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The Cost of Ownership and Minimum Sustainable Price of POLO BJ Cells Produced in Germany

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ABSTRACT

The p-type back junction (BJ) solar cell featuring n^+-type passivating poly-Si on oxide (POLO) rear contacts has the potential of being an alternative for the passivated emitter and rear cell (PERC) concept. The cost of ownership (CoO), minimum sustainable price (MSP), and the levelized cost of electricity (LCOE) of POLO BJ cells produced in Germany and in a facility with a production capacity of 5 GWp*a^{-1} are analyzed here. After assuming that POLO BJ can attain a cell efficiency of 24.2%, an investment of 256.8 million USD and variable and operating annual costs of 317.3 million USD are estimated. The CoO per Wp of cells with efficiency of 24.2% is estimated at 5.79 ¢*Wp^{-1}, whereas the MSP would be 7.16 ¢*Wp^{-1}, compared to PERC cells, for which an efficiency of 23.1% is assumed, resulting in a CoO and MSP of 6.31 and 7.75 ¢*Wp^{-1}. The benefits of the higher efficiency of POLO BJ also propagate downstream to LCOE, as cells of this concept with the mentioned efficiency allow a LCOE under Southern European conditions integrated in monofacial glass–backsheet and bifacial glass–glass modules of 3.32 and 3.02 ¢*kWh^{-1}, respectively. This is 0.14 ¢*kWh^{-1} less than that of PERC cells. Other cost-reduction pathways were explored.

1 | Introduction

1.1 | The Global Context

The global photovoltaic (PV) industry is experiencing rapid and sustained growth, driven by decarbonization goals, technological advancements, and cost competitiveness. Annual PV installations surged by 87%, reaching 447 GWp in 2023-up from 239 GWp in 2022 [1]. This growth brought total global installed PV capacity to approximately 1.6 TWp by the end of 2023, representing a 60% increase compared to the 1 TWp milestone reached in 2022 [1]. Current statistics describe a newly installed PV capacity of 602 GWp, reaching a cumulative capacity of 2.2 TWp in 2025 [2].

Despite the global surge in PV deployment, expansion remains highly concentrated: In 2023, 80% of newly installed PV capacity was deployed in just ten countries, with China alone contributing 57% of global additions [3]. This concentration extends beyond deployment into manufacturing: China dominates the entire PV supply chain with a share of 92% of the polysilicon production, 98% of the wafer production, 91.8% of the cell production, and 84.6% of the module production [3, 4]. In 2024, the European Union achieved a record-breaking installation of 66 GWp of PV capacity, elevating its cumulative installed PV capacity to an estimated 338 GWp [5]. Future additions are expected to reach 91.9 GWp by 2030 [5]. However, despite this substantial deployment, Europe's manufacturing sector remains critically underdeveloped or nonexistent. Along the supply chain, and by 2023, only a 4% of the polysilicon production was located in Germany [4]. Furthermore, only a 2.3 GWp*a^{-1} existing cell production capacity is known to exist in Europe by 2024 [6]. This stark imbalance highlights a significant strategic vulnerability, as the EU continues to rely heavily on imports to meet its expanding solar energy needs, with the EU currently importing over 98% [7] of its solar modules, primarily from China. Germany alone, the largest PV market in the EU, added 16.2 GWp of PV capacity in 2024 [8] and surpassed 100 GWp [9] of cumulative installed capacity by early 2025. However, domestic manufacturing remains modest: Germany's total PV module manufacturing capacity is estimated at approximately 1.8 GWp*a^{-1} [6, 10] As for cell production, a domestic capacity of 200 MWp*a^{-1} is known to exist by 2025 [6].

In response, the European Commission adopted the Net-Zero Industry Act (NZIA) in April 2024, which aims to meet at least 40% of the EU's annual net-zero technology demand—including solar PV—through domestic production by 2030 [11].

Rebuilding resilient and competitive PV manufacturing capacities in Europe—especially in upstream segments like wafers and cells—will be crucial to ensuring energy sovereignty and long-term industrial competitiveness. Looking ahead, projections suggest that global annual installations could reach 1 TWp*a^{-1} by 2028, assuming sufficient investments and grid flexibility. However, meeting global renewable energy goals—such as tripling the renewable capacity by 2030—requires mobilizing over 12 trillion USD in global capital [1].

China has invested more than 50 billion USD since 2011—ten times more than in Europe [3]. Prices in the Chinese PV industry are highly competitive: In 2025, weekly spot prices for crystalline silicon mono PERC cells averaged approximately 2.6 ¢*Wp^{-1}, while TOPCon cells traded between 5.2 and 6.5 ¢*Wp^{-1} depending on technology and region [11]. This results in PV module production costs that are approximately 20% lower than in the United States and 35% lower than in Europe [3].

1.2 | Technological Alternatives

The aluminum back surface field (Al-BSF) cells were the standard of the industry until 2013. This cell concept was succeeded by the passivated emitter and rear cell (PERC) concept, which improved the Al-BSF concept by dielectric passivation on the rear side of the cell. PERC cells were described as early as 1984 with efficiencies of up to 18.7% [12] and claimed staggering efficiency records of 22.8% by 1989 [13]. However, PERC had challenges for commercialization due to the absence of processes to create its rear passivation layer, local contact opening, and local doping at industrial scale. These challenges were eventually overcome, opening the door for commercial cells with higher efficiencies and making PERC the workhorse of the industry. Predicted physical limitations of the PERC concept toward an efficiency of 24% urged the industry to find new alternatives [14]. More recently, the tunnel oxide passivated contact (TOPCon) has become the incumbent cell type in the market, making use of n-type silicon. However, other possibilities are the subject of research, which might have potential toward commercialization.

As a possible cell concept, we investigate the p-type back junction (BJ) solar cell featuring n^+-type passivating poly-Si on oxide (POLO) rear contacts. The POLO BJ concept has a very similar process flow to the well-known PERC concept; hence, the proven PERC production lines need only minor modifications. It has a leaner process flow compared to the current mainstream TOPCon concept, because it has fewer processing steps, including the absence of the boron diffusion. In addition, the POLO BJ cell concept allows up to 50% less Ag consumption compared to TOPCon, as it uses Al metallization on the front side instead. Finally, further innovations are possible, such as an upgrade to the POLO IBC (interdigitated back contact) concept with only one additional laser process step or an Ag-free metallization by replacing the Ag rear contact with Al.

The production sequence for POLO BJ cells from a p-type silicon wafer is shown in Figure 1. The sequence starts by cleaning the wafer and by creating a silicon oxide (SiO_2) layer via wet processing on both sides of the cell. Following this, a n^+-type poly-Si layer is deposited via low-pressure chemical vapor deposition (LPCVD), which is subsequently thermally oxidized. After this step, a front side SiO_2 removal is carried out either using a wet-chemical process or a laser-ablation process, while the SiO_2 at the rear protects the poly-Si layer during the following texturing step. This protective SiO_2 will be removed during the subsequent cleaning step. Front AlO_x/SiN_y and rear SiN_y passivation layers are deposited via plasma-enhanced chemical vapor deposition (PECVD). Finally, laser contact opening (LCO) on the front side and screen printing to form the contacts are performed to finish the production of the cell.

Although the POLO BJ concept has demonstrated high efficiencies of up to 24.2% in practice [15], it has not undergone commercial production so far.

Simulation-based roadmaps suggest efficiency gains of +1.0% (BJ) to +1.8% (IBC) over standard PERC [16]. Nevertheless, these models focus on efficiency gains but not on manufacturing costs. This knowledge gap is exacerbated by Europe's current lack of established POLO BJ manufacturing capacity. Without pilot production or demonstration factories, it is impossible to validate assumptions in technoeconomic models, such as equipment utilization rates, yield losses, raw material sourcing efficiencies, and vertical integration effects. As a result, key stakeholders, including industry consortia and policymakers, lack clarity on whether European-scale POLO BJ production can achieve cost competitiveness—especially against established Chinese manufacturing with its high economies of scale and cost efficiencies.

Some previous publications have addressed the manufacturing costs of PV cells; however, they focus on heterojunction solar cells [17], PERC cells [18, 19], or TOPCon cells [20, 21]. As the manufacturing costs of POLO BJ in Europe have not yet been assessed, this publication fills this research gap by performing a bottom-up cost analysis of the production of this cell concept and estimating the volume of the investments necessary for establishing a production plant of the cell concept with a capacity of 5 GWp*a^{-1} in Germany. Cost differences between two alternative manufacturing sequences using either a wet chemical etching or laser ablation for single-side SiO_2 removal were also assessed. The main metrics assessed in this analysis were the cost of ownership (CoO) and the minimum sustainable price (MSP) of POLO BJ cells. Additionally, assuming that these cells are integrated into modules and PV systems, the levelized cost of electricity (LCOE) of electricity produced with POLO BJ cells was also estimated. All these calculations were contrasted against the production of PERC cells under similar assumptions.

