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The Value of High-performance PV Technology

PV Technology White Paper

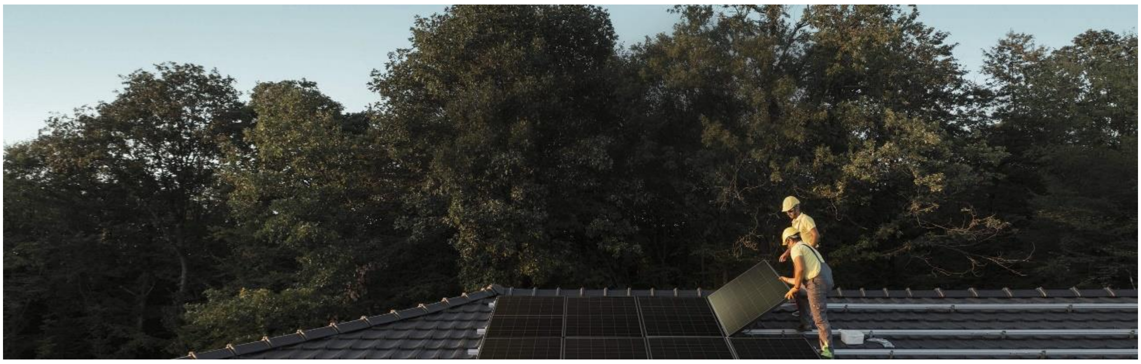
Contents

1. Introduction

The PV industry is ever evolving. Over the last decade, solar PV manufacturers have been highly effective at driving down manufacturing costs. This has been a key focus of the industry. However, the era of “easy wins” has ended. Gains will now be harder fought, likely relying on either alternative materials or new technologies.

The industry is now increasingly focused on improvements in module efficiencies, as manufacturers advance current technologies and adopt new ones. However, it can be difficult to contextualise technology advancements and efficiency gains and challenging to understand the benefit that these improvements can bring to distributors, installers and systems owners.

This white paper, built on analysis from Exawatt's Solar Technology and Cost Service, explores and compares key module parameters for different technologies and analyses the value these different technologies may bring to both residential and commercial installations. We provide professionals through the value chain with a useful resource to help enhance their understanding and develop their businesses profitably.



Source: AIKO Solar

2. The development of the PV industry

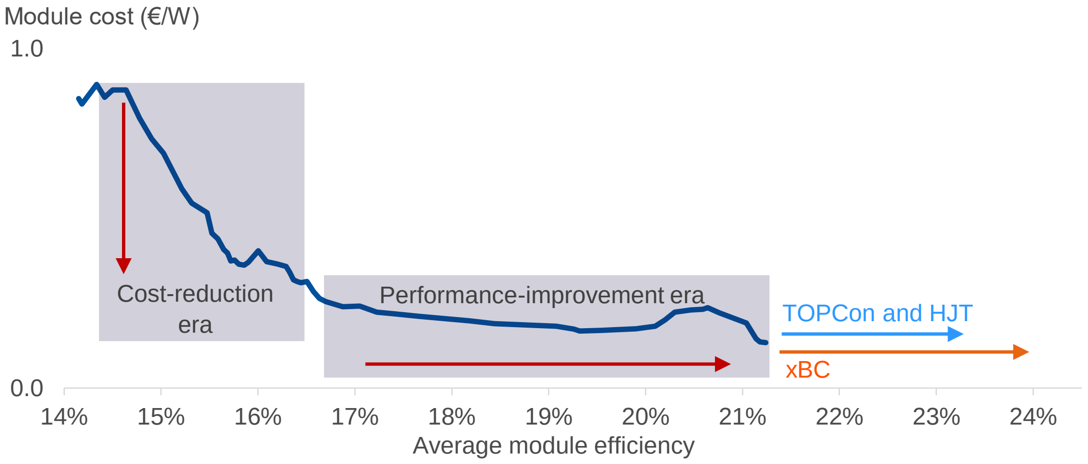
The history of the PV industry can broadly be divided into two eras: a cost-reduction era and a performance-improvement era.

Until the mid-2010s, module cost reductions were relatively easy to achieve. During this time module efficiency gains were gradual although modest, and cost reductions were the driving force of the industry. As manufacturing processes improved and materials costs reduced, boosted by scale effects as PV manufacturing migrated from its historical base in the west – notably Germany, the US and Japan – to China, module cost reductions became harder to achieve. From the mid-2010s, module efficiencies began to increase rapidly, in part due to the mainstream transition from now-obsolete multi BSF cells to mono PERC cells. As a result, performance increases through efficiency gains became the new driver of the industry; from about 2017 the PV industry entered a performance-improvement era.

In today's performance-improvement era, small cost reductions may still be achieved, but these are relatively minor in comparison to the potential efficiency gains offered by advanced technology offerings. High module efficiency is key to driving down system cost-per-watt, payback time, and levelized cost of electricity, since it can drive down the per-watt costs of many key non-module costs such as labour and mounting. This is especially important in a market where module cost is a relatively limited proportion of the whole system cost, for example rooftop systems.

While module manufacturing costs have less room to decline than in the past – particularly when considered in absolute terms, e.g. cost per module – prices can be highly volatile. In 2022 upstream supply shortages drove up polysilicon prices and, in turn, the manufacturing cost and price of modules; more recently, aggressive module price declines have been driven by overproduction and high inventory levels in key markets.

