

Analysis of transport costs structures of solar modules: international versus domestic scenarios

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Abstract. This study investigates the cost structure associated with transporting photovoltaic (PV) modules, comparing scenarios of international transport from China to Germany, a European manufacturing, and domestic transport within Germany. Utilizing a geometric model to calculate container utilization and transport logistics, we analyze the impact of module design, efficiency, and transportation routes on overall costs. The transport cost model considers module dimensions, container specifications, loading limits, transport modes, costs, packaging materials, and pallet prices. We apply this model to various module types, including M10, G12, and M10R wafer-based cells. Transport costs from China to Germany make up a significant part of the total PV module cost (14.7%–15.8%). In contrast, for German module manufacturing, the transport cost share is well below 2% and European manufacturing adds less than 3%. Transport costs have shown high volatility in the recent decade, and container prices are currently higher than prior to the Corona crisis. Disruptions in global logistics chains – such as shipping route blockages or spikes in container prices – can significantly impact cost structures. Transport costs for PV modules have quadrupled during Corona. We estimate that a transport cost share of ~10% will remain relevant for the future. Higher module efficiencies lower specific transport costs (€/Wp). An increase of 1%_{abs} leads to a transport cost reduction of 4.2%_{rel}. Sensitivity analyses demonstrate that transport costs can account for up to 43% of the final module price in scenarios of low factory-gate module price and high shipping container costs. This study highlights the need to include transport logistics in PV module design and sourcing decisions. We recommend future LCOE assessments for solar projects include detailed transport cost evaluations for decision-making.

Keywords: Photovoltaic modules / cost analysis / transport / logistics / shipping routes / economics / module design

1 Introduction

1.1 Problem statement

Solar modules are becoming cheaper with every year and installations are expected to increase in the future [1]. The installation of modules in the European Union, especially in Germany is growing [2,3]. China is dominating the manufacturing at all levels of the value chain [4,5], necessitating the transport of modules from China to installation locations around the world.

Transport costs have been very volatile in the past decade [6,7], raising questions about their share in overall module costs. Module design and dimensions have changed rapidly due to new wafer and solar cell formats and varying module thickness [8–11]. Since shipping containers have fixed dimensions, changes in module format impact the

number of modules per container and, thus the shipping costs per module. In this study, we aim to explore how the module design impacts the transport costs.

In the development of photovoltaic module designs the capacity of available shipping containers needs to be considered as hard restriction (i.e., a weight limit may not be exceeded). Additionally, in the techno-economic optimization of the module and to reduce the Levelized Cost of Electricity (LCOE) the costs of transport need to be minimized. Therefore, it is essential to minimize unused container space and maximize transported power (GWp/container). Since module design and techno-economic optimization are multi-parameter optimization problems, a model or a target function is required that can be added to other existing models. We present such a model that outputs the costs of transport in €/module or €/Wp. This allows analysis of module design (e.g., width) and transport parameters (e.g., orientation) in terms of costs.

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Our approach calculates the number of modules per container, necessary packing materials, and transport costs. This calculation assesses design changes in modules, including predicted future changes in solar cell or module dimensions [10,12].

We calculate the shipping costs for different module designs (132 and 144 half cells) based on three different solar cell formats ($182 \times 91 \text{ mm}^2$, $210 \times 105 \text{ mm}^2$, $182 \times 105 \text{ mm}^2$).

Additionally, we compare three different shipping routes (China to Germany via the Suez Canal, the Cape of Good Hope, and an Arctic route as an alternative). Transportation costs for domestic module manufacturing in Germany and a European manufacturing are calculated. We then determine the transport cost share of the module price. Finally, we perform sensitivity analyses on module efficiency, shipping container prices, and module price to assess the impact of future technology developments, global supply chain disruptions, and further cost decreases for photovoltaic modules.

1.2 Literature review

Cost calculations are usually not focused on or consider transport costs in detail [13–16]. Cost analyses are typically using a “factory gate” system boundary and do not consider the transport a separate cost center.

Publications on the cost structure of module manufacturing that include transportation as a cost factor exist [17] but here the module design itself is not an input parameter. Thus, these models are not suitable for module design optimization.

Only one previous study considers the impact of module design on transport costs [18]. The authors compare different module formats and find that transport costs significantly impact Balance of System (BoS) costs, varying by module design, similar to our findings. They also find the container costs to be relevant for the transport costs. However, the authors use a different approach and do not calculate container utilization based on module design. Our approach is a bottom-up calculation of the number of modules per container while [18] has a top-down approach on transport costs.

The transport of modules is also discussed in the context of module recycling or end of life handling [19,20] but assumptions for this recycling scenarios are usually based on much lower transport distances and no model is presented that takes the module design into consideration. This does not align with the current situation where China dominates solar module manufacturing, necessitating long-distance transport.

The concentration of module manufacturing capabilities in one region has been identified as a potential threat to supply chains. Risk assessments usually focus on factory concentration in one region (susceptible to natural disasters or political risks) but often overlook transport and potential route disruptions [21].

Cost input data is mostly not peer-reviewed or published by scientists but provided by industry associations, statistical authorities, commercial advisors, or consultants.

Compared to existing works, this study presents a more detailed transport model and considers the impact of module design on transport costs. We use a bottom-up approach to calculate modules per container based on design, unlike previous top-down methods. We for the first present results on the impact of disruptions in world-wide logistic chains on module prices. This work supplements previous studies by providing up-to-date cost data and first-time data on packaging material costs.

2 Material and methods

2.1 Model description – solar module transport

We analyze the transport cost structure for a Germany-based, a Europe-based and a China-based module manufacturing to assess the transport costs.