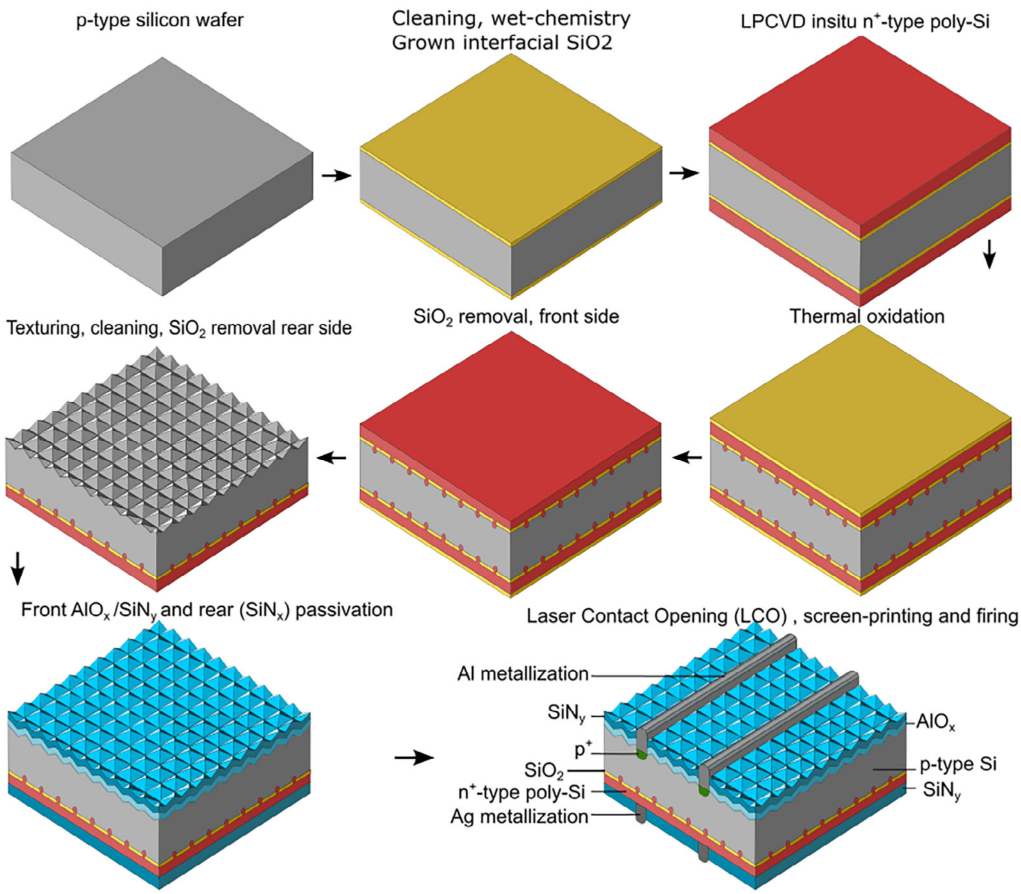

FIGURE 1 | Schematic representation of the production and final POLO BJ cells (not at scale). *Source:* Own figure.

2 | Methodology

As a first step in the modeling, a production capacity of 5 GWp*a^{-1} of POLO BJ PV cells was assumed as the basis for the following calculations. This production capacity was considered due to the scale of current facilities for PV cell production, like the one expected to be commissioned by the French company Carbon Solar by 2026 with a production capacity of 5 GWp*a^{-1} [22]. The yearly installation of PV systems in Germany totaled 16.2 GWp in 2024 [8], so a plant of this size could supply around 30% of the local demand. Current cell production plants under construction and known to the authors have capacities of up to 30 GWp*a^{-1} [23]. Although plants of these sizes are under construction, the base calculations were made for 5 GWp*a^{-1} on a conservative basis comparing afterward with the results of a 30 GWp*a^{-1} plant.

2.1 | Features of the POLO BJ and PERC Concepts

For the calculation, a power conversion efficiency of 24.2% was assumed as the baseline for POLO BJ cells. The plant capacity and correspondingly tool number and footprints were calculated assuming that the cells produced industrially have an efficiency of 24.2% for POLO BJ cells according to values reached in practice with this cell concept on a M2 format [15]. The wafer format assumed for the production of POLO was M12/G12. Efficiency variations were also examined to understand the effect of this parameter in the CoO, MSP, and LCOE. A value of 25% was assumed as the top efficiency for POLO BJ, close to the maximum efficiency expected for this concept. For this analysis, the plant's annual cell throughput was kept constant, while the peak power output increased proportionally with cell efficiency.

For a fair comparison of the POLO BJ against other concepts, the production of PERC cells was also modeled with the same production scale (5 GWp*a^{-1}) and wafer format (M12/G12). For PERC, a maximum efficiency of 23.1% was assumed, in line with the maximum efficiency reported for spot prices in the market [24]. This efficiency benchmark was used to compare the results obtained for POLO BJ in both considered production sequence variations (assumed as 24.2%). The same geographical scope, same base prices of chemicals, and tool costs were assumed for PERC, with differences only in the process steps required for cell production and the resulting power conversion efficiency.

A description of the production sequence assumed for the production of POLO BJ and PERC is shown schematically in Figure 2. The production sequence for POLO BJ was built upon the process flow described by Min et al. [15]. As seen in Figure 2, the distinction between the wet-chemistry process (POLO BJ-W) and the laser-ablation process (POLO BJ-L) is the one side removal step occurring after thermal oxidation (Step 5). In the wet-chemistry process, the one-side removal is assumed to take place using hydrofluoric acid in a chemical bench, whereas in the laser-based process, a laser beam ablates the SiO_2 from the surface of the cell. Both processes are assumed to yield comparable results. The production sequence shown for PERC in Figure 2

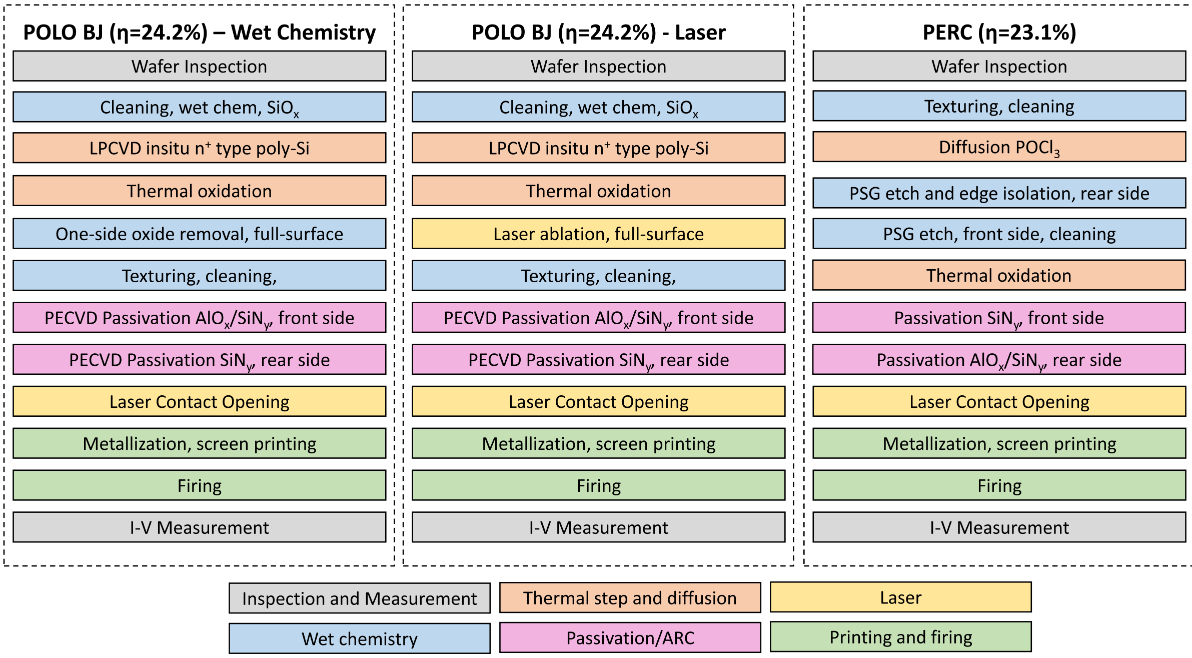

FIGURE 2 | Comparison of the assumed production sequence for POLO BJ using wet chemistry (POLO BJ-W), POLO BJ using laser ablation (POLO BJ-L), and PERC. *Source:* Own figure.

was taken from the description of industrial established production sequences and publications on the subject [18, 25–28]. When the production sequences for POLO BJ and the production sequence for PERC are compared, one additional step can be identified for POLO BJ; namely, LPCVD in situ n^+-type poly-Si followed. Additionally, the production sequence of POLO BJ lacks the phosphorous oxychloride ($POCl_3$) diffusion step necessary to create the emitter in the PERC concept. This step is followed by phosphorous-silicon glass (PSG) removal and etch insulation on the rear side and PSG removal on the front side. Moreover, there are also differences in the passivation layers: The front passivation for PERC consists of a SiN_y passivation, whereas the rear passivation includes AlO_x and SiN_y—different from the POLO BJ concept, for which the front passivation is AlO_x/SiN_y and the rear passivation is SiN_y. Also, differences in the order of the production sequence are noticeable. For instance, the texturing step is second in the PERC production sequence and sixth in the POLO BJ sequence, and a thermal oxidation step follows PSG etching steps in the PERC processing.

2.2 | CoO

The methodology of CoO was used to estimate the cost of producing POLO BJ cells. To carry out the calculations, a Microsoft Excel template based on a template and guidelines for the estimation of the total cost of ownership (TCO) originally prepared by SEMI and VDMA was used [29]. The original template considering a single production step was adapted to carry out calculations stepwise for the entire production sequence of POLO BJ cells [30]. Estimations on the unitary capital cost of the tools and their throughput, footprint, quantities of chemicals and gases, electricity consumption, and compressed air were collected from tool manufacturers. When the data was not available, data from public sources or secondary data from previous publications was assumed as input for the calculations [17–19]. Finally, as the throughput of single tools is not sufficient to meet the yearly capacity fixed for the plant, several tools for single steps in the sequence were assumed to operate in parallel, so the targeted output of 5 GWp*a^{-1} with cells with an efficiency of 24.2% could be achieved. This resulted in a model built for POLO BJ, with a total of 480 different variables to carry out the different calculations. A summary of key assumptions for cell production can be found in Tables S1, S2, S3, and S4. Upscaling of the production and the impact over different inputs was modeled according to Equation S1 and based on the exponential factors summarized in Table S6.

2.3 | MSP

From the consumer's point of view, prices—rather than production costs—are the relevant factor when evaluating an energy technology. Moreover, information on prices and not on production costs is often publicly available. As an approach to integrate the capital costs, operational expenditures, and taxes associated with the production of PV cells into the price and to compare the results obtained here on a fairer basis to those available in the market, the MSP for the PV cells was calculated. The approach followed here was previously described by Powell et al. and was used to calculate the MSP of the POLO BJ cells in comparison with PERC cells [31]. An average of 12.5% of operative expenditures including sales and administration (S&A) and research and development (R&D) was assumed conservatively by considering that the ratio between revenue and operative expenses for the company Canadian Solar between 2020 and 2023 fell into the range between 10.9% and 13.5% [32]. Moreover, a net working capital (NWC) of 3 months considering the operational expenditures and the variable production costs were also assumed for the initial investment and recovered by the end of the tool depreciation time. A 7-year depreciation time for the tools and 20 years for the facilities were also considered in the calculations. A nominal weighted average cost of capital (WACC) of 8%, as a representative value for industrial manufacturing, was assumed [33]. The main assumptions made for the calculations of the MSP are summarized in Table S5, and a description of the method can be also found under Section S1.4.

