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Project Scientific Abstract

The SiLEAN project deals with the development of advanced innovations to tackle the major drawbacks of silicon heterojunction solar cell technology, namely the high energy and material demand for Si wafer manufacturing, limited current generation, and the consumption of scarce materials like silver, bismuth and indium. Within the scope of the project, we will directly grow the wafers from the gas phase, apply alternative passivation concepts that show higher optical transparency, develop indium-free contact layers and apply silver and bismuth-free metallization with all-in-one cell interconnection and encapsulation. The project aims to achieve >25.5% solar cell efficiency and >23.5% module efficiency with 50% lower costs for Si wafers and contacting, as well as up to 75% lower carbon footprint. All processes applied allow upscaling to larger sizes as well as high manufacturing throughput. Eventually, the developments of SiLEAN will pave the way for a new, clean, generation of heterojunction solar cell technology that will both increment the energy conversion efficiency and unlock production at terawatt-scale.

Public summary

The SiLEAN project is developing the next generation of silicon heterojunction (SHJ) solar cell technology that is more efficient and contains significantly less critical raw materials. By substituting energy-intensive commercial silicon wafers with NexWafe epitaxially grown ones and eliminating the use of silver and indium in cell manufacturing, the SiLEAN technology will enable a more resilient, supply secure, and sustainable photovoltaic (PV) value chain in Europe.

Modelling is a powerful tool to simulate performance of solar cells and modules and optimize their structures for higher efficiency. In this report, the calculation of energy yield of three different full-size SHJ solar modules in three locations (Delft in The Netherlands, Catania in Italy, and Shanghai in China) are presented. The simulations were carried out by PV Works and supported by TUD, 3SUN, and FZJ. The modules were formed by reference solar cells and next generation SHJ solar cells developed in the SiLEAN project. The reference solar cell is a state-of-the-art SHJ solar cell with a stack of amorphous silicon-based layers. The next generation SHJ solar cells are a transparent passivating contact (TPC) SHJ solar cell with a stack of SiOx and nanocrystalline silicon-based layers, and a transition metal oxide SHJ solar cell with a stack of MoOx and amorphous silicon-based layers. The simulations used multi-scale modeling software developed by TUD and PVW. After validation of input parameters for the three different solar cells by matching available experimental data with simulation, performance characteristics of these solar cells under different temperature and irradiance conditions were calculated for the same thickness of 160 µm thick wafer. Using these performance characteristics, module performance and annual energy yield for three locations were calculated. The calculations were carried out for a monofacial module with 120 half-cut G12 cells in a butterfly configuration with the total area of 2.808 m^2. The simulated nominal power of the module with state-of-the-art SHJ solar cells, TMO-based SHJ cells, and TPC-based solar cells was 532.82 W_p, 594.95 W_p, and 595.39 W_p, respectively. The calculated energy yield for Delft/Catania/Shanghai was 628/1043/709 kWh, 684/1152/776 kWh, and 684/1145/776 kWh for reference, TMO-based, and TPC-based module, respectively. The results of energy yield show that the modules based on the novel solar cell structures developed in the SiLEAN project deliver comparable and even higher average annual energy than the modules based on state-of-the art industrial SHJ solar cells. The energy yield calculations serve as input for the life cycle analysis evaluating the environmental impact of the SHJ solar cell concepts.

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Abbreviations

Abbreviation	Explanation
AC	Alternating current
ARC	Anti-reflective coating
Ag	Silver
AM	Air mass
a-Si:H	Hydrogenated amorphous silicon
Bi	Bismuth
c-Si	Crystalline silicon
Cu	copper
Cz-silicon	Czochralski-grown silicon wafer
DC	Direct current
EVA	Ethyl Vinyl Acetate
EY	Energy yield
FF	Fill factor
IEA	The International Energy Agency
In	indium
ITO	Indium Tin Oxide
ITRPV	International Technology Roadmap for Photovoltaics
IWO	Tungsten-doped Indium Oxide
J-V, I-V, P-V	Current density – voltage, current – voltage, power – voltage
J_{sc}	Short circuit current density
LCA	Life-cycle analysis
MgF_2	Magnesium flouride
MoO_x	Molybdenum oxide
nc-Si(C):H	Hydrogenated nano-crystalline silicon (carbide)
Pb	Lead
PECVD	Plasma-enhanced chemical vapor deposition
Pout	Output power
PV	Photovoltaics
Si	Silicon
SiO_2	Silicon dioxide
SHJ	Silicon heterojunction
TCO	Transparent conductive oxide
TPC	Transparent passivating contact
TMO	Transition metal oxide
TW	Terra Watt
V_{oc}	Open circuit voltage
W, W_p	Watt, Watt peak
ZnO	Zinc oxide
η	Conversion efficiency

1 Introduction

Solar photovoltaic (PV) technology is widely recognised as a low-cost, low-emission alternative to fossil fuel-based electricity generation. The exponential growth in demand for PV systems will likely contribute to a corresponding increase in manufacturing and installed generation capacity. According to the IEA's Net Zero Emissions by 2050 Scenario and IRENA's 1.5 °C Scenario, global installed PV generation capacity is projected to increase by at least a factor of ten between 2023 and 2050, reaching 20 TWp by 2050 [1 , 2]. In contrast, the study by Bogdanov et al. projected 63 TWp of installed capacity by 2050 [3]. This higher projection reflects the assumption that 89% of total primary energy demand will be electrified by 2050, including electricity-based technologies for applications such as water desalination.