The calculation of transport costs follows this approach (Fig. 1):

- Calculation of the number of modules per container for the most optimal orientation.
- Consideration of loading limitations (i.e., weight restrictions, loading from one side only, no flat-laying modules, stackable pallets).
- Calculation of packaging material consumption and costs.
- Calculation of transport costs (including surcharges):
 - Pre-Carriage: Costs in the country of origin (i.e., transport to and loading onto a ship).
 - Carriage costs (i.e., ocean transport).
 - On-Carriage: Costs in the country of destination (i.e., transport by rail or truck to the destination).
- Calculation of capital costs:
 - Consideration of transportation time.
 - Consideration of the value of the modules.

For the calculation of the number of modules per container, the orientation of the modules within the container is important. Six possible orientations for modules exist as shown in Figure 2 (left).

Literature indicates that orientations 5 and 6 (modules lying flat) may increase transport damage [22]. Thus, we implemented the possibility to exclude those orientations and focus on orientations 1–4 in the following.

Modules can be packed up in boxes or be loaded onto pallets (Fig. 2 right). We assume the pallets/boxes to be identical. Boxes may be loaded on top of each other, but we also implemented the possibility to exclude this.

Between two modules, additional interlayers (cardboard) for protection during transport may be used. Typically, a cardboard edge protector is used. Each stack of modules is likely to be placed on a pallet with a certain thickness and weight. Each stack of modules might be protected by additional packaging material, typically cardboard and shrink wrap/stretch film. Different thicknesses of cardboard can be considered for the top and the sides of each stack of modules. For stability, each stack is secured by packaging strips, used twice per orientation (Fig. 2 right, yellow lines; Fig. 3, black lines). The edges of the pallets might be equipped with additional protectors.

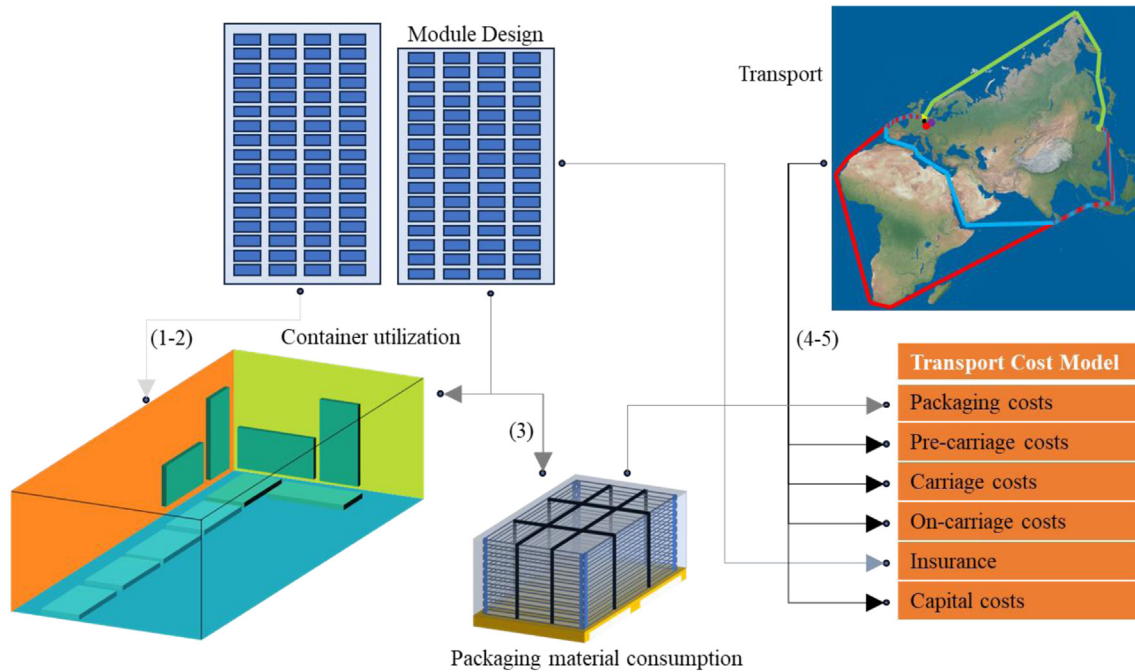


Fig. 1. Graphical abstract.

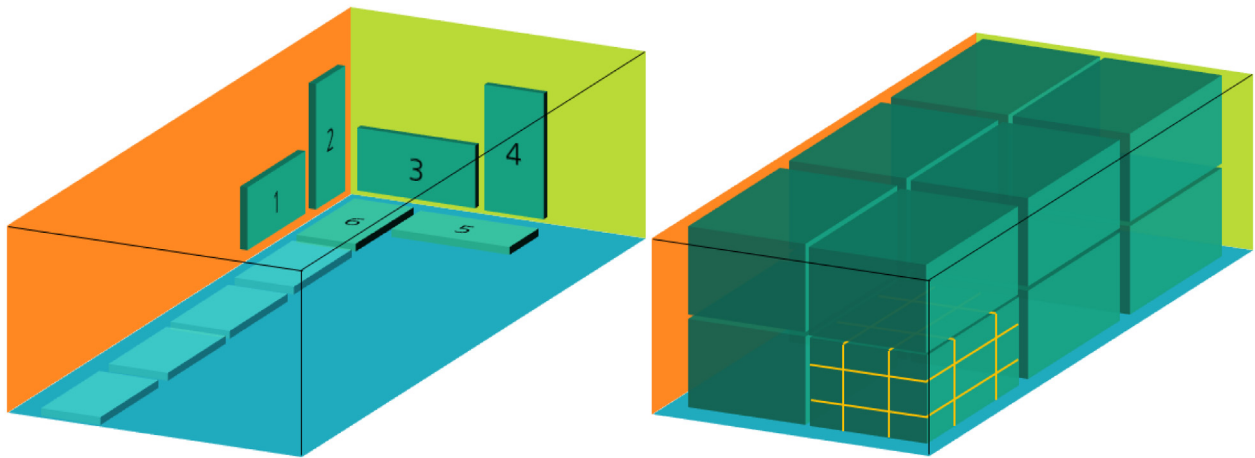


Fig. 2. Six possible module orientations within a container (left); boxes/pallets of modules in a container (right). 1. Standing on long module side, long edge of module parallel to long side of container. 2. Standing on short module side, short edge of module parallel to long side of container. 3. Standing on long module side, module parallel to short side of container. 4. Standing on short module side, module parallel to short side of container. 5. Module lying flat, short edge of module parallel to long side of container. 6. Module lying flat, long edge of module parallel to long side of container.

