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PhD in *Engineering for Energy and
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PhD Thesis

**Numerical modelling and simulation of
renewable energy sources technologies
and systems: study on a CPC system**

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A tutti i miei cari...

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Abstract

Energy demand has been increasing in the last decades, reason why both industrial and research field are trying to face the problem of fossil fuels-based dependence with RES-based innovative solutions. Both technical and economical benefits are studied to reach easy-to-apply technologies. In those terms, the simulative engineering contribution for R&D tasks is crucial. This work aims to provide a practical example of how much numerical simulation of multi-physical scenarios could support the design testing of an innovative compound parabolic concentrator (CPC). The CPC installation on PV plant allows the system to reach higher performances in terms of energy production if compared with standard PV plants. The multiphysical approach is implemented by means of COMSOL Multiphysical simulation software, providing the numerical result validation by comparing prototyping experimental campaign data. The validation leads to a maximum overall discrepancy that is suitable for engineering purposes. Then, validated scenarios are used to develop a standalone application which could provide a virtual laboratory to change both external environment and CPC geometry parameters. This strategy allows to conduct a parametric sweep to focus on the effects of on-site conditions variation on each one of the CPC components. Furthermore, a suitable solution for CPC cooling is implemented, in accordance with the planning activities of new experimental campaigns about enhanced CPC designs, to be installed in solar energy conversion plants contexts. Results show how a cooling-system provided CPC could increase photovoltaic solar cells efficiency, while reaching lower temperatures on the sun radiation exposed surface, even if the temperature gradient all over the CPC-powered plant could lead to a non-uniform production of power.

Keywords: Compound Parabolic Concentrator, PV efficiency, COMSOL Multiphysics, thermal analysis, FEM analysis, multiparametric analysis, cooling system.

Nomenclature and acronyms

Latin symbols

a	$[m^{-1}]$	Coefficient parabola equation
c_p	$[J/(kg \cdot K)]$	Specific heat capacity at constant pressure
$c_{p,si}$	$[J/kg \cdot K]$	Specific heat capacity at constant pressure of layer i in thin layer pressure
$c_{p,s}$	$[J/kg \cdot K]$	Specific heat capacity at constant pressure, solid phase
D	$[\%]$	Data discrepancy
d_s	$[m]$	Thickness of shell or thin layer
e_b (T)	$[W/m^2]$	Blackbody total emissive power
F_{ij}	$[1]$	View factor
FEP	$[1]$	Fractional blackbody emissive power
FF	$[1]$	Fill factor
F_{ext}	$[1]$	External view factor
G	$[W/m^2]$	Surface irradiation
G_{ext}	$[W/m^2]$	External irradiation
h	$[W/(m^2 \cdot K)]$	Heat transfer coefficient
i_s	$[1]$	Solar source direction
I_{sc}	$[A]$	Short-circuit current
J	$[W/m^2]$	Surface radiosity
k	$[W/(m \cdot K)]$	Thermal conductivity
k_{si}	$[W/(m \cdot K)]$	Thermal conductivity of layer i in thin layer
L	$[m]$	Total edge length
L_x	$[m]$	Total CPC prototype extension over x-direction
L_y	$[m]$	Total CPC prototype extension over y-direction
n	$[1]$	Normal vector toward exterior
P	$[W]$	Power output solar cell

P_m	[W]	Maximum power point
P_p	[W]	Peak power of solar cell
q	[W/m ²]	Conductive heat flux
q_0	[W/m ²]	Inward heat flux
$q_{0.s}$	[W/m ²]	Source heat flux (external radiation source)
q_{flux}	[W/m ²]	Radiative heat flux
Q_{irr}	[W/m ²]	Solar irradiance
$Q_{rad,i \rightarrow j}$	[W/m ³]	Radiative heat flux between surface
$Q_{rad,i}$	[W/m ³]	Radiative heat flux from surface
Q_{ref}	[W/m ²]	Reference solar irradiation for solar cell efficiency
Q_s	[W/m ³]	Heat source in solid phase
Q_{si}	[W/m ³]	Layer i heat source
T	[K]	Temperature
t_0	[s]	Initial time step of the simulation
T_d	[K]	Temperature, downside
T_{ext}	[K]	External temperature
T_{ref}	[K]	Reference temperature for solar cell efficiency
T_s	[K]	Temperature, solid phase
T_{sc}	[K]	Temperature solar cell
T_u	[K]	Temperature, upside
T_{amb}	[K]	Ambient temperature
V_{oc}	[V]	Open circuit voltage

Greek symbols

∇_n	[-]	Normal gradient operator
∇_t	[-]	Tangent gradient operator
β	[K ⁻¹]	Temperature coefficient
γ	[1]	Solar radiation coefficient
ε	[1]	Surface emissivity
ε_{B1}	[1]	Solar spectral band
ε_{B2}	[1]	Ambient spectral band
η	[%]	Solar cell efficiency
η_{system}	[%]	CPC system efficiency
$\eta_{T_{ref}}$	[%]	Solar cell efficiency in standard conditions

θ_c	[°]	Half-acceptance angle
θ_s	[rad]	Zenith angle
λ	[m]	Wavelength
ρ	[1]	Surface reflectivity
ρ	[kg/m ³]	Density
ρ_s	[kg/m ³]	Density of thin layer
ρ_{si}	[kg/m ³]	Density of layer i in thin layer
σ	[W/(m ² · K ⁴)]	Stefan-Boltzmann constant
φ_s	[rad]	Azimuth angle

Acronyms

BECCS	Bio-Energy with Carbon Capture and Storage
BHI	Beam Horizontal Irradiation
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CIRDER	Interdepartmental Center of RES Research and Dissemination
CM	COMSOL Multiphysics
CMAS	Control, Monitoring and Acquisition System
COP	Conference of Parties
CPC	Compound Parabolic Concentrator
CPV	Concentrators for PhotoVoltaics
CSP	Concentrated Solar Power
DHI	Diffuse Horizontal Irradiation
FEM	Finite Element Method
GHG	GreenHouse Gasses
IPCC	Intergovernmental Panel of Climate Change
IRENA	International Renewable Energy Agency
LCPV	Low Concentration PhotoVoltaics
LR	Left Reflector
MUX	Multiplexer
NDC	Nationally Determined Contributions
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
PV	PhotoVoltaics
R&D	Research and Development
RES	Renewable Energy Sources
RR	Right Reflector
RMW	Renewable Municipal Waste
RTD	Resistance Temperature Detector
SC1	Solar Cell #1
SC2	Solar Cell #2
SEAG	Solar Energy Applications Group
TCD	Trinity College Dublin
UNEP	United Nations Environment Program
W2E	Waste-to-energy
WMO	World Meteorological Organization

Introduction

The anthropic impact on the environment has been moving the international awareness in terms of sustainable development and reduction of pollutants emissions over the last decades, searching for strategies aimed for the application of both green and circular economy models [1, 2]. The industrial growth should be considered as one of the main actors indeed, playing a prevalent role within the "production chain" of emissions. European and International governmental institutions are trying to encourage the implementation of virtuous approaches to this kind of problem, promoting initiatives on both private and industrial sectors. By means of action plans and guidelines their efforts are aimed to improve renewable energy power production and waste-to-energy (W2E) synergies. Referring to the European context, the *Clean energy for all Europeans package* [3] and the *Circular Economy Action Plan* [4] as one of the main blocks of the *European Green Deal* [5, 6] should be considered as the main references to redirect energy supply towards renewable energy sources (RES) in Europe. In fact, all the efforts are oriented to reduce petroleum-based fuels dependency of the most part of high energy demand activities, also known as *energy hogs*. Exploitation of renewable energy by humans has been a topic of primary interest for the research field, supported as never before by companies that look at this concept as the key to access a future where human impact on the environment could change its sign, converting from negative to positive. However, economic interests act as the engine for that interest, reason why energy saving, environmental protection and production efficiency have merged to form the cardinal principles of the green economy and sustainable development approaches.

The research field has been working harder to investigate some possible solutions to increase the rate of RES exploitation, facing many times the economical feasibility of the proposed interventions. By a technical

point of view, the complexity of this kind of engineering problems request a multidisciplinary approach and high computation capacities. For this reason, the applied research field has been moving also by means of virtual prototypes that allow technicians to analyze every component and functioning in depth. The application of research algorithms to solve complex physic phenomena has been adapted to the applied field, as demonstrated by the growing number of CAD and numerical simulation software. Those kind of tools reduce the time required by the calculation and testing phase for prototyping. Indeed, a virtual environment can be set up to verify the operation and behavior of a certain prototype, once applied the boundary conditions properly.

This work reports some applications and case-studies of numerical simulation applied to RES exploitation prototypes. In particular, a multidisciplinary approach is implemented to model and simulate a compound parabolic concentrator prototype in variable conditions, investigating the influence of certain parameters on the response of the system's functioning.

Chapter 1

State of art about renewable energy sources

Nowadays, the human activities environmental impact is one of the most complex and studied issues of our society. The effects of climate changes and environmental alterations influence the balance of the ecosystem, with massive consequences not only for natural well-being, but also for economic, social and health prosperity of humanity. The magnitude of the question has taken, during the years, to the adoption of international planes and guidelines, aimed to reach an ever increasing sustainability of human activities all over the world.

The first step in this direction has been taken in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) with the constitution of the Intergovernmental Panel on Climate Change (indicated with the acronym of IPCC), that is the United Nations body for assessing the science related to climate change [7]. The IPCC was established to carry out accurately reviewed assessments about science, impacts and response options on climate change; at the moment, five of these documents have been published (the sixth one is still in production). Currently, the IPCC is composed by 195 members and provides governments at all levels with scientific information on which climate policies could be based. The first IPCC's assessment was published in 1990 and the contained warning led to widespread calls for global treaty. For this reason, the Conference on Environment and Development (also known as “the Earth Summit”) was opened in 1992 in Rio de Janeiro, Brazil. During this important summit the first global agreement

on climate change was reached, obtaining a near universal membership with 197 Countries (also called Parties). The intention of the Treaty is to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” [8]. Since this Earth Summit, a Conference of Parties (COP) has been convened every year. During the COPs, the Parties reevaluate the Convention and make decisions to better its application.

Another important milestone of the global climate change negotiations is the Kyoto Protocol [9], ratified by 192 parties. Approved and adopted in 1997, the Kyoto Protocol entered in force in 2005. The negotiations behind this protocol focused on the reduction of GHG (greenhouse gasses) emissions from industrialised countries. The Doha Amendment extended the engagement of the Kyoto Protocol until 2020, providing the basic principles of the Paris Agreement.

Paris Agreement is “the first-ever universal, legally binding global climate change agreement, adopted at the Paris climate conference (COP21) in December 2015” [10]. This important document establishes a global framework aimed to limit the increasing of global warming “well below 2°C” and to “pursue efforts to limit the temperature increase to 1.5°C” [11]. The Agreement requires to each one of the 190 parties to submit nationally determined contributions (NDCs), which are a proof of the effort of a nation to reach a reduction of emissions, adapting its policies/activities to the climate changes [12]. In order to ensure the transparency, Governments agreed to assess every 5 years the collective progress, to report how the climate actions have been implemented and to track every kind of progress. Guidelines, procedures and rules, useful to operationalise the Paris Agreements, have been adopted in 2018 with the Katowice package [13].

The European Union and its member states joined the global effort to reach environmental sustainability. The European Community signed the Kyoto Protocol on 29 April 1998 [14], joining the Paris Agreement. In order to reach the commitments taken under the Agreement, the European Union identified a strategy for ensure a sustainable growth: the European Green Deal. This is a 2050-long term strategy aimed at reaching by 2050 the climate neutrality and at decoupling between the economic growth and resource, avoiding to leave behind people and places [15]. Climate

neutrality is the condition in which the GHG emissions do not exceed the capability of the environment and habitats to absorb these emissions by themselves.

The European Green Deal, endorsed by the European Parliament on January 2020 [16], provides an action plan, in order to restore biodiversity and minimize pollution while boosting circular economy strategies [17,18]. The objectives proposed for 2050 are ambitious, requiring intermediate steps, by which assess the statement of the progresses, reached both by each Nation and by the entire Community. A first important milestone has been placed at 2030, with the “2030 Climate & Energy Framework” [19]. In fact, the Commission proposed in September 2020 to reduce greenhouse gas emissions to at least 55% compared to 1990. This target could be declined into three practical goals, which have to be reached by 2030:

- reduction of greenhouse gas emission by at least 40% in comparison to the level of the reference year (1990);
- an improvement of 32.5% of the energy efficiency;
- an energy supply from renewable sources of at least 32%.

In this context, the link between carbon neutrality and employment of renewable energies is clear.

1.1 World Framework

A worldwide report of the trends in renewable energy sector is given by Figure 1.1 (as highlighted by the International Renewable Energy Agency) where the cumulative installed capacity of plants per year and per technology are reported. The most exploited technologies by a graphical point of view, that consist in those systems characterized by major installed capacity, are renewable hydropower, the PV energy and onshore wind energy, reaching approximately 1,130,594 MW, 578,533 MW and 594,253 MW, respectively.

Considering 2020 as the reference year, the increasing percentages for every single technology are the ones given by Table 1.1. It is important to specify that geothermal and liquid biofuels at year 2000 take into account only the installed capacity in North America and Oceania, respectively.

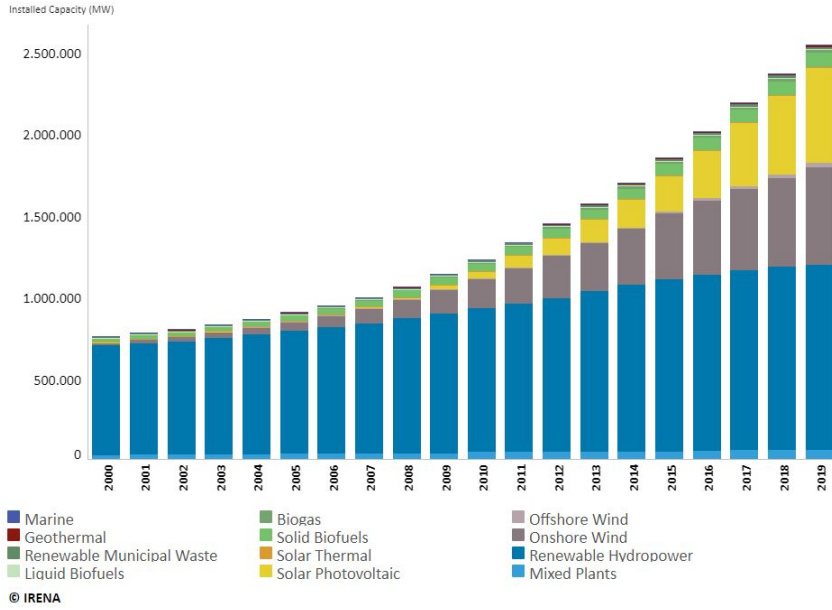


Figure 1.1. Worldwide cumulative trends in renewable energy sources and technologies [20].

Table 1.1. Installed capacity variation (2000-2019) [20].

Technology	Installed capacity [MW]		% increase
	Year 2000	Year 2019	
Mixed plants hydropower	22,790	56,556	+148.2
Renewable hydropower	675,159	1,130,594	+67.5
Onshore wind	16,860	594,253	+3,424.6
Offshore wind	67	28,155	+51,922.4
Solar PV	808	578,553	+71,503.0
Solar thermal	419	6,289	+1,400.9
Bioenergy from solid biofuels	23,151	86,870	+275.2
Bioenergy from biogas	2,455	19,381	+689.4
Bioenergy from liquid biofuels	<1	3,219	+2,090,159.7
Bioenergy from RMW	3,677	14,556	+295.9
Geothermal	8,236	13,909	+68.9
Marine energy	238	531	+122.7

Visualizing the trends of net additions in terms of installed capacity all over the world, as reported by Figure 1.2, the solar photovoltaic energy has been growing massively during the last two decades, followed by onshore wind energy.

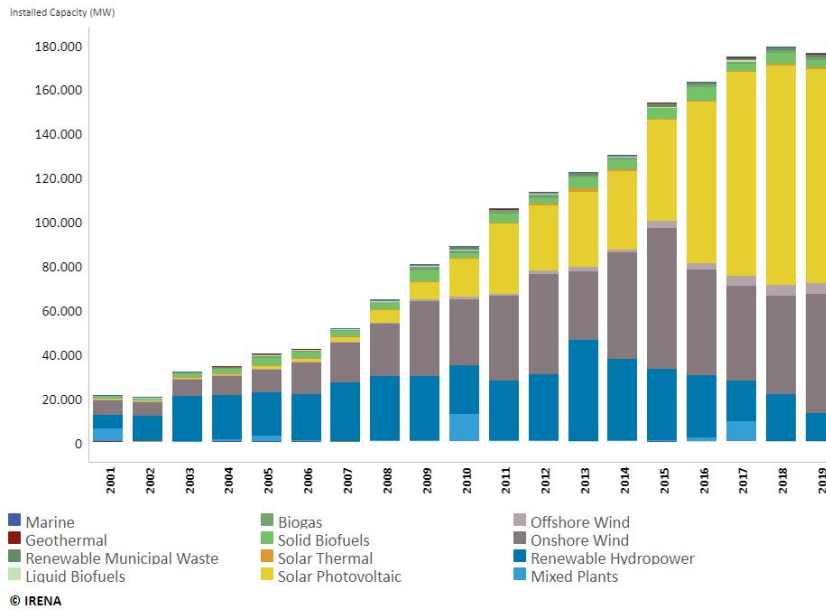
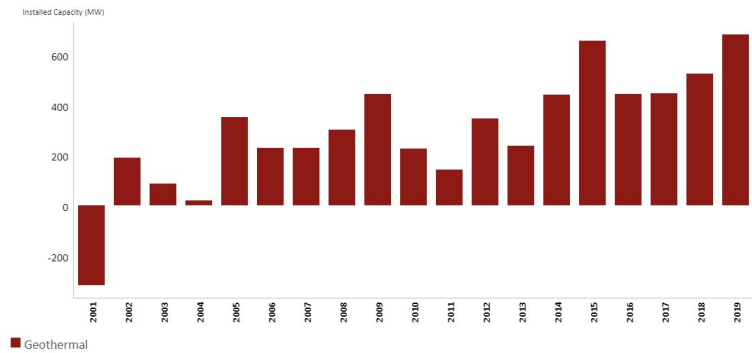


Figure 1.2. Worldwide net additions trends in renewable energy sources and technologies [20].