Wafer-based crystalline silicon (c-Si) photovoltaic (PV) technology is a widely used solar energy solution, offering relatively high efficiency, and making it a key player in renewable energy generation. In particular, the innovative approach of silicon heterojunction (SHJ) solar cells reduces recombination losses at the cell interfaces, enabling the use of thinner silicon wafers yielding improved overall efficiency. The successful development of SHJ cell technology has significantly increased the power conversion efficiency of c-Si silicon solar cells to 27.30% [4]. However, despite these benefits, SHJ-based c-Si PV faces challenges in terms of manufacturing costs, material utilization and efficiency (e.g., the use of Indium in the contact layers, the use of Ag and Bi in the metallization and interconnection) and parasitic absorption in the front layers that limits the photocurrent generation.

The SiLEAN consortium has strong ambitions to develop the next generation of SHJ solar cells with low-cost low energy manufacturing process, lower life cycle environmental footprint, and higher efficiency than commercial cells. The consortium seeks to achieve these targets with indium-free contact layers, silver-free metallization, and bismuth-free interconnections. As such, assessing the resource-use of SiLEAN solar cells and benchmarking them against other PV cell technologies can support efforts to minimise supply risks and position SiLEAN as a key enabler for TW-scale PV deployment.

In this deliverable, the calculation of performance and energy yield of SiLEAN SHJ solar cells and modules are presented. The simulations were carried out by PV Works supported by TUD, 3SUN, and FZJ. The reference solar cell is a state-of-the-art SHJ solar cell with a stack of amorphous silicon-based layers. Transparent passivating contact (TPC) SHJ solar cell with a stack of SiOx and nanocrystalline silicon-based layers and transition metal oxide (TMO) SHJ solar cell with a stack of MoOx and amorphous silicon-based layers represent the next generation SHJ solar cells developed in the SiLEAN project.

After validating the input parameters for simulation of solar cells by matching the experimentally available J-V curves of the investigated solar cell, a set of J-V curves as function of temperature and irradiance was generated for each type of the solar cell. These J-V curves are needed to accurately calculate the annual energy yield of these solar cell technologies taking into account annual variations in illuminated and ambient conditions. A lumped element model is used to calculate the IV-curves of each solar cell for every hour of the year, considering the average meteorological data of location where the system is located. The I-V curves of the cells are combined factoring in the interconnection to obtain the module I-V curve. Performance of a PV system is expressed in terms of an annual yield based on simulated modules. In the simulations of the annual energy yield, a free horizon was assumed implying that the modules have uniform illumination over the whole area. The energy yield of the three different types of SHJ modules were determined for three geographical locations, namely Delft in the Netherlands, Catania in Italy, and Shanghai in China. The energy yield calculations serve as the input for the life cycle analysis evaluating the environmental impact of the SHJ solar cell concepts.

2 Simulation of silicon heterojunction solar cells

2.1 Silicon heterojunction (SHJ) solar cell structures

Wafer-based c-Si PV technology is a widely used solution for solar energy conversion, offering relatively high efficiency, and making it a key player in renewable energy generation. Currently, SHJ solar cells are applying an intrinsic amorphous (a-Si:H) silicon layer to passivate unsaturated bonds at the wafer's surface, followed by doped a-Si:H or nanocrystalline (nc-Si:H) layers to form the carrier selective contacts. Those layers are prepared by plasma-enhanced chemical vapor deposition (PECVD) and are prone to parasitic absorption losses, limiting current generation in the solar cell.

SiLEAN will develop new approaches to industrial wafer size without using a-Si:H or nc-Si:H layers that show excellent passivation and higher transparency to reduce parasitic absorption losses in the solar cells. Those alternatives are based on nc-SiC:H or transition metal oxides, like MoOx. All those innovations will be demonstrated on epitaxially grown, thin wafers that have a significantly lower energy demand in manufacturing, thereby lowering the global warming potential of PV electricity.

Currently, indium tin oxide (ITO) is used in SHJ solar cells as contact layer. Since indium is a scarce material, it is expected that its price will strongly increase when TW production is installed. It is projected that In production will be insufficient for the multi TW annual production required to reach 60 TWp by 2050 [5]. SiLEAN will replace indium-containing ITO as transparent conductive oxide (TCO) by developing a technology for integration of cost-effective, indium-free contact layer by using more abundant ZnO-based TCOs deposited by PECVD instead of being sputtered to avoid damage of passivation. Besides, PECVD-deposited ZnO can generally be fabricated within the same vacuum system as the passivation and carrier-selective layers.

Figure 1 shows schematic SHJ solar cells structures studied and developed in SiLEAN project. In this phase of the project the properties of epi-grown Si wafer and SHJ solar cell with epi-Si wafers were not available, therefore in simulations we used solar cell structures fabricated with Cz-silicon wafer.

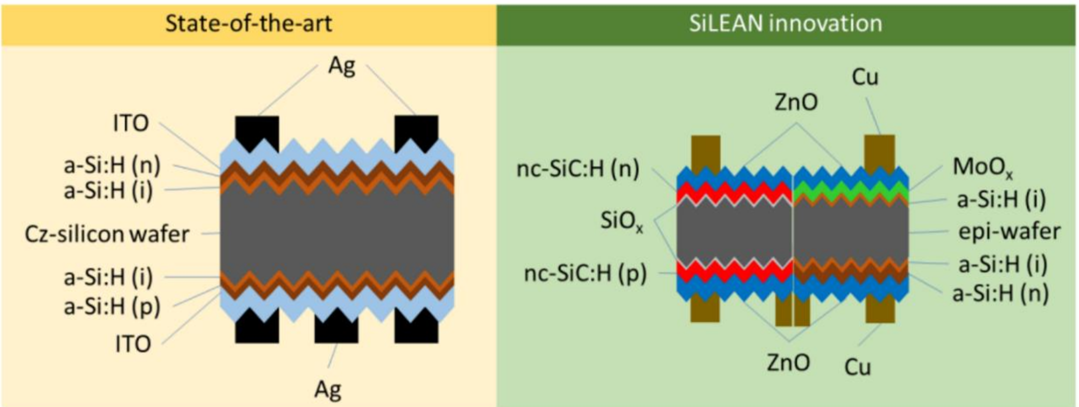


Figure 1: Schematic solar cell structures of three different Si-HTJ solar cells.