Packaging material consumption is calculated based on the module dimensions, the number of modules per pallet, the number of pallets per container, and specific information on where and what kind of packaging material is used.

We use the following assumptions:

- Stretch foil is used in a single layer on top of the pallet and in two layers on the sides.
- The top of the pallet is covered by a 1-wave cardboard layer.
- The sides of the pallet are covered by a 2-wave cardboard layer.
- Cardboard edges are used on all four edges of each module but only every second module is equipped with them.
- Packaging strip is wrapped around each side of the pallet twice in every direction.
- No additional edge protectors for the module stacks are considered.
- Three labels are attached to each pallet.

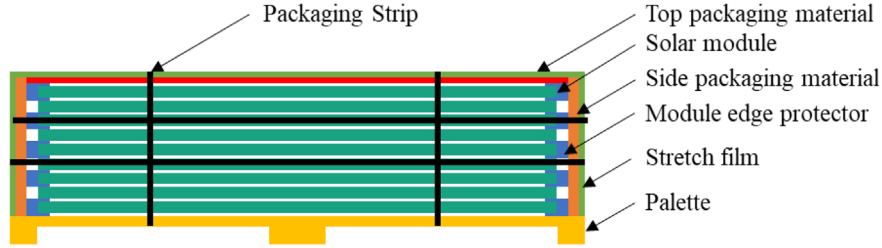


Fig. 3. Schematic drawing of a pallet of modules with packaging material (cross section through a pallet).

The following equation describes the dimensions of the modules and their packaging:

$$t_i = n_i (m_i (w_{\text{module},i} + d_{\text{edge protector}}) + d_{\text{packaging},i}) + d_{\text{palette},i}, \quad (1)$$

t_i = length of the total payload in direction i ;

n_i = number of modules in direction i ;

m_i = number of modules per pallet in direction i ;

$w_{\text{module},i}$ = length of the module in direction i ;

$d_{\text{packaging},i}$ = thickness of the packaging material in direction i ;

$d_{\text{palette},i}$ = thickness of the pallet in direction i .

Depending on the direction, no stacking of modules or pallets occurs ($n_i = 1$ or $w_i = 1$), pallet thickness may not need consideration ($d_{\text{palette},i} = 0$ mm) or packaging layers (cardboard plus stretch film thickness) need to be added to calculate $d_{\text{packaging},i}$.

To calculate the maximum number of modules per container, container dimensions l in each direction i must be known. Typically, 40' High Cube (HC) containers are used with inner dimensions of $12,032 \times 2350 \times 2700$ cm³ (length $\times$ width $\times$ height).

For existing module designs, calculating the number of modules per container is not necessary as this information is typically in the module datasheet. For novel module designs, a transport cost model is needed for a holistic cost calculation beyond manufacturing.

The general optimization problem is then formulated as seen in equation (2) where the total number of modules n per container needs to be maximized. Container dimensions are needed as boundaries since no module or pallet stack may exceed them.

$$\max(n) \text{ with } n = n_x \cdot n_y \cdot n_z. \quad (2)$$

The number of modules in each direction is the rounded off ratio of the length t_i (Eq. (1)) and the container dimensions.

As mentioned above, restrictions may apply when no stacking of pallets is allowed, and modules may not be lying flat. Since pallets are usually compatible with forklifts, they are not accessible from each side. If the container only allows entry on one side, the pallet orientation needs to account for this. This possible restriction has been implemented in the model but will not be further considered in this analysis.

Modules and packaging material have a weight, and the container has a weight limit (26.33 t payload for a 40' HC container). Along with geometric limits, a weight limit is also considered in the model.

The model has been tested with several different module designs from several different manufacturers and the calculated number of modules matches given datasheet values perfectly. This indicates that industry already uses such models and considers module transport in design. The model correctly calculates the number of modules also for different types of containers (i.e. a semi-truck instead of a shipping container).

2.2 Transport scenarios

We model and analyze three scenarios for transport that represent typical applications for module installation in Germany:

- Transport from China to a German location via ship and truck.
- Transport from a European manufacturing site to a German location via truck.
- Transport from a German manufacturing site to a German location via truck.

The location for module installation is Veitshöchheim (Germany) since it is the geographical center of the European Union. Ship transfer is assumed to be between Shanghai (China) and Rotterdam (Netherlands). The transfer from Rotterdam to Veitshöchheim is via truck. The German module manufacturing site is assumed to be Grillenburg (the geographical center of Saxony). Saxony is chosen due to the high density of German solar module manufacturing sites. Transport from Grillenburg to Veitshöchheim is by trucks. The European manufacturing is not located in a specific region. Instead we assume a truck transport of 750 km which represents the average cross-trade transport distance in the European Union [23] and 2 days of transport.

Stacking of pallets within a container is possible and modules are to be placed standing (not lying flat).

The scenarios both include the transport of modules, based on cells of different formats. The differences in cell format result in different module sizes. Table 1 shows the final module dimensions. The modules are based on commercially available module designs [24–26].

Please note the nomenclature we applied on the cell formats. We find the most relevant dimension of the cells for module design and module transport to be their width. Therefore, we name the 182×105 mm² cell M10R instead of G12R indicating the relevant width of 182 mm.

Table 1. Module designs for transport.