More in depth, it's possible analyse the trend of growth of the installed capacity of each renewable energy technology by consulting the net capacity installed graphs (Figure 1.3, Figure 1.4, Figure 1.5). Figure 1.3 highlight for geothermal plants (a), biomass (b) and wind plants (c) a fluctuating trend in terms of growth.

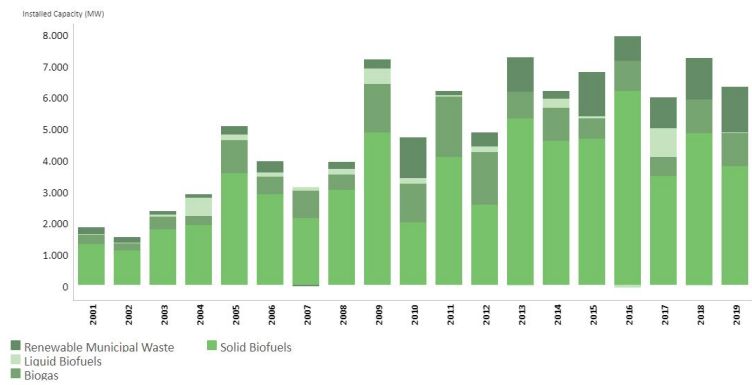
The installed capacity of marine plants Figure 1.4 has not been subjected to important variations during the years (except for the year 2011).

The net installed capacity of hydropower and mixed plants (see e.g. Figure 1.5(a)) decreases during the two decades, with a maximum peak in 2013. Besides that, solar thermal and photovoltaic (refer to Figure 1.5(b)) show both a continuous growth from 2001 to 2019, with a net addition of the installed capacity of 97,388 MW and 97,569 MW, respectively in 2018 and 2019.



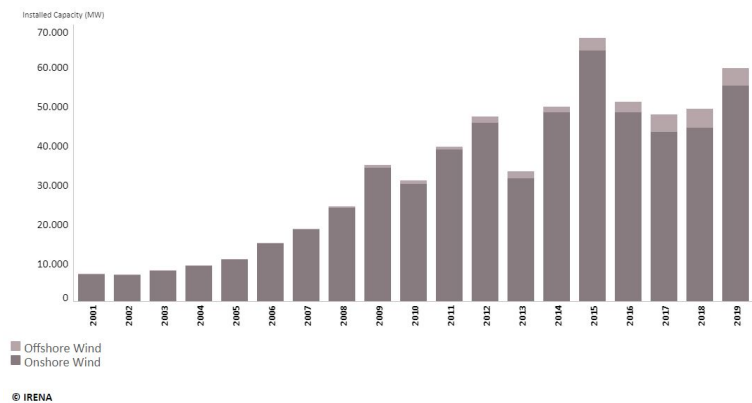
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(a) Net addition of installed capability of geothermal plants.



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(b) Net addition of installed capability of bioenergy plants.



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(c) Net addition of installed capability of wind plants.

Figure 1.3. Worldwide net additions trends in renewable energy sources for geothermal, bioenergies and wind technologies [20].

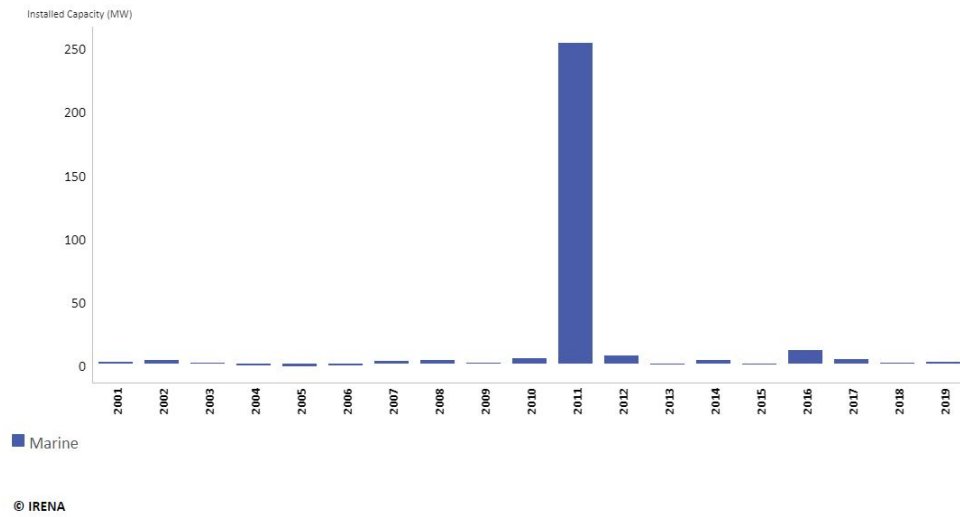
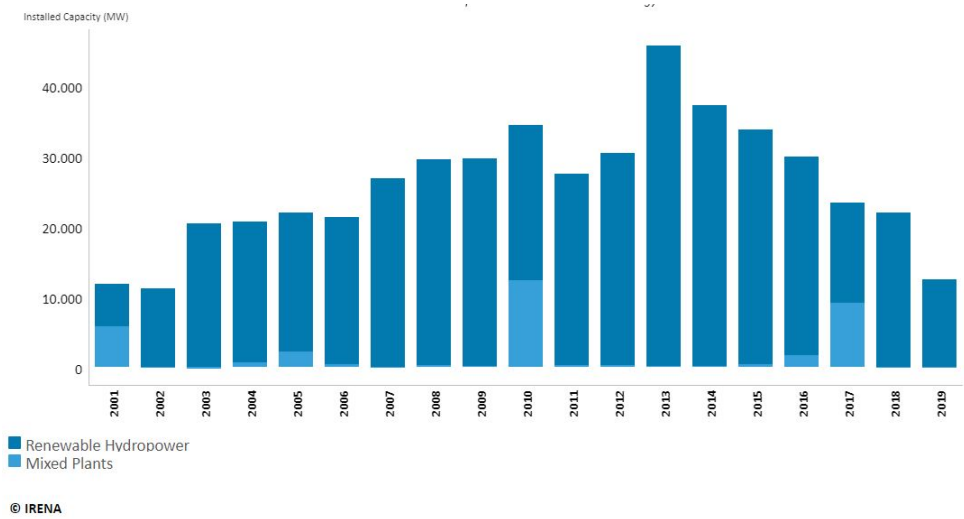
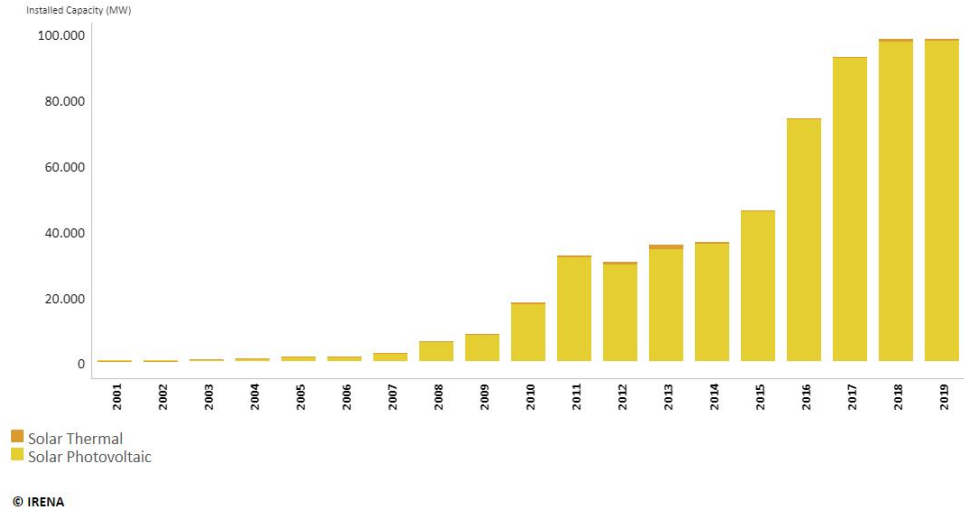


Figure 1.4. Worldwide net additions trend of installed capacity of marine plants [20].



(a) Net addition of installed capability of hydropower plants.



(b) Net addition of installed capability of solar plants.

Figure 1.5. Worldwide net additions trends of installed capacity of hydropower and solar technologies [20].

A cumulative trend in terms of electricity generation is given by Figure 1.6. As expected, PV energy has been increasing thanks to the incentives and government-backed investments.

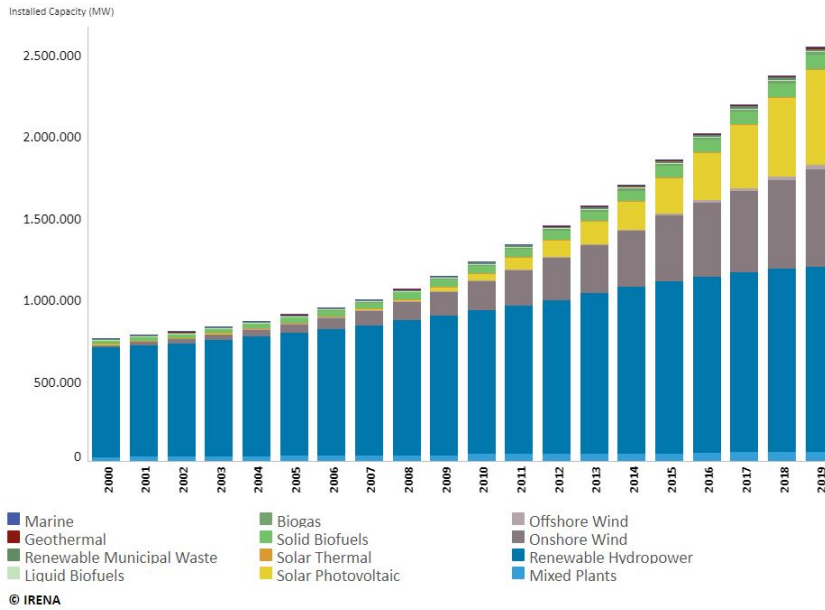


Figure 1.6. Worldwide cumulative electricity generation trends in renewable energy sources and technologies [20].

Following the reports published by IRENA in 2019 for the reference year 2018, it is possible to assert the total installed capacity could be attributed as follows (as by Figure 1.7):

- 47.5% of renewable hydropower plants;
- 2.4% of mixed hydroplants;
- 22.9% of onshore wind energy plants;
- 20.4% of solar photovoltaic plants;
- 3.5% of solid biofuels energy plants;
- 1.0% of offshore wind energy plants;
- 0.8% of biogas energy plants;
- 0.6% of RMW energy plants;
- 0.6% of geothermal energy plants;
- 0.2% of solar thermal energy plants;

- 0.1% of liquid biofuels energy plants;
- <0,1% of marine energy plants.

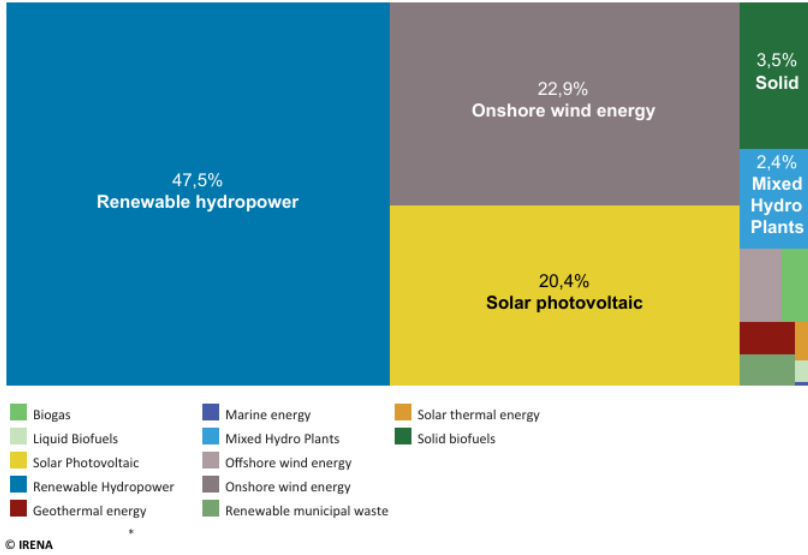


Figure 1.7. Installed capacities percentages for technologies in 2018 [20].

Analysing the contributes of each continent on the global energy production from renewable sources (Figure 1.8), it could be interesting to notice that from 2010 to 2018 Asia has been significantly improving its contribution. In fact, in 2010 this region covered about the 30% of the world total, with a production of 1,272,708 GWh, reaching in 2018 a production of 2,643,589 GWh with a contribute of about about 40%. Europe, instead, has maintained its contribution on the total approximately on the 20%. The European production has gone from 899,180 GWh in 2010 to 1,297,883 GWh in 2018. Another important amount on the total production is attributable to the North and South America. North America has maintained its quota oscillating between 18% and 20%, producing in 2010 857,471 GWh and in 2018 1,226,317 GWh. On the other hand, South America contribution is decreased from about 17% to 12%. Also the quantity of energy from renewable sources produced by this region has not recorded an important increase: in 2010, an amount of 711,340 GWh was produced, while in 2018 794,164 GWh have been scheduled. Contributions of the other region of the word to the total renewable energy

produced are lower than 10%.

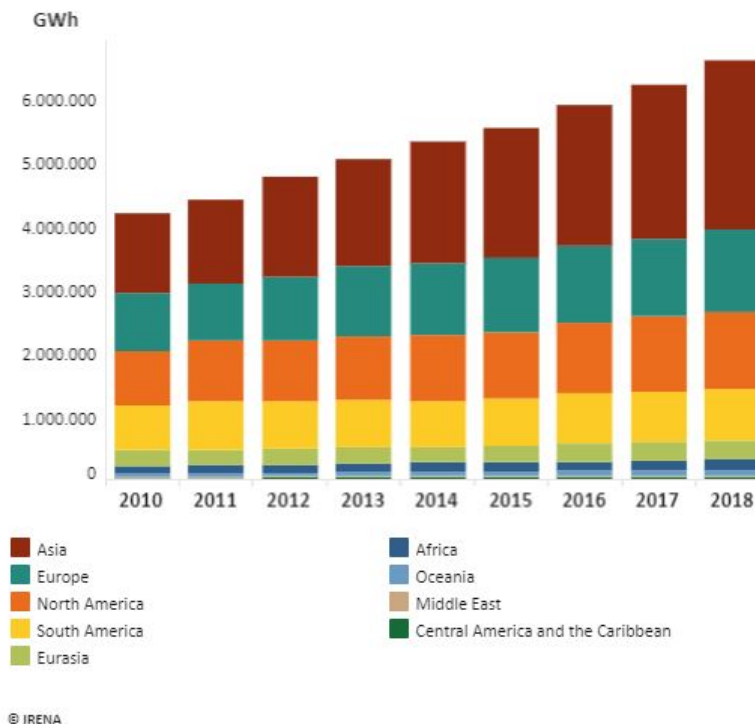


Figure 1.8. Trends in renewable energy by region [20].

On one hand, the exploitation of typical by-products of human activities, that is biomasses and wastes, could represent a possible way to face emissions of pollution and the growing energy request. Obviously, conversion processes have to fit environmental requirements so many researches are still in progress to optimize existing technologies in those terms. On the other hand, exploitation of natural sources of energy such geothermal, solar, wind and sea energy represent another vital strand in each response to the peak of oil request, climate chaos and economic instability. On both ways, research plays a fundamental role, trying to reach the maximum overall conversion rate by every single process of *green* energy exploitation policies.

1.2 European framework

Operating a focus on the European framework, it's confirmed the ascendent trend of the employment of renewable energies [20]. The installed capacity of renewable energy technologies, showed in terms of cumulative (Figure 1.9), evidences the increasing trend.

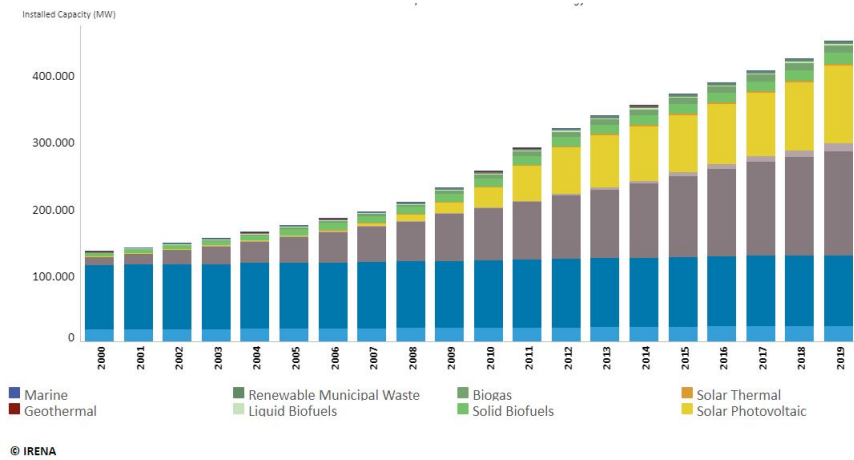


Figure 1.9. Trends of cumulative installed capacity in Europe [20].

The year 2020 was the first stage to verify and assess the commitment taken by European Community in terms of energy production from renewable sourced. The result achieved by EU28 in 2020 is shown in Figure 1.10. Analysing Figure 1.11 it is clear that the most employed renewable sources for electricity production in Europe are hydropower, wind energy, biomass and solar power.



Figure 1.10. Share of energy from renewable sources in gross final energy consumption in 2017, 2018 and 2020 targets [21].

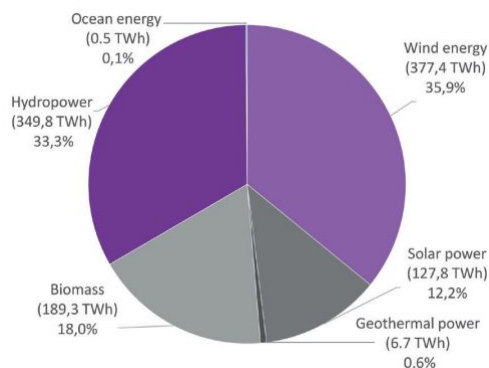


Figure 1.11. Renewable electricity generation (in TWh) and share of overall renewable generation (in %) in 2018 in the EU28 [21].

In order to define the state of art of the most used renewable technologies, data collected by EUROBSERV'ER have been studied. The following information is expressed in toe (acronym for Tonne of Oil Equivalent). A unit of toe is equal to 11,630,000 Wh.