2.2 Modelling framework for performance evaluation of c-Si solar cells and modules

Advanced opto-thermo-electrical modelling plays a crucial role in performance assessment of new solar cell structures and modules. Modelling enables design choices at the materials and cell levels, optimizing their combinations, and evaluating their impact on module and system performance in real-world environments. In this work the multi-scale PVMD Toolbox [6, 7, 8] was used to evaluate performance of novel SiLEAN solar cells, modules and system performance at three different locations, namely Delft in The Netherlands, Catania in Italy and Shanghai in China. Figure 2 presents the flow diagram of the modelling framework that was used in this work. The detailed description of individual stages is given in reference [8].

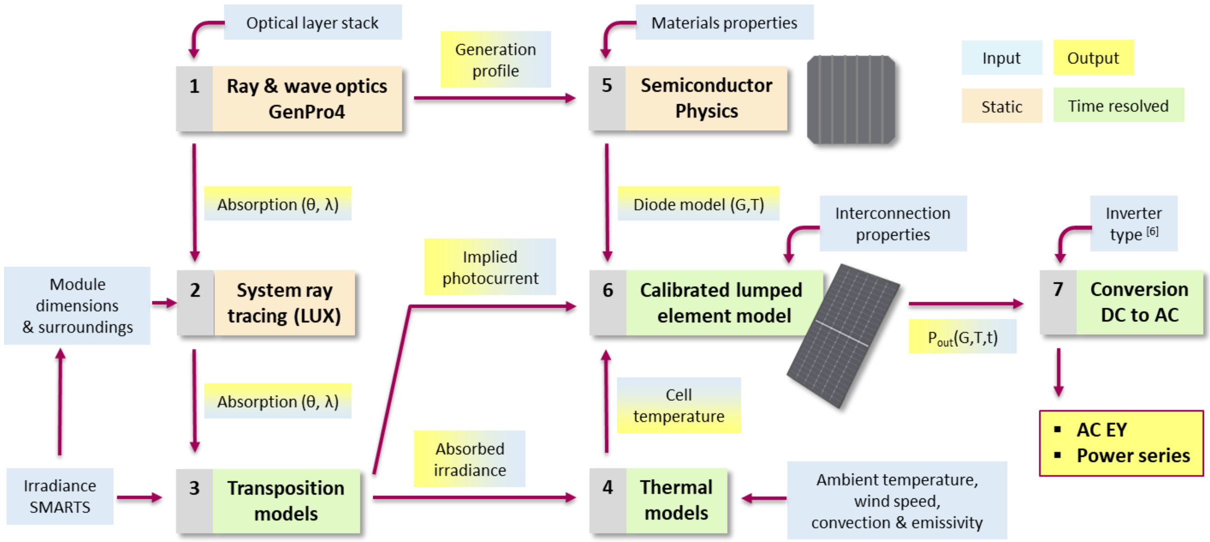


Figure 2: Flow diagram of the simulation framework, illustrating the sequential stages from optical modelling (stage 1) up to AC energy yield and power series analysis (stage 7). Adopted from reference [8].

2.3 Optical properties of solar cell layers

In the first step, the optical simulations of SHJ solar cells were carried out. In these simulations the active area of the solar cells is taken into consideration. The optical simulations deliver an absorption profile in the solar cell that is used as generation profile of carriers in further opto-thermal-electrical simulation of the cell. From the optical simulations a total absorptance in the individual layers of the solar cell is determined together with its total reflectance and transmittance. The absorptance, reflectance and transmittance in combination with the AM1.5 spectrum can be expressed in terms of photocurrent density, that indicates the potential losses in the supporting layers. The optical simulations were carried out with optical constants of standard layers available at the TU Delft/PVMD group. These optical constants are presented in Figure 3.

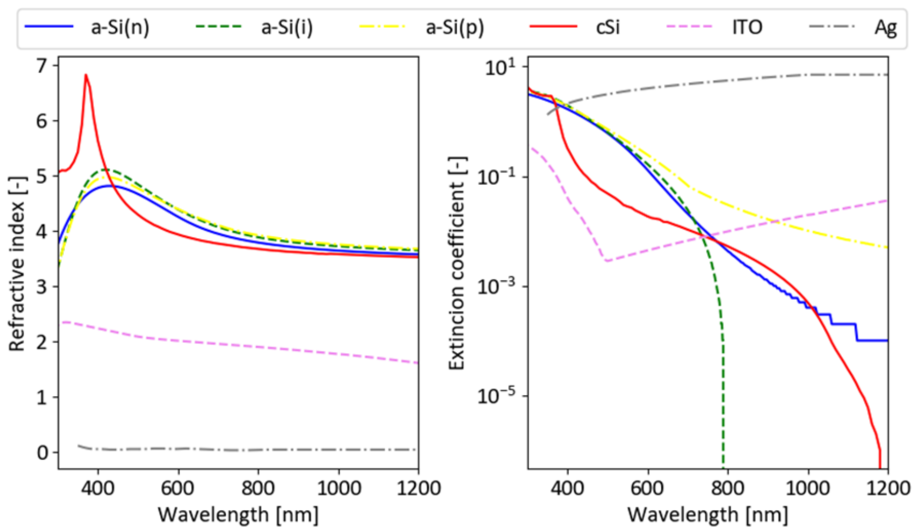


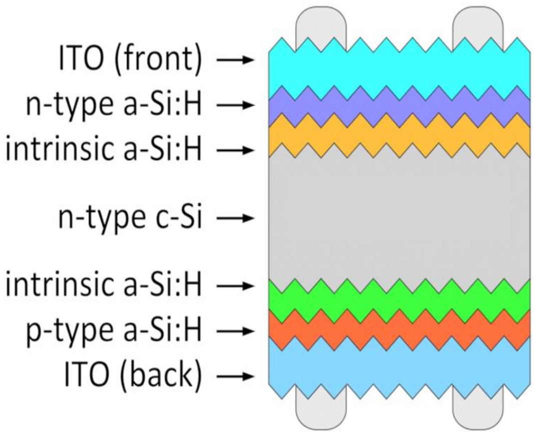
Figure 3: Optical properties of wavelength of layers used in the simulations SHJ solar cells.