2.4 | LCOE

The LCOE of using the different cell alternatives was also computed and analyzed for utility scale plants, assuming a 5 MWp capacity plant. Two types of modules were considered, namely, monofacial modules built with front 3.2 mm glass and rear backsheet and bifacial modules built with front 2.0 mm glass and 2.0 mm rear glass. As a first step, high-level estimates for the production costs of glass–backsheet and glass–glass modules were carried out based on the spot price of the materials [34], for both types of modules. Then, to account for the gap between material costs and final product price, the sum of the material costs was multiplied by a markup factor obtained by comparing the material production cost and the MSP obtained for the production of cells (see Section S1.5). Based on this, the estimated production costs of modules were calculated and further used for the estimation of the capital costs for PV systems. Further cost items for system integration, such as inverter, racking and mounting, grid connection, cabling and wiring, safety and security, monitoring and control, mechanical installation, electrical installation, inspection, installation margin, installation financing costs, system design, permitting, and customer acquisition, were also integrated according to data obtained from recent studies on the installation costs of renewable energies [35]. Further on, two installation locations were analyzed and considered for the PV system electricity output, namely, Germany and Spain, the latter representative of Southern European conditions. For Germany, a global horizontal irradiance (GHI) of 1050 kWh*m^{-2}*a^{-1} and an irradiation on the module plane of 1250 kWh*m^{-2}*a^{-1} were assumed, whereas for Spain, GHI of 1700 kWh*m^{-2}*a^{-1} and irradiation on module plane of 1870 kWh*m^{-2}*a^{-1} were assumed. For bifacial operation, an albedo of 0.2 was assumed. Moreover, temperature coefficients of −0.295%*°C^{-1} and −0.34%*°C^{-1} were assumed for POLO BJ [36] and PERC cells [37], respectively. These values were used to carry out temperature corrections in the efficiency. Cell-to-module (CTM) losses of −0.9% were assumed in all cases [21], and additionally, CTM geometrical losses were also considered by obtaining the ratio between the total area of the cells in a module and the total module area, resulting in a factor of 0.94. Other losses in the output, such as soiling (2%), shading (3%), mismatch (2%), wiring (2%), connections (0.5%), light-induced degradation (1.5%), nameplate rating (1%), and availability (3%), were also factored in, resulting in a performance ratio of 0.86 [38]. A degradation of 1.5% of module performance was assumed in the first year, and 0.5%/year was assumed in the further years. A system lifetime of 25 years was considered for the modules and 15 years for the inverters, therefore requiring a replacement of this component after 15 years of installation. A nominal WACC for LCOE calculation of 5% was assumed. A 1% CAPEX*a^{-1} operational expenditure (OPEX) was considered in the LCOE calculation. Details on the assumptions for the calculation of the LCOE can be found in Tables S7, S8, S9, and S10. Furthermore, the equation used for the calculation of the LCOE can be found under Section S1.6.

2.5 | Geographical Scope

The geographical scope assumed for the analysis considers Germany as production site of the cells. This choice affects the electricity prices, the labor costs, and the income taxes, which directly influence the MSP calculated for the cells. According to this, the electricity industrial price of 0.217 USD*kWh^{-1} considered as basis for the 330 MWp*a^{-1} pilot plant was used as reference and corrected using Equation (1) to obtain the electricity price for a 5 GWp*a^{-1} plant, resulting in a value of 0.181 USD*kWh^{-1}. Yearly labor costs per full-time employee (FTE) of 68,000 USD*FTE^{-1}*a^{-1} were assumed according to statistics [39]. Moreover, a 15% corporate federal income tax, with a solidarity surcharge of 5.5% resulting in a total tax rate of 15.825%, was assumed [40]. In addition, a trade tax of 3.5% with a collection rate of 450%, therefore resulting in a local trade tax of 15.75%, was considered for the MSP calculations. Therefore, the total corporative income tax considered for the calculation of the MSP was the addition of the corporate federal income tax and the local trade tax, which sum up 31.575%.

3 | Results

3.1 | Plant General Features and Workforce

Table 1 compares the main features obtained for the two options under consideration for POLO BJ and for PERC cells. The number of tools necessary to reach the capacity of 5 GWp*a^{-1} is similar for all the alternatives, requiring 157 tools for PERC, compared to 156 and 155 tools for POLO BJ-W and POLO BJ-L, respectively. Because the assumed efficiency for PERC cells is 23.1%, lower than the 24.2% assumed for POLO BJ cells, the resulting power per piece is 10.19 Wp*cell^{-1} for PERC and 10.67 Wp*cell^{-1} for POLO BJ. Therefore, a higher number of PERC cells must be produced, to achieve the assumed production of 5 GWp*a^{-1}. Parameters like the cell loss, the clean room, industrial hall, and land area are also influenced by the number of steps, being similar for all the alternatives. Finally, the

TABLE 1 | Main plant features and workforce for the production of POLO BJ-W, POLO BJ-L, and PERC cells.

Item	Unit	POLO BJ-W	POLO BJ-L	PERC
Yearly output	GWp*a^{-1}	5.0	5.0	5.0
Cell efficiency	%	24.2	24.2	23.1
Power per cell	Wp*cell^{-1}	10.67	10.67	10.19
Production steps	—	12	12	12
Number of tools	—	156	155	157
Wafer input	wafers*h^{-1}	55,485	55,485	58,795
Cell output	cell*h^{-1}	55,250	55,250	57,402
Cell loss	%	2.34%	2.34%	2.35%
Clean room area	m^2	17,548	17,242	17,255
Industrial hall area	m^2	21,057	20,690	20,706
Land area	m^2	42,115	41,381	41,413
Workforce	FTE	702	698	706

workforce necessary for the production of POLO BJ cells is lower than for PERC cells, due to the higher number of tools necessary for the production of the latter concept, mainly due to the higher number of cells that require to be processed upstream, resulting in an additional tool compared to POLO BJ-L and two tools compared to POLO BJ-W. Overall, a workforce of 698 and 702 FTE would be necessary for the operations at the plant producing either POLO BJ-W or POLO BJ-L cells, and a slightly higher workforce of 706 FTE would be necessary for the PERC-producing plant.

3.2 | Investment Costs

The investment costs calculated for the construction of the production facilities of POLO BJ cells in its two alternative sequences and of PERC cells as well as the NWC are shown in Figure 3. The investment costs in tools, clean room, industrial hall, and land area total 182.1, 177.5, and 171.0 million USD for POLO BJ-W, POLO BJ-L, and PERC production lines, respectively. Thus, the investment costs for a POLO BJ-W production facility excluding NWC exceed the investment costs of a production line via the POLO BJ-L sequence by 4.6 million USD. Compared to PERC, the investment costs before NWC for POLO BJ-W and POLO BJ-L exceed the investment costs of a plant producing PERC cells by 11.1 and 6.5 million USD, respectively. This stems mainly from the additional costs in tools required for the production of POLO BJ. The specific investment costs before NWC for the production plants would be 36.4, 35.5, and 34.2 USD*kWp^{-1}*a^{-1} for the POLO BJ-W, POLO BJ-L, and PERC production facilities, respectively.

Figure 3 also shows that the NWC has an important share of the investment. The NWC would total 82.1, 79.3, and 87.7 million USD for the POLO BJ-W, POLO BJ-L, and PERC production plants, therefore being slightly lower in the POLO BJ-L case. If the NWC is included in the initial investments, then the investment costs reach an absolute value of 264.2, 262.2, and 258.7 million USD and a specific value of 52.8, 51.4, and 51.7 USD*kWp^{-1}*a^{-1} for POLO BJ-W, POLO BJ-L, and PERC producing plants, respectively. Based on this, the laser-ablation process has a slightly lower investment-specific cost before NWC, and this effect is amplified after NWC due to reduced operational expenditures compared to the POLO BJ-W sequence. Consequently, the specific investment in a POLO BJ-L production plant would be 0.7% lower compared to a PERC production plant. Finally, the NWC represents between 31.1% and 33.9% of the total investment. Although the NWC is assumed to be recovered after the depreciation of the production tools, this initial capital is necessary to operate the facility and therefore included in the investment assessment.

3.3 | Variable and Operational Costs

The variable costs and operational costs are shown in Figure 4. Overall, the estimated variable costs after considering the operating expenses total 328.6 million USD*a^{-1} for the POLO BJ-W alternative, 317.3 million USD*a^{-1} for the POLO BJ-L alternative, and 350.7 million USD*a^{-1} for the PERC alternative. An important share of the variable costs can be allocated to the wafers and the materials used for the production process, followed by labor and utilities. Minor contributions are made in all cases by yield loss costs as well as waste management. In general, the variable costs of PERC cells in terms of wafers and materials result higher than the costs estimated for both POLO BJ-W and POLO BJ-L processes. The main reason for this is the higher output necessary for the production of PERC, which exceeds that of POLO BJ due to the lower efficiency of PERC. When it comes to the labor costs, all the alternatives have similar labor costs corresponding to the similar workforce necessary in each case. Finally, the operating expenses for PERC are comparatively higher than those for POLO BJ-W and POLO BJ-L concepts because these were assumed as a fraction of the revenue necessary to compensate the variable costs, taxes, and interest. As the variable costs result higher for PERC, the sum of variable and operating costs results higher for the PERC alternative.

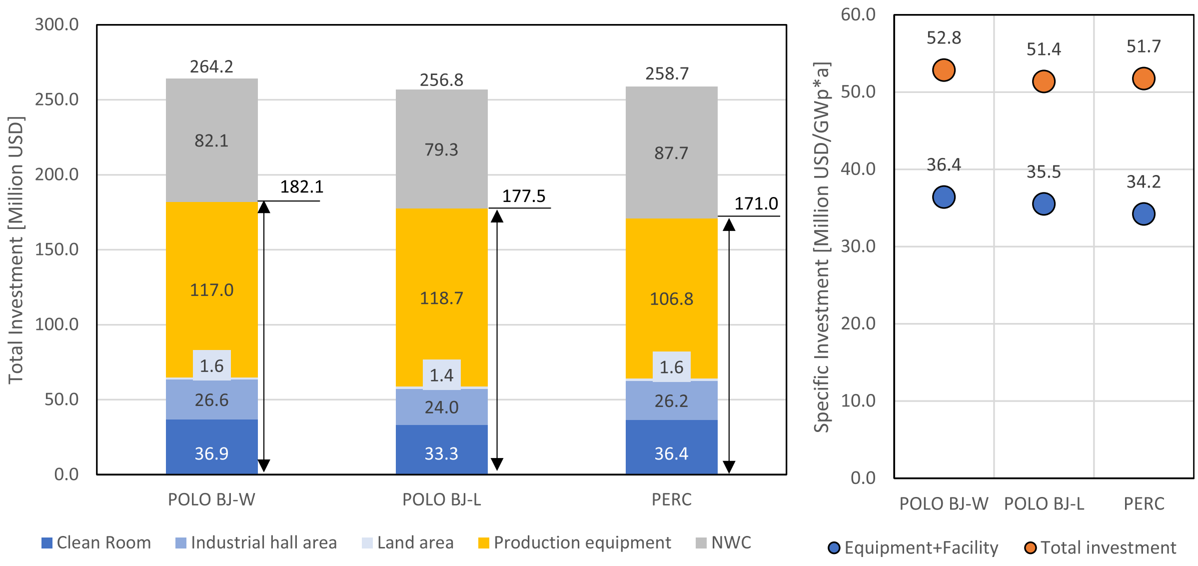

FIGURE 3 | Left: total investment costs. Right: specific investment cost for the POLO BJ-W, POLO BJ-L, and PERC production processes with an annual output of 5 GWp. *Source:* Own figure.