Module	144x M10	132x G12	132x M10R
Solar Cell	M10 – 182×91	G12 – 210×105	M10R – 182×105
Module Power [Wp]	576.6	705.9	611.8
Module Length [mm]	2278.0	2384.0	2384.0
Module Width [mm]	1134.0	1303.0	1134.0
Module Height [mm]	30	33	30
Module Weight [kg]	31.8	38.3	32.6

**Fig. 4.** Schematic depiction of the analyzed transport routes, routes not to scale [29].

To estimate the impact of route changes, we consider a Suez Canal blockage and rely on the Cape of Good Hope route (Fig. 4, orange). This route is ~31% longer (25,580 km compared to 19,560 km) and thus transport time is assumed to increase by 7 days to 35 days. A future alternative is an arctic route, approx. 27% shorter (14,260 km vs. 19,560 km), potentially reducing transport to 21 days (Fig. 4, green) [27,28]. The container costs are changed accordingly with the changes in travel distance.

Transfer from a manufacturing site in China to Shanghai port is not separately considered.

Trucking from Rotterdam (Fig. 4, white), the European manufacturing or from Grillenburg to Veitshöchheim is considered. The distance from Rotterdam port to Veitshöchheim is 580 km, and from Grillenburg to Veitshöchheim is 370 km. 750 km are used for the European manufacturing scenario.

2.3 Data input for cost modelling and uncertainty

Based on information provided by module manufacturers the assumptions for packaging material costs as stated in Table 2 are used. Packaging material consumption varies for each module design due to changes in palette form factor. Table 3 shows packaging material consumption per palette.

Capital costs depend on interest rates for equity and debt capital, used to calculate the Weighted Average Costs of Capital (WACC), and on transport duration. WACC is assumed to be 4.4% based on data for China [30].

A period of 24 days at sea is assumed for transport from Shanghai to Rotterdam (via Suez Canal) [31]. The distance travelled is 19,560 km for the Suez Channel route [28,32].

Transport to Shanghai harbor, temporary storage in Shanghai and Rotterdam, and transport from Rotterdam port to the destination are assumed to take four days,

Table 2. Packaging material price assumptions.

Packaging Material	Price [€]	Per Unit
Palette	8.00	Piece
Cardboard edges	0.01	Piece
Cardboard 1-wave	0.20	m ²
Cardboard 2-wave	0.40	m ²
Packaging strip	0.01	m
Stretch film	0.05	m ²
Transport label	0.05	Piece

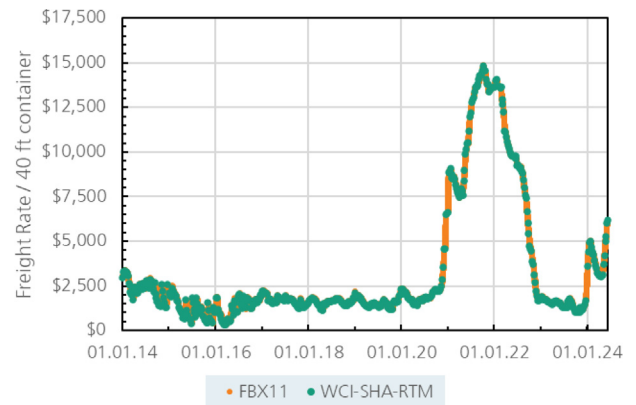
Table 3. Packaging material consumption.

Module	144× M10	132× G12	132× M10R	
Palette	1	1	1	Pieces/palette
Cardboard edges	72	72	72	Pieces/palette
Cardboard 1-wave	2.5	1.5	2.7	m ² /palette
Cardboard 2-wave	8.4	12.0	8.7	m ² /palette
Packaging strip	37.1	39.3	37.9	m/palette
Stretch film	19.3	25.5	20.0	m/palette
Transport label	3	3	3	Pieces/palette

totaling four weeks (28 days) of transport time. Capital costs are calculated based on the value of the shipped modules plus transport costs (pre-, main-, and on-carriage), packaging, insurance, and fees.

The calculation of transport costs includes pre-, main-, and on-carriage costs. Pre-carriage costs consist of the costs of loading onto a transport device at the place of dispatch and the transport to the export terminal or port. Export customs declaration, export terminal or port handling fees (THC), and loading charges may apply. Carriage costs include the transport from the export to the import terminal. On-carriage costs include unloading charges at the import terminal, import processing and taxation, as well as costs of loading onto a transport device and the transport to the destination. Surcharges such as ISPS (International Ship and Port Facility Security), CSF (Carrier Security Fee), IFS (Inland Fuel Surcharge), other security charges, Atlas system fees, low sulfur fuel surcharge, etc., are considered. Insurance is set at 0.5% of the module value plus a fixed fee of 35 €. Loading at the module manufacturer and loading from truck to ship at Shanghai port are not separately listed.

Container costs are based on the Drewry World Container Index (WCI-SHA-RTM) and the Freightos Baltic Index FBX11, which indicate costs of around 6,200 € per 40' container at the time of this study [6,7] (Fig. 5). Both indices show maximum container costs of around 15,000 \$ during the Corona pandemic which is used as a maximum value in the sensitivity analysis. Current price levels may be distorted by political events reducing the availability of a safe Suez Channel passage, leading to higher container prices [33–35].

**Fig. 5.** Drewry World Container Index WCI-SHA-RTM (green) and Freightos Baltic Index FBX11 (orange) [6,7].

Other costs as shown in Table 4 are taken from commercial offers of shipping companies.

