteria not explicitly framed by the regulatory framework. Overall, the NZIA offers numerous degrees of liberty for the implementation of non-price criteria at the country level.

### Appendix B. Demonstration: solar module consumption

Let us consider the demand model described by eqs. 6, 7, 8 and 10. Each country $j$ is subject to the following equilibrium problem:

$$\max_{x_{ij}} \frac{1}{A_j} \sum_{i=1}^{N} x_{ij} \left[ NM_j \frac{m^{sup} - m(i)}{m^{sup} - m^{inf}} + NC_j \frac{C^{sup} - C(i)}{C^{sup} - C^{inf}} + K_j(i) \right]$$

$$\sum_{i=1}^{N} x_{ij} = A_j \qquad (\alpha_j)$$

$$x_{ij} \geq 0 \qquad (\gamma_{ij})$$

where $\alpha_j$ and $\gamma_{ij}$ denote the dual variable associated respectively with the constraint on the volume auctioned by country $j$ and the positivity constraint on module consumption. $K_j(i)$ are coefficients that aggregate the score of non-price criteria such that:

$$K_j(i) = \sum_{\gamma \in \Gamma m} K_j^{\gamma}(i)$$

With eq. 10 expressing linear economies of scale, the objective function can be expressed as follows:

$$\frac{1}{A_j} \cdot \sum_{i=1}^{N} x_{ij} \left( \frac{NC_j \cdot (C^{sup} - C(i))}{C^{sup} - C^{inf}} + \frac{NM_j \cdot m}{m^{sup} - m^{inf}} \left( \sum_{k=1}^{M} x_{ik} \right) + K_j(i) \right)$$

Assuming that $N$ types of solar module have non-zero production at equilibrium, we can express their first-order conditions of optimality with the following set of equations:

$$\frac{NC_j \cdot (C^{sup} - C(i))}{C^{sup} - C^{inf}} + \frac{NM_j \cdot m}{m^{sup} - m^{inf}} \left( \left( \sum_{k \neq j}^{M} x_{ik} \right) + 2 \sum_{i=1}^{N} x_{ij} \right) + K_j(i) = A_j \cdot \alpha_j$$

$\gamma_{ij}$ is set to zero because production is assumed strictly positive. Expressing this equality in country $j$ for two technologies $(i, y)$, we get:

$$\frac{NC_j \cdot (C(i) - C(y))}{C^{sup} - C^{inf}} - [K_j(i) - K_j(y)] = \frac{NM_j \cdot m}{m^{sup} - m^{inf}} \left( x_{ij} - x_{yj} + \sum_{k=1}^{M} (x_{ik} - x_{yk}) \right) \tag{B.1}$$

Expressing this equality for two countries $(j, g)$, and computing the difference to eliminate the summation, we get:

$$\frac{m^{sup} - m^{inf}}{m} [C(i, y, j, g) - K(i, y, j, g)] = (x_{ij} - x_{yj}) - (x_{ig} - x_{yg}) \tag{B.2}$$

with

$$C(i, y, j, g) = \frac{C(i) - C(y)}{C^{sup} - C^{inf}} \cdot \left( \frac{NC_j}{NM_j} - \frac{NC_g}{NM_g} \right)$$
$$K(i, y, j, g) = \left(\frac{K_j(i)}{NM_j} - \frac{K_j(y)}{NM_j}\right) - \left(\frac{K_g(i)}{NM_g} - \frac{K_g(y)}{NM_g}\right)$$

Equivalently, we have:

$$(x_{ig} - x_{yg}) = (x_{ij} - x_{yj}) - \frac{m^{sup} - m^{inf}}{m} [C(i, y, j, g) - K(i, y, j, g)]$$