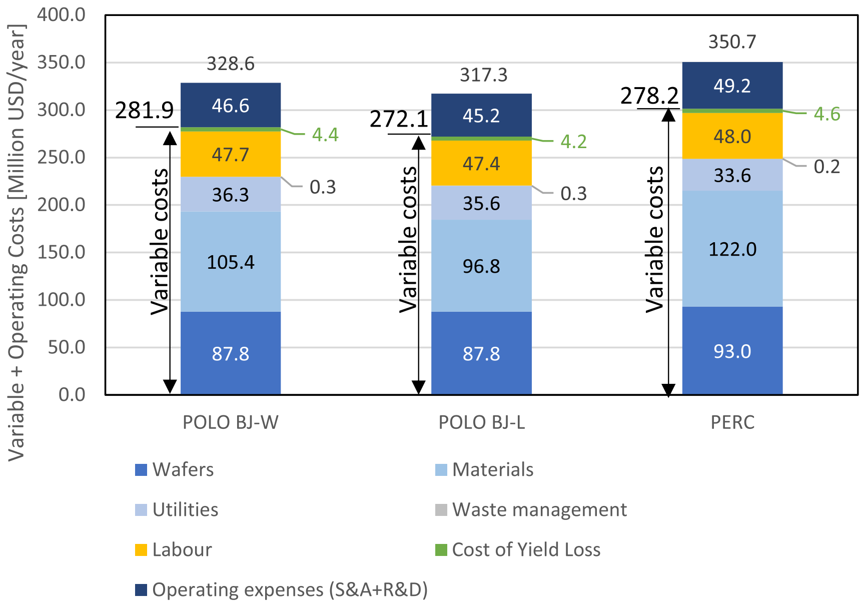

FIGURE 4 | Variable and operating costs for the POLO BJ-W, POLO BJ-L, and PERC production processes with an annual output of 5 GWp. Depreciation, taxes, and debt interest are not shown in the figure. *Source:* Own figure.

3.4 | CoO

The results for the CoO are summarized in Figure 5 for the two considered production sequences for POLO BJ and for PERC. As baseline, the production of PERC results in a CoO of 6.31 ¢*Wp^{-1}. For the alternatives POLO BJ-W and POLO BJ-L, a CoO of 5.98 and 5.79 ¢*Wp^{-1} was calculated, respectively. Compared to PERC, the CoO of the POLO BJ-W is 5.3% lower than the value determined for PERC. For POLO BJ-L the CoO is in turn 8.3% lower than the CoO calculated for PERC. As shown in Figure 5 in general for all the alternatives analyzed, the main contribution to the CoO results from the materials and consumables used in the production process. For PERC, POLO BJ-W and POLO BJ-L, the material and consumable costs are estimated to make 2.41, 2.09, and 1.92 ¢*Wp^{-1}, respectively. Therefore, this cost item has a share of between 33.1% and 38.3% of the CoO in all the cases. The lower costs for the POLO BJ-L compared to the POLO BJ-W alternative arise from the lower chemical consumption in the one-side SiO_2 removal (Step 5), as in the POLO BJ-L alternative, this process is carried out using a laser. The wafer costs are the second largest contributor to the costs, accounting for 1.73 ¢*Wp^{-1} for the POLO BJ alternatives and 1.82 ¢*Wp^{-1} for the PERC, the latter being higher due to the lower efficiency assumed for this alternative. In third place, the labor costs contribute with around 0.95–0.94 ¢*Wp^{-1} of the CoO for the POLO BJ-W and POLO BJ-L and 0.95 ¢*Wp^{-1} for PERC, being therefore similar in all the cases. Utility costs are in fourth place with 0.66, 0.72, and 0.71 ¢ *Wp^{-1} for PERC, POLO BJ-W, and POLO BJ-L, respectively. The additional expense for POLO BJ production sequences stems especially from the additional thermal steps demanding additional electricity for the production sequence, being slightly lower in the

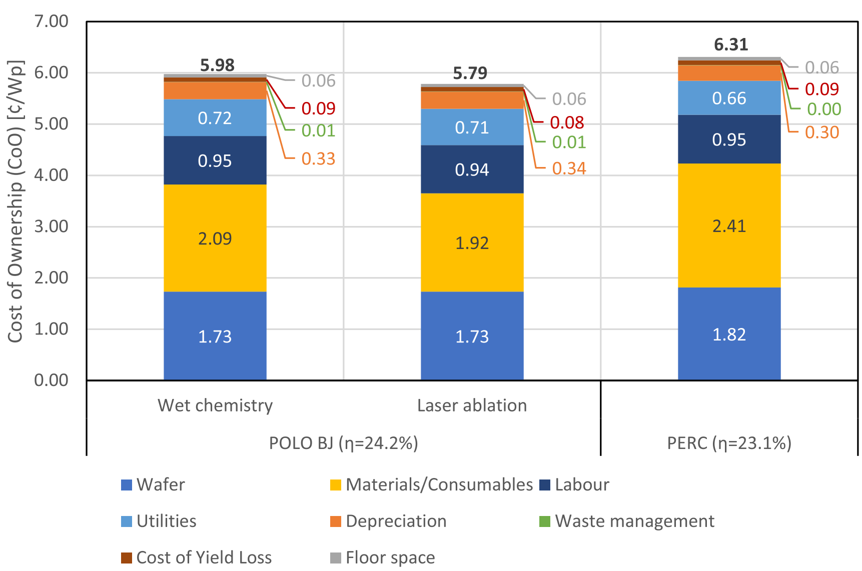

FIGURE 5 | Cost of ownership (CoO) for the POLO BJ-W (wet chemistry), POLO BJ-L (laser ablation), and PERC cells. *Source:* Own figure.

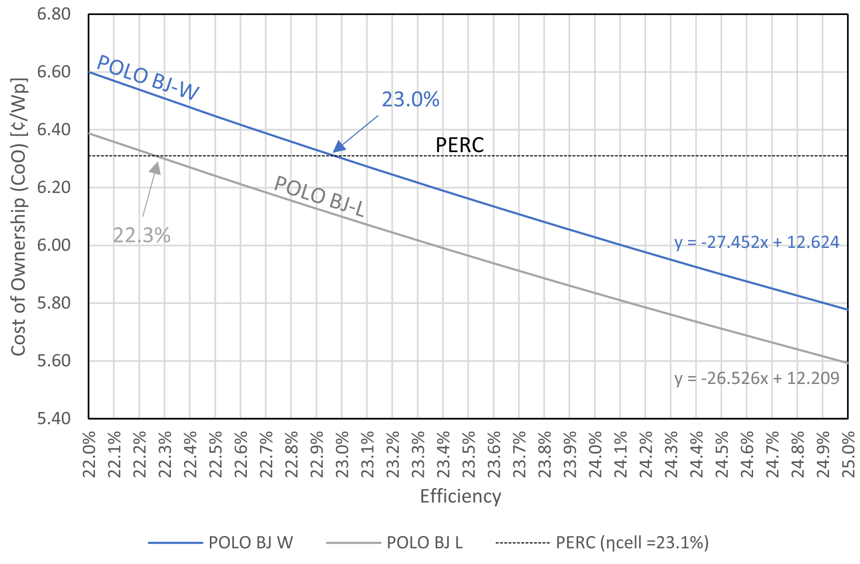

FIGURE 6 | Impact of the cell efficiency on the cost of ownership (CoO) for the POLO BJ-W (wet chemistry) and POLO BJ-L (laser ablation) compared to the CoO of PERC cells ($\eta = 23.1\%$). *Source:* Own figure.

POLO BJ-L case due to the lower electricity consumption in one-side ablation step under this alternative compared to the wet-chemical process. In fifth place, the depreciation of tools and facilities adds 0.30 ¢*Wp^{-1} for PERC and 0.33 and 0.34 ¢*Wp^{-1} for POLO BJ-W and POLO BJ-L, respectively. Additional costs in the tools for POLO BJ sequences increase these costs (see Figure 5). Finally, other items like waste management, floor space, and the cost of yield loss add in total 0.15, 0.16, and 0.15 ¢*Wp^{-1} to the CoO of PERC, POLO BJ-W, and POLO BJ-L, respectively.

Figure 6 shows the CoO as a function of the efficiency for the POLO BJ-W and POLO BJ-L alternatives. In particular, POLO BJ-L results in lower CoO compared to PERC after an efficiency of 22.2% is achieved, whereas the same occurs for POLO BJ-W when the efficiency achieved by cells produced by this sequence exceeds 23.0%. In addition, and according to the obtained slopes, an improvement of 0.1% in the efficiency leads to a reduction in the CoO for POLO BJ-W of 0.026 and 0.025 ¢*Wp^{-1}. Therefore, assuming that the POLO BJ cells can be produced with the assumed processes and that an efficiency of 24.2% is achieved with this production sequence, the POLO BJ cells have CoO values under those of PERC with an efficiency of 23.1%.

Additional results per cell or on area basis can be found in Table S11.