Figure 1: Module cost vs. module efficiency



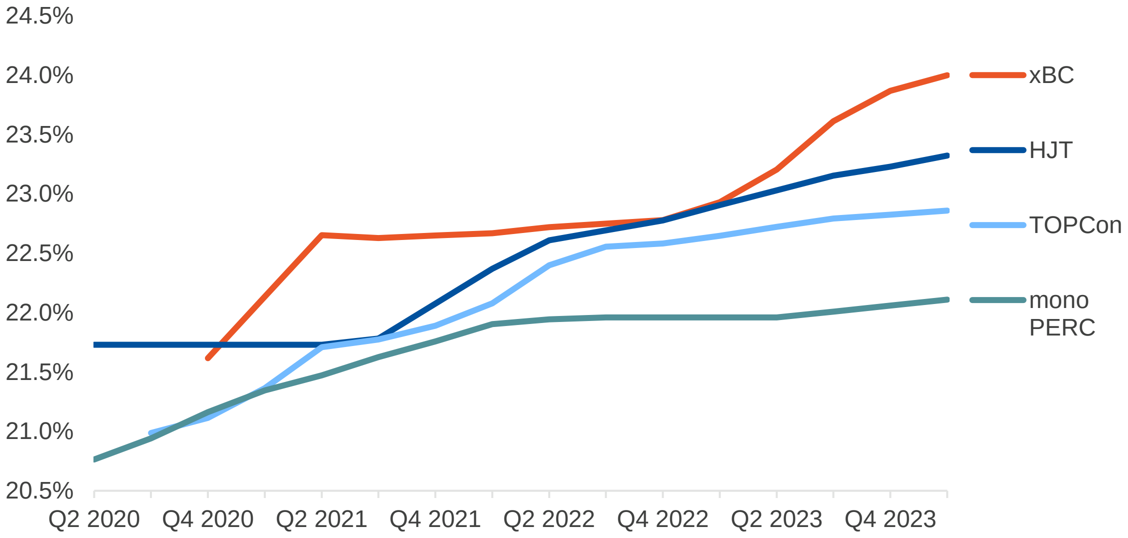
Data: CRU/Exawatt

Note: Average module cost of goods sold (COGS) and average module efficiency from 2010 to 2023, based on financial reports, manufacturer statements and publicly available module datasheets. Average module COGS and efficiency here are dominated by multi BSF and then mono PERC technologies. Mono PERC currently dominates the industry, with a market share of approximately 60% at the end of 2023 and an average efficiency of ~21%. The remaining 40% of market share at the end of 2023 is largely attributable to TOPCon technology, with average efficiency of ~21.8%. Many modules on the market today can offer efficiencies greater than the 21.2% shown in this figure.

For many years, PV market share was dominated by mono PERC cell technology – enabled by mono PERC's consistent, impressive efficiency gains. However, mono PERC's rapid efficiency gains began to slow in 2021 and have now largely stagnated.

To continue driving increases in module efficiencies – which mono PERC can no longer sustain in mass production – the industry has begun to turn to other cell technologies, primarily TOPCon, heterojunction (HJT) and back contact (xBC, used to denote all variations of back contact technologies).

Figure 2: Module efficiency trends by cell technology in 2020-2024



Data: CRU/Exawatt

Note: Rolling average of the maximum efficiency of xBC, HJT, TOPCon and mono PERC technologies, based on Exawatt's Module Tracker (see Section 3). Efficiencies here are on a three-quarter rolling basis to reduce fluctuations and so show the key trends more clearly.

Despite the rapid evolution of PV technologies, the industry has ensured high-quality products, and the mainstream offerings – such as PERC modules today – offer efficiencies, reliability, and aesthetics that were unachievable a decade ago.

As already mentioned, a key consideration for module buyers in today's market is that module efficiency "plays" at the system level. That is, a high module efficiency (i.e., high module power for a given size of module) helps to drive down many system-level costs in a per-watt sense such as labour and mounting costs in a per-watt sense, helping to enable lower system cost per watt and driving down LCOE and payback time.

3. Key module parameters

The performance of a module can be evaluated though several different parameters. The key performance metrics to consider when selecting a module for installation include efficiency, temperature coefficient and degradation.

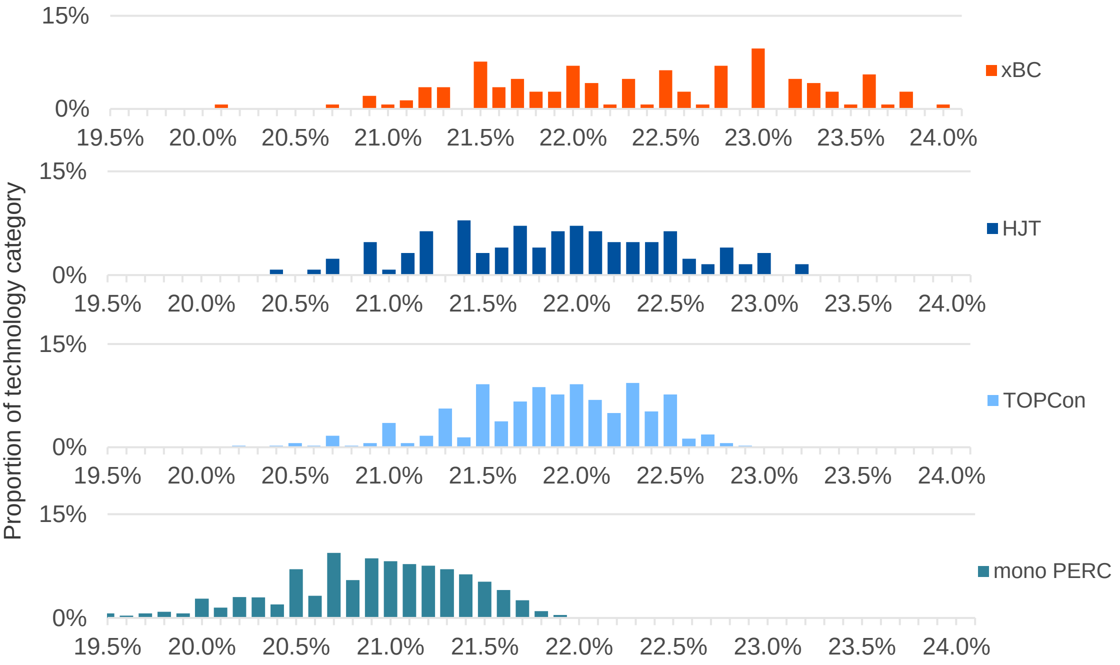
In this white paper we compare the key parameters for mono PERC, TOPCon, HJT and xBC technologies using extracts from the 2024 Q1 Exawatt PV Module Tracker, the full version is available to Exawatt's Solar Technology and Cost subscribers. This is a quarterly analysis of publicly available datasheets, covering the largest module manufacturers globally as well as a subset of specialist manufacturers focussed on emerging technologies.