Solid Biofuels consumption has been increasing in Europe during 2019 of about 2.2%, referring to the data of 2018 [22]. The primary energy production from this renewable source by the EU28 has been equal to 96.9 Mtoe, while the inland consumption has reached 102.6 Mtoe (Figure 1.12).

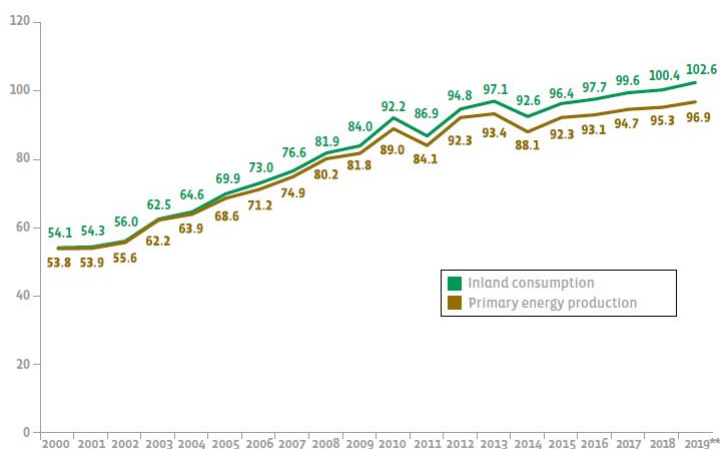


Figure 1.12. Solid biofuels primary energy production and inland consumption growth figures for the EU28 since 2000 (in Mtoe) [22].

The top five Nations for primary energy consumption and production of solid biofuels are Germany, France, Sweden, Finland and Italy, as reported by Table 1.2.

Table 1.2. Top 5 countries for primary energy production and gross inland consumption of solid biofuels in Europe in 2019 [22].

	Production [Mtoe]	Consumption [Mtoe]
Germany	12.778	12.922
France	10.194	10.411
Sweden	9.458	9.583
Finland	8.949	9.006
Italy	7.256	8.741

The gross electricity production from solid biofuels in European Union in 2019 has been equal to 106.019 TWh, of which 46.043 TWh (with an increasing of 5.8% compared to 2018) have been produced by electricity only plants, while the remaining amount is from CHP plants. The top producer of electricity from solid biofuels are given by Table 1.3.

Gross heat production from solid biofuels in 2019 has grown by around 4.6 % referred to 2018, reaching the production of 11.494 Mtoe of heat. Heat only plants have produced 4.350 Mtoe of heat, while CHP plants have had a contribution of 7.144 Mtoe. Sweden, Finland, Denmark, France and Austria are the five most productive countries in this sector (Table 1.4).

It's important to notice that bioenergy plants operators are implementing a new technology, called Bioenergy with carbon capture and storage (BECCS), with which capture of carbon is made possible.

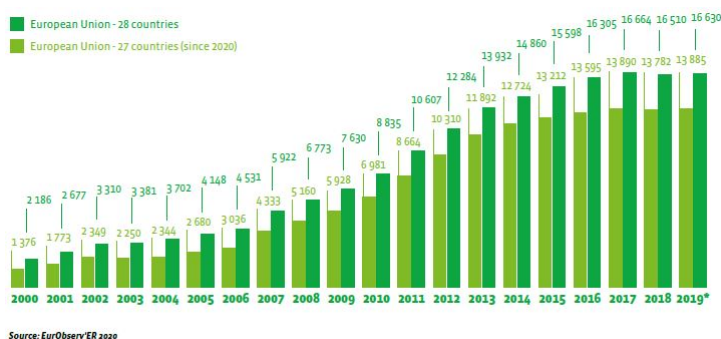
Table 1.3. Top 5 countries for gross electricity production from solid biofuels in Europe in 2019 [22].

	Gross electricity production [TWh]
United Kingdom	25.935
Finland	12.317
Sweden	11.129
Germany	11.100
Poland	6.247

Table 1.4. Top 5 countries for gross heat production from solid biofuels in Europe in 2019 [22].

	Gross heat production [Mtoe]
Sweden	2.485
Finland	1.641
Denmark	1.420
France	1.213
Austria	0.893

Biogas primary energy production has increased between 2018 and 2019, even if only by 0.7%. In fact in 2018 the energy produced from biogas was equal to 16,510 ktoe (13,782 ktoe without the contribution of UK), while in 2019 it grows, reaching 16,630 ktoe (13,885 without UK). This production has been ascendent from 2000 to 2019, as shown in Figure 1.13.

**Figure 1.13.** Evolution of primary biogas energy production in Eu28 and EU27 since 2000 (in ktoe) [23].

The total produced primary energy can be divided into different contributions, due to the provenience process of biogas:

- 2,259.5 ktoe are linked to landfill gas;
- 1,593.5 ktoe comes from sewage sludge gas;
- 12,612.1 ktoe are produced by other biogas from anaerobic fermentation;
- 164.7 ktoe come from biogas from thermal processes.

In Table 1.5 the are the top five EU countries with the most important production of primary energy from biogas.

Table 1.5. Top 5 countries for primary energy production from biogas in Europe in 2019 [23].

	Primary energy Production [ktoe]
Germany	7,547.5
United Kingdom	2,745.1
Italy	1,828.0
France	976.6
Czechia	581.2

The gross electricity production from biogas in Europe (UK included) has decreased during 2019. In fact, 62,714.4 GWh of gross electricity were produced in 2018, while in 2019 a lowering of 0.40% happened, with a production of 62,463.1 GWh. This amount is divided into two contributions: 17,595 GWh have been produced by electricity only plants, while 44,8681 GWh came from CHP plants. The top five countries for electricity production from biogas are described in Table 1.6

Table 1.6. Top 5 countries for gross electricity production from biogas in Europe in 2019 [23].

	Gross electricity production [GWh]
Germany	32,900.0
Italy	8,276.8
United Kingdom	7,569.2
France	2,587.5
Czechia	2,524.3

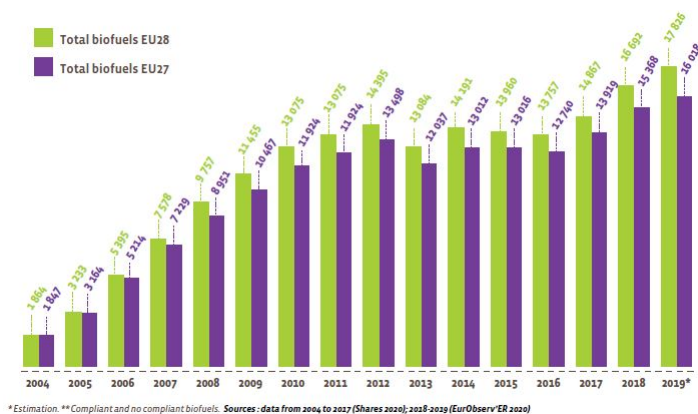
Gross heat production from biogas is increased between 2018 and 2019, instead. In 2018 the production has been equal to 859.0 ktoe, while in 2019 it reached 893.4 ktoe, with a growth of 4.0%. In this sector, CHP plants hold the major contribution in terms of production (857.6 ktoe) while the remaining quota is produced by heat only plants. Also in this case there's a top five collection, shown in Table 1.7.

Table 1.7. Top 5 European countries for gross heat production from biogas in 2019 [23].

	Gross heat production [ktoe]
Germany	392.7
Italy	211.3
France	77.1
Denmark	48.7
Poland	22.5

Biogas is CO₂-emissions neutral and has many employment fields: it can be used as fuel in natural gas vehicles or it could be injected into the network, as natural gas.

Extending the analysis to all the biofuels, both gas and liquid, it is possible to appreciate an increasing of their use in the transport sector. During the 2018, in fact, 16,692.0 ktoe of biofuels were consumed by EU28. In 2019, instead, the consumption has increased, reaching a total consumption in 2019 of 17,826.0 ktoe (+ 6.8%), of which 3,206.7 ktoe are from employment of bioethanol, 14,349.7 ktoe are linked to the use of biodiesel and 269.6 ktoe are referred to the biogas use. The increasing trend of this fuels is confirmed in Figure 1.14.

**Figure 1.14.** EU28 biofuels consumption trends for transport in ktoe [24].

As seen by the data, the breakdown of biofuels consumption shows an important contribution of biodiesel, which has reached the 80.5% part on the total EU28 biofuels consumption in 2019 (Figure 1.15).

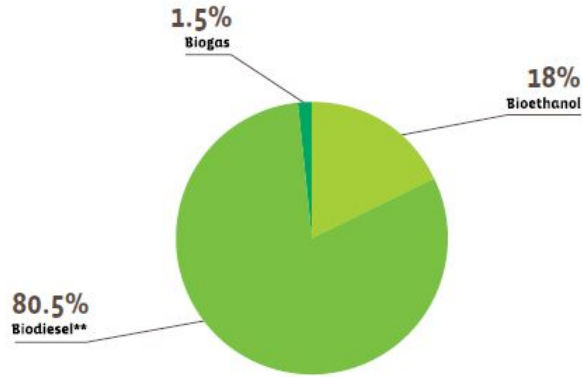


Figure 1.15. Breakdown of total EU 2019 biofuel consumption in energetic content for transport by biofuel type in EU28 [24].

The five countries with the major biofuels consumption for transport in Europe are described in Table 1.8, referring to 2019.

Table 1.8. Top 5 countries in Europe for biofuels consumption for transport in 2019 [24].

	Consumption [ktoe]
France	3,197.0
Germany	2,746.0
United Kingdom	1,807.8
Spain	1,721.9
Sweden	1,520.8

Technologies, linked to the employment of solar radiation, show increasing trends of installed capacity between 2018 and 2019. Solar thermal market in EU28 have had an increase of 1.5% [25]. The 2018 has been characterized by the installation of 2,244,825.0 m² of surfaces, with an equivalent power of about 1,571.4 MW_{th}. In 2019, instead, the installation of 2,278,280.0 m² of surface was provided, being associated to an equivalent capacity of 1,594.8 MW_{th}. The total installed surfaces are divided in different types of collectors:

- glazed collector, in turn divided in flat plate collectors and vacuum collectors, of which were installed 2,110,895 m² and 160,882 m², respectively;

- unglazed collectors, of which an installed surface of 6503 m² is provided.

The countries with a major number of thermal collector installations in Europe (2019) are given by Table 1.9.

Table 1.9. Annually installed surfaces and capacity equivalent in 2019 [25].

	Installed surface [m ²]	Capacity equivalent [MW _{th}]
Germany	511,000.0	357.7
Greece	361,500.0	253.1
Poland	263,000.0	184.1
Spain	201,150.0	142.9
Denmark	194,310.0	136.0

Analysing the cumulative data about this technology, it's possible to affirm that the EU28 has reached in 2019 the cumulative installation of 54,018,867 m² of solar thermal collector surface, with an equal cumulated capacity of 37,813.2 MW_{th}. The five countries with major cumulative installed surfaces are shown in Table 1.10.

Table 1.10. Cumulated capacity of thermal solar collectors installed in European Union in 2019 [25].

	Installed surface [m ²]	Capacity equivalent [MW _{th}]
Germany	19,325,790.0	13,528.1
Austria	5,044,954.0	3,531.5
Greece	4,867,500.0	3,407.3
Spain	4,409,920.0	3,086.9
Italy	4,341,676.0	3,039.2

PV plants installed capacity has grown of about 13.5 percentage points. In fact, in 2019 a power of 15,634.9 MW has been installed in European Union (include UK), which increased the cumulated capacity up to 130,670.4 MW, against the 115,148.9 MW cumulated in 2018 [26]. Also the electricity production from solar photovoltaic is increasing: in fact, referring to 2019, 131.776 TWh have been produced, that is 7.2% more than the production related to 2018 (122.936 TWh). In Table 1.11 the five European countries with the higher cumulated capacity and electricity production in 2019 are reported.

Table 1.11. Annually installed surfaces and equivalent capacity in 2019 [26].

	Cumulative capacity [MW]	Installed capacity in 2019 [MW]	Electricity production [TWh]
Germany	49,016.0	3,856.0	47.517
Italy	20,864.0	759.0	23.688
United Kingdom	13,616.0	497.7	12.677
France	10,575.9	965.6	11.357
Spain	9,232.8	3,992.9	9.351

As the previous discussed technologies, also wind energy plants have been increasing between 2018 and 2019 [27]. In fact, during the 2018 the cumulative wind power installed capacity by EU28 was equal to 179,479.0 MW (18,764.1 offshore). In 2019 the installation of additional 12,238.3 MW has been provided (3,050.0 MW offshore). The growth is equal to 6.7% between 2018 and 2019, with the achievement of a power production equal to 191,509.3 MW. Table 1.12 shows the five European countries with the higher wind power capacity installed in 2019.

Table 1.12. Top 5 countries for wind power capacity installed in 2019 in Europe [27].

	Cumulative capacity [MW]	Installed capacity in 2019 [MW]
Germany	60,840.0	2,074.0
Spain	25,742.0	2,148.0
United Kingdom	23,931.0	2,177.6
France	16,494.0	1,316.0
Italy	10,512.0	281.8

The electricity production from wind power in Europe has increased of about 11.4 percentage points. In 2018 European countries (UK included), produced 377.470 TWh (of which 58.613 offshore), while in 2019 the production has been equal to 425.984 TWh, with 70.602 TWh by offshore plants. It's possible to notice that, between these two years, the production from offshore plants has grown of about 20.5%. The top five European countries for electricity production from wind power plants are shown in Table 1.13.

Table 1.13. Top 5 countries for electricity production from wind power plants in Europe in 2019 [27].

	Electricity production [TWh]
Germany	126.000
United Kingdom	63.468
Spain	54.212
France	34.100
Italy	20.200

For hydropower plants and geothermal plants state of art, available data is referred to the years 2017 and 2018 (not 2018-2019) [28]. Net capacity of hydropower plants in 2018 has been 0.22 % higher than the one of 2017. In fact, in 2017 this capacity was equal to 155,256.0 MW, while in 2018 it reached 155,603.0 MW (107,079.0 MW from pure hydropower plants, 23,260.0 MW linked to mixed hydropower plants and 25,264.0 from pure pumped hydropower). The five EU countries with the higher hydropower capacity are reported by Table 1.14.

Table 1.14. Top 5 countries for net capacity installation in Europe (2018) [28].

	Net capacity [MW]
France	25,793.0
Italy	22,499.0
Spain	20,080.0
Sweden	16,431.0
Austria	14,516.0

The hydraulic gross electricity production in Europe has increased its numbers of about 16.5%. In 2017 the electricity production from this source has been equal to 300.248 TWh, while in 2018 the amount has been equal to 349.846 TWh. The top five EU producers of gross electricity from hydraulic resource are itemized in Table 1.15.

Table 1.15. Top 5 countries for hydraulic gross electricity in Europe in 2018 [28].

	Net capacity [TWh]
France	62.285
Sweden	62.210
Italy	48.786
Austria	37.638
Spain	34.334

Geothermal energy has reported a slight increase between 2017 and 2018. The capacity installed by EU28 during 2017 was equal to 1,009.2 MW_e, with a net usable capacity of 848.2 MW_e [28]. Considering the year 2018, these numbers have grown of 1.7% and 1.62 %, respectively, reaching an installed capacity of 1,026.7 MW_e and 862.2 MW_e. The first five countries for installed capacity and net capacity of geothermal electricity plants are summerized by Table 1.16.

Table 1.16. Top 5 countries for capacity installed and net capacity usable of geothermal electricity plants in EU28 (2018) [28].

	Installed capacity [MW _e]	Net Capacity [MW _e]
Italy	915.5	767.2
Germany	38.0	36.0
Portugal	34.3	29.1
Croatia	17.5	10.0
France	17.1	15.9

The gross electricity production derived from the employment of geothermal energy was equal to 6,715.0 GWh in 2017 and to 6,657.7 GWh in 2018 (-0.86 %). Top European producers are given in Table 1.17.

Table 1.17. Top 5 countries for gross electricity generation from geothermal energy in EU28 (2018) [28].

	Gross energy production [GWh]
Italy	6,105.4
Portugal	230.4
Germany	178.0
France	129.7
Hungary	12.0

The capacity of geothermal district heating systems installed in Europe

has increased of 6.5% between 2017 and 2018, reaching 1,942.0 MW_{th}. More information are shown in Table 1.18.

Table 1.18. Top 5 countries for capacity of geothermal district heating systems installed in Europe (2018) [28].

	capacity of geothermal district heating systems installed MW _{th}
France	544.0
Germany	353.0
Hungary	254.0
Netherlands	208.0
Italy	153.0

Heat consumption from geothermal energy in Europe has been increasing from 833.5 ktoe in 2017 to 867.6 ktoe in 2018 (+4.0%). The five most important European consumers in those terms are reported by Table 1.19.

Table 1.19. Top 5 countries for heat consumption from geothermal energy in Europe (2018) [28].

	Heat consumption [ktoe]
France	187.3
Italy	149.1
Hungary	124.2
Germany	106.6
Netherlands	89.1

Chapter 2

Software and hardware tools for R&D applications

Experimental campaigns require the implementation of both hardware and software tools to provide a suitable acquisition system. After all, experimental data is needed to compare the computed trends of influence parameters such as temperature, incoming solar radiation and other environmental conditions. Engineering applications push the technician to consider the integration of multiple tools to achieve the goal of the experimental campaign. Indeed, a multidisciplinary knowledge is required while designing and optimizing an acquisition campaign for R&D applications.

This work is related to the modelling, multiphysical simulation and development of an innovative solar concentrator for enhanced PV systems. The main results need to be validated by means of a comparison with experimental campaigns output data. The following discussion refers to the main scientific methods and materials, which has been used to conduct the whole study. In effect, many concepts and principles have to be mastered by the engineer, so a short overview of the main technical approaches to the developing and simulation campaign are discussed below.