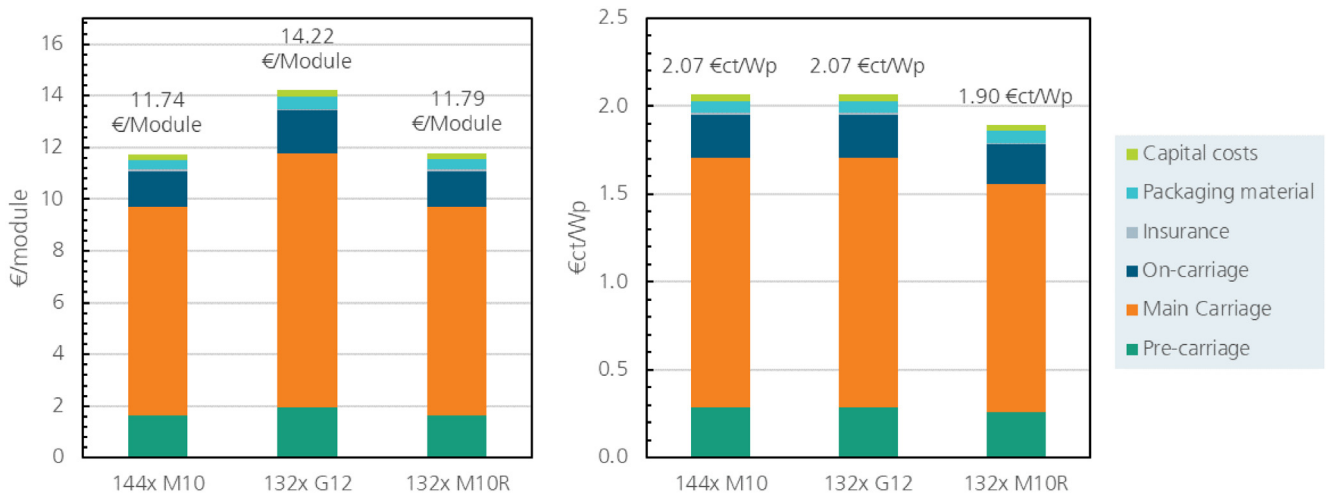
The costs of the European part of the transport are mostly handled in Euro (€) while the costs of shipping and pre-carriage are handled in US-Dollar (\$). Therefore, prices in Table 4 are shown in both US-Dollar and Euro. Converted values have been added to the On-carriage costs for easier accessibility.

Trucking costs are assumed to be 1.30 €/km [36]. The exchange rate US Dollar to Euro is set to 0.931 [37]. Module prices for all three module designs are set to 0.11 €/Wp (0.87 RMB/Wp; 0.12 \$/Wp) [37–39].

The authors acknowledge that there is some uncertainty in the data used, as cost information is typically not publicly available.

Table 4. Costs of carriage.

	Cost description	Costs
Pre-carriage	Loading onto transport at place of dispatch	
	Transport to export terminal or port	800 \$
	Loading charges export terminal	
	Export customs declaration	100 \$
	Export terminal or port handling (THC)	325 \$
Main Carriage	Container costs	6,200 \$
	Additional surcharges or fees	50 \$
On-carriage	Import processing & taxation	72 € (77 \$)
	Loading charges import terminal	98 € (105 \$)
	Loading onto transport at import terminal or port	0 €
	Unloading at destination	0 €
	Transport to destination	728 € (782 \$)
	Additional surcharges or fees	78 € (84 \$)
	Insurance	0.5% + 35 € (38 \$)

**Fig. 6.** Transport cost analysis for different types of solar modules (China to Germany, multimodal transport using ship and truck).

The container costs being the most significant cost driver are assumed to be well-documented via the container price indices (Fig. 5) and we attribute no major uncertainty here ($\pm 5\%$). The transport costs within Europe are based on statistical data [36] and we attribute a low uncertainty to the trucking ($\pm 20\%$). For all other costs (capital costs, handling of modules in China, packaging materials, surcharges, etc.) we assume a higher uncertainty ($\pm 50\%$) since they are based on company statements that cannot be easily verified.

The portion of costs with a higher uncertainty is lower compared to the portion of costs with a lower uncertainty (Fig. 6). By calculating transport costs using error propagation, we estimate an uncertainty below 16% for the first scenario (China), below 27% for the second scenario (Europe) and below 32% for the third scenario (Germany). Uncertainty is higher for the

two latter scenarios due to the higher share of uncertain inputs as the container costs are not included in those scenarios.

We conclude that the general trend of the results will hold, even though the absolute numbers might vary.

2.4 Sensitivity analysis

We perform a sensitivity analysis on container costs, module costs, and module efficiency. The first is done to analyze if previous disruptions in the logistic chain (i.e., Suez Canal blockage, Corona Crisis) have a significant impact on transport costs. The latter is done to estimate the share of transport costs for modules based on novel solar cell technologies that offer benefits in power output. Module prices are changed to predict the

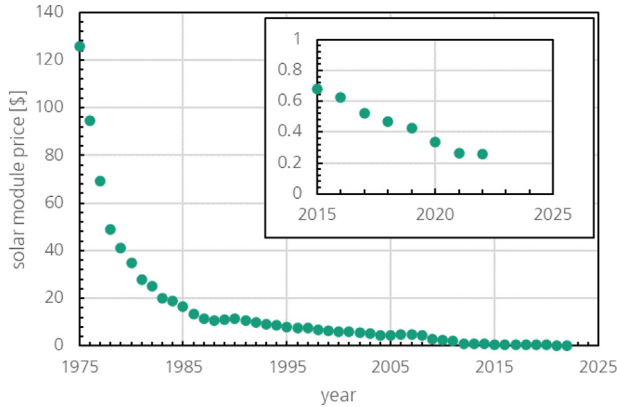


Fig. 7. Historic module price development; data by International Renewable Energy Agency (2023); Nemet (2009); Farmer and Lafond (2016) – with major processing by Our World in Data [40].

impact of a future decline in module costs following the historic trend (Fig. 7). We combine module price and container price variations to determine the impact of transport cost increases on final module costs (after delivery).

3 Results

3.1 Container utilization for different solar module designs

We create a model to calculate the possible number of modules based on their dimensions, container dimensions, and loading limitations.

For all three module designs, the number of modules per container is calculated. It is noteworthy that we find the number to match statements in technical datasheets by commercial module manufacturers. The model, therefore, seems to be capable of predicting the correct number of modules, which is necessary to analyze different module designs.