3.1. Module efficiency

Module efficiency is the ratio of the electrical power output of the module to the incident light power input (or alternatively, energy output as a function of energy input). A module with a higher efficiency would generate more power (and energy) than an identical, but less-efficient, module under standard test conditions. Under standard test conditions, a module of 20% efficiency would generate 200 W of power per m^2.

Therefore, using more-efficient modules reduces the system area required to produce a certain power output, or increases the power output for a system with a fixed area. Module efficiency is of particular importance when designing systems for residential or commercial and industrial (C&I) applications, where rooftop space may be a constraint and non-module costs (e.g., installation costs) are often relatively high.

Figure 3: Module efficiency [%] frequency by PV technology



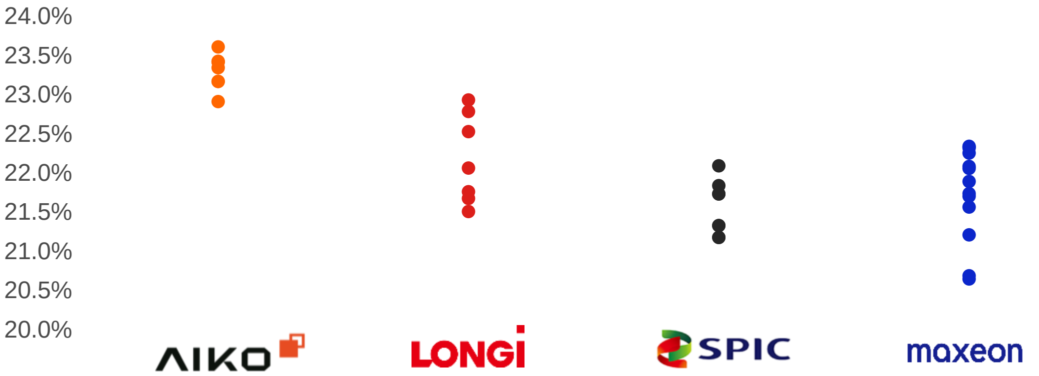
Data: CRU/Exawatt

Note: Module efficiency spread for xBC, HJT, TOPCon and mono PERC within Exawatt's Q1 2024 PV Module Tracker dataset. Module efficiencies here are rounded to the nearest 0.1%. xBC modules can be manufactured as either n-type or p-type, which somewhat accounts for the relatively large spread in efficiencies within the xBC technology category.

Comparing the different technologies, it is evident that xBC, TOPCon and HJT categories all offer higher average and maximum efficiencies in comparison to mono PERC. TOPCon and HJT currently offer broadly similar average efficiencies, but with the highest-efficiency HJT modules outperforming the highest efficiency TOPCon modules. The xBC category outperforms both the TOPCon and HJT categories in terms of both average and maximum efficiencies.

While the best-performing xBC modules hold a meaningful efficiency lead over their HJT and TOPCon counterparts, we see a very broad spread of efficiencies on offer in the xBC category. But there is variation within the back-contact technology. For example, back contact cells can be n-type or p-type and can feature different passivation technologies, resulting in very different cell and module efficiencies. Figure 4 shows the average module efficiency for each xBC module series within Exawatt's 2024 Q1 dataset, with one of AIKO Solar's Comet module series currently offering the highest average efficiency.

Figure 4: xBC module series average efficiency by key in-house manufacturers



Data: CRU/Exawatt

Note: Module efficiency spread of the key in-house xBC manufacturers from Exawatt's 2024 Q1 PV Module Tracker dataset. Module efficiencies here are the average for each module series and include both monofacial and bifacial modules.