2.1 Simulation approach: the Finite Element Method (FEM)

The Finite Element Method (FEM) is a numerical approach, particularly suitable for engineering applications. FEM theoretical background

was presented in 1965 by Zienkiewicz and Cheung. Its use in engineering problems has been increasing in the last years given its implicit ability to reduce the complexity of scenarios, once geometry characteristics cannot be further lighten by both computational and physical aspects. Indeed, the complexity of analytical solution is often related to geometrical discontinuity of the domain. By using FEM, the spatial domain is assumed to be divided into small elements (Figure 2.1): each one has its own physics. Differential equations that describe the phenomena will be discretized, that is to say they will be reduced to linear equation to be solved simultaneously. The unknown variables (finite number) are located on each node of the grid. FEM is an iterative procedure, so approximation error cannot be completely removed. Thus, a limit divergence has to be identified, in order to fix the *precision* of the solution convergence. Obviously, higher accuracy in the solution means higher computational resources. It could be useful to consider the flowchart of operations in FEM as reported by Fig. 2.2, once related to heat transfer phenomena. We should identify the following concepts:

1. discretization of spatial domain;
2. kind of interpolation;
3. equation formulation on each node obtained by the discretization;
4. matrix assembly;
5. equations system resolution;
6. secondary variables computing.

Alternatives to FEM approach. In principle any numerical method suited for solution of partial differential equations is a potential alternative to the FEM approach. The FEM and the Finite Difference Method (FDM) are the most used for simulation of engineering problems. The FDM gives a point-wise approximation to a problem with an array of grid points subdividing the geometry along each coordinate axis, while the FEM gives a piece-wise approximation to a problem with an assemblage of elements subdividing the geometry along the boundaries. The FDM can run very fast because it solves the governing equations by direct

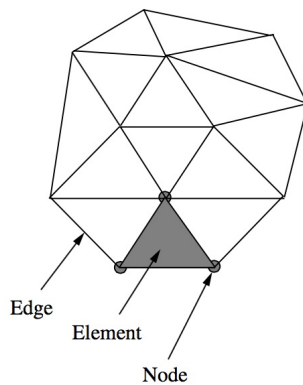


Figure 2.1. FEM discretization [29].

differentiation along each coordinate axis. The FEM solves the governing equations by discretization of the domain with elements of a selected shape and assembling them into the entire system, thus it runs usually slower than the FDM. Therefore, FDM is an older method than FEM that requires less computational power but it is also less accurate in some cases, where higher-order accuracy is required; on the other hand, FEM allows to reach a higher order of accuracy, although it requires both higher computational power and mesh quality than the FDM.

The Finite Volume Method (FVM) is another method that could be used. The FVM's approach is comparable to the known numerical methods such as FEM and FDM, which means that its evaluation of volumes is referenced to discrete places over a meshed geometry. Furthermore, the FVM transforms the set of Partial Differential Equations (PDE) into a system of linear algebraic equations. With FEM and FVM, both methods share some similarities since they both represent a systematic numerical method for solving PDEs. However, one crucial difference is the ease of implementation. Among most engineers, the prevailing opinion is that the FDM is the easiest to implement, while FEM is the most difficult, leaving FVM somewhere in the middle. The FVM is a natural choice for solving CFD issues because the PDEs to resolve for CFD are conservation laws. However, it is possible to use both FDM and FEM for CFD, as well.

Finally, another usable approach is the Boundary Element Method (BEM). This method solves the PDE with the discretization relating only

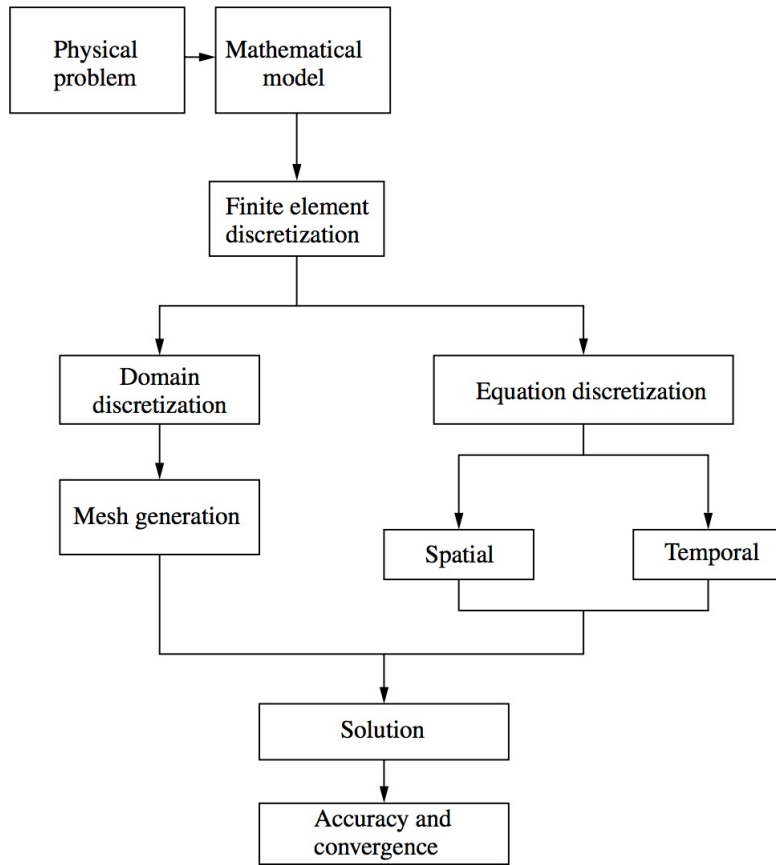


Figure 2.2. FEM flowchart [29].

to the system boundary. BEM is derived through the discretization of an integral equation which is equivalent mathematically to the original PDE. Then, this integral equation will be defined at the boundary of the domain and it relates the boundary solutions to the solutions at points inside the domain. Since in BEM, the discretization is done at the boundary only, it will result in more efficient computation and easier to be used compared with FEM. Besides, regarding its characteristics, BEM is also very suitable for modelling symmetrical problems as well as problems which involve infinite domains BEM is also especially popular to solve Laplace and Helmholtz problems. However, regarding its characteristics, BEM also poses several disadvantages compared with FEM. Since the formulation of integral equation cannot be done for all types of PDE, BEM is not so widely applicable compared with FEM. Besides, in the case of inhomoge-

neous and non-symmetric or non-linear problems, fully populated system of equations will often occur in BEM thus making the storage requirement and computational time become increasing significantly. Further, BEM also requires higher knowledge about the suitable fundamental solutions if compared with FEM approach. Therefore, depending upon the type of analysed physical systems, it is possible to identify the most suitable method to be implemented.

A variety of engineering problems commonly use FEM approach for their solution and consequently for the development of products. The applications of FEM are:

- mechanical and energetic engineering: where FEM applications include steady and transient thermal analysis in solids and fluids, stress analysis in solids, automotive design and analysis and manufacturing process simulation;
- geotechnical engineering: FEM applications include stress analysis, slope stability analysis, soil structure interactions, seepage of fluids in soils and rocks, analysis of dams, tunnels, bore holes, propagation of stress waves and dynamic soil structure interaction.
- aerospace engineering: FEM is used for several purposes such as structural analysis for natural frequencies, modes shapes, response analysis and aerodynamics;
- nuclear engineering: FEM applications include steady and dynamic analysis of reactor containment structures, thermo-viscoelastic analysis of reactor components, steady and transient temperature-distribution analysis of reactors and related structures;
- electrical and electronics engineering: FEM applications include electrical network analysis, electromagnetics, insulation design analysis in high voltage equipment, dynamic analysis of motors and heat analysis in electrical and electronic equipment;
- metallurgical, chemical engineering: in metallurgical engineering, FEM is used for the metallurgical process simulation, moulding and casting. In chemical engineering, FEM can be used in the simulation of chemical processes, transport processes and chemical reaction simulations;

- meteorology and bio-engineering: in the recent times, FEM is used in climate predictions, monsoon prediction and wind predictions. FEM is also used in bio-engineering for the simulation of various human organs, blood circulation prediction and even total synthesis of human body.

2.2 Simulation tools: COMSOL Multiphysics

Engineering problems require multi-disciplinary approaches to be solved in most of cases, reason why the engineer would consider specific tools to reach the solution in the shortest time and also with lower costs. In those terms, one of the most suitable strategies should be the numerical simulation, which allows the technician to implement and visualize complex phenomena in a virtual environment, allowing any manipulation of data and resolution algorithms to make the solving procedure much comfortable. To compute the physical quantities which characterize a certain scenario by both thermal and fluid-dynamics points of view, a FEM-based software called COMSOL Multiphysics has been identified as the most suitable solution to fit both academic and industrial R&D requirements [30]. This method could be applied to many scientific sectors, such as electromagnetic behavior of elements, thermal and mechanical analysis, transport of chemical species and much more.



Figure 2.3. Software for multiphysical simulation: COMSOL Multiphysics.

COMSOL Multiphysics (CM) is a proprietary cross-platform FEM-based simulation software which allows the user to implement coupled systems of PDEs, solving those kinds of scenarios where many physics phenomena are involved. The source code of CM has been developed by Svante Littmarck and Farhad Saeidi at the Royal Institute of Technology in Stockholm (Sweden). The software was called FEMLAB until 2005, with a clear reference to the method implemented for resolution. CM is powered by a built-in feature and kernel to communicate with third-part software, bidirectionally. One of these features is the LiveLink which

allows the user to use external software in addition to the CM interface itself, simultaneously (e.g. SolidWORKS, CATIA, Microsoft Excel, MATLAB and more over). Both stationary and time-dependent analysis are allowed, such as any geometrical space dimension (from 0D up to 3D) could be selected to host the computational domain entities (points, edges, boundaries and volumes). Some advanced features such as the perturbation study in terms of frequency domain are also available to be selected by user. The kind of phenomena which could be solved by CM are those which fall into the categories of physics modules/interfaces shown in 2.4. Any of the listed categories can be purchased and added to the owner license.



Figure 2.4. Modules/interfaces provided by COMSOL Multiphysics [30].

User interface. The COMSOL interface is reported by Figure 2.5 and it can be considered both user-friendly and stable if compared with other proprietary simulation software interfaces. A graphic view of the object

to be simulated is available by default. Every node reported by the model builder tree can be selected to access its specific settings [31]. By this way, the user can modify any standard value as initialized by the default scenario once opened.

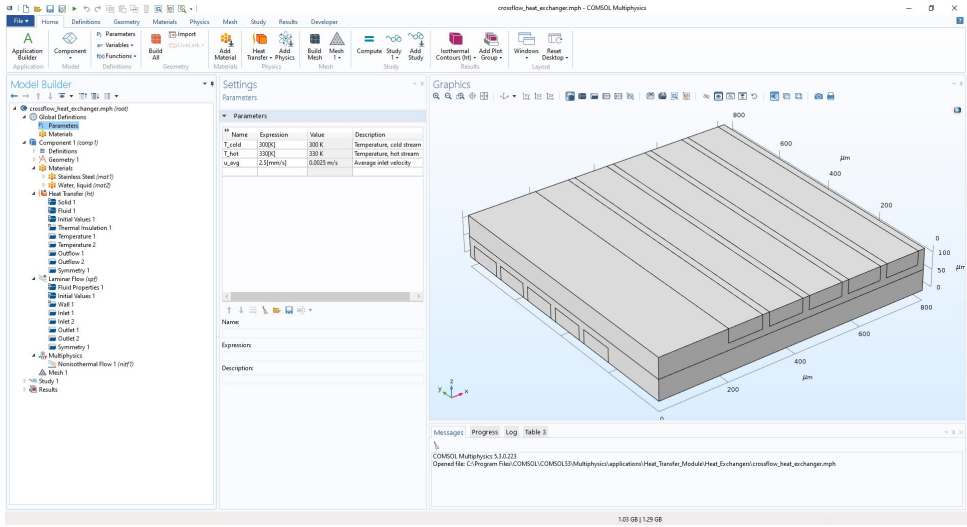


Figure 2.5. Default user interface of COMSOL Multiphysics.

The model and its settings within the simulation scenario are organized by a default model-tree structure as given by Figure 2.6. It is composed by the following sections:

- *global definitions*, that is the container of any pre-processing declaration by user, such as parameters and variables to be called while building up the geometry and implementing physics phenomena;
- *component*, where any specification related to the geometrical domain properties (e.g. materials and parameterized variables) and implemented modules/interfaces (e.g. boundary conditions and physic phenomena to solve) can be addressed and edited;
- *study*, where any parameter related to the study type can be edited and restored by user;
- *results*, where the user could conduct any post-processing operation related to the computed set of data.

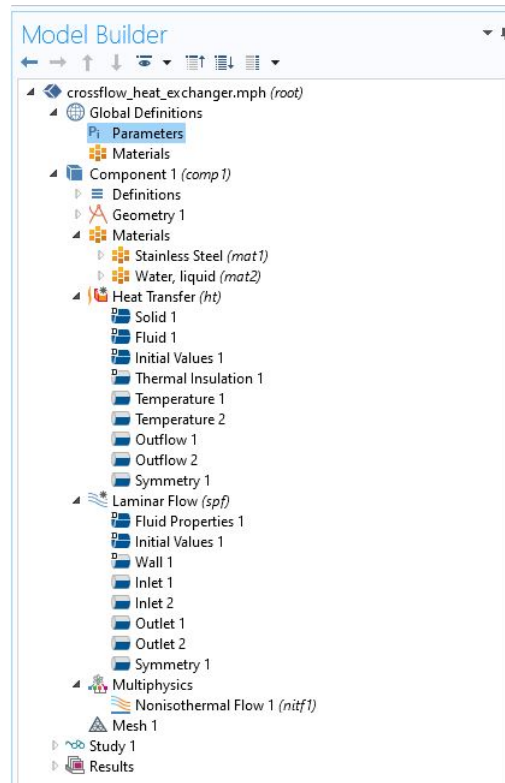


Figure 2.6. Typical model builder structure in COMSOL Multiphysics.

Referring to the model builder tree-structure, it has to be considered very useful since the order of every setting influences the way the computing kernel interprets the various boundary conditions, determining its overwriting or coupling with other conditions. The Graphical User Interface (GUI) is composed by many elements to interact with the virtual environment and to develop both pre-processing and post-processing routines. A debug and information window is located on the bottom right side by default: the kernel gives information about the status and the percentage of completion of every single operation the software is processing in a specific time. Another important feature of CM is the built-in application builder¹, that is a specific development environment where the

¹In most of cases, single features have to be required to COMSOL staff, specifying every term of predictable use. Once done, the user could require a quotation to enable that specif feature. The application builder and the COMSOL Compiler have to be bought to release executable applications of scenarios.

user could design and create its own executables (.exe) to be performed on unlicensed computing platforms. By an engineering point of view, it is an important advantage to be taken into account while releasing scenarios which require some kind of change in the pre-parameterized variables, but the software is not available.

Available packages for simulation. Simulations reported by this work are related to thermal and fluid dynamics phenomena, reason why the *Fluid flow & Heat Transfer modules* is implemented to solve the numerical scenarios. In detail, the solved phenomena equations are the Navier-Stokes equations for the CFD module [32], while for the thermal field computation both thermal energy balance and heat transfer equations are considered [33].

2.3 Data processing: MATLAB

MATLAB software has been used for data pre-processing and fitting once required by the experimental campaign. Even if built-in components of COMSOL Multiphysics allow the user to visualize, import and process data, MATLAB features are suitable for advanced data processing and trend analysis.



Figure 2.7. Software for data processing: MATLAB.

By a technical point of view, MATLAB is a programming platform for engineers, economics and scientists to analyze, implement and design any kind of complex system. The programming language is designed specifically to manage even huge amount of data by means of matrix-based representation (not by chance its name refers to a "MATrix LABoratory"). The implementation of algorithms is mainly related to numerical computing or modelling and the user interface makes easy the access to additional features and plugins. In particular, one of the main additional packages is Simulink, which adds a graphical multi-domain environment to all this kind of usages, being suitable for the dynamic systems analysis.

2.4 Data acquisition tools: NI LabVIEW and cDAQ

NI LabVIEW software has been used to acquire data from measurement systems and monitor the prototype functioning by means of specific probes.



Figure 2.8. Software for data acquisition system development: NI LabVIEW.

The software itself should be considered as a suitable integrated development environment for engineering applications. It is based on a visual coding language which allows the user to develop both block diagram (which is the main logic code) and the front panel (that is the Graphical User Interface), by connecting control objects to indicators. Low level functions could be implemented to reach high-frequency sampling (>1 kHz) if required. Debug operations are also allowed while implementing virtual instruments.



Figure 2.9. Compact DAQ (cDAQ) from National Instruments.

However, National Instruments (NI) provides specific hardware and acquisition shields for any kind of purpose. Those hardware systems are

typically modular, to provide an high level of versatility, being also powered by specific real-time operating systems (also called RTOS), which make those kind of boards standalone instruments with their one external peripherals interfaces to connect (VGA, HMDI, RJ-45, USB, etc.). The reliability and the precise-timing of implemented tasks are the main concepts to consider while developing a virtual instrument (VI) by means of NI LabVIEW. In this case, the chosen NI hardware is the cDAQ (Figure 2.9), powered with a ad-hoc developed standalone application to be used for sensors monitoring and experimental acquisition purposes. The cDAQ modular system is also provided with the external shield in Figure 2.10 to allow acquisition operations from different kind of sensors and probes.



(a) NI 9203: input current (n.8 channels, ± 20 mA, 16-bit resolution).
 (b) NI 9219: input current (± 20 mA) or voltage (± 60 V).
 (c) NI 9263: analog voltage output (n.8 channels, 0-10 V, 16-bit resolution, 100 kS/s).



(d) NI 9472: digital voltage output (n.8 channels, 24 V DC).

Figure 2.10. External modules for cDAQ.

Chapter 3

Thermal modelling and simulation of an innovative Compound Parabolic Concentrator

Solar energy exploitation should be considered as one of the most efficient strategies to reduce the consumption of fossil-based fuels such as petroleum. Many systems allow to convert the radiation from the sun into electric and/or thermal energy. The installation costs of this kind of systems are such that also the use in the private sector has grown rapidly in the last years, followed by the release of incentives. It follows a decreasing cost per installed kW of PV plant (see e.g. Figure 3.1). Considering the PV-related technologies, the cost of components has been decreasing too, as reported by Figure 3.2. However, the daily uncertainty of this resource represents a critical issue to be solved for the industrial sector, where production chain technologies often require large amounts of both electric and thermal energies so that demand peaks cannot be fed by PV or solar thermal plants, respectively. In order to make up for this lack, electric energy storage systems have been investigated but their cost is still relevant for the private use. At the same time, concentrator systems have been studied to increase the incident solar radiation, improving the photo-generation of free charge carriers and so the electric energy production rate.