Because, this is true for any country $g$, we can substitute this expression in the sum defined in eq. B.1:

$$\frac{NC_j \cdot (C(i) - C(y))}{C^{sup} - C^{inf}} - [K_j(i) - K_j(y)] =$$
$$\frac{NM_j \cdot m}{m^{sup} - m^{inf}} \left( x_{ij} - x_{yj} + \sum_{k=1}^{M} \left[ (x_{ij} - x_{yj}) - \frac{m^{sup} - m^{inf}}{m} [C(i, y, j, k) - K(i, y, j, k)] \right] \right)$$

This yields:

$$\frac{m^{sup} - m^{inf}}{m} \cdot (M+1) \cdot (x_{ij} - x_{yj})$$
$$= \left[ \frac{NC_j}{NM_j} \cdot \frac{C(i) - C(y)}{C^{sup} - C^{inf}} - \left[ \frac{K_j(i)}{NM_j} - \frac{K_j(y)}{NM_j} \right] \right] + \left[ \sum_{k=1}^{M} (C(i,y,j,k) - K(i,y,j,k)) \right]$$

Using eq. 7, we have:

$$A_j = N \cdot x_{ij}$$
$$- \frac{1}{M+1} \cdot \frac{m^{sup} - m^{inf}}{m} \cdot \sum_{y \neq i}^{N} \left( \left[ \frac{NC_j}{NM_j} \cdot \frac{C(i) - C(y)}{C^{sup} - C^{inf}} - \left[ \frac{K_j(i)}{NM_j} - \frac{K_j(y)}{NM_j} \right] \right] \right)$$
$$- \frac{1}{M+1} \cdot \frac{m^{sup} - m^{inf}}{m} \cdot \sum_{y \neq i}^{N} \left( \sum_{k=1}^{M} (C(i,y,j,k) - K(i,y,j,k)) \right)$$

Finally, we get:

$$x_{ij} = \frac{A_j}{N}$$
$$- \frac{1}{M+1} \cdot \frac{1}{N} \cdot \frac{m^{sup} - m^{inf}}{m} \cdot \sum_{y \neq i}^{N} \left( \left[ \frac{NC_j}{NM_j} \cdot \frac{C(i) - C(y)}{C^{sup} - C^{inf}} - \left[ \frac{K_j(i)}{NM_j} - \frac{K_j(y)}{NM_j} \right] \right] \right)$$
$$- \frac{1}{M+1} \cdot \frac{1}{N} \cdot \frac{m^{sup} - m^{inf}}{m} \cdot \sum_{y \neq i}^{N} \left( \sum_{k=1}^{M} (C(i,y,j,k) - K(i,y,j,k)) \right)$$

Summing over the different countries, we get:

$$\sum_j x_{ij} = (I) + (II) \tag{B.3}$$

with

$$(I) = \frac{1}{N}\sum_{j=1}^{M} A_j - \frac{m^{\text{sup}} - m^{\text{inf}}}{m} \cdot \frac{1}{M+1} \cdot \frac{1}{N} \cdot \left[\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}\right] \left[\sum_{k=1}^{M} \frac{\text{NC}_k}{\text{NM}_k}\right]$$

$$(II) = -\frac{m^{sup} - m^{inf}}{m} \cdot \frac{1}{M+1} \cdot \frac{1}{N} \cdot \left[\sum_{k=1}^{M}\sum_{l=1}^{N} \left(\frac{K_k(i)}{NM_k} - \frac{K_k(l)}{NM_k}\right)\right]$$

## Appendix C. Demonstration: Budget

Given a solar module of type $h$ and its scoring $K_k(h)$ regarding non-price criteria in country $k$, we aim to differentiate the total budget $\sum_i^N B_i$ with respect to $NC_j$ and $K_k(h)$.