2.4 Validation of input parameters

The validation of input parameters for solar cell performance simulations was carried out by matching the experimental measurements of J-V curves of solar cells with simulated ones.

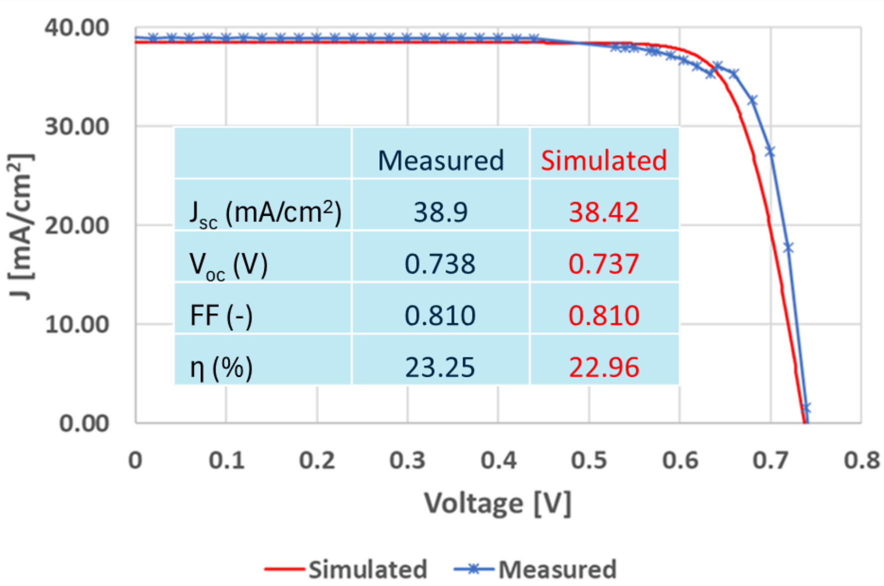
2.4.1 Reference SHJ solar cell

Figure 4 shows the schematic structure of the reference bifacial SHJ solar cell fabricated by 3Sun. Measured and simulated J-V curves of the reference SHJ solar cell is presented in Figure 5. The values of measured and simulated external solar cell parameters are included in Figure 5. There is a good matching between the measured and simulated J-V curves with an absolute difference of less than 0.3% in measured and calculated efficiency.



Material	Layer thickness
ITO (front)	70 nm
(n) a-Si:H	7.1 nm
(i) a-Si:H	5.97 nm
(n) c-Si	160 µm
(i) a-Si:H	9.15 nm
(p) a-Si:H	11.67 nm
ITO (back)	100 nm

Figure 4: Schematic structure of the reference SHJ solar cell with thicknesses of individual layers.

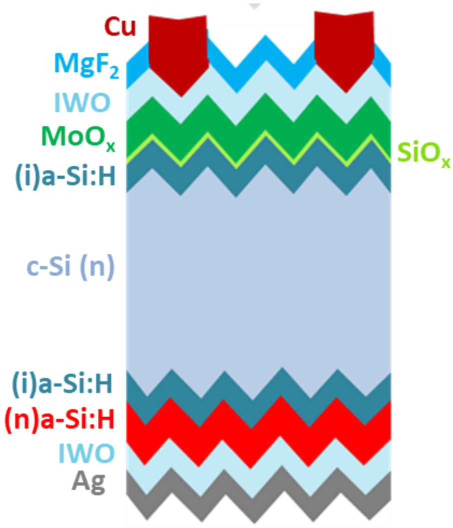


	Measured	Simulated
J_{sc} (mA/cm^2)	38.9	38.42
V_{oc} (V)	0.738	0.737
FF (-)	0.810	0.810
η (%)	23.25	22.96

Figure 5: Measured and simulated J-V curves of the reference SHJ solar cell.