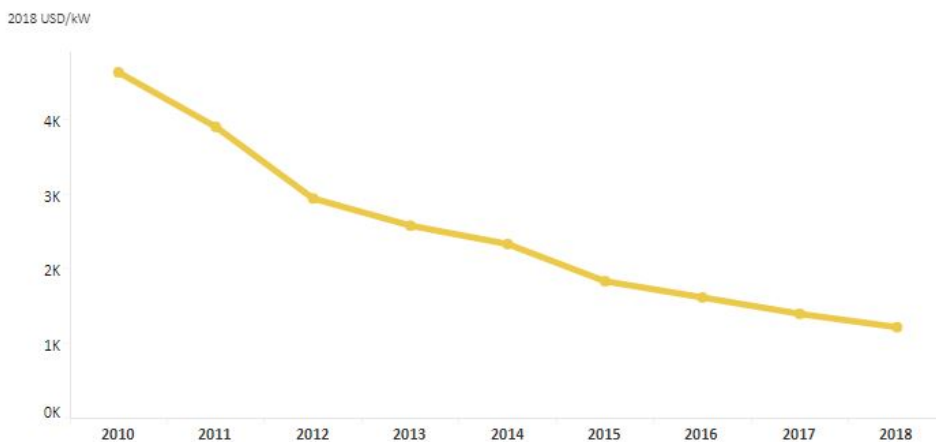


Figure 3.1. Cost per installed kW of PV plant [20].

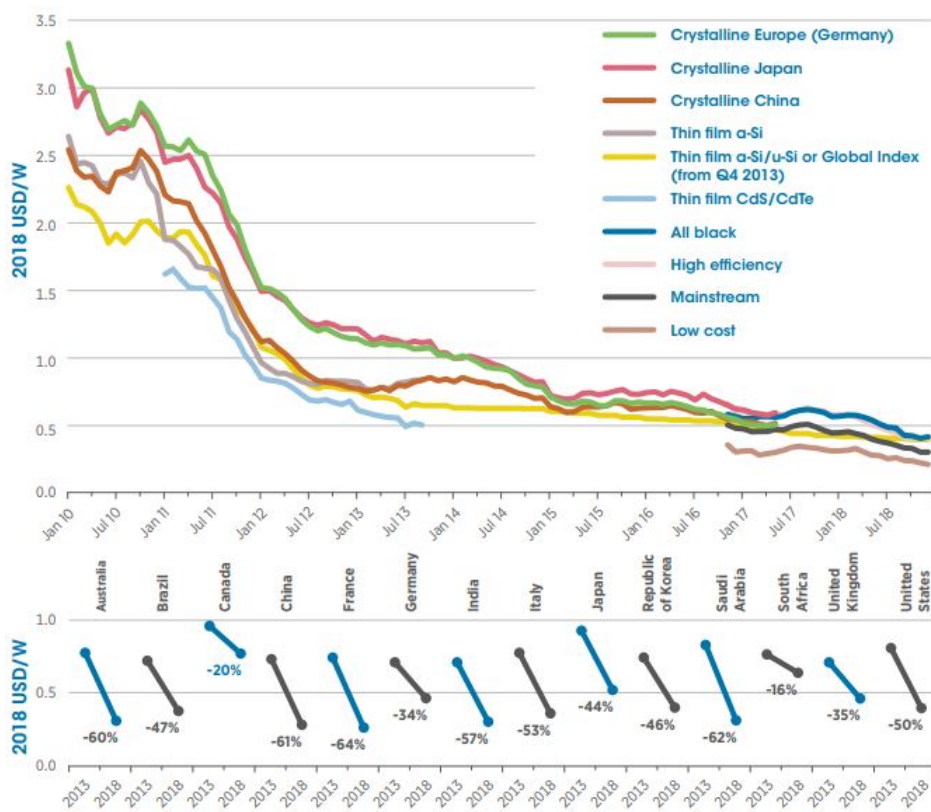


Figure 3.2. PV cost trends per technology and per Country [34].

Effectively, referring to PV plants the incident solar radiation leads to the production of electric energy by means of the photovoltaic effect, established within the semi-conductive layers of the solar cell. Costs from all commercially available renewable power generation technologies declined in 2018. The global weighted-average cost of electricity declined 26% year-on-year for concentrated solar power (CSP), followed by bioenergy (-14%), solar photovoltaic (PV) and onshore wind (both -13%), hydropower (-12%), geothermal and offshore wind (both -1%). If compared with other fossil-fuel-based option, the solar PV power, such as the onshore wind one, it is less expensive without any financial assistance, as reported by [34]. Concentrator photovoltaics (CPV) is a photovoltaic-related technology that generates electricity from sunlight. Sun rays can be concentrated on the solar cell with various types of concentrators: lens concentrator, mirror concentrator, reflector concentrator, static concentrator, luminescent solar concentrator [35,36]. Systems using low-concentration photovoltaics (LCPV) have the potential to become competitive in the near future with low cost. Reflector concentrators' family is a kind of LCPV, and the Concentrator Parabolic Compound (CPC) is one of the most studied. The costs trend encourages the economical feasibility of concentrators for solar photovoltaic. By that, many researches about how to improve solar cells efficiency have been conducted in the last half century [37–40]. By that, edge-ray and identical optical path principles have been applied to reach an ideal solar radiation concentrator such as the compound parabolic concentrator (CPC), characterized univocally by specific geometrical parameters (e.g. the parabolic reflectors shape and extension). Optical analysis aimed to optimize the geometry of the CPC are discussed by author in [41]. Winston (1960) was the precursor in the study of CPCs and he could be considered as the inventor of compound parabolic concentrators. Initially, the theoretical foreground, on which the CPC shape assignment is based, was related to the research on Cherenkov radiation light collectors. Effectively, it was necessary to wait until 1974 [42] for the invention and first validation of solar application-related CPCs. By that point, many experimental campaigns have been conducted to reach the most convenient geometry configuration of reflectors in order to increase and focus on the target the highest possible solar radiation in certain conditions. Rabl presented the truncated version of the CPC only 2 years later [43]; by investigating the solar performance of the collectors, it was noticed that a portion of the CPC as presented by Winston could be removed.

Then, this assertion was deeply considered for specific applications as the one discussed by [39], where an asymmetric concentrator suitability is studied and compared with a symmetric version of the concentrator. It followed the confirmation of the higher optical performances of asymmetric concentrators than the symmetric ones once applied on building façades. However, the efficiency of the solar PV cell strictly depends on its temperature. In fact, an incident radiation means and increasing temperature on the solar PV cells, resulting in a decreasing efficiency as discussed later. This prompted the researchers to analyze possible solutions for the CPCs cooling [44], considering both natural and forced convection. Despite a lower efficiency of photo-generation of free charge carriers process within the doped semiconductor, CPCs are still considered a suitable solution to increase the output power of the solar PV cells. This conclusion could be supported by the analysis of the electric response of the solar PV cell itself: every solar PV cell is characterized by a typical current-voltage curves as reported by Figure 3.3.

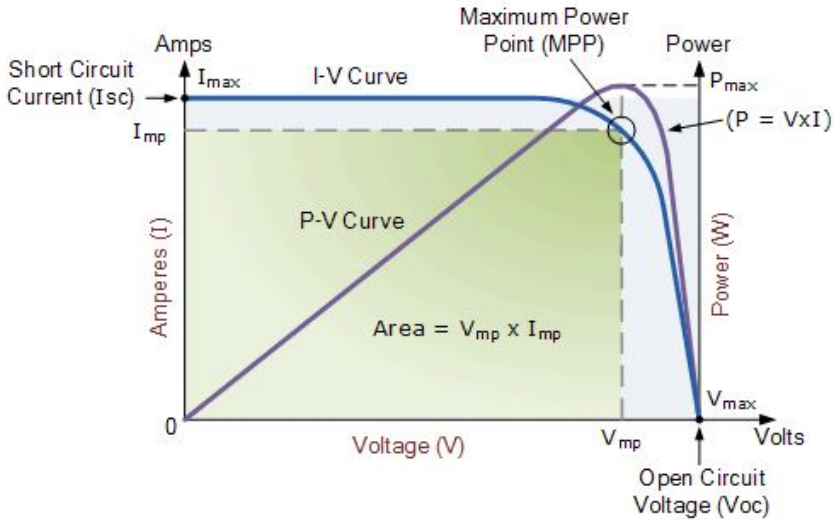


Figure 3.3. Typical silicon solar PV cells current-voltage curve, operating under normal conditions [45].

The *fill-factor* FF of solar cells should be defined as the ratio between maximum obtainable power and the product of open-circuit voltage and

short-circuit current, that is

$$FF = \frac{P_p}{V_{oc} \cdot I_{sc}} \quad [1] \quad (3.1)$$

The FF shows an opposite trend to that one of temperature. It follows how solar rays concentrating conditions cause a fill-factor drop. However, this drop in terms of solar PV cell efficiency could be considered as neglectable if compared to the increase of whole system efficiency (higher output power from the solar PV plant). Further details about that will be provided in the rest of the discussion.

The study discussed by the present work is related to the modelling and to the numerical scenario implementation of an innovative Compound Parabolic Concentrator (CPC) for solar PV cells. In particular, experimental data is used first to validate the scenario, then the same setup is used to investigate different operating conditions for the CPC-powered solar PV cells. Finally, the addition of a cooling system to the CPC is analyzed, searching for any improvement in terms of energy production and efficiency. The modelling and validation of the scenario have been conducted within the cooperation program between CIRDER and the Solar Energy Applications Group (SEAG) at the Trinity College Dublin (TCD) in Dublin, Ireland.

3.1 CPC description: structure and components

The SEAG at TCD developed a CPC prototype, characterized by two possible configurations: an external environment-exposed structure, also defined as "uncovered configuration", and an external covers-provided setup, also known as "covered configuration". These systems have been studied by SEAG to choose the most suitable geometry of the reflectors with optical analysis. Then, the whole geometry of the CPC system has been designed and built to carry out experimental characterizations, by which experimental data for numerical scenario validation is obtained, as described by the following discussion.

Figure 3.4 reports the CPC structure with n.4 solar cells identified. Detailed measures of each part of the reference prototype of the CPC are given by author in [41].

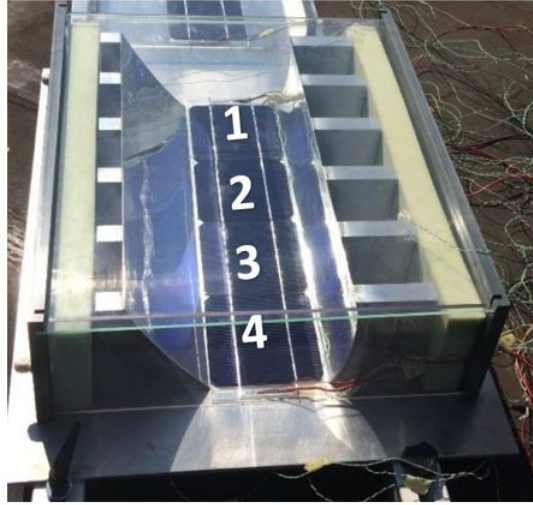


Figure 3.4. CPC structure from experimental campaign setup.

Structure components could be listed as follows:

- backplate, provided for both configurations. The backplate is an aluminum made structural base on which CPC components are installed. Dimensions of the CPC backplate are given by Figure 3.5;
- frame structure, provided for both configurations. Dimensions of the external frame structures are reported by Figure 3.6. The chosen material is a 18-mm-thickness plastic. Two lateral slots are reported by Figure 3.6 to allow both uncovered and covered configurations, removing the upper and side covers, by sliding them in slot 2 and slot 1, respectively;
- foam, provided only for the covered configuration. To provide some kind of insulation, reducing thermal stress on frame structure components, two elements made of thermal insulation foam are applied to the system, each one with a 35-mm-thickness and 125 x 546 mm dimensions. Those insulation foams are placed between the frame structure and reflectors supports;
- upper cover, provided only for the covered configuration. A low iron glass from NSG Group is used to provide an upper cover to the CPC system, closing the whole structure as a box once side covers are applied also. In terms of dimension, a 4-mm-thickness and an

exposed surface of 457 x 556 mm has to be considered, while solar transmittance and normal emissivity are equal to 0.91 and 0.89, respectively [41];

- side covers, provided only for the covered configuration. Made of Perspex sheets with a 5-mm-thickness and dimensions of 140 x 457 mm [41], those elements provides the closure of the system laterally, avoiding at the same time shading effects on solar cells;
- reflectors, provided for both configurations. The choice of the reflectors is crucial since of their functions. Aluminum foil with an average reflectivity of 0.76 and 1 mm-thickness (by Easygrow company) is chosen [41]. The total area of the reflector is 0.143 m², considering that the right reflector and the left one are characterized by a 155 x 506 mm and 128 x 506 mm dimensions, respectively;
- reflectors supports, provided for both configurations. Those structures are needed to hold the aluminum foil reflectors are made of. Measures of reflectors supports are reported by Figure 3.7. Also those supports are made of aluminum, because of its low height, good thermal conductivity and low cost;
- solar cells, provided for both configurations. Those components, with the reflectors, are the critical area to be considered while developing a performance analysis for the PV power generation. The PV cell system is composed by n.4 125-mm-squared mono-crystalline solar cells (as by Figure 3.4), manufactured by Sun Power, characterized by a standard conditions efficiency of 17.8% [41];
- solar cells supports, provided for both configurations. Those glass-made supports, located between the semi-conductive layers of PV cells and the backplate, allow the positioning of solar cells on the target position.



Figure 3.5. Backplate dimensions [41].

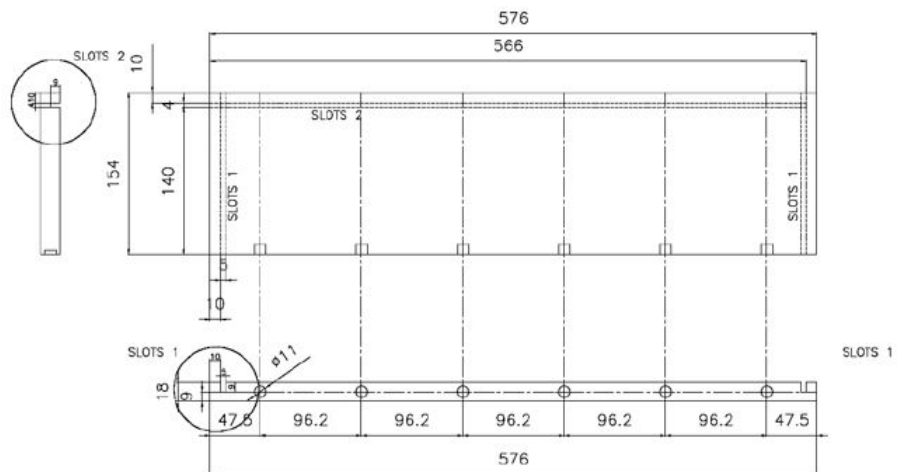


Figure 3.6. Frame structure dimensions [41].

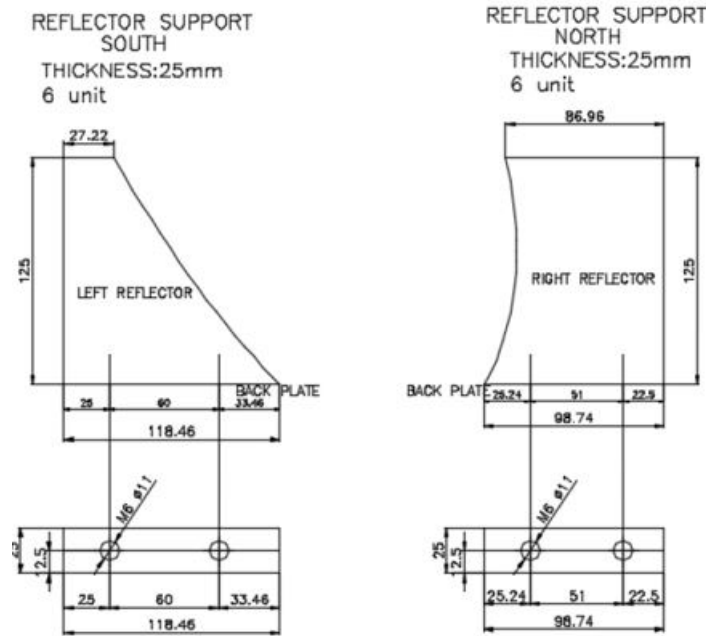


Figure 3.7. Reflectors supports dimensions [41].

3.1.1 Optical performances analysis

In order to optimize the CPC geometrical components design, optical characterization and analysis have been conducted by [41]. Incoming radiation has been studied by means of optical rays tracing software, predicting the performance of the CPC system. Parameters to be considered are the total PV absorber surface and the hypothesis of a perfect black body conditions. The reflectors have been characterized by a typical reflectivity value (that is 0.8) and the studied configuration is the uncovered one. The source of incoming radiation is implemented by considering 10^5 random angles rays within a 3D coordinate system. The irradiance has been set to 1 kW/m^2 , with an average radiation wavelength of 750 nm. Moreover, absorber efficiency has been set up to 21%. Another important assumption as considered while implementing the sun rays tracing is that the source is taken always in the same position, not following the natural route of the sun itself and not considering the shadow effects. In addition to that, randomic directions of rays are assumed [41].

Results from the ray-tracing software computation are provided by

Table 3.1.

Table 3.1. Results from ray tracing algorithm for different CPC systems (TR and NTR stay for truncated and non-truncated CPC geometry, respectively) [41].

Configuration	TR	TR	TR	NTR	TR
Half-acceptance angle	45°	50°	60°	60°	65°
Geometrical concentration ratio	2.54	2.27	1.83	2.24	1.64
Optical concentration ratio	0.403	0.477	0.626	0.508	0.690
n. rays absorber	40316	47740	62589	50811	69042
n. reflections	194656	164338	126649	193173	103789
Irradiance absorber [W/m ²]	495.90	583.65	726.54	490.99	783.14
Power [W]	6.51	7.66	9.54	6.44	10.28

It is interesting to notice how from previously reported data to a half-acceptance angle increase multiple effects should be highlighted, such as:

- decrease of geometrical concentration ratio;
- increase in terms of optical concentration ratio;
- increase in terms of number of rays reaching the absorber surface;
- increase of irradiance absorber;
- decrease in terms of reflected rays by reflectors.

A 65°-half-acceptance angle system should be a suitable solution to investigate in terms of overall performance, since it guarantees the maximum output power if compared with the other benchmarking solutions. Due to geographical reasons, a 60° half-acceptance angle truncated asymmetric CPC has been chosen to be submitted to the analysis: actually, the experimental campaign has been conducted in Ireland, where a 60°-limit of maximum altitude of the sun has to be considered.