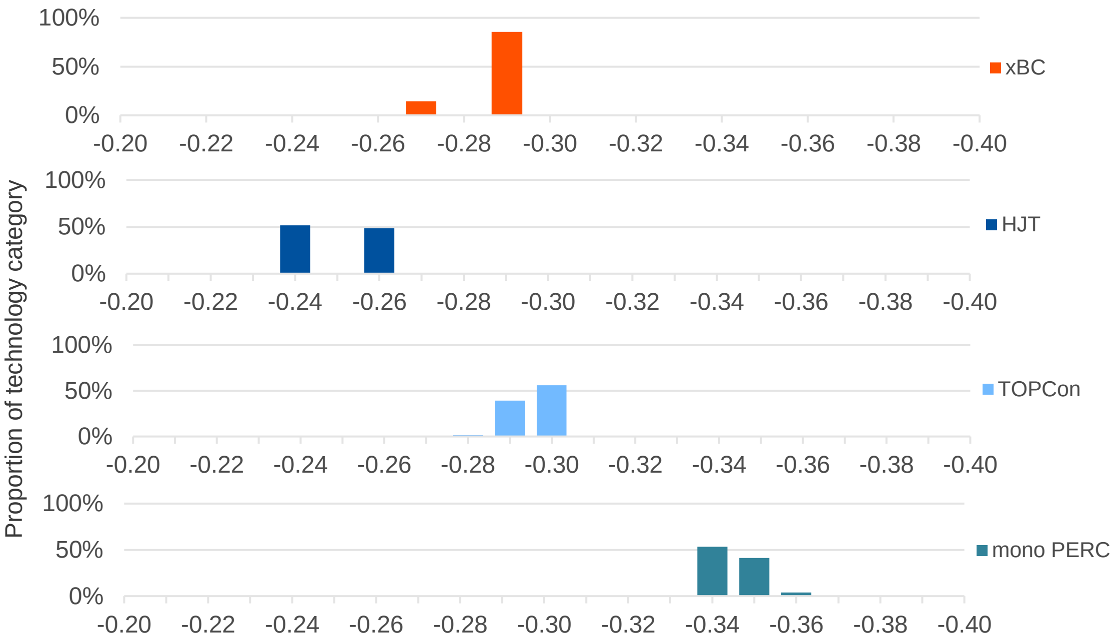
3.2. Temperature coefficient

The temperature coefficient of a PV module quantifies how the performance of the module changes with changes in temperature. Modules are tested, and therefore rated for maximum power, under Standard Test Conditions at a cell temperature of 25°C. In real-world situations, modules commonly operate at higher temperatures than this, and as temperatures increase, module power (or efficiency) decreases, all other factors being equal. The temperature coefficient of P_{max} describes how the maximum power of a module changes as its temperature changes – for example, a module with a P_{max} temperature coefficient of -0.35%/°C and an operating temperature of 45°C will have a maximum power output 7% lower than the rated power of the panel. For comparison, a module with a temperature coefficient of -0.26%/°C and an operating temperature of 45°C will have a maximum power output only 5.2% lower than the rated power of the panel.

Choosing a panel with a less-negative (i.e., closer to zero) temperature coefficient means that it will produce more power when operating at elevated temperatures. Although this parameter may seem relatively unimportant to those unfamiliar with PV – such as most homeowners – it can have a significant impact on the overall energy generation of a system, particularly in a hot climate.

There is a clear divide between the average P_{max} temperature coefficient of mono PERC and those of the other technologies – with HJT having the most impressive temperature coefficient.

Figure 5: Temperature coefficient of P_{max} [%/°C] frequency by PV technology



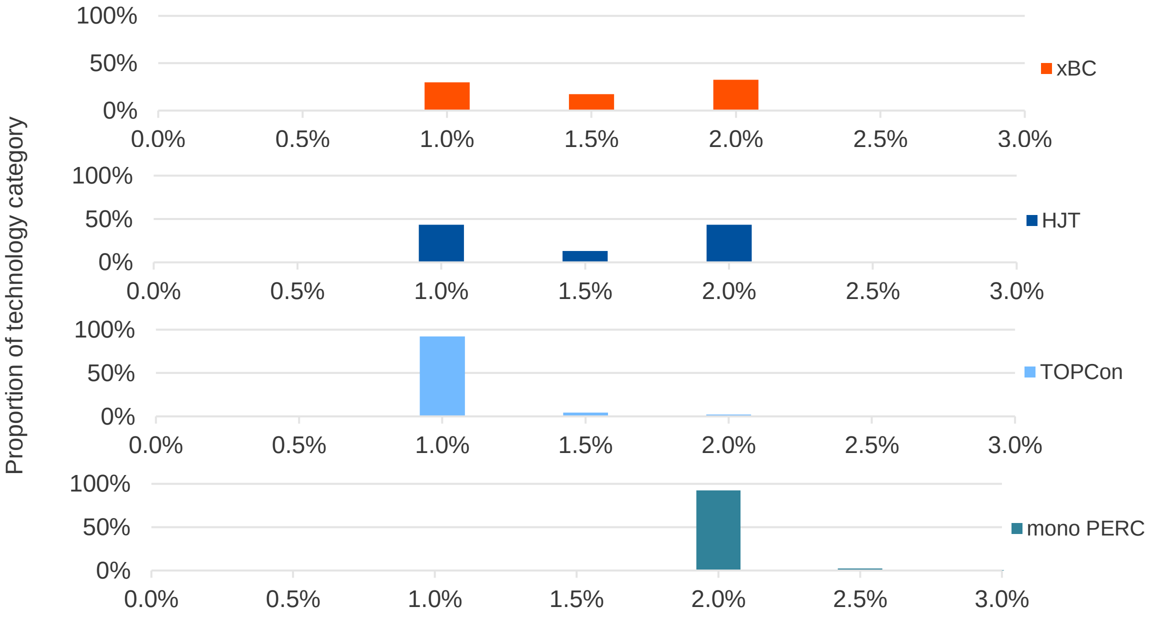
Data: CRU/Exawatt

Note: Temperature coefficient of P_{max} (%/°C) of xBC, HJT, TOPCon and mono PERC from Exawatt's 2024 Q1 PV Module Tracker dataset.