3.5 | MSP

The results for the MSP are summarized in Figure 7. The lowest MSP was calculated for POLO BJ-L cells and resulted in 7.16 ¢ *Wp^{-1}, followed by the MSP for POLO BJ-W cells with 7.38 ¢ *Wp^{-1} and finally by the MSP of PERC cells with 7.75 ¢*Wp^{-1}. Therefore, the MSP of POLO BJ-L and POLO BJ-W is 7.6 and

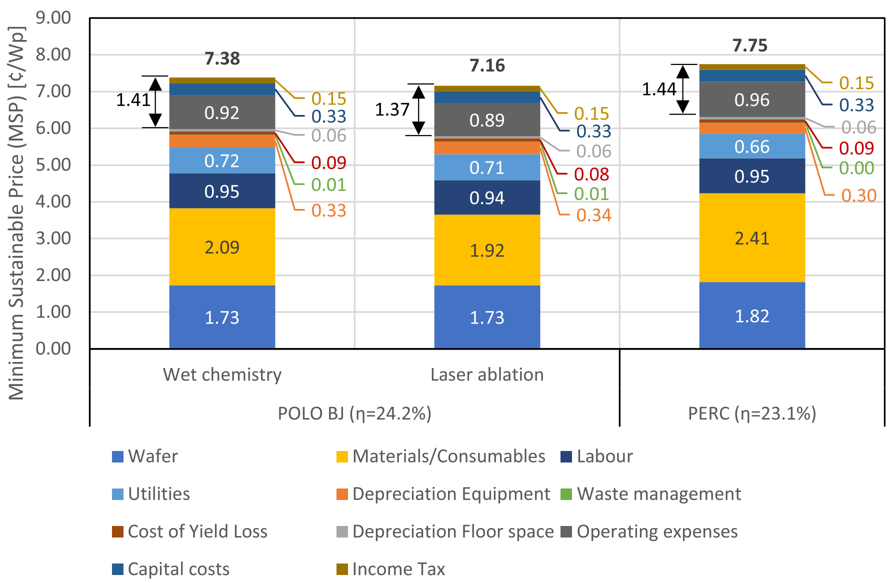

FIGURE 7 | Minimum sustainable price (MSP) of POLO BJ cells produced with the wet-chemistry and laser-ablation processes in comparison with PERC cells. *Source:* Own figure.

4.7% lower than the MSP of PERC cells. In contrast with Figure 5, the MSP adds the operating expenses including S&A and R&D, which add between 0.89 and 0.96 ¢*Wp^{-1} in all the analyzed cases. Moreover, the income tax adds for all the alternatives around 0.15 ¢*Wp^{-1} and the capital costs around 0.33 ¢*Wp^{-1}. All in all, these items sum in addition to the CoO around 1.37, 1.41, and 1.44 ¢*Wp^{-1} and result in a share of 19.2%, 19.1%, and 18.6% of the MSP estimated for the POLO BJ-L, POLO BJ-W, and PERC cells, respectively. As also seen in Figure 7, the results for POLO BJ-W are higher compared to POLO BJ-L mainly due to higher material costs, operating expenses, and in addition small differences in the contributions of other items. Materials and consumables is also the main item contributing to the difference between PERC and POLO BJ-L cells, making a difference of 0.49 ¢*Wp^{-1} between the alternatives, which is partially compensated with the lower utilities costs for PERC, reducing the MSP of the latter alternative in 0.05 ¢*Wp^{-1} compared to POLO BJ-L.

Figure 8 shows the impact of the variation of the efficiency in the MSP for the POLO BJ cells. Cells produced under the POLO BJ-L sequence have lower MSP than PERC after an efficiency of 22.4% is achieved, whereas for the POLO BJ-W alternative, the cells result in lower MSP if the efficiency achieved is higher than 23.1%, thus higher than the efficiency value assumed for PERC. In addition, the slopes shown in Figure 8 reveal that the MSP decreases at a higher pace than the CoO, decreasing at a rate of 0.0327 and 0.0333 ¢*Wp-1 for cells produced using the POLO BJ-L and POLO BJ-W alternatives, respectively. Additional results per cell or on area basis can be found in Table S12.

3.6 | LCOE

Going one step further and adding the perspective of a final consumer, this section presents the results of the LCOE, which are calculated assuming that cells of different concepts are integrated into modules and complete PV systems. The LCOE results of PV systems using modules fitted with POLO BJ-W, POLO BJ-L, and PERC cells in monofacial and bifacial configurations are presented in Figure 9. A comparison of the LCOE results for the two explored locations—Germany and Spain—is shown as well. In general, the bifacial glass–glass modules—represented with circles—result in a lower LCOE compared to the monofacial glass–backsheet modules shown with squares, even after considering that such modules are more expensive to produce than monofacial glass–backsheet modules. The higher cost for glass–glass modules results from the additional cost of using a front and rear glass, rather than a front glass and a rear backsheet. Considering the results for the systems using monofacial glass–backsheet modules, the LCOE obtained for systems installed in Germany and using PERC cells was 5.19 ¢*kWh^{-1}. The use of higher efficiency POLO BJ-W cells allows a reduction down to 5.00 ¢*kWh^{-1}, further reduced to 4.98 ¢*kWh^{-1} when POLO BJ-L cells are considered. For Spain, the LCOE was estimated at 3.46, 3.34, and 3.32 ¢*kWh^{-1} for systems using modules containing PERC, POLO BJ-W, and POLO BJ-L cells. The LCOE results for PV systems with bifacial PERC-based modules in Germany are 4.78 ¢*kWh^{-1}, compared to 4.60 ¢*kWh^{-1} obtained for systems with modules containing POLO BJ-W cells and 4.58 ¢*kWh^{-1} for systems with modules based on POLO BJ-L cells. Further reductions are obtained assuming the installation of the systems in Spain, with LCOE values of 3.16, 3.04 and 3.02 ¢*kWh^{-1} when systems with modules built with PERC, POLO BJ-W, and POLO BJ-L are assumed, respectively. Thus, in general, a reduction of the LCOE of up to 0.20 ¢*kWh^{-1} for Germany or up to 0.14 ¢*kWh^{-1} for Spain can be expected when POLO BJ cells are considered instead of PERC cells.

A summary of the contributions to the LCOE by different items related to PV systems considering the different module and cell types and assuming environmental conditions in Spain (Southern Europe) can be found in Figure 10, where it can be seen that the modules contribute to between 0.60 and 0.61 ¢*kWh^{-1} for monofacial glass–backsheet modules based on POLO BJ-L and POLO BJ-W cells and 0.65 ¢*kWh^{-1}for monofacial glass–backsheet modules based on PERC cells. Compared to the total

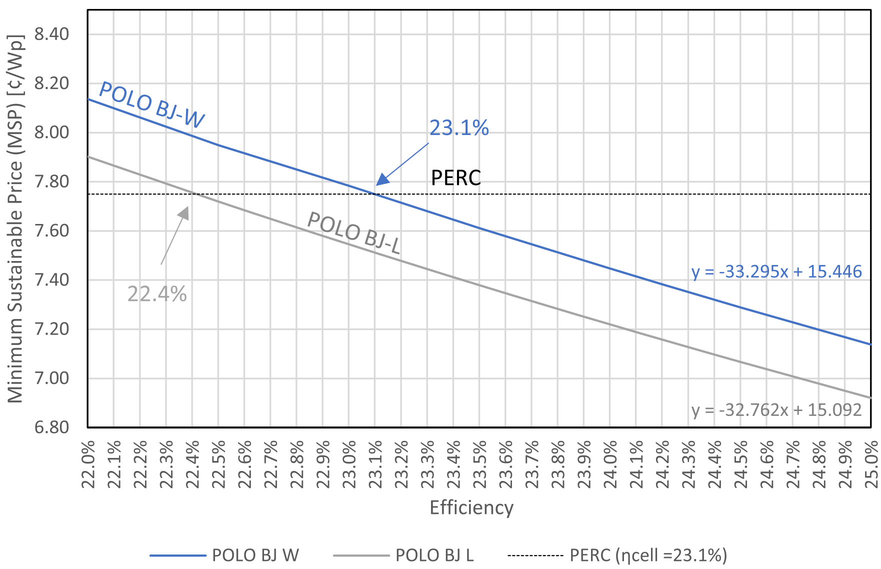

FIGURE 8 | Impact of the cell efficiency in the minimum sustainable price (MSP) for the POLO BJ-W (wet chemistry), POLO BJ-L (laser ablation) compared to the CoO of PERC cells ($\eta = 23.1\%$): *Source:* Own figure.

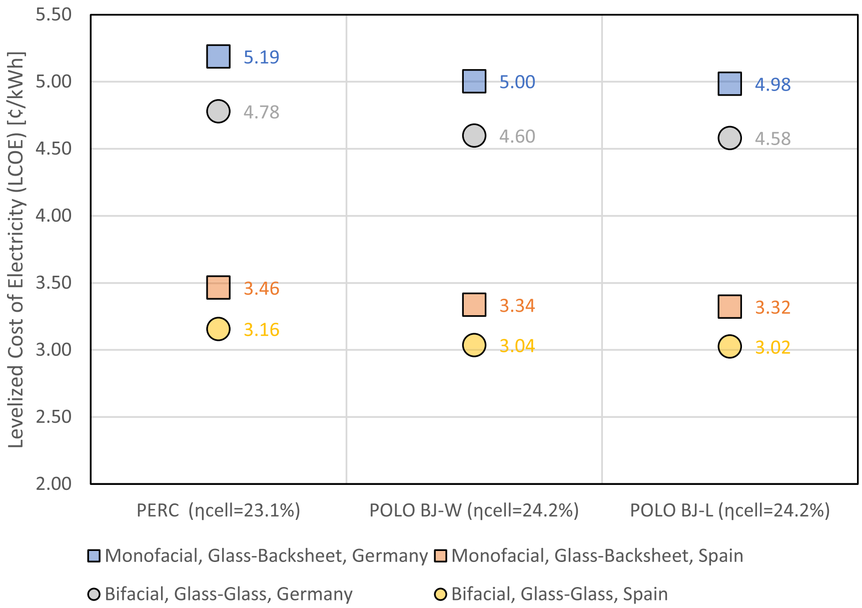

FIGURE 9 | Comparison of the levelized cost of electricity (LCOE) for systems using monofacial glass–backsheet modules and bifacial glass–glass modules built with POLO BJ-W ($\eta_{cell} = 24.2\%$), POLO BJ-L ($\eta_{cell} = 24.2\%$), and PERC cells ($\eta_{cell} = 23.1\%$). A global horizontal irradiance (GHI) of 1700 kWh/m^2*year and an irradiance in plane of array of 1870 kWh/m^2*year found Spain, whereas the same parameters were assumed as 1050 and 1250 kWh/m^2*year in Germany. In addition, other inputs for the calculation of LCOE were also adapted according to the location. *Source:* Own figure.