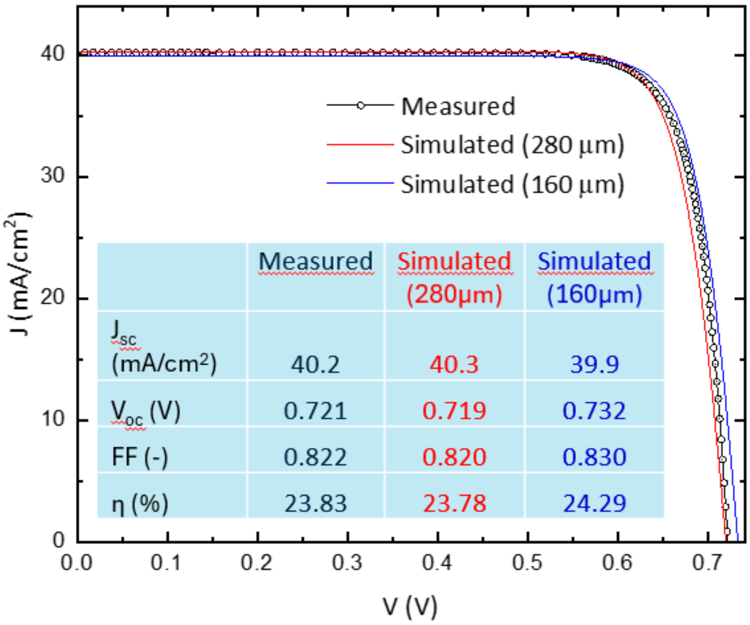
2.4.2 TMO SHJ solar cell

For the calibration purpose we used a TMO SHJ solar cell fabricated at TUD [9, 10]. Figure 6 shows the schematic structure of the SHJ solar cell with transition metal oxide layer (TMO). Instead of a thin epi-wafer, a c-Si wafer of 280 µm that was used by TUD was applied. Measured and simulated J-V curves of the TMO SHJ solar cell fabricated at TUD is presented in Figure 7. A good matching between the measured and simulated J-V curves was obtained with an absolute difference of less than 0.05% in measured and simulated efficiency. To have a fair comparison with the reference SHJ cell the simulation of a TMO SHJ cell with 160 µm thick wafer was carried out. The values of measured and simulated external solar cell parameters are included in Figure 7. It is interesting to note that the efficiency of the TMO SHJ cell with 160 µm thick wafer is higher that the cell with 280 µm thick wafer.



Material	Layer thickness
MgF2	106 nm
IWO	57 nm
MoOx	2 nm
SiO2	1.8 nm
(i)a-Si	12 nm
(n)c-Si	280 µm
(i)a-Si	7 nm
(n)nc-SiOx	7 nm
IWO	150 nm
Ag	300 nm

Figure 6: Schematic structure of the TMO SHJ solar cell with thicknesses of individual layers.

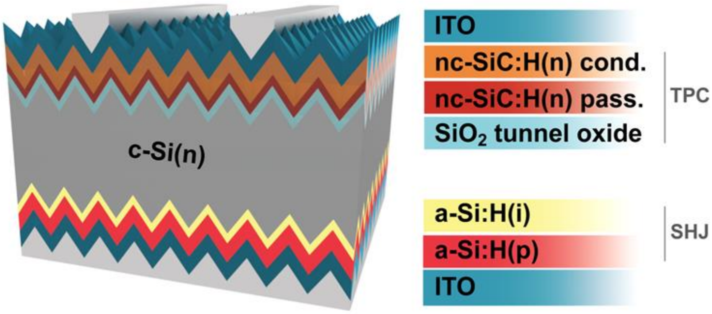


	Measured	Simulated (280µm)	Simulated (160µm)
J_{sc} (mA/cm^2)	40.2	40.3	39.9
V_{oc} (V)	0.721	0.719	0.732
FF (-)	0.822	0.820	0.830
η (%)	23.83	23.78	24.29

Figure 7: Measured and simulated J-V curves of the TMO SHJ solar cell.

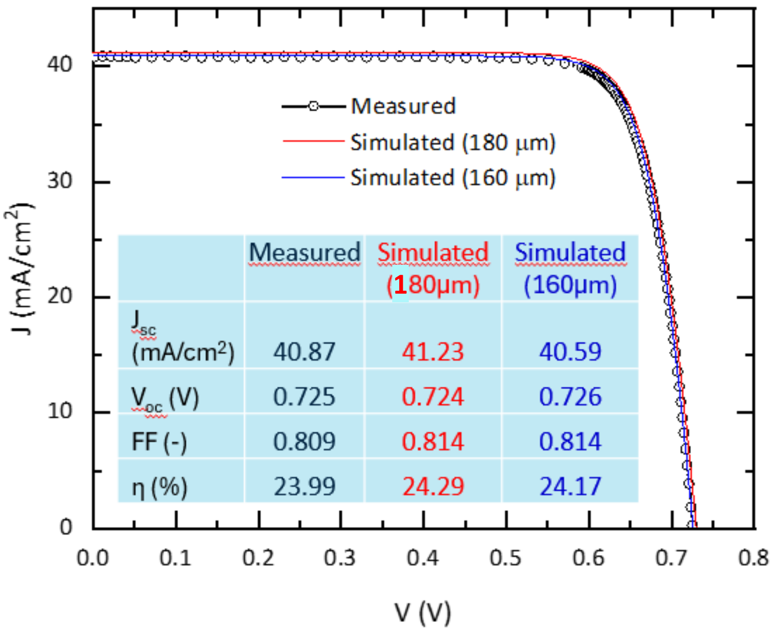
2.4.3 TPC SHJ solar cell

For validation of the input parameters for a SHJ solar cell with transparent passivating contacts (TPC) a solar cell fabricated by FZJ was used [11]. Figure 8 shows the schematic structure of the SHJ solar cell with transparent passivating contacts. Measured and simulated J-V curves of the reference SHJ solar cell is presented in Figure 9. The values of measured and simulated external solar cell parameters are included in Figure 9. A good matching between the measured and simulated J-V curves with an absolute difference of less than 0.3% in measured and calculated efficiency was obtained when the wafer thickness was set to 180 µm. To have a fair comparison with the reference SHJ cell the simulation of a TMO SHJ cell with 160 µm thick wafer was carried out. The values of measured and simulated external solar cell parameters are included in Figure 7.



Material	Layer thickness
MgF2	100 nm
ITO	70 nm
(n)nc-SiC	25 nm
a-SiC	3 nm
SiO2	1 nm
(n)c-Si	180 µm
(i)a-Si	6 nm
(p)a-Si	7.4 nm
ITO	69.8 nm
Ag	300 nm

Figure 8: Schematic structure of the TPC SHJ solar cell with thicknesses of individual layers.