The container utilization is calculated for each of the three module designs. The introduction of M10R cells improves the container utilization in terms of GWp/container compared to modules based on squared G12 and M10 wafers (Tab. 5). Modules based on G12 cells lead to a lower container weight but offer no GWp/container advantage over smaller M10 cells.

Container utilization results show that different module designs lead to varying numbers of modules per container and different shipping costs. Therefore, module design needs to take a holistic approach considering not only the module manufacturing but also subsequent steps towards system integration. Our cost-focused analysis matches previous findings where module design was part of a holistic approach considering power losses from wafer to system [41].

We find module weight not to be the limiting factor in container utilization (payload 40' HC container = 26.3 t).

3.2 Transport cost analysis

We create a model to calculate transport costs for PV modules based on container utilization, transportation

means and costs, packaging material prices, and capital costs for the transported goods. Surcharges and insurance are considered as well.

We find the absolute transport costs per module are highest for the G12 module (Fig. 6, left). The transport costs per piece are similar for M10 and M10R based modules. Considering the transported power per container, the lowest specific costs (€/Wp) can be found for the M10R module (−8.2% compared to M10 and G12). The number of modules per container is the same for the M10 and the M10R module but the transported power is higher for M10R (Tab. 5). Therefore, increasing module power per container is necessary, motivating improvements in module efficiency and more modules per container (e.g., reduced module thickness). Sea transport costs make up about two-thirds of the total costs (at a container price of 6200 \$).

Comparing module import costs with domestic procurement, we find significantly lower transport costs (Fig. 8). Costs of domestic transport are only ~10% of the international China-Rotterdam-Germany logistic chain and account for only 1.6%–1.7% of the module price. Costs of pre-carriage and carriage become nil, and the capital costs are drastically reduced due to the short transport time (1 day). Trucking costs are reduced due to the shorter route (370 km instead of 580 km). If a European manufacturing is assumed, transport costs are still low compared to transport costs from China (Fig. 9). We find the costs of module transport to be between 2.6% (M10R) and 2.8% (M10, G12) of the module price. Local module manufacturing has a significant advantage in transport costs.

Nonetheless, this difference cannot be fully utilized by domestic module manufacturing since the possible transport (import or local sourcing) of components needs to be considered. Component prices will have different transport cost shares, determining the need for domestic or international sourcing for each component. Low-cost components with high bulkiness (i.e., glass) will be preferably bought locally, while components with higher value and lower bulkiness (i.e. solar cells) can be shipped without significant additional costs.

Taking publicly available module prices of 0.11 €/Wp (ex-works: Chinese module manufacturing site) we can calculate the transport cost share in the total module price.

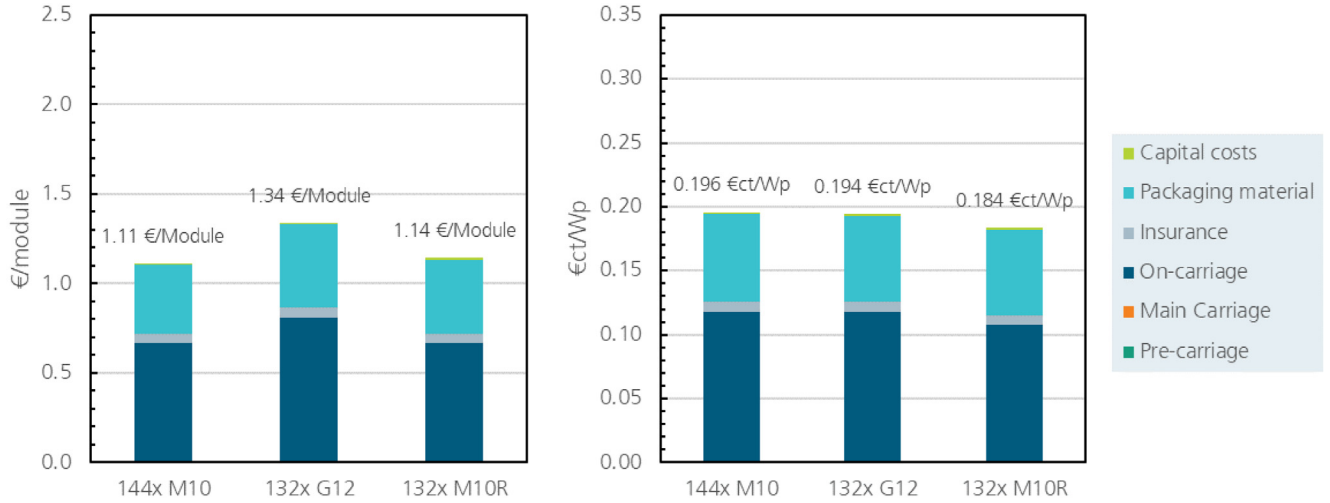
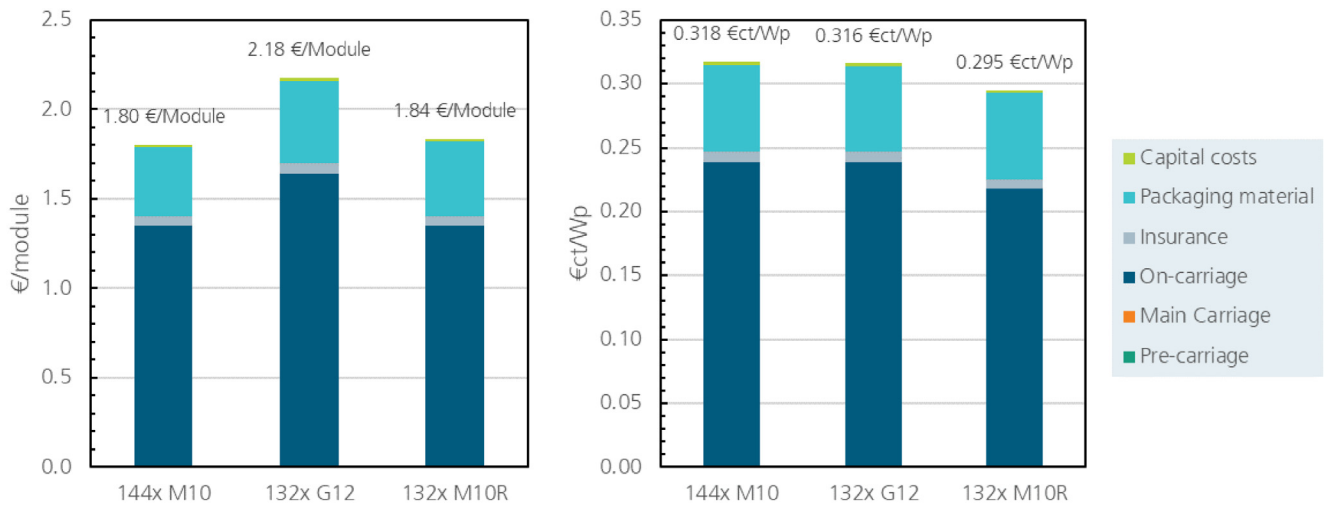
We calculate the transport cost share as the share of transport costs to the total costs including delivery to the destination (Eq. (3)).