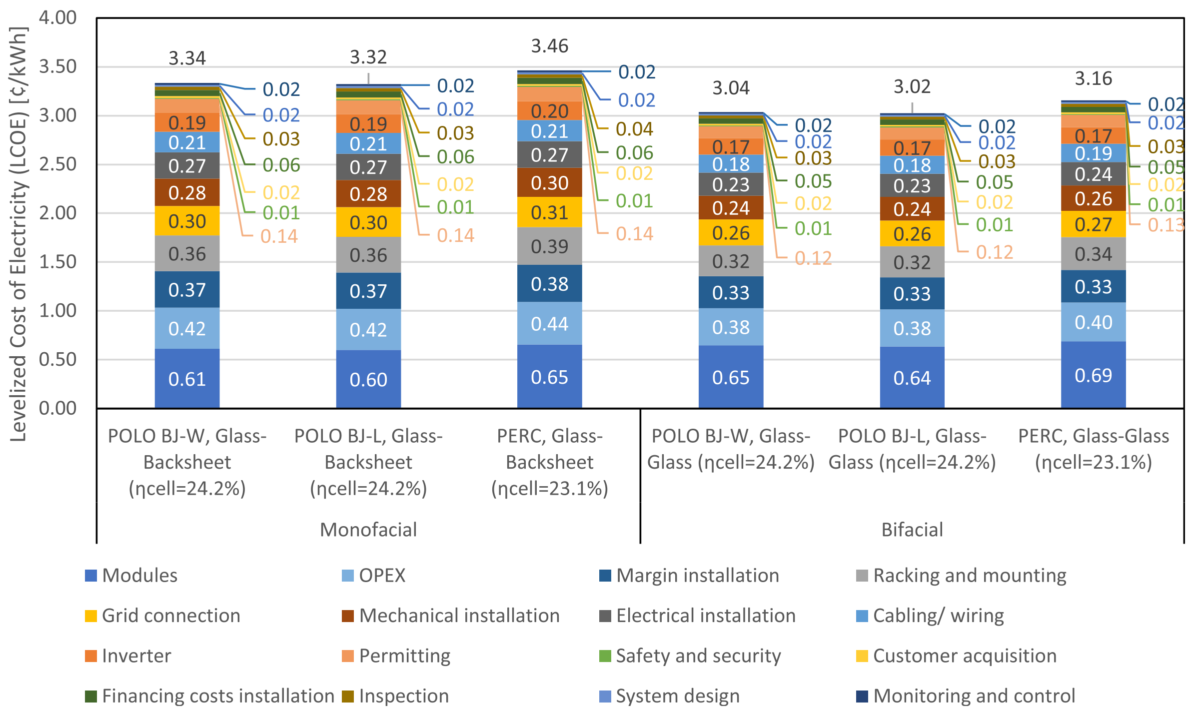

FIGURE 10 | Contributional analysis of the levelized cost of electricity (LCOE) for systems using monofacial glass–backsheet modules and bifacial glass–glass modules built with POLO BJ-W ($\eta cell = 24.2\%$), POLO BJ-L ($\eta cell = 24.2\%$), and PERC cells ($\eta cell = 23.1\%$). A global horizontal irradiance (GHI) of 1700 kWh/m^2*year and an irradiance in plane of array of 1870 kWh/m^2*year found in the south of Europe (Spain) are assumed in the analysis. *Source:* Own figure.

LCOE in each case, this makes a share of between 18.1% and 18.7% of the total values. Slightly higher values are seen for bifacial glass–glass modules, for which the contribution of the module increases to 0.64 and 0.65 ¢*kWh^{-1} when POLO BJ-L and POLO BJ-W and 0.69 ¢*kWh^{-1}when PERC-based modules are considered. Despite the higher costs of modules, the higher yield expected for this type of modules reduces the contributions of other items. This leads to an overall lower LCOE of bifacial glass–glass alternatives compared to monofacial glass–backsheet alternatives.

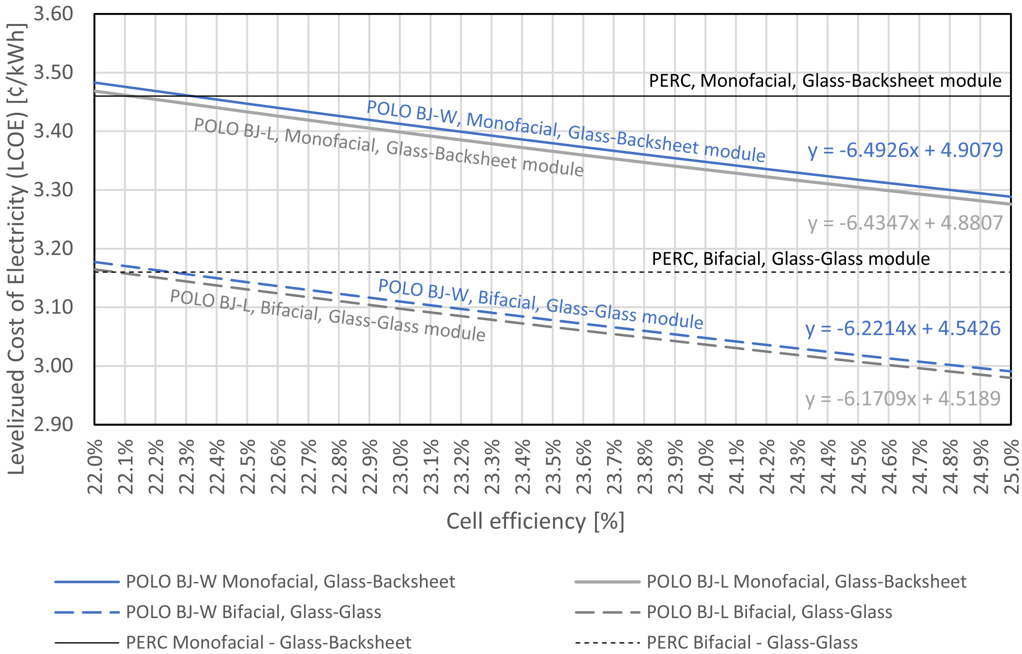

FIGURE 11 | Impact of the cell efficiency on the levelized cost of electricity for the POLO BJ-W (wet chemistry), POLO BJ-L (laser ablation) compared to the CoO of PERC cells ($\eta = 23.1\%$) in typical Southern European conditions (Spain). The effect is shown considering the use of monofacial glass–backsheet modules with lower electricity output and comparatively lower cost (continuous lines) and bifacial glass–glass modules with higher electricity output and comparatively higher costs (dashed lines). *Source:* Own figure.

The effect of the cell efficiency on the LCOE is shown for Southern European conditions (Spain) in Figure 11, where the LCOE of systems built with POLO BJ-W and POLO BJ-L cells distances—both for monofacial and bifacial modules—from the PERC alternatives as the efficiency of the cells increases. According to the linear regressions shown in Figure 11, an increase of 1% in cell efficiency would result in a reduction of 0.061 ¢*kWh^{-1} in the LCOE for the monofacial glass–backsheet POLO BJ-W and POLO BJ-L alternatives and 0.059 ¢*kWh^{-1} for the bifacial glass–glass POLO BJ-W and POLO BJ-L alternatives. Slightly lower slopes are estimated for systems built with POLO BJ-L cells compared to systems built with POLO BJ-W cells because of the smaller changes in MSP observed for this sequence. For bifacial systems, LCOE values under 3.00 ¢*kWh^{-1} are expected if cell efficiencies beyond 24.9% are obtained. A similar contributional assessment for which the conditions in Germany were assumed can be consulted in Figure S5.

4 | Discussion and Limitations

4.1 | Technical Pathways for the Reduction of CoO, MSP, and LCOE

The effect of the variation of cell efficiency was shown in the previous section. In the following section, the plant scale and the reduction of silver content will be addressed as possible alternatives for reducing further the CoO, MSP, and LCOE.

4.1.1 | Plant Scale

There is evidence that currently some manufacturers of PV cells are building bigger plants. The company Longi reported in its annual reports in 2024, the construction of a 30 GWp*a^{-1} plant [23]. Assuming a similar capacity of 30 GWp*a^{-1} for a POLO BJ-L plant leads to a reduction in the CoO and MSP from 5.79 and 7.16 ¢*Wp^{-1} with the 5 GWp*a^{-1} plant to a CoO and MSP of 5.21 and 6.37 ¢*Wp^{-1} after assuming economies of scale for the tools, facilities, material inputs, and utilities (see Section S1.2 and Figures S3 and S4). Therefore, scaling up the yearly production to six times the 5 GWp*a^{-1} assumed as a basis would decrease the MSP in about 11% compared to the original estimations. In turn, the investments increase to 774 million USD in equipment, facility, and land, reaching 1.2 billion USD after considering the NWC. Variable yearly costs of the plant would be about 1.5 billion USD*a^{-1} and operating expenditures to about 240 million USD/year, resulting in a total of 1.74 billion USD*a^{-1}. This plant would employ 3973 persons, would have a land footprint of approximately 233 hectares and would have a contribution of 17.0 million USD*a^{-1} in federal income tax, 9.9 million USD*a^{-1} in solidarity surcharges, and 17.9 million USD*a^{-1} in trade tax, provided that the cells are sold at the MSP calculated here. However, this production capacity widely exceeds the yearly installed capacity of PV systems in Germany of between 16.2 and 17.5 GWp in 2024 [8, 41]. Moreover, it would represent an important share of 45% of the current yearly installation rate of 66 GWp*a^{-1} in Europe [5].

4.1.2 | Silver Content

Alone, the metallization paste represents a cost of around 51 million USD for a 5 GWp*a^{-1} plant. A 5 GWp*a^{-1} would have a silver consumption according to the assumed quantities of around 47.5 ton*a^{-1}. To put this into perspective, the global mine production of silver in 2024 amounted to 25,000 tonnes*a^{-1} and current recycling rate to 6032 tonnes/year, and current reserves amount to 640,000 tonnes [42, 43]. Only the current demand of silver for PV in 2024 was estimated at 6086 tonnes*a^{-1} [43].