Let us define $R$, such that:

$$R = \frac{m^{\text{sup}} - m^{\text{inf}}}{m} \cdot \frac{1}{M+1} \cdot \frac{1}{N}$$

Let $X_i = \sum_j^M x_{ij}$. Using eq. B.3, the derivatives of $X_i$ with respect to $NC_j$ and $K_k(h)$ are given by:

$$\frac{d(X_i)}{dNC_j} = -R\left[\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}\right] \cdot \frac{1}{NM_j}$$

$$\text{When } h \neq i: \quad \frac{d(X_i)}{dK_k(h)} = R \cdot \sum_{k=1}^{M} \frac{1}{NM_k}$$

$$\text{When } h = i: \quad \frac{d(X_i)}{dK_k(h)} = -R \cdot \sum_{k=1}^{M} \frac{N-1}{NM_k}$$

With eq. 14 defining total budget, we get:

$$\sum_{i=1}^{M} B_i = m^{\text{sup}} \sum_{j=1}^{M} A_j - m \sum_{i=1}^{N} X_i^2$$

Computing the derivative of $\sum_i^M B_i$ regarding $NC_j$ yields:

$$\frac{d(\sum_i^N B_i)}{dNC_j} = -m \sum_{i=1}^{N} 2X_i \frac{dX_i}{dNC_j}$$

Substituting the derivatives:

$$\frac{d(\sum_i B_i)}{dNC_j} = -2m \left( \sum_{i=1}^{N} (-R \cdot \left[ \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right] \cdot \frac{1}{NM_j})(X_i) \right)$$
$$= (\frac{2m \cdot R}{NM_j}) \left[ \sum_{i=1}^{N} \left[ \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right] (X_i) \right]$$

Using eq.B.3 to express $X_i$, let us notice that the first term $\frac{1}{N} \sum_{j=1}^{M} A_j$ is independent of $i$. We get:

$$\sum_{i=1}^{N} \left( \left( \frac{1}{N} \sum_{j=1}^{M} A_j \right) \cdot \left[ \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right] \right) = \left( \frac{1}{N} \sum_{j=1}^{M} A_j \right) \cdot \left( \sum_{i=1}^{N} \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right) = 0$$

Also, we have:

$$\sum_{i=1}^{N} \left[ (\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}})(\sum_{o=1}^{M} \sum_{l=1}^{N} \left( \frac{K_o(i)}{NM_o} - \frac{K_o(l)}{NM_o} \right)) \right]$$
$$= \sum_{i=1}^{N} \left[ (\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}) \cdot (\sum_{o=1}^{M} N \cdot \frac{K_o(i)}{NM_o}) \right] - \left[ \sum_{o=1}^{M} \sum_{l=1}^{N} \frac{K_o(l)}{NM_o} \right] \left[ \sum_{i=1}^{N} \sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}} \right]$$
$$= \sum_{i=1}^{N} \left[ (\sum_{k=1}^{N} \frac{C(k) - C(i)}{C^{\text{sup}} - C^{\text{inf}}}) \cdot (\sum_{o=1}^{M} \frac{N \cdot K_o(i)}{NM_o}) \right]$$

Therefore

$$\sum_{i=1}^{N}\left[\sum_{k=1}^{N}\frac{C(k)-C(i)}{C^{\text{sup}}-C^{\text{inf}}}\right](X_i)$$

$$= -R\left((\sum_{k=1}^{M}\frac{1}{NM_k})\cdot\sum_{i=1}^{N}\left[(\sum_{k=1}^{N}\frac{C(k)-C(i)}{C^{\text{sup}}-C^{\text{inf}}})\cdot(\sum_{o=1}^{M}N\cdot K_o(i))\right]\right)$$

$$-R\left((\sum_{k=1}^{M}\frac{\text{NC}_k}{\text{NM}_k})\cdot\sum_{i=1}^{N}\left[\sum_{k=1}^{N}\frac{C(k)-C(i)}{C^{\text{sup}}-C^{\text{inf}}}\right]^2\right)$$