Geometrical characteristics for this studied CPC system are shown in Figure 3.8, as by the optical analysis, which corresponds the incoming radiation flux (in terms of rays concentration) reported by Figure 3.9.

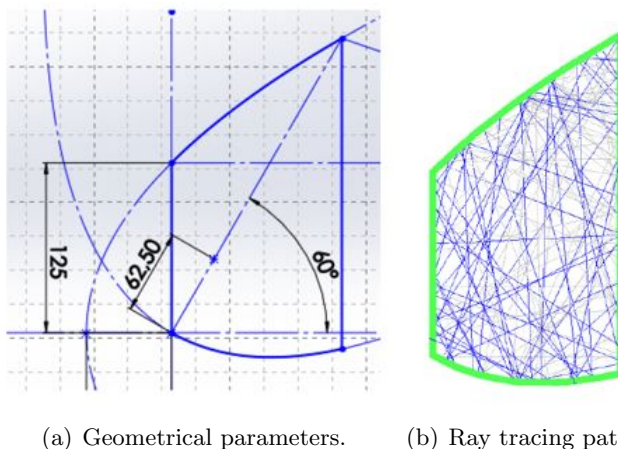


Figure 3.8. Geometrical characteristics of reflectors from the optical analysis [41].

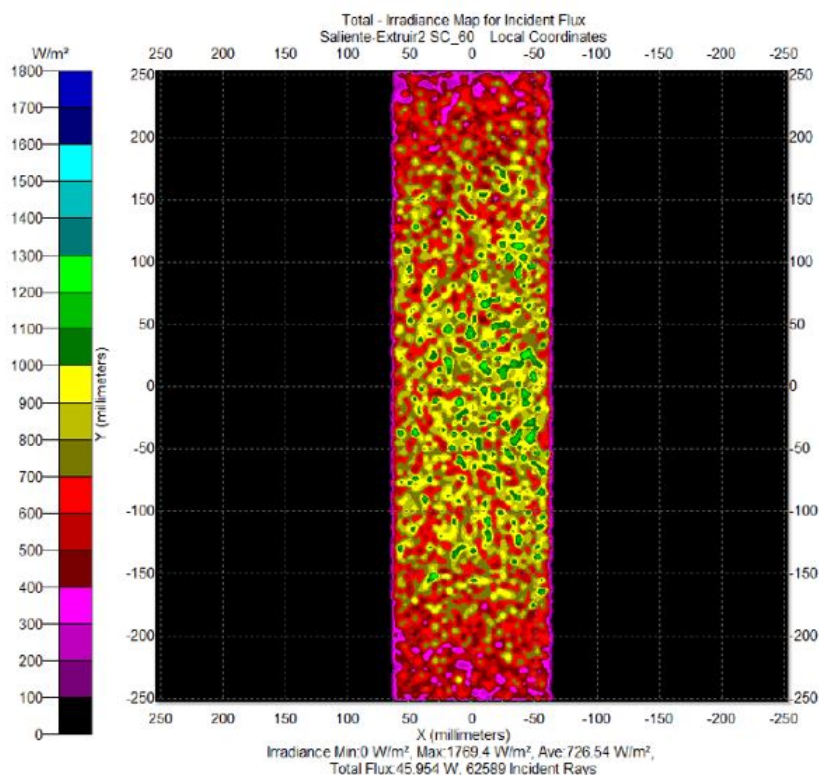
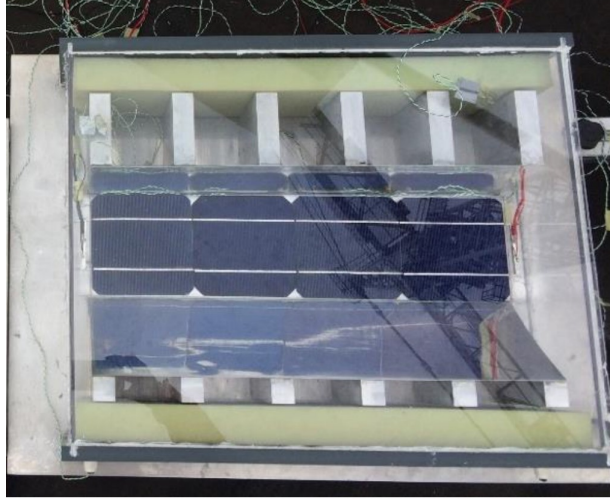


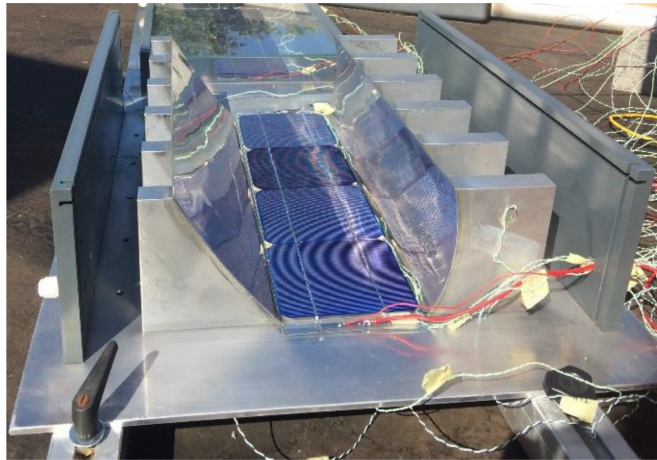
Figure 3.9. Flux distribution in the absorber for a truncated 60° half-acceptance angle CPC system [41].

3.2 Data from experimental campaigns

The aim of the experimental campaign was to obtain the temperature fields on the CPC solar cells surfaces, computing their overall average temperature. The experimental campaign was conducted by considering two different exposures to the external environment, once placed on a facing south roof at TCD Simon Perry's Building in Dublin, Ireland.



(a) Covered CPC.



(b) Uncovered CPC.

Figure 3.10. Compound parabolic concentrator (CPC) prototype installation.

The first acquisition was conducted by installing the CPC provided with a side and upper cover, which defines the covered configuration as reported by Figure 3.10(a) so that an air volume remained trapped within the closed CPC; the second acquisition was conducted once both side and upper covers have been removed, as shown by Figure 3.10(b). Details about the experimental setup and framework are provided by the following section.

3.2.1 Experimental setup and framework

The whole monitoring and data acquisition system is reported in Figure 3.11, where some RTDs should be noticed.

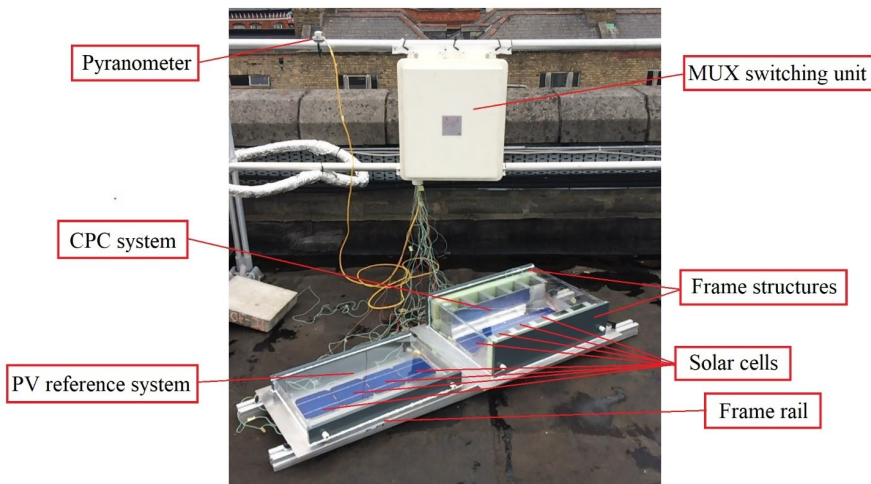


Figure 3.11. Data monitoring and acquisition system setup for the experimental campaign.

The structure closed to the left side of the CPC is a reference configuration of solar cells, where no compound parabolic concentrator is installed: such reference has been used to define the efficiency of solar cells when no concentrator is used. In fact, the experimental campaign is conducted to define the electrical behavior of PV cells simultaneously to the temperature acquisitions. The used MUX switching unit is an Agilent 3472A LXI data logger, interfaced with NI hardware and software, installed to detect output voltage and current from the CPC and from the reference system, to compare both electrical efficiencies and highlight the CPC-related improvements. Twelve K-type thermocouples are fixed on both CPC sys-

tems, and a pyranometer is used to measure the solar incident radiation. An insulated box from Campbell Scientific Ltd. (Logan, UT, USA) is installed in order to host the electric circuit, the data logger, and two 220 V power supply plugs.

3.2.2 Reference experimental data

The experimental campaign was conducted on the aforementioned CPC configurations in 2017 on the roof of Simon Perry's building at Trinity College Dublin, Ireland, South-oriented. Experimental data for numerical scenario validation are taken by [41], considering two days of characterization with similar external conditions to compare the configurations. In fact, the data for the covered CPC system is referred to 17 July 2017 while for the uncovered one to 18 July 2017. Exact data from [41] is reported by Figure 3.12. The red circle highlights a relevant gradient for the period that goes from hour 15:00 up to hour 18:00. Actually, pyranometer acquisitions show that atmospheric conditions in terms of incoming sun radiation changed relevantly, probably because of some precipitations. This causes an improvement in terms of thermal losses for the CPC prototype, following a rapid temperature drop. For the simulation approach, this change in terms of radiation conditions is neglected¹: in fact, it is due by a modification of weather conditions which are neglected for the simulation scenario implementation. It follows that experimental temperature values for that specific time frame are neglected for the validation of the scenarios. A further justification may be associated with the fact that, for the definition of the thermal response of the system, the investigation of those conditions that lead to the achievement of the temperature peak should be considered as more relevant.

¹Experimental data acquisition campaign was designed to investigate both the electric energy production efficiency and the temperature values in correspondence of strategic zones of the CPC, while typical summer radiation conditions play a fundamental role for the thermal field definition all over the prototype structure. However, being the experimental campaign mainly oriented to the study of the electrical behavior of solar cells, those parameters such as the exact exposure of the CPC to the wind flows or the local air moisture content that should be useful while implementing a thermal and fluid dynamic simulation approach have not been acquired specifically.

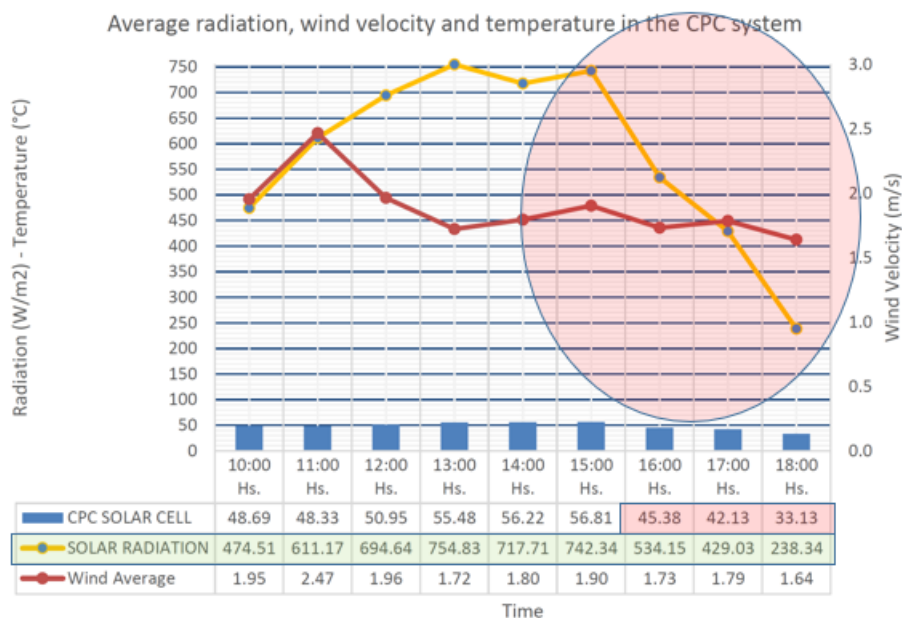


Figure 3.12. Flowchart of the simulation campaign.

By that, the temperature distribution on the solar cells surfaces of the CPC systems is summarized by Table 3.2 and Table 3.3 for the covered and uncovered CPC systems, respectively. Data is given by approximate each value to the closer integer as suitable for this kind of numerical analysis and validation. Only the solar cells are considered to validate numerical data since the acquired temperature values from other components should not be consistent for this specific purpose, due to the adopted sampling procedure.

Table 3.2. Solar cells average reference temperatures on surfaces for the covered CPC prototype (17 July 2017).

17 July 2017, solar cells average temperatures								
10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
46°C	59°C	68°C	76°C	81°C	79°C	75°C	71°C	62°C

Table 3.3. Solar cells average reference temperatures on surfaces for the uncovered CPC prototype (18 July 2017).

18 July 2017, solar cells average temperatures								
10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
49°C	48°C	51°C	55°C	56°C	57°C	45°C	42°C	33°C

Investigating the electrical response of the solar cells installed within the CPC prototype, a comparison between the simple PV and CPC-powered PV systems is conducted. The maximum values achieved on 17 July 2017 for different hours are given by Table 3.4. The CPC system reaches higher efficiency values than the PV system, even if its average solar cells temperature is higher. However, a deeper analysis demonstrates that the concentrator increases the incoming sun radiation as input energy to be converted into electric energy by PV effect. On one hand, it causes the increase of the whole CPC system efficiency in terms of output power. On the other hand, an increase in terms of temperature leads to a decrease in terms of PV effect efficiency. Despite this, the overall conversion rate increases enough to make the drop of efficiency for PV effect almost negligible (by an engineering point of view). Then, the economic appeal of this kind of improving-solar-PV technology comes with it.

Table 3.4. Best electric performance of the CPC system compared to the standard PV system (17 July 2017) [46].

Time	System	Efficiency [%]	Power [W]	Avg. SC temp. [°C]
12:19	CPC	18.6	8.7	74.9
	PV	13.8	6.4	63.2
12:45	CPC	18.3	8.9	76.8
	PV	16.2	7.9	65.5
13:58	CPC	17.2	8.4	83.6
	PV	16.6	8.1	73.0

3.3 Simulation campaign design

The temperature on the solar cells influences its efficiency since these parameters are inversely proportional; for the solar cell, the module efficiency decreases with temperature typically of $-0.2\%/K$ up to $-0.5\%/K$ [47]. Therefore, it is important to check and monitor the temperature in the system. The numerical simulation scenario is implemented by consid-

ering a multi-physical approach to define the influence of each one of the involved parameters: the heat convection due to the ambient conditions and the sun varying position lead to consider a time-dependent study. The aim is to obtain the temperature field on solar cells surfaces once the CPC has been installed: locally-evaluated temperature values allow to compute the efficiency (η) of the PV cell once its trend is given as a function of temperature and incoming solar radiance, that is $\eta = f(T, Q_{irr})$. This kind of analysis should give an important contribution to the design of solar concentrators, since every specific geometry configuration of the reflector should be investigated by computing the local influence of solar cell surface temperature due to the solar radiation increase.

Considering the acquisition campaign conducted on the CPC prototype as discussed by the previous section, for the simulation campaign two different scenarios have been studied. Thus, both the covered and uncovered configurations of the CPC are investigated to define the thermal response of the whole system. The main differences between covered and uncovered CPC configurations are related to the presence of a trapped air domain, two-sides and upper transparent covers for the uncovered setup. Numerical results are compared with the ones from the acquisition campaign to validate the computed scenarios. In fact, once validated, the numerical scenarios could be used to implement a virtual environment (such as a standalone application) to investigate different operational conditions for the compound parabolic concentrator. The whole implementation diagram is reported by Figure 3.13, to be applied on both configuration scenarios (covered and uncovered CPC). First, the geometry model is initialized. The physical phenomena identification allows to detect any involved influence process on the CPC functioning; in this case, the thermal field has to be investigated so heat transfer dynamics have to be accounted. Once the mathematical scenario is implemented as coupled systems of equations, involved parameters such as the materials properties are needed. In most of cases, material properties depend on unknown variables (e.g. the density which is strictly related to the temperature) and this dependence needs to be declared while implementing the scenario (pre-processing). Then, boundary and initial conditions have to be initialized as requested by the equations solving procedure. This phase should be considered as critical for the convergence control, since by declaring the initial and boundary conditions, the state of the analyzed

system at the time t_0 and the involved constants by ODEs and PDEs solutions are given, respectively. The spatial discretization, that is the *mesh*, has to be designed all over the computational domains, including boundary surfaces, volumes and edges.

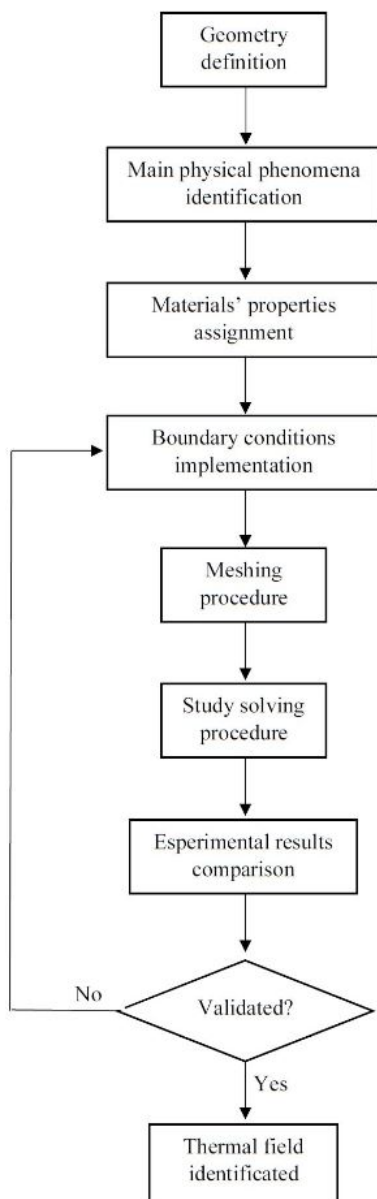


Figure 3.13. Flowchart of the simulation campaign.