According to our analyses, the metallization paste represents around 24.8% of the CoO of POLO BJ-L, therefore being a relevant step subject to optimization. The assumed metallization resulted in total silver content of 100 mg Ag*cell^{-1}. Assuming an efficiency of 24.2% for an M12 format results therefore in a specific consumption of 9.4 mg Ag*Wp^{-1}, in line with the current trends on metallization reporting an average quantity of 9 mg Ag*Wp^{-1} for p-type silicon-based technologies like PERC [44]. A reduction down to 6 mg Ag*Wp^{-1} would allow a reduction in the CoO for POLO BJ-L from 5.79 ¢*Wp^{-1} down to 5.47 ¢*Wp^{-1}, therefore allowing a reduction of 5.5% in the CoO after assuming no changes in efficiency. In addition, the MSP would decrease from 7.16 to 6.79 ¢*Wp^{-1}, therefore decreasing by 5.2%. Reductions in the metallized area can lead to lower cell shadowing, but decreasing the amount of conducting material can also increase ohmic resistance. Alternatively, the use of other materials with lower price like copper or aluminum can also offer some economic advantage against silver metallization, but proven solutions with similar performance are yet to be seen. Therefore, it is yet to be seen if the cell efficiency can be maintained while reducing the of silver metallization.

For alternative concepts like TOPCon, which have an estimated silver consumption of around 13.5 mg Ag*Wp^{-1}, alone the paste used in the metallization step would have a cost of 1.56 ¢*Wp^{-1} at an efficiency of 24.2%. The same step for POLO BJ-L has a paste cost of 1.01 ¢*Wp^{-1} at the same efficiency. Therefore, the additional costs in the metallization of concepts like TOPCon represents around 0.55 ¢*Wp^{-1}. Although future reductions in the use of silver are also expected for the TOPCon concept, foreseen values are similar to those currently estimated for PERC and p-based silicon technologies of around 9 mg Ag *Wp^{-1}. If further reductions for p-type wafer-based technologies like POLO BJ can be achieved, a clear advantage against n-type wafer-based technologies like TOPCon would materialize.

4.2 | Tax and Financial Pathways for the Reduction of the MSP

Other reductions of the MSP would be possible via reduction in taxes or lower capital costs. For instance, a reduction of the WACC from 8% to 6%, which could materialize as a consequence of lower debt rates, would decrease the MSP for POLO BJ-L from 7.16 to 7.02 ¢*Wp^{-1}, therefore 1.9% compared to original MSP obtained. On the other hand, complete tax waivers would decrease the MSP of POLO BJ-L down to 6.98 ¢*Wp^{-1}, therefore a relative 2.5% reduction. However, this would mean a drop in terms of income tax, solidarity surcharges, and trade tax revenues of approximately 37.5 million USD. These changes are relying rather in policies to stimulate industrial production and financing at lower rates.

4.3 | Combined Reductions

Figure 12 summarizes the combined impact in the MSP of the different aspects previously described, namely, a higher cell efficiency, plant upscaling from 5 to 30 GWp*a^{-1}, lower silver content, lower WACC, and lower income taxes. The values differ from the previously described values because in the latter cases, only individual changes were considered, whereas here, the changes were considered sequentially. If both the technical aspects (efficiency of 25% achieved, silver reduction down to 6 mg*Wp^{-1}, and plant upscaling to 30 GWp*a^{-1}) and lower cost of capital of 6% and income tax are considered, an MSP of 5.64 ¢*Wp^{-1} for POLO BJ-L can be achieved. Therefore, all these technical and policy aspects can together decrease the MSP by 21.2% compared to the reference level of 7.16 ¢*Wp^{-1}. It can also be seen that the largest contribution is made by plant upscaling, followed by silver reduction, higher efficiency, and finally lower capital costs and income taxes.

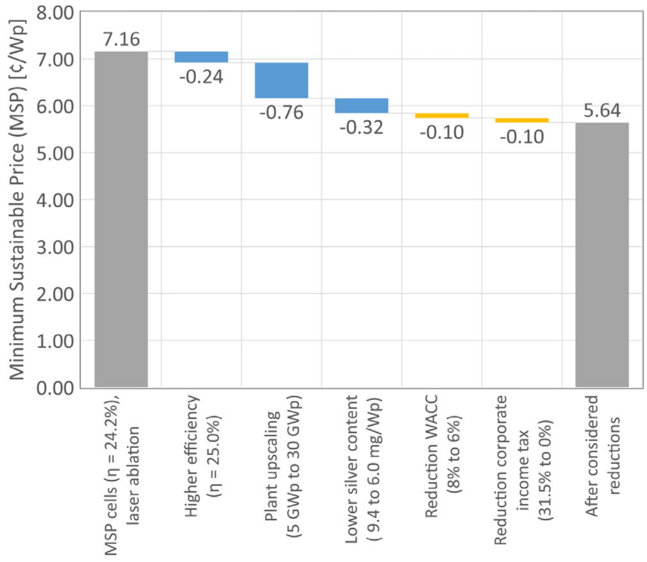

FIGURE 12 | Contributions from each considered aspect in the reduction of the minimum sustainable price (MSP) of POLO BJ-L cells. Technical aspects are shown in blue, whereas tax and financial are shown in yellow. *Source:* Own figure.

4.4 | Comparison Against Other Studies

According to a recent publication by Chen et al., single tools for processing had a throughput in most of the cases above 5000 pieces*h^{-1}, except for PECVD for which a throughput of around 4000 pieces*h^{-1} was assumed [45]. Similar assumptions were made in this study, except for the tools for which primary information was not available and which were assumed according to the secondary data available (see Supporting Information). Regarding CAPEX, Chen et al. reported around 210 million RMB*GWp^{-1} of production. Considering that the RMB had an exchange rate of between 0.158277 and 0.136933 USD*RMB^{-1} in 2022, this equates to a value of about 28.8 and 33.2 million USD, similar to the values between 34.2 and 36.4 million USD for all the plants described here [45]. The number of employees per GWp was also described by Chen et al. at around 170 persons*GWp^{-1} [45]. The assumptions made in this study led to 702, 698, and 706 persons in total employed in the 5 GWp plants producing POLO BJ-W, POLO BJ-L, and PERC, thus having labor demand of FTEs of about 141, 140, and 141 FTE*GWp^{-1} for POLO BJ-L, POLO BJ-W, and PERC production lines, resulting 17% lower but in line with the data reported by Chen et al. [45].

Comparisons against other studies in the subject are relatively difficult due to differences in the assumptions, production sequences, and calculation methods. In addition, and as mentioned at the beginning, the costs of the POLO BJ concept have not been estimated extensively in literature, so no benchmarks are available for comparison. Nevertheless, comparing against other studies, Kafle et al. 2021 reported "all-in cell" production costs of 11.9 ¢*Wp^{-1} for bi-PERC cells and between 12.9 and 13.2 ¢*Wp^{-1} for TOPCon cells with six different production sequences using different deposition processes after including wafer and cell production [21]. Therefore, with MSP values of 7.75 ¢*Wp^{-1} for PERC and 7.16–7.38 ¢*Wp^{-1} for POLO BJ, our results show a considerable difference to the results obtained by Kafle et al. Despite assuming the same production capacity of 5 GWp*a^{-1} as in this study, Kafle et al. analyzed the production of TOPCon cells with a M4 format, efficiency of 23.5%, and Ag paste consumption of 90 mg in the front and 100 mg on the rear side. In addition, the labor costs considered in the work of Kafle et al. are considerably lower and the CAPEX including equipment, buildings and facilities considerably higher than those estimated in this study. Additionally, the prices for M4 p-type and n-type wafers were assumed as 34.7 and 37.5 ¢*Wp^{-1}, whereas current spot market prices for M12 p-type wafers as assumed in this study are close to 18.5 ¢* Wp^{-1} wafer. Finally, Kafle et al. assumed a WACC of 5.0% and a corporate tax rate of 25%, in contrast to our assumption of a WACC of 8% and corporate tax rate of 31.6% in Germany. Kafle et al. reported an LCOE of 3.18 ¢*kWh^{-1} under Southern European conditions with TOPCon cells reaching 23.5%, whereas we found an LCOE 3.02 ¢*kWh^{-1} for bifacial glass–glass modules. However, as shown previously, modules contribute to around 0.64 ¢*kWh^{-1} to the LCOE, being the LCOE also considerably affected by other items such as OPEX, margin on the installation, racking and mounting, grid connection, mechanical and electrical installation, wiring, inverters, and permitting, among others.

Another study published by Chang et al. analyzed the production of PV modules encompassing from the production of polysilicon down to modules and predicted production costs falling between 10 and 18 ¢*Wp^{-1} by 2025, based on PERC cells with a module efficiency of between 22.9% and 25% [19]. Median cost distributions assuming the production of PERC modules in Italy were estimated at 15 ¢*Wp^{-1}, in comparison to 12.66 ¢*Wp^{-1} for monofacial glass–backsheet and 15.29 ¢*Wp^{-1} bifacial glass–glass PERC modules obtained in this work. In contrast, the results for POLO BJ-W and POLO BJ-L fell in the range between 11.84 and 14.57 ¢*Wp^{-1}. However, differences in terms of the location, electricity costs, depreciation period (5 years assumed by Chang et al., 7 years assumed here), production sequences, and material costs are remarkable, rendering comparisons difficult.

Recent studies carried out by Nold et al. reported an average MSP for fully locally produced TOPCon cell manufacturing in Europe of 12.8 ¢*Wp^{-1} [20]. When only wafer to cell conversion is considered, an MSP of 5.2 ¢*Wp^{-1} was found in Europe in the same study, compared to the MSP of 5.43 ¢*Wp^{-1} found for POLO BJ-L cells, after subtracting the wafer costs of 1.73 ¢*Wp^{-1} from the total MSP of 7.16 ¢*Wp^{-1} found for this concept (see Figure 7). Thus, our results score 4.4% higher relative to the results obtained by Nold et al. for TOPCon cell manufacturing. Besides the different cell concepts analyzed, several factors were found as making our results comparatively higher. Although the values for overhead and financing and profit are not explicitly reported in the study of Nold et al., it can be assumed by subtracting from the total MSP reported that these items represent around 0.6 ¢*Wp^{-1}. Comparatively, our study included operating expenses (S&A and R&D), capital costs, and income taxes—which after aggregation total 1.3 ¢*Wp^{-1}, exceeding by 0.7 ¢*Wp^{-1} the values reported by Nold et al. for these items. In turn, equipment and factory depreciation were estimated in our study at 0.40 ¢*Wp^{-1}, whereas Nold et al. reported equipment and depreciation costs of 1.0 ¢*Wp^{-1}, thus exceeding our calculations by 0.60 ¢*Wp^{-1} and compensating partially the higher results for the previous items. Smaller differences can be found for other items. In this study, the material costs estimated for POLO BJ-L cells were 1.92 ¢*Wp^{-1}, exceeding by 0.12 ¢*Wp^{-1} the ones reported by Nold et al. of 1.8 ¢*Wp^{-1}. Labor costs estimated in this study were 0.94 ¢*Wp^{-1}, thus 0.14 ¢*Wp^{-1} higher compared to the ones reported by Nold et al. of 0.8 ¢*Wp^{-1}. In turn, utility costs in this study were 0.09 ¢*Wp^{-1} lower than those estimated by Nold et al.. Therefore, although a relatively good correlation in terms of material, labor, and utility costs was found between this study and those of Nold et al., important differences for other costs like overhead expenditures, capital costs, and depreciation were found, being the main reason to which the differences in MSP can be allocated to.