	Measured	Simulated (180µm)	Simulated (160µm)
J_{sc} (mA/cm²)	40.87	41.23	40.59
V_{oc} (V)	0.725	0.724	0.726
FF (-)	0.809	0.814	0.814
η (%)	23.99	24.29	24.17

Figure 9: Measured and simulated J-V curves of the reference TPM SHJ solar cell.

2.5 Irradiance and temperature dependent J-V curves

Before calculating the module performance, irradiance- and temperature-dependent J-V and P-V characteristics were calculated. The irradiance was varied from 10 W/m² to 1200 W/m² in steps of 100 W/m². The temperature was varied from 10 °C to 90 °C in steps of 10 °C. The J-V and P-V curves of the reference, TMO and TPM SHJ cells are presented in Figure 10, Figure 11 and Figure 12, respectively.

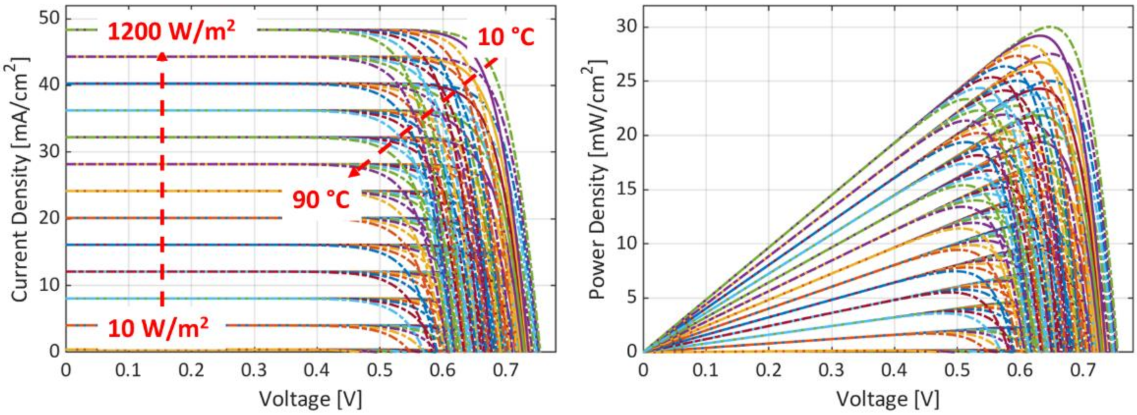


Figure 10: J-V and P-V characteristics of the reference SHJ solar cell as function of irradiance and temperature.

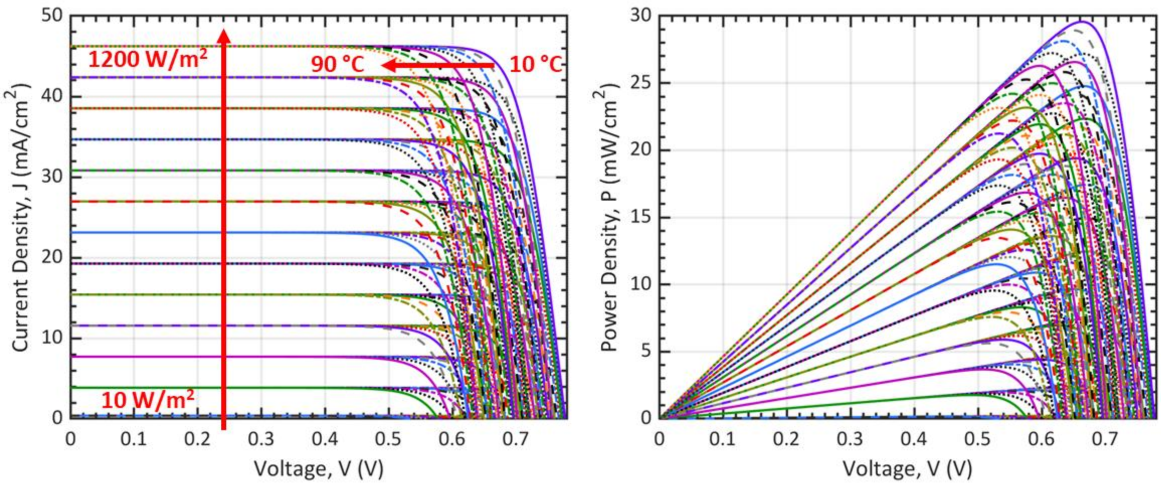


Figure 11: J-V and P-V characteristics of the TMO SHJ solar cell as function of irradiance and temperature.

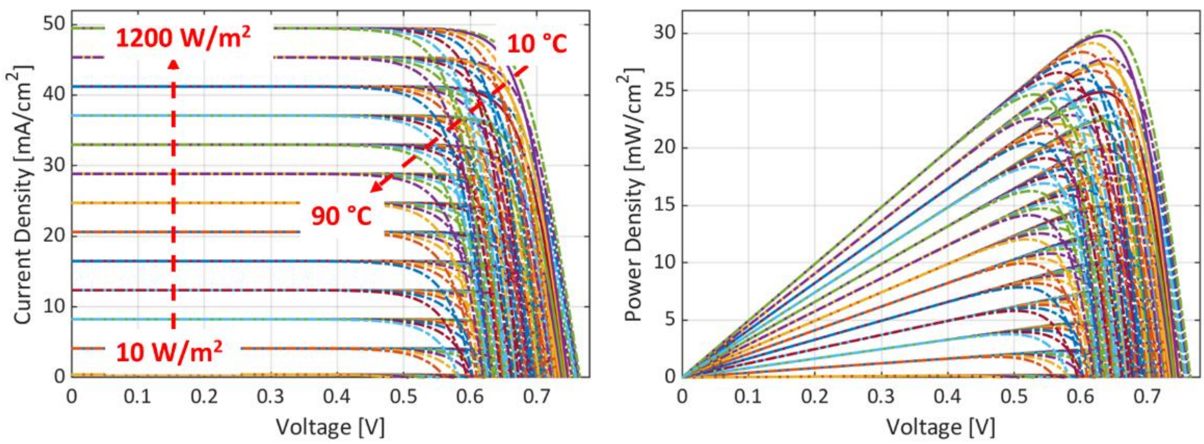


Figure: 12 J-V and P-V characteristics of the TPC SHJ solar cell as function of irradiance and temperature.