$$\text{transport cost share} = \frac{\text{transport costs}}{\text{module price} + \text{transport costs}}. \quad (3)$$

The transport share is 15.8%, 15.8%, and 14.7% for the M10, G12, and M10R modules, respectively. German-based module manufacturing would only add 1.6–1.7% of transport costs to the module price (assuming they are identical). In the European manufacturing scenario, transport contributes 2.6–2.8% to the module price. The difference in costs between the German and the European scenario are caused by the different route

Table 5. Container utilization for different solar module designs.

Module	144× M10	132× G12	132× M10R
Modules per 40' HC	720	594	720
Palettes/Boxes in container	20	18	20
GWp per 40' HC	0.409	0.409	0.448
Container per GWp	2.45	2.45	2.23
Weight per 40' HC	24.1	23.4	25.1

**Fig. 8.** Transport cost analysis for different types of solar modules (Germany to Germany, transport using truck).**Fig. 9.** Transport cost analysis for different types of solar modules (Europe to Germany, transport using truck).

lengths (370 km and 750 km). Other costs, like insurance or capital costs, do not change, highlighting that manufacturing should be as close to installation as possible to lower trucking costs.

For the three different transport routes from China to Germany (via Suez Canal, via Cape of Good Hope, via Arctic Sea), we find that the shorter route via the Arctic has the lowest costs with -22% compared to the Suez Canal route. Without additional effects (e.g., increased

container prices), rerouting via the Cape of Good Hope increases costs by 19% compared to the Suez Canal transfer (Fig. 10).

3.3 Sensitivity analysis

We find that increasing module efficiency reduces transport costs. The absolute costs slightly increase (€/container) due to a higher product value and therefore a higher

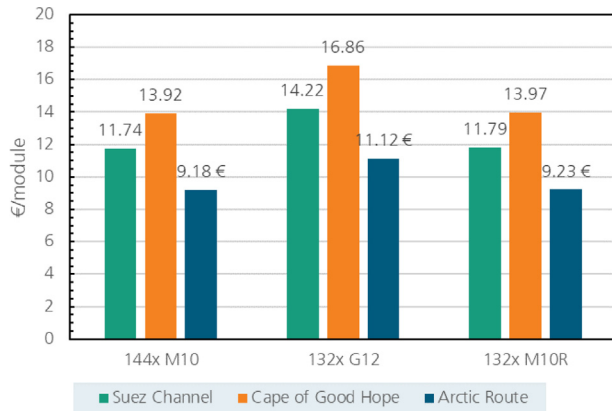


Fig. 10. Transport cost analysis for different types of solar modules (China to Germany, multimodal transport using ship and truck, three different transport routes).

insurance fee, but the specific costs (€/Wp) are lower for modules with higher efficiency. We find that a 1%_{abs} increase in module efficiency reduces the transport costs by 4.2%. An increase in module efficiency from 22.6% to 23.0% reduces the transport costs by 1.7%, and a 24% module would reduce transport costs by 5.7%.

Container prices have a high impact on transport costs (Fig. 11). Reference costs for this sensitivity analysis are container costs of 6,000 \$ (=100%). We analyze costs between 1,000 and 15,000 \$. Transport costs double at 15,000 \$. Module price increases by 15% for a disruption of the transport chain that escalates container costs. On the other hand, container prices of 1,000 \$ reduce module costs by 8% compared to the 6,000 \$ reference price level.

Pre-Corona (2019) pricing levels of 1,000 \$ for shipping containers (Fig. 5) resulted in ~5 €/module transport costs. Peak-Corona container pricing (15,000 \$) resulted in ~23 €/module transport costs. This proves the economic importance of undisrupted logistic chains for photovoltaic modules.

Changes in module prices do not significantly affect absolute transport costs (<1%) since only the value of the transported goods changes, impacting only capital costs and insurance. However, the share of transport costs on module manufacturing costs is severely impacted.

A combination of container cost analysis and module price variation reveals that for low module prices and high container prices, up to 43% of the final module price may result from the transport (Fig. 12). Thus, module prices will be more vulnerable to disruptions in global logistics and peaks in container prices.