Overall

$$\frac{d(\sum_i B_i)}{dNC_j} = -(\frac{2m\cdot R^2}{NM_j})\cdot(\sum_{k=1}^{M}\frac{1}{NM_k})\cdot\sum_{i=1}^{N}\left[(\sum_{k=1}^{N}\frac{C(k)-C(i)}{C^{\text{sup}}-C^{\text{inf}}})\cdot(\sum_{o=1}^{M}N\cdot K_o(i))\right]$$
$$-(\frac{2m\cdot R^2}{NM_j})\cdot(\sum_{k=1}^{M}\frac{\text{NC}_k}{\text{NM}_k})\cdot\sum_{i=1}^{N}\left[\sum_{k=1}^{N}\frac{C(k)-C(i)}{C^{\text{sup}}-C^{\text{inf}}}\right]^2$$

Computing the derivative of $\sum_i^M B_i$ regarding $K_k(h)$ yields:

$$\frac{d(\sum_i^N B_i)}{dK_k(h)} = -m\sum_{i=1}^{N}2X_i\frac{dX_i}{dK_k(h)}$$

Splitting for the cases where $h = i$ and $h \neq i$

$$\frac{d(\sum_i^N B_i)}{dK_k(h)} = -2m\left(X_h\cdot\frac{dX_h}{dK_k(h)} + \sum_{i\neq h}^{N}X_i\cdot\frac{dX_i}{dK_k(h)}\right)$$

Substituting the derivatives:

$$\frac{d(\sum_i B_i)}{dK_k(h)} = -2m\left(X_h\cdot\left(-(N-1)\cdot R\cdot\sum_{k=1}^{M}\frac{1}{NM_k}\right) + \sum_{i\neq h}^{N}X_i\cdot\left(R\cdot\sum_{k=1}^{M}\frac{1}{NM_k}\right)\right)$$

Simplifying:

$$\frac{d(\sum_i B_i)}{dK_k(h)} = -2m \cdot R \cdot \sum_{k=1}^{M} \frac{1}{NM_k} \cdot \left( (\sum_{i \neq h}^{N} X_i) - (N-1) \cdot X_h \right)$$

$$\frac{d(\sum_i B_i)}{dK_k(h)} = -2m \cdot R \cdot \sum_{k=1}^{M} \frac{1}{NM_k} \cdot \left( (\sum_{i=1}^{N} X_i) - N \cdot X_h \right)$$

Let us notice that $\sum_{i=1}^{N} X_i = \sum_{j=1}^{M} A_j$. Therefore, we get:

$$\begin{aligned}(\sum_{i=1}^{N} X_i) - N \cdot X_h = N \cdot R \left[ \sum_{k=1}^{N} \frac{C(k) - C(h)}{C^{\text{sup}} - C^{\text{inf}}} \right] \left[ \sum_{k=1}^{M} \frac{\text{NC}_k}{\text{NM}_k} \right] \\ + N \cdot R \left[ \sum_{k=1}^{M} \sum_{l=1}^{N} \left( \frac{K_k(h)}{NM_k} - \frac{K_k(l)}{NM_k} \right) \right]\end{aligned}$$

Finally, we have:

$$\begin{aligned}\frac{d(\sum_i B_i)}{dK_k(h)} = &- \sum_{k=1}^{M} \frac{2m \cdot R^2 \cdot N}{NM_k} \cdot \left( \left[ \sum_{k=1}^{N} \frac{C(k) - C(h)}{C^{\text{sup}} - C^{\text{inf}}} \right] \left[ \sum_{k=1}^{M} \frac{\text{NC}_k}{\text{NM}_k} \right] \right) \\ &- \sum_{k=1}^{M} \frac{2m \cdot R^2 \cdot N}{NM_k} \cdot \left( \left[ \sum_{k=1}^{M} \sum_{l=1}^{N} \left( \frac{K_k(h)}{NM_k} - \frac{K_k(l)}{NM_k} \right) \right] \right)\end{aligned}$$