3 Simulations of energy yield of SHJ modules

3.1 Modelling of module characteristics

J-V curves at different temperatures and irradiance are needed to accurately calculate the annual energy yield of solar cell technologies when real daily variations in illuminated and ambient conditions are taken into account. Figure 13 presents a procedure that was used to determine module characteristics at different external conditions. A lumped element model is used to calculate the I-V curves of each solar cell for every hour of the year, considering the average meteorological data of location where the system is located. The I-V curves of the cells are combined factoring in the interconnection to obtain the module IV-curve. More detailed description of the procedure is given in reference [8]. The calculations were carried out for a module with 120 half-cut G12 cells in a butterfly configuration. The module area is 2.808 m^2. The module has glass-to-glass configuration with an antireflective coating (ARC) on the top and UV-transparent EVA layers. The electrical topology, visual rendering of the simulated module, and thickness of encapsulation layers are shown in Figure 14.

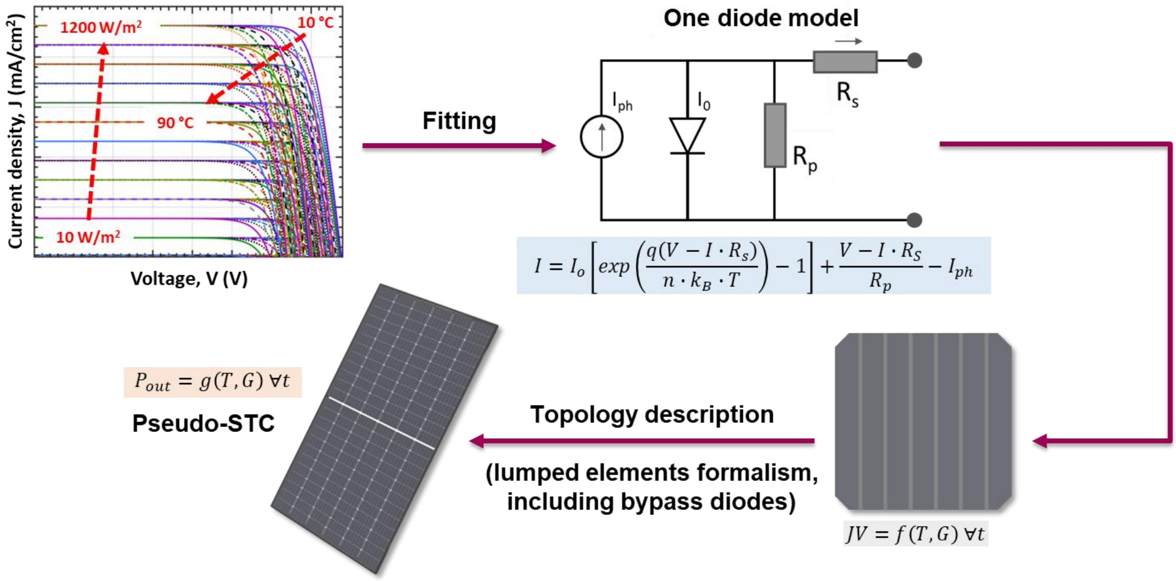
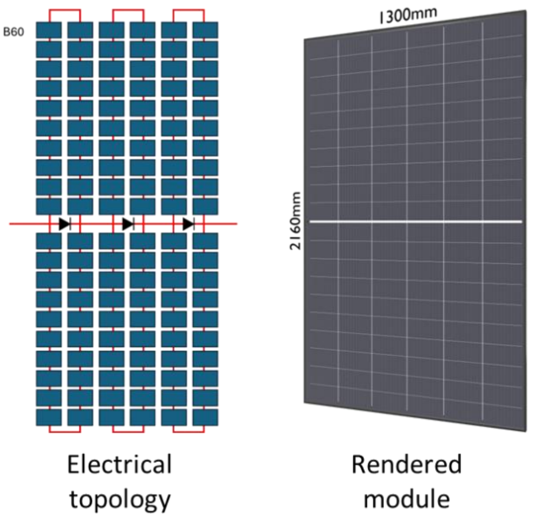


Figure 13: Method to determine module characteristics at different external conditions, where T, G and t are temperature, irradiance and time, respectively. JV and P_{out} are functions of T and G at each time step t.



Encapsulation material	Layer thickness
Glass ARC	53 nm
Glass	2.0 mm
EVA	0.45 mm
SHJ cells	-
EVA	0.45 mm
Glass	2.0 mm

Figure 14: The electrical topology, visualization, and thicknesses of encapsulation layers of simulated module.

3.2 Energy yield calculations of PV systems

Performance of a PV system is expressed in terms of an annual yield of the simulated modules. In this study the energy yield of the three different SHJ modules was determined for three geographical locations, namely Delft in the Netherlands, Catania in Italy, and Shanghai in China. The energy yield calculations serve as the input for the life cycle analysis evaluating the environmental impact of the SHJ solar cell concepts.

As the sites are situated in the Northern Hemisphere, the PV arrays are oriented with an azimuth angle directed southward to optimize solar energy utilization. In this study we fixed the tilt angle to 25°, which maximizes annual production during summer in the selected locations. The height at which the module is mounted (h_M) was 1.5 m. The horizon was considered free from obstructions, ensuring an unrestricted sky view factor for the PV module and system. A visualization of the system configuration is shown in Figure 15.