Similarly to what was said for the initial and boundary conditions, also in this case the definition of the mesh is to be considered fundamental to define both the convergence and the relative error of the simulation. The maximum/minimum relative error could be set by declaring the study parameters. The simulation as planned requires a time-dependent approach. Once computed, the post-processing of numerical data allows to analyze and visualize the temperature field within the entire volume of the CPC system. Then, temperature values are compared to the ones from experimental campaigns. In particular, the maximum global discrepancy of data between numerical and experimental temperature values is fixed at 12% in accordance with the research staff: this value is acceptable for a preliminary validation of the numerical results also because of difficulties while defining numerically the real external convection conditions on every surface of the CPC system.

3.4 Preliminary assumptions and conditions

The simulation software (i.e. COMSOL Multiphysics) allows the user to implement complex phenomena in different ways, depending on the choice to highlight specific results from the selected interfaces or modules. Identical results could be reached by solving the scenario by means of different (but equivalent) modules. The main difference is related to the discretization procedure that could vary a lot while implementing analogue modules. Many conditions, once merged correctly in the same scenario, could give the same results of other approaches (and interfaces once coupled) even if more complicated. Additional packages are available in CM to reduce pre-processing procedure to built-up a scenario. Specific algorithms and packages are codified within the built-in interfaces to increase the accuracy of meshing procedures and equation discretization. A lumped condition such as the *thin layer boundary condition* makes available a simplified approach to represent thin layers where a standard approach could fail due to extreme local geometrical gradients (while the geometry scale is much higher than the local element resolution). This kind of condition makes possible to avoid many problems while reducing the finite element size, with a negligible cost in terms of accuracy when no high-resolution trends are required to be solved in those regions. Moreover, CM gives the opportunity by means of the *External radiation source condition* to simulate the moving position of the Sun into the sky once latitude, longi-

tude, time zone, date and time are initialized to identify the geographical location influence on solar radiation for the solving scenario.

It follows an overview of main involved physical phenomena, as confirmed by a benchmark on how to solve a transient scenario where both external varying conditions and solar radiation source have to be taken into account in order to solve their influence on the thermal field. It should be useful to notice that when a stationary study is implemented, the steady-state imposes that the temperature does not change with time, so that the terms with time derivatives disappear. Current simulation campaign requires a time-dependent analysis, so all $\partial/\partial t$ terms are needed.

3.4.1 Involved physical phenomena

Once referring to the simulation model definition, the involved heat transfer phenomena could be summarized as follows:

- conduction between solid components of the CPC;
- convection within the trapped air volume (only for the covered configuration of the CPC);
- convection due to the external conditions exposure;
- incident solar radiation, characterized by the movement of the radiation source (i.e. the Sun);
- surface-to-surface radiation on exposed-to-environment CPC surfaces.

The following discussion gives some theoretical details about government equations, introducing the parameters required by the simulation scenarios.

Conduction within the CPC structure

Heat transfer phenomena involving the solid components of the scenario is described by the heat transfer in solids equation [33]:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u}_{trans} \cdot \nabla T \right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_r) = Q_{ted} + Q \quad (3.2)$$

where ρ is the material density, T is the absolute temperature, c_p is the heat capacity at constant stress, $\mathbf{u}_{trans}$ is the velocity vector field once a

certain displacement is assigned to the parts of the material frame (translational motion), $\mathbf{q}$ is the heat flux by conduction, $\mathbf{q}_r$ is the heat flux by radiation, Q_{ted} is the thermoelastic damping and accounts for thermoelastic effects in solids while Q represents additional heat sources. However, the additional terms which refers to the thermoelastic damping Q_{ted} is neglected for the current analysis. Furthermore, following Fourier's law of heat conduction, it is possible to define the heat flux as:

$$\mathbf{q} = -k\nabla T \quad (3.3)$$

once k has been assigned as the thermal conductivity. All these assumption led to the implemented equation to define the heat transfer dynamics in solids:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u}_{trans} \cdot \nabla T \right) + \nabla \cdot (-k\nabla T + \mathbf{q}_r) = Q \quad (3.4)$$

Convection for the air volume within the CPC structure

Heat transfer phenomena involving the fluid components of the scenario is described by the heat transfer in fluids equation [33]:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_r) = Q_p + Q_{vd} + Q \quad (3.5)$$

where the velocity vector $\mathbf{u}$ appears in addition to the variables of Equation 3.4. The first term of the right-hand side of Equation 3.5, that is Q_p , is the work done by pressure changes and is the result of heating under adiabatic compression as well as some thermoacoustic effects. It is generally small for low Mach number flows and it is defined as:

$$Q_p = \alpha_p T \left(\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p \right) \quad (3.6)$$

where α_p is the coefficient of thermal expansion and p is the pressure. The viscous dissipation within the fluid domain are described by the Q_{vd} term, defined as:

$$Q_{vd} = \tau : \nabla \mathbf{u} \quad (3.7)$$

where τ represents the viscous stress tensor. While modeling a heat transfer scenario, the main requirement is that all government equations need to be respected. For the velocity field, introduced once the convection in a fluid has to be solved, the continuity equation needs to be satisfied to reach the consistency of the solution:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (3.8)$$

External convection due to environmental conditions

To investigate the influence of CPC exposure to external environment, an external convection condition has to be applied all over the external surfaces of the structure. Many options are available to fit user requirements while implementing this kind of boundary condition. Choosing a typical heat flux due to convection, it results in [32, 33]:

$$q_0 = h \cdot (T_{ext} - T) \quad (3.9)$$

once T_{ext} , T and h are initialized as the external temperature, the computed temperature and the convective heat transfer coefficient, respectively. The external forced convection condition could be taken into account while a wind flow needs to be implemented. This approach allows the user to compute the convective heat transfer coefficient before being inserted into Equation 3.9. Once the wind velocity has been identified, it is possible to use dimensionless parameters to define the h coefficient to be used by the simulation software. Otherwise, also the direct assignment of the convective heat transfer coefficient is possible, even if it depends by the available data. Generally, to implement the convection phenomena, the involved parameters are combined to form dimensionless numbers, described as follows [48] (symbols definition is provided by Nomenclature section):

- the Nusselt number (Nu) defines the increase in thermal power transmitted by convection through a layer of fluid with respect to that transmitted by conduction at the same conditions, equal to:

$$Nu = h \cdot L/k \quad (3.10)$$

- the Prandtl number (Pr) is considered to identify the ratio between the molecular diffusivity of the momentum and that of heat. In the case of gases it assumes the value 1, while in liquids it is considered a value much lower than 1, since the quantity of motion is greater than the transport of energy. Its numeric definition is given by:

$$Pr = \nu/\alpha \quad (3.11)$$

- the Reynolds number (Re) defines the ratio between inertial and viscous forces to identify the laminar or turbulent flow, being equal to:

$$Re = \rho u L / \mu \quad (3.12)$$

- the Grashof number (Gr) is the ratio of the buoyancy to viscous forces acting on a fluid and it is defined as:

$$Gr = \frac{g\beta (T_p - T_\infty) \cdot L^3}{\nu^2} \quad (3.13)$$

To compute the external convective coefficient, to define the external convection a certain object is exposed to, Re and Pr are used into the experimental relation of forced convection-based Nu , that for vertical plates assumes the following definition²:

$$Nu = 0.288 \cdot Re^{0.731} \cdot Pr^{1/3} \quad (3.14)$$

Others formulations correlate the Prandtl and the Grashof dimensionless numbers to define the Rayleigh one:

$$Ra = Gr \cdot Pr \quad (3.15)$$

by which it is possible to define the non-forced convective heat transfer coefficient.

Incoming solar radiation and sun position variability

The sun radiation is the main source of thermal energy within the reference scenario. Incoming solar radiation impacts on the CPC structure surfaces, increasing its temperature once providing an incoming heat flux. Shadowing effects have to be implemented to preserve the consistency of the simulation scenario: due to that, the heat source position (i.e. the sun in the sky) is changed during the analyzed period. It depends on both the geographic position of the CPC and time. It follows that the view factor is introduced:

$$F_{ij} = \frac{Q_{rad,i \rightarrow j}}{Q_{rad,i}} \quad (3.16)$$

As deductible, Equation 3.16 defines how much of the emitting radiation from a certain surface i is intercepted by surface j . Roughly speaking, the view factor represents how much of the incident radiation on a generic body (i) leaves the same to reach another body (j). Obviously, F_{ij} should be assumed to be indirectly related to the heat source position: on one

²The experimental formulation for the Nusselt number depends strictly on the analyzed case study (e.g. vertical plates, horizontal plates, etc.).

hand, any obstacle between surfaces should decrease the incident radiation on the target surface (j); on the other hand, once a solar radiation condition is imposed as the main thermal source the Q_{rad} from surface i depends strictly on how much of the effectively incident solar radiation (depending on the geometrical configuration of the computing domain). This kind of parameter could be assigned by applying the *hemicube or direct area integration approach*, as done by COMSOL Multiphysics software to obtain view factors related to each one of the exposed to radiation surfaces, even if an user-defined initialization of each F_{ij} is available [33]. To describe analytically the varying position of the sun in a time dependent scenario, zenith angle θ_s and azimuth angle φ_s are considered. In detail, those parameters are converted into a directional vector i_s , defined by n.3 components in Cartesian coordinates ($i_{s,x}$, $i_{s,y}$ and $i_{s,z}$). The correlation between zenith angle, azimuth angle and directional vector is given by:

$$i_s = (i_{s,x}, i_{s,y}, i_{s,z}) \quad \text{where} \quad \begin{cases} i_{s,x} = -\cos(\varphi_s) \cdot \sin(\theta_s) \\ i_{s,y} = \sin(\varphi_s) \cdot \sin(\theta_s) \\ i_{s,z} = \cos(\theta_s) \end{cases} \quad (3.17)$$

North (N), East (E) and up directions are assumed to be x^+ , y^- and z^+ directions, respectively. A graphic overview of cardinal points assignment is reported by Figure 3.14. The assignment is the same implemented by the simulation software.

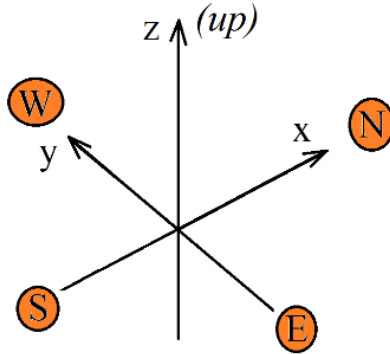


Figure 3.14. Main directions and cardinal points assignment.

Surface-to-surface radiation on exposed CPC surfaces

Once simulating the effect of incoming solar radiation on the CPC structure, sun movement across the sky has to be taken into account because of changing incident angle of radiation itself. Moreover, shadowing effects acting on the CPC components need to be implemented while investigating the thermal response of the whole computing domain. Due to that, the analytic problem of heat fluxes by radiation is defined by:

$$q_{flux} = \int_0^{\infty} \varepsilon(\lambda) \cdot \sigma \cdot (T^4 - T_{amb}^4) d\lambda \quad (3.18)$$

The emissivity ε defines how much of incident solar radiation is reflected by a specific body. Its value depends on many factors, such as the material which constitutes the target body, the kind of mechanical processes to which it was submitted to (influencing its surface finish), the kind of surface coating or applied treatment and much more. However, the emissivity value strictly depends on the wavelength of the incident radiation. It is interesting to notice that Equation 3.18 holds equivalently if $T_{amb} > T$. Indeed, in that case the emissivity should be considered as absorptivity α . This behavior is analytically described by Kirchhoff's Law on thermal radiation. According to the *black body theory*, emissivity equals absorptivity all over the electromagnetic spectrum. The black body emits the whole absorbed/incident radiation. Roughly speaking, ε value indicates how much the real body (i.e. the grey body) is far from the condition of the reference ideal body (i.e. the black body). Following this assumption, the emissivity gives an idea of the ration of incident radiation that is absorbed by the target body. High values of emissivity mean low values of reflectivity in terms of incoming radiation. That happens because the emissivity parameter has to be considered once the incoming radiation is absorbed and then re-irradiated by the target body. By the simulation approach, this concept is typically attributed to surface entities. In addition to that, opaque materials response to the incoming radiation needs to be deeply specified declaring the diffuse radiation ratio as described by author in [49]. Moreover, the conducted benchmarks remark how any absorptivity dependence on incident radiation direction should be neglected for this kind of numerical approach, to reduce computation requirements in terms of both costs and time: this assumption remains valid as long as we are dealing with mirrored and very clean surfaces. Referring to the wavelength dependence of emissivity, λ value

should be treated as discussed by the benchmark available at [49]. It is interesting to notice how the analytic approach gives us the opportunity to split solar spectral distribution into n.2 regions: it has been investigated that, approaching Earth atmosphere from the outside area, solar spectral distribution is really close to the one of a black body at 5800 K. Perhaps the presence of atmospheric gases which absorb and modify the incoming solar radiation spectrum, once approaching the ground level the spectrum remains mostly the same. As discussed by the example provided in [49], let's consider a black body at different temperatures³ and the fraction of total emitted power: this one varies depending on the wavelength, as reported by Figure 3.15.

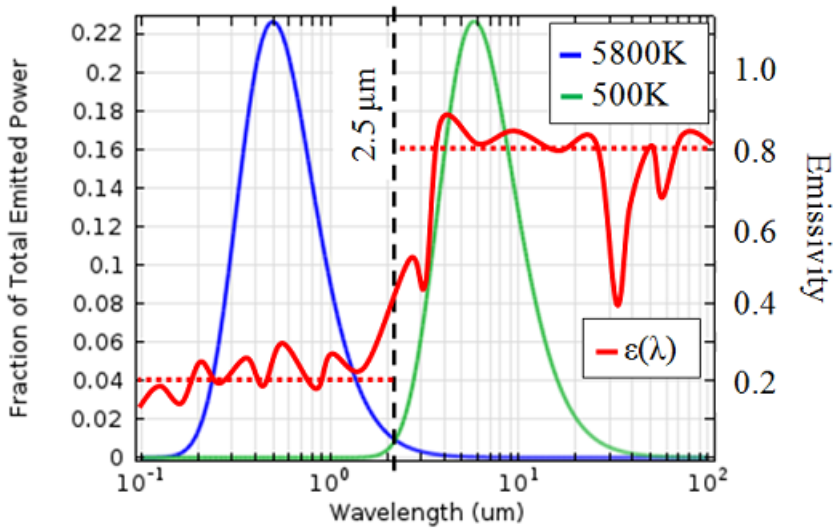


Figure 3.15. Total emitted power and emissivity dependence on wavelength [49].

For this kind of applications, referring to the measured trends of both fraction of total emitted power and emissivity, short-wavelength ($<2.5 \mu\text{m}$) and long-wavelength ($>2.5 \mu\text{m}$) areas should be identified. A further classification could be the solar spectral band region and the ambient spectral band region (Figure 3.16), related to the short-wavelength and long-wavelength area, respectively.

The red curve in Figure 3.15 shows the emissivity trend: being in the

³A 5800 K-temperature is considered for the Sun; for most of engineering applications a reference temperature of 500 K is also suitable.

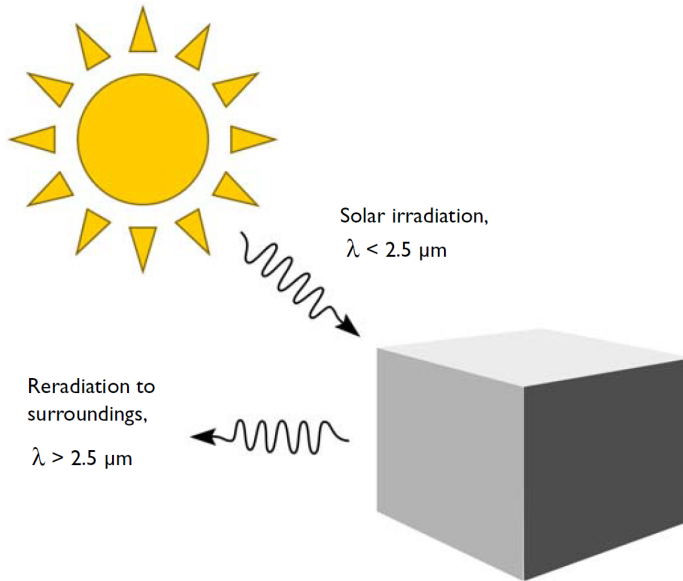


Figure 3.16. Ambient and solar spectral bands: absorption/emission of solar radiation from/to the surrounding environment [33].

solar spectral band region means a lower emissivity if compared to the one measured for the ambient spectral band region. That specific trend should be the typical emissivity response of an insulating material, specifically designed to maximize the insulation from solar radiation. Lower values of emissivity (or absorptivity) mean higher reflectivity to incident radiation. Another important information that could be deduced by Figure 3.15 is that for the solar spectral band, the fraction of total emitted power of a 500 K black body is negligible if it is compared to the one of the Sun (i.e. the black body at 5800 K), and vice versa. Some fluctuations could be observed by the emissivity trend, even if for engineering approaches a mean value is initialized for each one of the spectral bands. Obviously, many other spectral bands could be used to reach an higher resolution in terms of emissivity dependence on wavelength definition. However, two values of emissivity are suitable to define the characteristics of a certain material in terms of optical response to incident radiation [46, 49, 50]. Absorbed solar radiation by the gray body is characterized by a wavelength less than $2.5 \mu\text{m}$, while release radiation by the same body (i.e. re-radiation) to the surroundings is emitted from a wavelength value of $2.5 \mu\text{m}$, as reported by Figure 3.16. Then, to implement the emissivity dependence

on wavelength, for this kind of simulation approach average values of ε for the solar spectral band (ε_{B1}) and the ambient spectral band (ε_{B2}) are needed. For the condition of transparency the emissivity equals 1, which denotes that 100% of incident radiation is re-radiated by the same body. In case of transparent body, the whole radiation is transmitted through the body. Analytically describing this concept, it should be appropriate to consider the concept of radiosity J , defined as the total of radiation (reflected and emitted) by a certain surface. Once emissivity ε , total emitted power at a certain temperature $e_b(T)$ and reflectivity ρ are given, it is possible to compute the radiosity as:

$$J = \rho G + \varepsilon e_b(T) \quad (3.19)$$

which could be strictly related to the view factor to define also the exposure to radiation between each one of the involved surfaces.