## Appendix D. Supplementary materials: Renewable development targets

| Country | Installed capacity 2023 (MW) | Solar PV target 2030 (MW) | Yearly development (MW/year) |
|---|---|---|---|
| Austria | 6832 | 25200 | 2624 |
| Belgium | 8549 | 22500 | 1993 |
| Bulgaria | 2937 | 15800 | 1837 |
| Croatia | 461 | 4700 | 605 |
| Cyprus | 606 | 2800 | 313 |
| Czechia | 2499 | 17100 | 2085 |
| Denmark | 3529 | 23600 | 2867 |
| Estonia | 690 | 3900 | 458 |
| Finland | 900 | 11500 | 1514 |
| France | 20542 | 67700 | 6736 |
| Germany | 81737 | 231600 | 21409 |
| Greece | 7030 | 29600 | 3224 |
| Hungary | 5835 | 16400 | 1509 |
| Ireland | 738 | 14400 | 1951 |
| Italy | 29789 | 81600 | 7401 |
| Latvia | 353 | 3500 | 449 |
| Lithuania | 1165 | 3800 | 376 |
| Luxembourg | 432 | 2600 | 309 |
| Malta | 231 | 1200 | 138 |
| Netherlands | 23904 | 62400 | 5499 |
| Poland | 15809 | 70100 | 7755 |
| Portugal | 3876 | 30400 | 3789 |
| Romania | 1917 | 20700 | 2683 |
| Slovakia | 631 | 2400 | 252 |
| Slovenia | 1034 | 6600 | 795 |
| Spain | 28712 | 154600 | 17984 |
| Sweden | 3488 | 21700 | 2601 |

Table D.2: Installed capacity, Solar PV target, and Yearly development by country (source: SPE, 2024)

## Appendix E. Supplementary materials: Production cost estimation

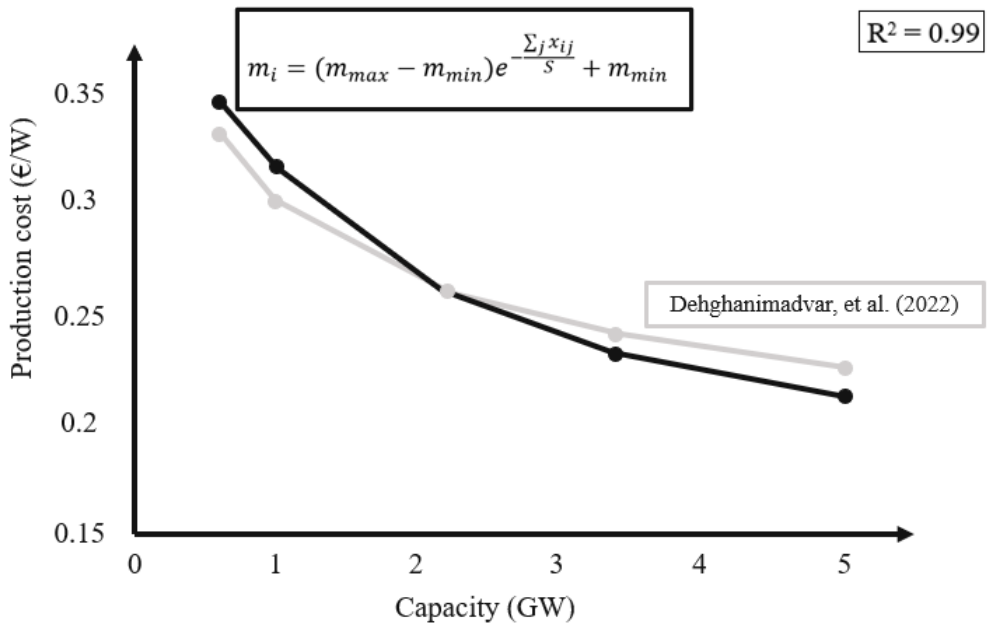


Figure E.5: Production cost estimation

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