4.5 | Comparison Against Market Spot Prices

A recent report issued by IRENA reported average PV module prices of 13.4, 21.7, 30.5, and 37.7 ¢*Wp^{-1} for low cost, mainstream, high efficiency, and bifacial modules, respectively, between April 2023 and March 2024 [35]. This contrasts with the prices found here for POLO BJ modules of between 11.84 and 14.57 ¢*Wp^{-1} and between 12.66 and 15.29 ¢*Wp^{-1} for the PERC technology. The same publication depicted a weighted average cost of complete PV installations of 758 USD*kWp^{-1}, with estimated average installation costs in Germany of 731 USD*kW^{-1}. With the assumptions for POLO BJ and PERC technologies, we obtained installation costs for utility-scale PV systems of between 573 and 612 USD*kWp^{-1}, which result under the values described by the IRENA study but also reflect higher efficiencies achieved between the time of publication and present.

The weighted average LCOE in 2023 for PV electricity at utility scale was 4.4 ¢*kWh^{-1}, a 5th percentile of 3.1 ¢*kWh^{-1} and a 95th percentile of 11.0 ¢*kWh^{-1}. Specifically, in Germany, the LCOE reported was 6.3 ¢*kWh^{-1} [35]. The results obtained here of between 4.58 and 5.19 ¢*kWh are lower compared to the study of IRENA.

When it comes to the spot prices of cells and modules, the last data published by the consulting company PV Infolink for 23.1% PERC cells in M12 format were 3.7 ¢*Wp^{-1}, and high, low, and average prices of 8.5, 3.5, and 3.6 ¢*Wp^{-1}, respectively, were reported for PERC cells in M10 format, mainly considering Chinese production [24]. Therefore, the estimated MSP results in values on the upper side of the range with local production. If some of the inputs are adapted by the decreasing the salaries to approximately 15,000 USD*FTE^{-1}*a^{-1} and electricity prices 0.08 USD*kWh^{-1}—similar to averages in China—and considering the routes for cost minimization described in the previous section, the MSP would result in values of 4.5 ¢*Wp^{-1} for POLO BJ-L cells, which are comparable with the current spot prices reported elsewhere [24].

4.6 | Limitations

This study was limited to the scope of cell production, with a simplified approach for module production. However, this approach does not allow to integrate synergies for integrated supply chains, comprising the production of polysilicon, wafers, cells, and modules. Therefore, future assessments should include as well the production considering integrated supply chains. Moreover, this study analyzed the CoO, MSP, and LCOE of POLO BJ considering two different production sequences based on wet chemistry and laser ablation. More advanced POLO-based concepts like POLO interdigitated back contact (IBC) are under development and have achieved higher efficiencies exceeding considerably those of the POLO BJ concept, so additional comparisons against the POLO IBC with higher potential efficiencies would be also relevant. Although possible technical measures like reduction in cells' silver content could bring considerable reductions in the CoO and MSP of cells, it is yet to be seen if these can be implemented in practice without compromising cell performance. In addition, with an increasing share of the n-based silicon technology TOPCon in the market, a comparison against this alternative concept under a common basis is also necessary for POLO-based technologies, based on the same assumptions for comparability.

5 | Conclusions

This study analyzed the investments for a POLO BJ PV cell production plant with a capacity of 5 GWp*a^{-1} at a cell efficiency of 24.2% considering two alternative production sequences, with different front silicon dioxide removal processes, based either on wet-chemistry or laser-ablation processes. Comparisons against the widely known PERC concept were also carried out. The initial investments are 264.2 million USD for a POLO BJ wet-etching process and 256.8 for a POLO BJ laser-ablation process—including facilities, equipment, and NWC for 3 months of variable costs and operational expenditures in Germany. In contrast, a PERC PV cell production facility considering cell efficiencies of 23.1% would need an initial investment of 258.7 million USD. The CoO of the production of POLO BJ using the wet-chemistry and laser-ablation pathways was estimated at 5.98 and 5.79 ¢*Wp^{-1}, respectively. In contrast, the CoO for PERC cells was estimated at 6.31 ¢*Wp^{-1}. Moreover, the MSP for POLO BJ cells produced using the wet-chemistry and laser-ablation processes were calculated at 7.38 and 7.16 ¢*Wp^{-1}, which resulted higher than that of PERC cells of 7.75 ¢*Wp^{-1}. POLO BJ cells were assumed to offer a superior efficiency of 24.2%, compared to the efficiency of PERC at around 23.1%. Moving forward to the perspective of the final consumer, the LCOE of systems using POLO BJ and PERC cells was also assessed. In monofacial glass–backsheet modules built with POLO BJ cells via laser ablation and considering Southern European conditions (GHI of 1700 kWh*m^{-2}*a^{-1}), the LCOE was calculated at 3.32 ¢*kWh^{-1}, whereas for bifacial glass–glass modules also with the same cell type, a value of 3.02 ¢*kWh^{-1} was obtained. For systems fitted with monofacial glass–backsheet PERC and bifacial glass–glass PERC modules, the LCOE obtained under similar conditions was 3.46 and 3.16 ¢*kWh^{-1}, respectively. Under German conditions (GHI of 1050 kWh*m^{-2}*a^{-1}), the LCOE for systems fitted with monofacial glass–backsheet modules POLO BJ and bifacial glass–glass POLO BJ modules resulted in 4.98 and 4.58 ¢*kWh^{-1}, respectively. Finally, several technological, financial, and tax alternatives were explored and showed a pathway to reduce the MSP of POLO BJ cells down to 5.64 ¢*Wp^{-1} after considering higher cell efficiency of 25%, lower silver in metallization of 6 mg Ag*Wp^{-1} instead of 9.4 mg Ag*Wp^{-1}, plant production upscaling from 5 to 30 GWp*a^{-1}, lower capital costs by access to lower rates of 6% instead of 8%, and federal income tax, solidarity surcharges, and trade tax exemptions. Although the results are comparatively higher than spot market prices for modules of Chinese origin, this cell concept might represent a potential candidate for local production of PV cells in EU. Moreover, from the technical point of view, enhanced properties compared to other technologies like TOPCon, like lower silver quantities in the metallization of POLO BJ cells, might be an argument in favor of POLO BJ technologies. Additionally, the local employment impact, with a plant estimated to have a workforce of approximately 700 employees, might be as well a relevant argument in favor of domestic production of these POLO BJ cells.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Fig. S1**: Summary of the ratios between cost of revenue and revenue for selected PV manufacturers. *Source:* Own figure with data extracted from Forms 20-F of the different companies or financial statements. **Supporting Fig. S2**: Summary of the ratios operating expenses (S&A + R&D) and revenue for selected PV manufacturers. *Source:* Own figure with data extracted from Forms 20-F of the different companies or financial statements. **Supporting Fig. S3**: Comparison of the effect of the scale of the production plant on the cost of ownership (CoO) of POLO BJ-L cells (ηcell = 24.2%). *Source:* Own figure. **Supporting Fig. S4**: Comparison of the effect of the scale of the production plant on the minimum sustainable price (MSP) of POLO BJ-L cells (ηcell = 24.2%). *Source:* Own figure. **Supporting Fig. S5**: Contributional analysis of the levelized cost of electricity (LCOE) for systems using monofacial glass–backsheet modules and bifacial glass-glass modules built with POLO BJ-W (ηcell = 24.2%), POLO BJ-L (ηcell = 24.2%), and PERC cells (ηcell = 23.1%). A global horizontal irradiance (GHI) of 1050 kWh/m^2*year and an irradiance in plane of array of 1250 kWh/m^2*year found typically in Germany are assumed in the analysis. *Source:* Own figure. **Supporting Table S1**: Tool costs, throughput and footprint assumptions for the production sequences of POLO BJ-W and POLO BJ-L cells. *Source:* Own table. **Supporting Table S2**: Tool costs, throughput and footprint assumptions for the additional step in the production sequence of PERC cells. *Source:* Own table. **Supporting Table S3**: Material, utility, and waste disposal costs for the production of POLO BJ-W, POLO BJ-L, and PERC cells. *Source:* Own table. **Supporting Table S4**: Clean room, building. and land costs. *Source:* Own table. **Supporting Table S5**: Summary of tax and WACC, depreciation, and net working capital assumptions. *Source:* Own table. **Supporting Table S6**: Scaling exponent assumed for different items involved in the production of PV cells. *Source:* Nold, 2019 [17]. **Supporting Table S7**: Module material price assumptions. *Source:* Own table. **Supporting Table S8**: System calculations and levelized cost of electricity. *Source:* [18]. **Supporting Table S9**: Module assumptions for utility scale 5 MWp system electricity yield. **Supporting Table S10**: System and location assumptions for utility-scale 5 MWp system electricity yield and LCOE calculations. *Source:* Own table. **Supporting Table S11**: Alternative reporting units of CoO of POLO BJ-W, POLO BJ-L, and PERC cells. *Source:* Own table. **Supporting Table S12**: Alternative reporting units of MSP of POLO BJ-W, POLO BJ-L, and PERC cells. *Source:* Own table. **Supporting Table S13**: Module estimated prices. *Source:* Own table. **Supporting Table S14**: Specific CAPEX for 5 MWp utility-scale systems. *Source:* Own table. **Supporting Table S15**: Lifetime electricity yield for 5 MWp utility-scale systems. *Source:* Own table.