3.3. Module degradation

The degradation of a PV module quantifies the decrease in efficiency, and hence power/energy output, over its lifetime. A module with a lower degradation rate compared to an otherwise identical module will produce more energy over its lifetime. Module degradation is commonly split into two metrics: first-year degradation and second-year-onwards degradation. Figure 6 shows the degradation within the first year; Figure 7 shows the degradation for the second year onwards.

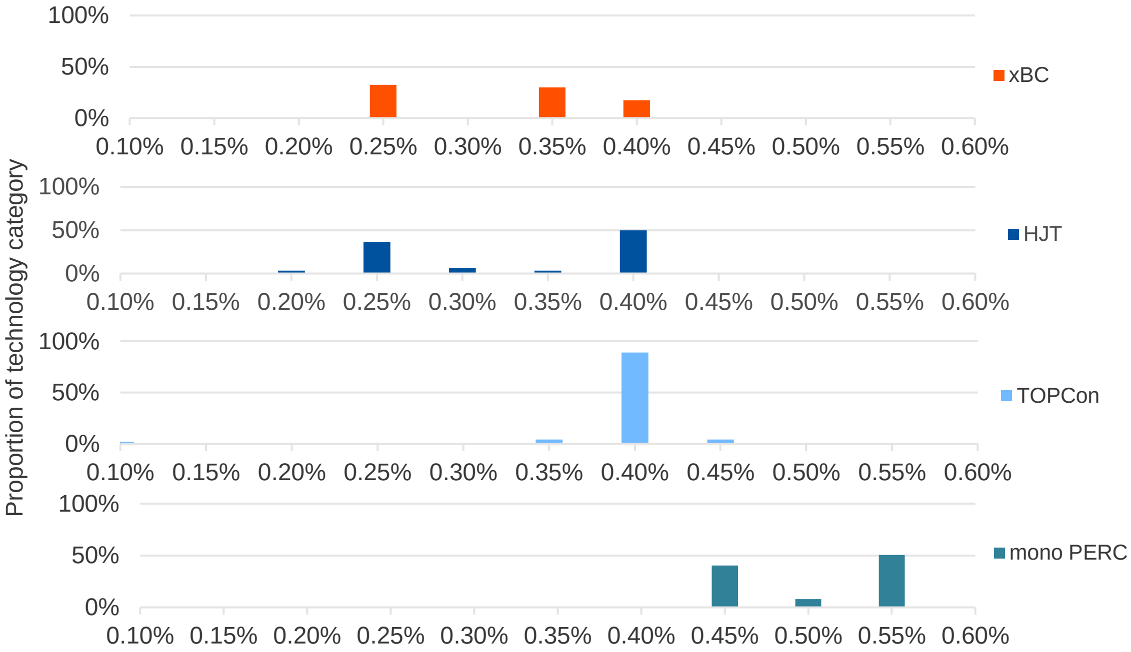
Figure 6: First-year degradation frequency by PV technology



Data: CRU/Exawatt

Note: First-year degradation rates of xBC, HJT, TOPCon and mono PERC technology categories from Exawatt's 2024 Q1 PV Module Tracker. Technology categories here include both monofacial and bifacial modules.

Figure 7: Second-year-onwards degradation frequency by PV technology



Data: CRU/Exawatt

Note: Second-year-onwards degradation rates of the xBC, HJT, TOPCon and mono PERC technology categories from Exawatt's 2024 Q1 PV Module Tracker. Technology categories here include both monofacial and bifacial modules.

Of the technologies analysed, advanced technologies have a lower average degradation rate than mono PERC, with xBC and HJT offering broadly similar advantages in terms of degradation.

3.4. Other important considerations

Aside from the key parameters described in the Sections 3.1, 3.2 and 3.3, there are many other considerations when selecting a PV module.

One example is the length of the performance warranty of a module, which is typically either 25 or 30 years. When evaluating Exawatt's Module Tracker dataset, n-type modules are more likely to offer a 30-year performance warranty than their p-type counterparts. However, in practice, performance warranty will depend on the individual module selected from any technology category.

Another aspect module buyers may want to consider is the availability of a manufacturer's local technical and after-sales services in their region.

The financial health of the manufacturer is also worth consideration, and a buyer may wish to purchase from a manufacturer less likely to enter bankruptcy. There are different ways to assess a manufacturer's financial health, one common example being the Altman Z-Score (although there are some disputes over the usefulness of this metric). Given the oversupply in the PV market in 2024, and the resulting exceptionally low module prices being offered by some suppliers, it is likely that several manufacturers with weaker financial positions may be forced out of the market, and hence be unable to offer ongoing support to the buyer. However, note that the financial health of a manufacturer does not necessarily reflect the quality of its products.

The optimal module choice for a given system may also vary depending on the specific system and the priorities of the system owner. For example, some homeowners may value aesthetics above all else, while others may be more focussed purely on the system's financial metrics or the peace of mind of a longer performance warranty or by using modules from a well-known manufacturer.

4. The Value of High-performance PV Technology

Common metrics used to make financial assessments of residential and C&I PV installations include payback time and levelized cost of electricity (LCOE). The metric that a system owner will consider most important will vary depending on the type of system and the owner's individual needs. For example, homeowners are usually focused on payback time, while owners of larger systems are commonly more engaged with LCOE.