Current module prices are at an all-time low and are considered unsustainable due to high competition and manufacturing overcapacities in China [42–46] which may result in increasing prices for modules. On the other hand, module prices have been following the price learning curve, resulting in ever-lower prices (Fig. 6), and economies of scale and technological advancements make increasing prices unlikely. We use a 0.10 €/Wp price for

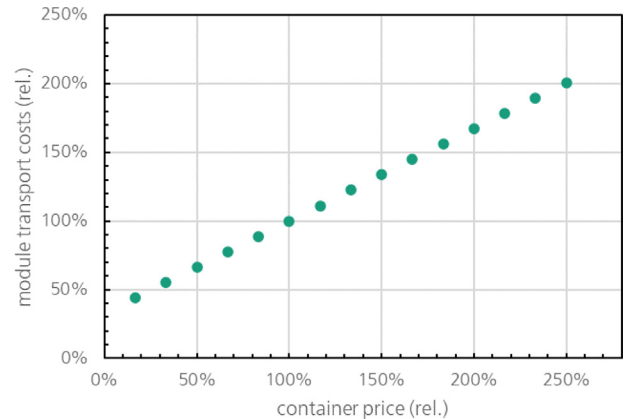


Fig. 11. Sensitivity analysis for the impact of container costs on total transport costs (reference container costs = 6000 \$), M10R module, Suez Channel route.

typical future module prices and a container price of 2,000 \$, which was comparatively stable before the Corona crisis. We calculate a transport cost share of 9.4% for these assumptions which may be more suitable to use than the current 15–16%.

The analyses show that a future decline in module prices and an increase in transport cost share will make transport a more relevant issue for module sourcing in power plants. An impact assessment of transport costs on the Levelized Cost of Electricity (LCOE) is advised.

4 Conclusion

Our analysis shows that transport costs significantly impact the overall costs of photovoltaic (PV) modules, especially as module prices decline.

We find that the module based on rectangular wafers (cell size M10R: $182 \times 105 \text{ mm}^2$) has lower transport costs (€/Wp) than the module designs based on square wafers (M10, G12). The transport costs are 8.2% lower compared to the M10 and G12 module. The transported power (GWp/container) is highest for the M10R module.

Transport costs make up a substantial portion of total costs, especially when modules are sourced from international locations like China (currently 15–16%). The most relevant cost factor is trans-ocean container shipping. Therefore, Germany-based manufacturing reduces transport costs to below 1.7% of the module price, and transport from a European manufacturing accounts for approx. 2.8%.

Transport costs are sensitive to disruptions in global logistics, such as blockages in key shipping routes or spikes in container prices. Pre-Corona (2019) container prices of 1000 \$ resulted in ~5 €/module transport costs. Peak-Corona container pricing (15,000 \$) resulted in ~23 €/module transport costs. Transport costs can account for up to 43% of the final module price in scenarios of low factory-gate prices and high container costs. This highlights the need for robust supply chain strategies to

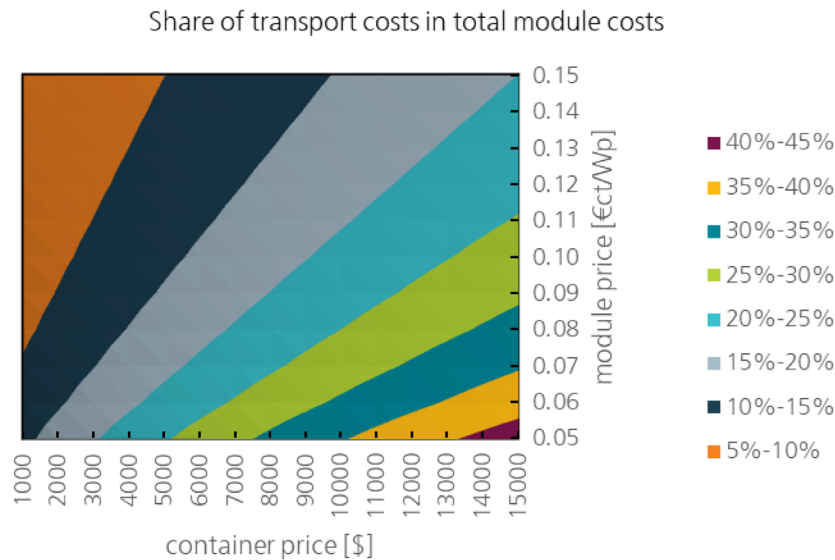


Fig. 12. Share of transport costs in the total module costs (including transport) as a combination of the analysis of module price and container price variation (Figs. 11 and 13).

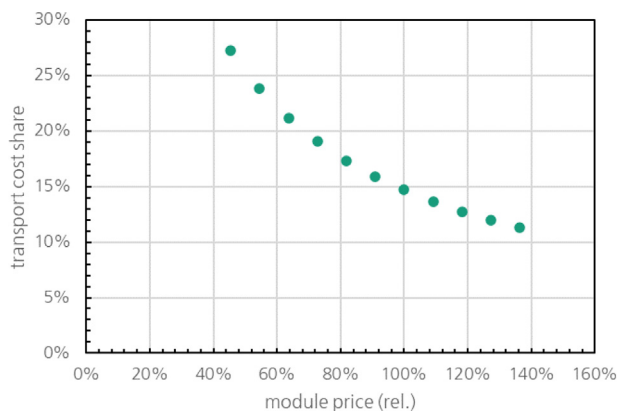


Fig. 13. Sensitivity analysis for the impact of module price on the transport cost share (reference module costs = 11 €/ct/Wp), M10R module, Suez Channel route.

minimize risks. The findings underscore the importance of considering transport logistics in PV module design and sourcing decisions.

Higher module efficiencies contribute to lower specific transport costs (€/Wp), suggesting that advancements in module technology can mitigate some of the logistic expenses (+1%_{abs} in module efficiency reduces transport costs by 4%_{rel}).

Given these findings, future research and industry practices should incorporate detailed transport cost evaluations when calculating the Levelized Cost of Electricity (LCOE) for solar projects. This holistic approach will ensure more accurate cost assessments and better-informed decisions for the sustainable growth of solar energy.

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Conflicts of interest

There are no conflicts of interest.

Data availability statement

This article has no associated data and/or data associated with this article cannot be disclosed due to legal reason.

Author contribution statement

Max Mittag: Methodology, Visualization, Data Curation, Investigation, Resources, Writing – Original Draft Preparation, Writing – Review & Editing. Tim Straube: Methodology. Christian Reichel: Supervision.

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