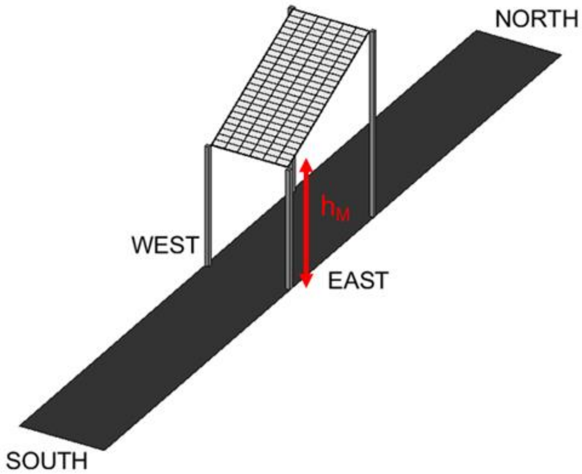


Figure 15 Visualization of the PV system placement and positioning.

In case of the reference SHJ solar cell, the validation of the input parameters was done on the bifacial SHJ solar cell. The TMO- and TPC-based SHJ solar cells are monofacial solar cells. For a fair comparison of the energy yield among these three SHJ cell technologies, we calculated the annual energy yield for a monofacial module archetype. For the calculation of energy yield of modules based on TMO and TPC SHJ solar cells we used the simulation results of cells with 160 µm thick wafer. The results of the calculated annual energy yield at DC level are presented in Table 1. The nominal power and efficiency of the module at standard test conditions (STC) is included per module in Table 1.

Table 1: Calculated annual energy yield for three different locations for PV modules with different SHJ solar cells.

Module type	Reference SHJ module		TMO-based SHJ module		TPC-based SHJ module	
Power (STC)	532.83 W_p		594.95 W_p		595.39 W_p	
Efficiency [%]	18.97		21.19		21.20	
Location	**Energy yield** [kWh/year]	Specific yield [kWh/kWp]	**Energy yield** [kWh/year]	Specific yield [kWh/kWp]	**Energy yield** [kWh/year]	Specific yield [kWh/kWp]
Delft	628.06	1178.72	684.67	1150.80	684.39	1149.48
Catania	1043.58	1958.56	1152.67	1937.42	1145.04	1923.18
Shanghai	709.57	1331.70	776.62	1305.35	776.18	1303,65

The annual irradiation per location and the calculated performance ratio of PV modules with different SHJ solar cells is presented in Table 2. The best performance ratio for all three locations has the reference SHJ module.

Table 2: Annual irradiation and calculated performance ration of PV modules for three different locations.

Location	Delft	Catania	Shanghai
Annual Irradiation [kWh/m²]	**1168.2**	**2014.5**	**1346.5**
	Performance ratio [%]	**Performance ratio** [%]	**Performance ratio** [%]
Reference SHJ module	**100.9**	**97.3**	**98.9**
TMO-based SHJ module	**98.5**	**96.1**	**96.9**
TPC-based SHJ module	**98.4**	**95.5**	**96.8**

3.3 Contribution to project objectives

As demonstrated in the previous sections, the multi-scale modelling framework developed at TUD is a powerful tool to evaluate the performance of solar cells and modules that even do not exist yet. The results presented in this deliverable directly contribute to Objectives 5 (Assessment and demonstration of reduced environmental impact of the production process and materials and increased circularity for the SiLEAN products) of the project. The results will be used to assess a full life-cycle analysis (LCA) including the Global Warming Potential (GWP) of the novel solar modules to industrial state-of-the-art modules.

4 Conclusion and Recommendation

In this deliverable, a multi-scale modelling framework was presented and applied to assess annual energy yield of three different SHJ cell technologies, namely the reference state-of-the-art industrial SHJ solar cells and next generation SHJ solar cells developed in the SiLEAN project. The annual energy yield was calculated for three locations: Delft in The Netherlands, Catania in Italy, and Shanghai in China.

After validation of input parameters for the three different solar cells by matching available experimental data with simulation, performance characteristics of these solar cells under different temperature and irradiance conditions were calculated for the same thickness of 160 µm thick wafer. Using these performance characteristics, module performance and annual energy yield for three locations were calculated. The calculations were carried out for a monofacial module with 120 half-cut G12 cells in a butterfly configuration with the total area of 2.808 m^2. The simulated nominal power of the module with state-of-the-art SHJ solar cells, TMO-based SHJ cells, and TPC-based solar cells was 532.82 W_p, 594.95 W_p, and 595.39 W_p, respectively. The calculated energy yield for Delft/Catania/Shanghai was 628/1043/709 kWh, 684/1152/776 kWh, and 684/1145/776 kWh for reference, TMO-based, and TPC-based module, respectively. The main conclusion is that the results of energy yield show that the modules based on the novel solar cell structures developed in the SiLEAN project deliver comparable and even higher average annual energy than the modules based on state-of-the art industrial SHJ solar cells.

The predictive power of modeling can be further used to optimize structures of SHJ solar cells developed in the SiLEAN project for obtaining record-high efficiency. Sensitivity studies of several solar cell parameters can be carried out to propose an optimized SHJ solar cell structures with higher efficiencies. Similar study for assessing the annual energy yield that was carried out in this work for the monofacial module with 120 half-cut G12 cells in a butterfly configuration, can be carried out for different mono- and/or bifacial module configurations.

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3	TUD	TECHNISCHE UNIVERSITEIT DELFT
4	UNR	UNIRESEARCH BV
5	NXW	NEXWAFE GMBH
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