Here we have chosen to model two parameters for two different example systems:

- **Payback time for a residential system**. This is the time taken for financial savings from the system to offset the initial cost of the system (accounting for the time value of the investment), i.e. the time taken for owners to fully recover their investment in the system.
- **LCOE for a C&I system**. The LCOE of a system is the average cost of the energy generated over the course of its lifetime, defined as the total lifetime cost (a composite of capital and operating costs) divided by the lifetime energy yield.

For each system, we have modelled for the six key solar markets in Europe: France, Germany, Italy, the Netherlands, Poland and Spain, using weather data for the capital city of each country. Payback time for residential systems and LCOE for C&I systems have been modelled using NREL's (National Renewable Energy Laboratory) System Advisor Model (SAM). Here we aim to show savings estimates based on representative systems for both residential and commercial applications. Of course, the precise savings of any high-efficiency technology will vary depending on the detailed specifications of the system, the financial assumptions used, and the exact location of the system.

The modelling has been performed using module prices for each technology that we believe broadly reflect the current market (see exact pricing assumptions in Section 4.1 and 4.2). Of course, actual module pricing may vary with many factors including time, market dynamics, exact module specification (both efficiency and materials specifications), and module brand.

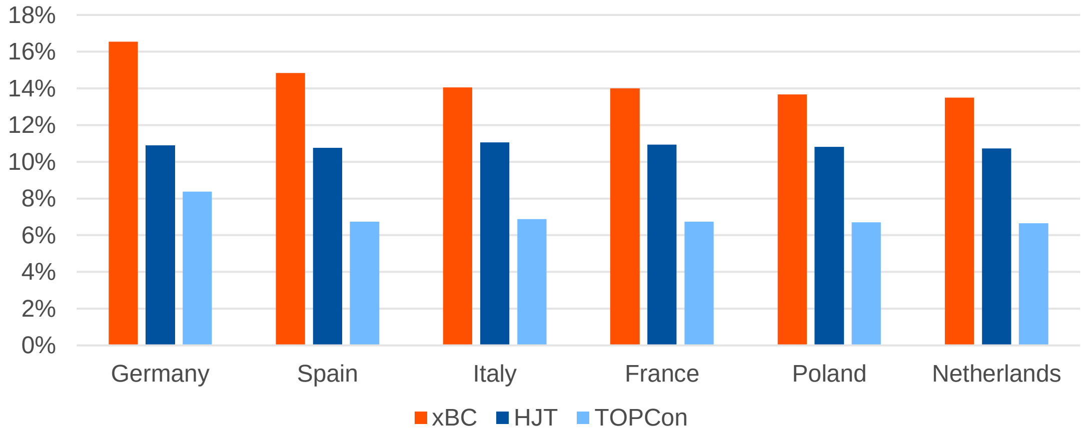
4.1. Residential application modelling

For residential applications, a system of approximately 5 kWp (kilowatt peak power output of a system) was modelled with a fixed physical system area for all technologies.

Key assumptions for the residential systems modelled include:

- For each technology, the module selected was the central power bin from the highest-efficiency module series from Exawatt's 2024 Q1 Module Tracker (considering only modules of an appropriate physical size for most residential applications):
    - Mono PERC: Longi Hi-MO 5m, 415W
    - TOPCon: Suntech Ultra V Pro, 430W
    - HJT: Huasun Himalaya G10 Series, 440W
    - xBC: AIKO Neostar series, 460W
- 12 modules per system, resulting in a DC system size of 4.9 kWp to 5.5 kWp
- Inverter load ratio of 1.2:1
- Module price per watt was modelled as 0.18, 0.17, 0.15 and 0.14 €/Wp for xBC, HJT, TOPCon and mono PERC technologies respectively. Inverter price per unit was fixed across all locations. Other capital costs were varied by country
- Incentives, feed-in tariffs, annual operations and maintenance costs, and fixed monthly costs for the system were varied by country based on estimates for 2023
- Electricity rates were varied by country, with estimates sourced from the European Union's Eurostat based on available 2023 averages. An annual inflator of 2.5% per year was assumed

Figure 8: Percentage gain in energy generation in key European countries by technology, in comparison to mono PERC (Residential – 5 kWp)



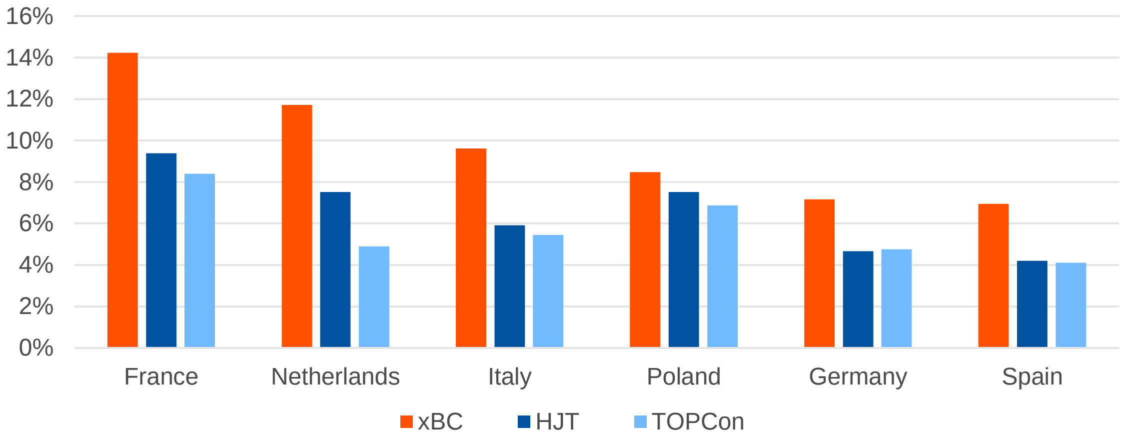
Data: CRU/Exawatt

Note: The percentage increase in lifetime energy generation is modelled using a system with a 30-year lifetime. Energy generation gain is presented for xBC, TOPCon and HJT technologies in comparison to mono PERC – xBC provides the greatest gain in energy generation across all locations modelled.

For residential applications, across the locations modelled, xBC provides the highest average increase in lifetime energy generation of 14.4% in comparison with mono PERC, followed by HJT with 10.9% energy generation gain and TOPCon with 7.0%.

The payback time of a system depends on the energy generated by a system, until the point at which the financial savings from the system have offset the initial cost of the system. Greater energy generation (in kWh) in the early years will result in a lower payback time (all other things being equal). While greater energy generation in the later years of a systems lifetime will not contribute to a system's payback time, it will continue to provide the homeowner with extra value in the long run.

Figure 9: Savings in payback time in key European countries in comparison to mono PERC (Residential – 5 kWp)



Data: CRU/Exawatt

Note: The payback time is modelled using a system with a 30-year lifetime. xBC provides the greatest savings in payback time across all locations modelled.

Across the six key European countries modelled, the advanced high-efficiency technologies outperform the payback time of mono PERC for the modelled residential system. xBC provides the best payback performance, with an average saving of 9.7% vs mono PERC, followed by TOPCon with 6.5% and HJT with 5.7%. I.e., under our assumptions, a residential system employing xBC modules would reach the point where the financial savings from the system had offset its initial cost sooner than if employing HJT, TOPCon or mono PERC modules.

As the results show, locations where the advanced technologies deliver the highest gains in energy generation do not always correspond to locations where these technologies deliver the highest gains in payback time. The benefit of the favourable energy generation gain in Germany and Spain on payback time is dampened by financial considerations, for example a relatively large delta between the electricity buy and sell rates.

There are, of course, many considerations for residential system owners when selecting modules beyond the purely financial. For example, aesthetics may be particularly important to some homeowners. In recent years, there has been a shift in residential applications towards “all black” modules – typically offered with a black frame and black backsheet, but with interconnection ribbon between cells still being visible. Back contact modules have no interconnection on the front side of the cells, meaning the technology can offer aesthetic benefits over mono PERC, TOPCon and HJT.

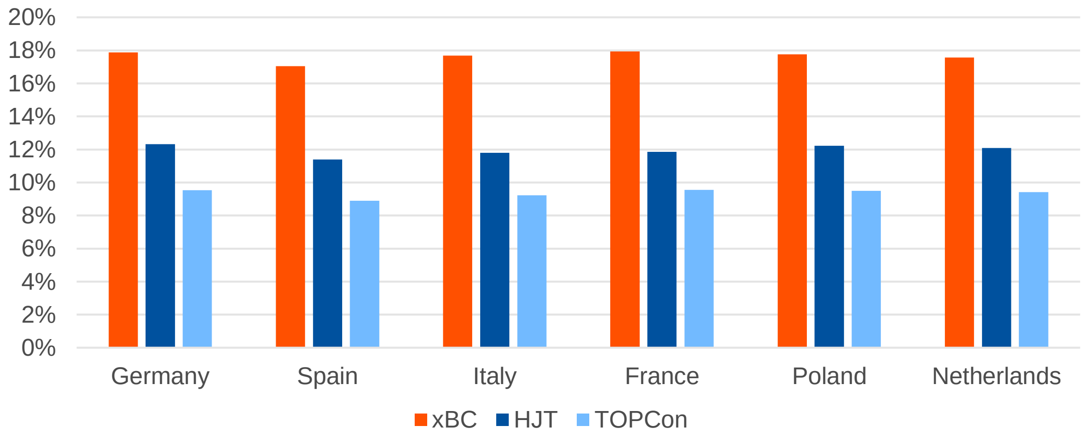
4.2. Commercial & industrial application modelling

For commercial and industrial applications, a system of approximately 150 kWp was modelled with a fixed physical system area for all technologies.

Key assumptions for the C&I systems modelled include:

- For each technology, the module selected was the central power bin from the highest efficiency module series from Exawatt's 2024 Q1 Module Tracker (considering only modules of an appropriate physical size for most C&I applications):
  - Mono PERC: GCL M10/72H, 550W
  - TOPCon: Yingli Panda 3.0 Pro, 570W
  - HJT: Huasun Himalaya G10 Series, 590W
  - xBC: AIKO Comet 2N Series, 620W
- 260 modules per system, resulting in a system size of 143 kWp to 158 kWp
- Inverter load ratio of 1.15:1
- Module price per watt was modelled as 0.15, 0.14, 0.13 and 0.12 €/Wp for xBC, HJT, TOPCon and mono PERC technologies respectively. Inverter price per unit was fixed across all locations. Other capital costs were varied by country
- Annual operations and maintenance costs for the system were varied by country in line with the European Commission Clean Energy Technology Observatory's Photovoltaics in the European Union 2022 report, IEA 2022 National Survey Reports and European Union 2023 labour costs

Figure 10: Percentage gain in energy generation (kWh) in key European countries by technology, in comparison to mono PERC (C&I – 150 kWp)

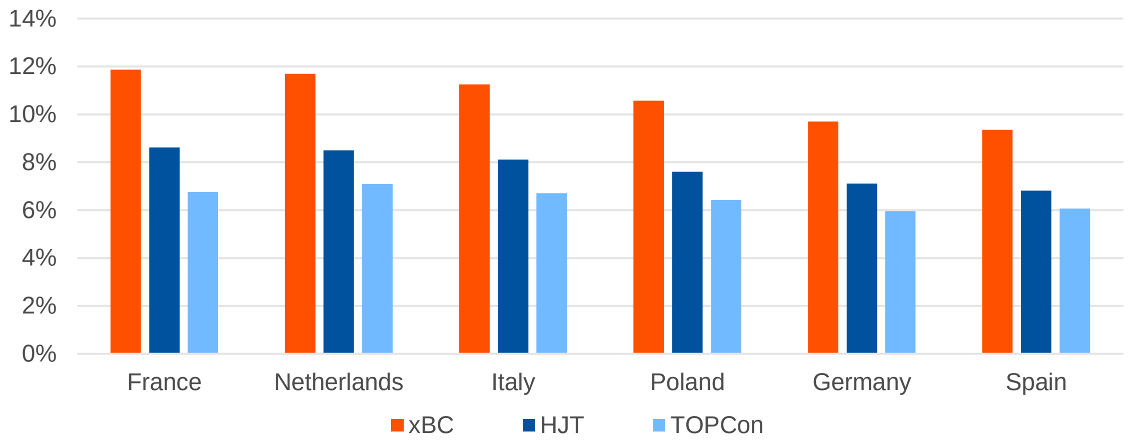


Data: CRU/Exawatt

Note: The percentage increase in lifetime energy generation is modelled using a system with a 30-year lifetime. Energy generation gain is presented for xBC, TOPCon and HJT technologies in comparison to mono PERC – xBC provides the greatest gain in energy generation across all locations modelled.

Across the six locations modelled, under our assumptions for C&I systems, xBC provides an average increase in lifetime energy generation of ~17.6% in comparison with mono PERC, followed by HJT with 11.9% and TOPCon with 9.3%. The LCOE of a system depends on the energy generated by the system; greater energy generation (in kWh) of a system will result in a lower LCOE (all other things being equal).

Figure 11: Savings in LCOE in key EU countries compared to mono PERC (C&I – 150 kWp)



Data: CRU/Exawatt

Note: The LCOE is modelled using a system with a 30-year lifetime. xBC provides the greatest savings in LCOE across all locations modelled.

Across the six key European countries modelled, the advanced high-efficiency technologies outperform the LCOE of mono PERC for the modelled C&I system. xBC provides the lowest LCOE, with an average reduction of ~10.7% vs. mono PERC, followed by TOPCon with 7.8% and HJT with 6.5%. Of course, these savings in LCOE are lower than the gain in energy generation (shown in Figure 10) due to the higher module prices for the higher efficiency technologies in comparison to mono PERC.

In comparison to the residential system, for the C&I system we see less country-to-country variation in the modelled savings afforded by high-efficiency technologies. We attribute this to the higher country-by-country variation in financial inputs for the payback time modelling, where local incentives, regulations and electricity prices have a meaningful impact on the results of the modelling.

5. Conclusion: High-performance can enable financial savings

xBC, HJT and TOPCon PV technologies have been compared with mono PERC, the current mainstream technology in the industry, through parameters including module efficiencies, temperature coefficients and degradation rates.

In each European location modelled, xBC, HJT and TOPCon technologies have significant improvements in lifetime energy generation compared to mono PERC. For both residential and C&I modelling, xBC provides the greatest lifetime energy generation among all the technologies modelled with an average increase of 16.0% over mono PERC; HJT and TOPCon offer generation gains of 11.4% and 8.2% respectively over mono PERC.

Profitability of residential and commercial installations has been investigated using payback time and LCOE respectively; in both cases, the xBC, HJT and TOPCon provide improvements over mono PERC, with the best performance provided by xBC, with an average of 9.7% shorter payback time and 10.7% lower LCOE across all modelled locations.

After the rapid development of PV technologies in recent years, the industry has evolved from ‘cost-reduction era’ to ‘performance-improvement era’. The modelling in this whitepaper shows that despite the larger upfront cost of the premium modules, their higher energy generation means they can be financially beneficial over the lifetime of the system. By considering the potential savings of the advanced solar PV technologies, distributers, installers and end users are able to make informed decisions on which technology has the greatest value for a specific application.

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6. Glossary

COGS	Cost of goods sold
Exawatt PV Module Tracker	A quarterly analysis of publicly available module datasheets from leading manufacturers and a subset of specialist manufacturers focussed on emerging technologies
HJT	Heterojunction solar cell
LCOE	Levelized Cost of Electricity: the average cost of the energy generated by a system over the course of its lifetime (a composite of capital and operating costs) divided by the lifetime energy yield of the system
Module degradation	Quantifies the decrease in efficiency, and hence output, as a module ages
Module efficiency	The ratio of power output of the module to solar power input
Module temperature coefficient	Quantifies how the performance of the module changes with changes in temperature
mono PERC	Monocrystalline Passivated Emitter and Rear Cell
Payback time	The time taken for owners to fully recover their investment into the system
NREL SAM	NREL's System Advisor Model – a techno-economic analysis tool developed to model a range of renewable energy systems: https://sam.nrel.gov/
STC	Standard Test Conditions: the conditions under which solar PV panels are tested to determine their rated power. STC are cell temperature of 25°C, irradiance of 1000 W/m^2 and air mass 1.5 (AM1.5) spectrum
TOPCon	Tunnel Oxide Passivated Contact
xBC	A catch-all term used to cover several variations of back contact solar cell technologies

7. Acknowledgements

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