3.4.2 Environmental conditions definition

One of the most difficult problems to define while implementing a numerical simulation approach is related to environmental conditions. Actually, many parameters such as moisture content of air, weather conditions and wind flows are needed to take into account the external convection dynamics. External conditions interact with the CPC directly, causing many effects such as the cooling one. In accordance with the researchers involved by the experimental campaign, the following conditions are considered to be implemented by the numerical approach:

- daily ambient temperature, as given by the Dublin Airport Weather Station [51] for the reference periods;
- daily solar radiation, as given by CMAS Radiation Service webpage [52]. In this case, the scenario implementation requires a subdivision of the total beam solar radiation into its components, that is beam horizontal irradiation (BHI) and diffuse horizontal irradiation (DHI). This is the reason why solar radiation trend by pyranometer experimental acquisitions is neglected (no split is possible to obtain required BHI and DHI);
- external convection, since the heat flux feature adds a convective flux to the external surfaces. The specific used condition is the wind

velocity. A preliminary study related to the real experimental setup external conditions determines a wind velocity of 0.5 m/s [46].

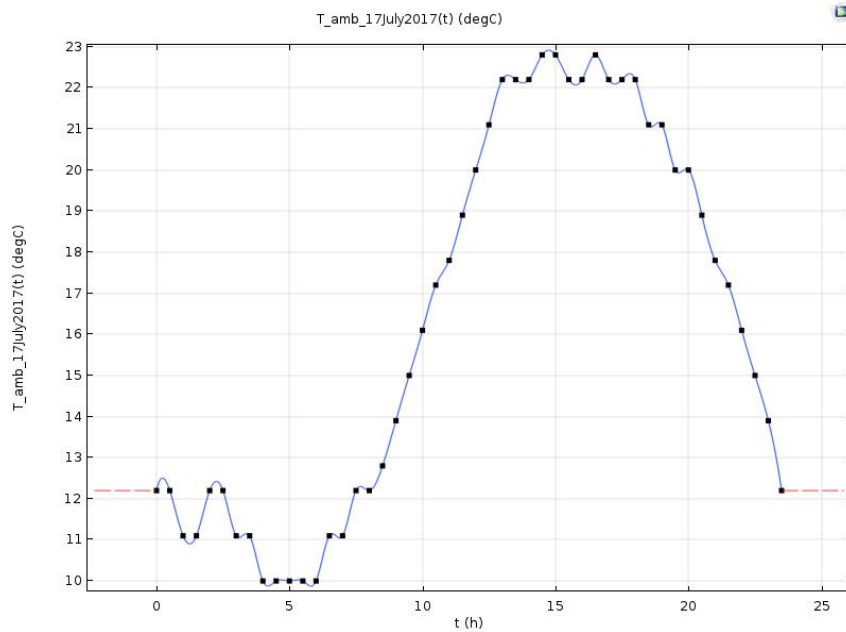
Each one of the described daily trends is obtained for the 17 July 2017 and to the 18 July 2017 (refer to Table 3.5), referring to the covered and to the uncovered CPC configurations, respectively. To avoid instability issues while solving the scenario, every set of data has been imported in COMSOL and submitted to a polynomial fit, considering a cubic spline primitive for contiguous points. This is one of the typical pre-processing operations once implementing complex simulation scenarios, deleting any source of discontinuity within the imported data.

The daily temperature trends are reported by Figure 3.17, while the solar radiation components (BHI and DHI) are given by Figure 3.18 and by Figure 3.19 for the covered and uncovered CPC scenarios, respectively. Because of the extreme variability of external environment conditions in terms of convection, it is necessary to make some assumptions while implementing the external convection condition. Referring to the trends exposed by experimental data, a constant wind velocity is implemented in accordance with the research plan. It follows a preliminary simulation study on wind velocity influence on thermal response of the CPC prototype, comparing numerical results with experimental data. Further details are given by subsection 3.5.3, where imposed boundary conditions are described in detail.

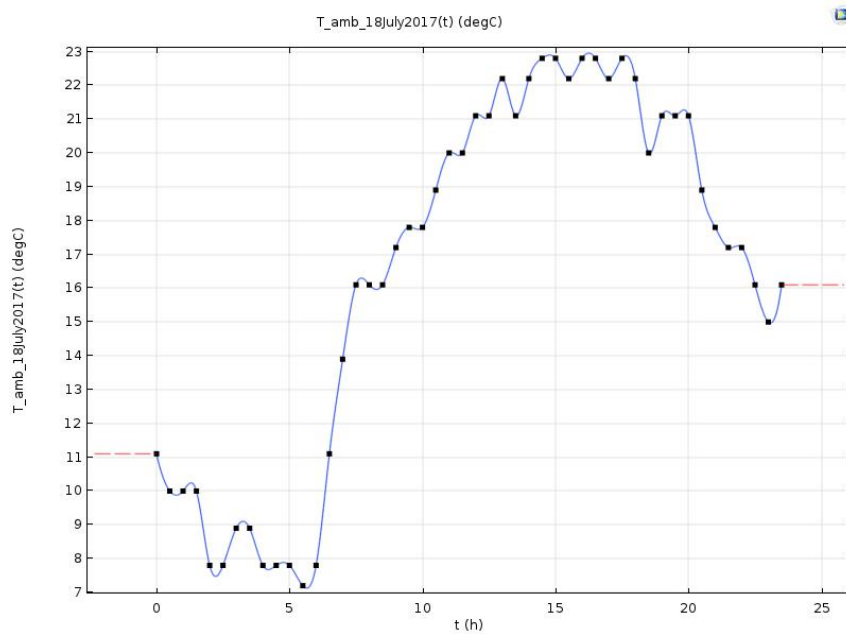
Table 3.5. Environmental parameters as exported by [51, 52] (reference year: 2017).

Daily temperature trend $T_{amb}(t)$ [°C]											
t_{step} [h]	July 17	July 18	t_{step} [h]	July 17	July 18	t_{step} [h]	July 17	July 18	t_{step} [h]	July 17	July 18
0.0	12.2	11.1	6.0	10.0	7.8	12.0	20.0	21.1	18.0	22.2	22.2
0.5	12.2	10.0	6.5	11.1	11.1	12.5	21.1	21.1	18.5	21.1	20.0
1.0	11.1	10.0	7.0	11.1	13.9	13.0	22.2	22.2	19.0	21.1	21.1
1.5	11.1	10.0	7.5	12.2	16.1	13.5	22.2	21.1	19.5	20.0	21.1
2.0	12.2	7.8	8.0	12.2	16.1	14.0	22.2	22.2	20.0	20.0	21.1
2.5	12.2	7.8	8.5	12.8	16.1	14.5	22.8	22.8	20.5	18.9	18.9
3.0	11.1	8.9	9.0	13.9	17.2	15.0	22.8	22.8	21.0	17.8	17.8
3.5	11.1	8.9	9.5	15.0	17.8	15.5	22.2	22.2	21.5	17.2	17.2
4.0	10.0	7.8	10.0	16.1	17.8	16.0	22.2	22.8	22.0	16.1	17.2
4.5	10.0	7.8	10.5	17.2	18.9	16.5	22.8	22.8	22.5	15.0	16.1
5.0	10.0	7.8	11.0	17.8	20.0	17.0	22.2	22.2	23.0	13.9	15.0
5.5	10.0	7.2	11.5	18.9	20.0	17.5	22.2	22.8	23.5	12.2	16.1

Solar radiation components											
t_{step} [h]	BHI [W/m ²] July 17	BHI [W/m ²] July 18	t_{step} [h]	BHI [W/m ²] July 17	BHI [W/m ²] July 18	t_{step} [h]	DHI [W/m ²] July 17	DHI [W/m ²] July 18	t_{step} [h]	DHI [W/m ²] July 17	DHI [W/m ²] July 18
0.0	0.00	0.00	12.0	693.58	685.62	0.0	0.00	0.00	12.0	134.05	136.54
1.0	0.00	0.00	13.0	720.24	691.30	1.0	0.00	0.00	13.0	131.65	148.23
2.0	0.00	0.00	14.0	707.06	646.56	2.0	0.00	0.00	14.0	125.29	163.23
3.0	0.00	0.00	15.0	653.49	565.10	3.0	0.00	0.00	15.0	116.77	172.61
4.0	0.00	0.00	16.0	561.28	460.81	4.0	0.00	0.00	16.0	108.50	170.24
5.0	1.64	1.76	17.0	439.03	342.95	5.0	6.29	5.78	17.0	99.75	155.50
6.0	42.02	45.41	18.0	301.93	217.59	6.0	44.11	41.73	18.0	86.97	131.73
7.0	143.17	150.72	19.0	165.80	104.34	7.0	77.82	73.12	19.0	68.55	96.30
8.0	273.42	283.17	20.0	53.53	26.01	8.0	101.03	94.80	20.0	41.36	49.66
9.0	407.85	418.31	21.0	2.59	0.78	9.0	116.93	109.88	21.0	6.81	6.38
10.0	530.61	537.75	22.0	0.00	0.00	10.0	126.89	121.17	22.0	0.00	0.00
11.0	629.16	628.97	23.0	0.00	0.00	11.0	132.14	130.18	23.0	0.00	0.00

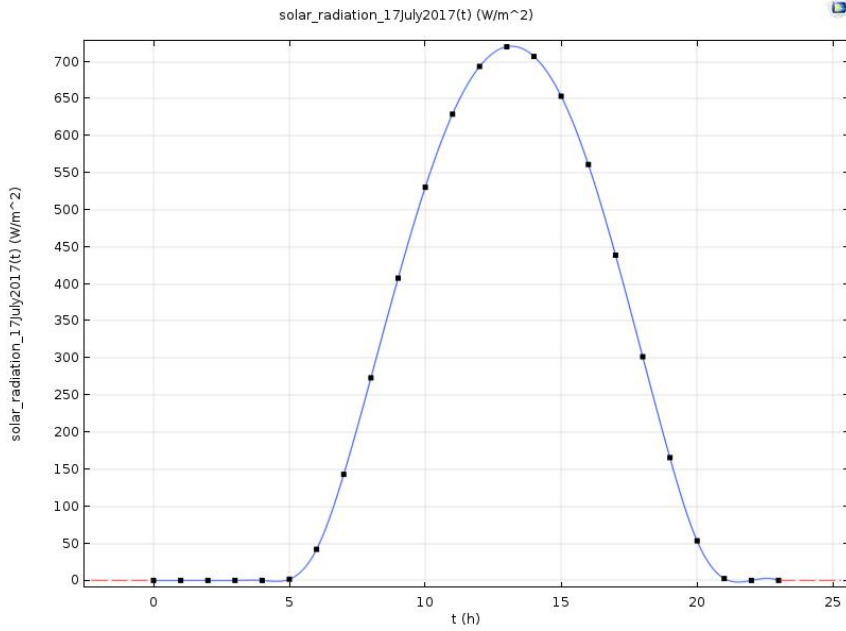


(a) Covered CPC (17 July 2017).

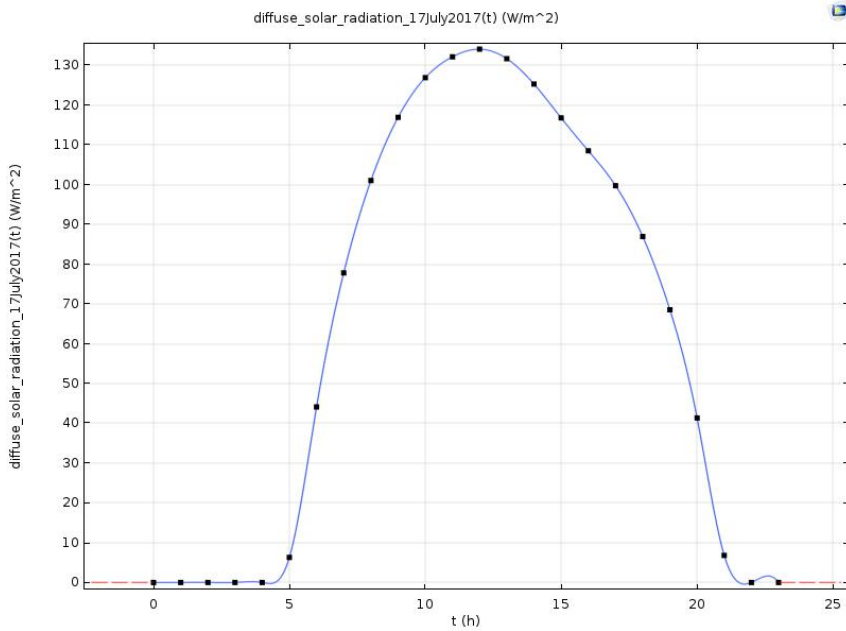


(b) Uncovered CPC (18 July 2017).

Figure 3.17. Daily temperature trend for the simulation scenarios.

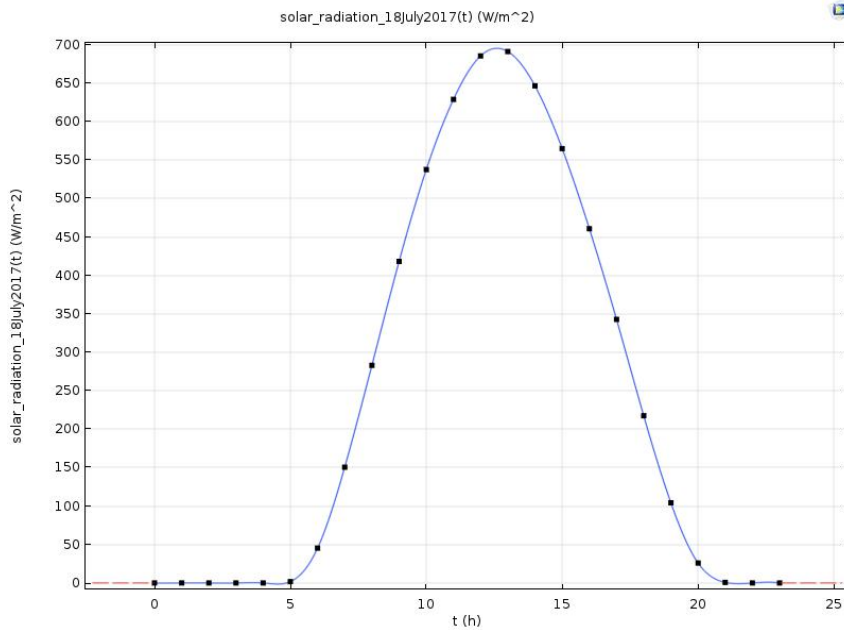


(a) BHI.

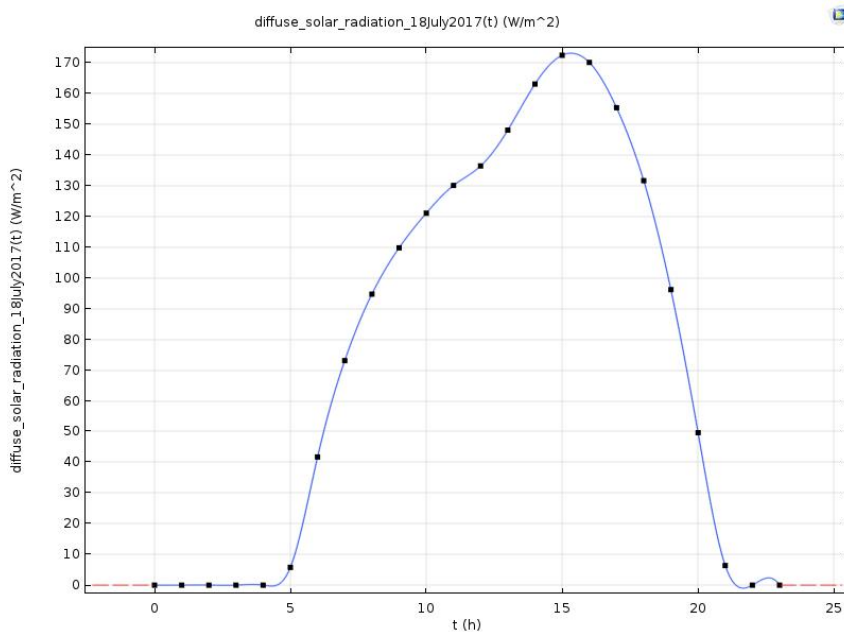


(b) DHI.

Figure 3.18. Solar radiation components for the covered CPC scenario (17 July 2017).



(a) BHI.



(b) DHI.

Figure 3.19. Solar radiation components for the uncovered CPC scenario (18 July 2017).

3.4.3 Geometry model definition

The built-in geometry builder is used to initialize the geometrical entities to be submitted to FEM approach in CM. The following discussion is related to the implemented procedures while building-up every CPC component, as designed and discussed by section 3.1 and section 3.2. Domains to be computed by the numerical simulation software should be listed as:

- back-plate;
- frame structure;
- foam;
- side and upper covers;
- reflectors and reflectors supports;
- solar cells and solar cells supports;
- air domain.

It should be useful to specify that CM allows the existence of typical geometrical objects and entities (in 3D), as identified by 3.20.

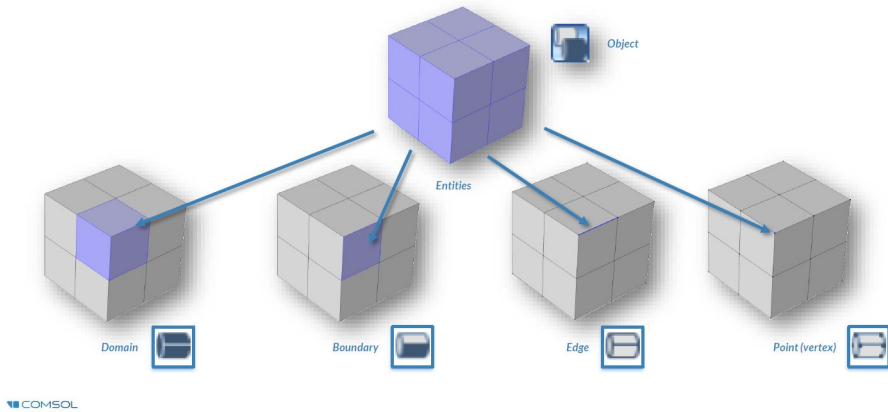


Figure 3.20. Geometry entities in COMSOL Multiphysics [53].

The dimensional space in which objects are inserted assigns automatically a different name to the target geometrical entity (see e.g. Table 3.6). This process is guaranteed by the geometry builder itself in CM. It's easy

to assert how geometric entities of the maximum dimension are called domains.

Table 3.6. Assignment of geometrical entities hierarchical order in CM [53].

Entity dimension	3D space	2D space	1D space	0D space
3D object	Domain	/	/	/
2D object	Boundary	Domain	/	/
1D object	Edge	Boundary	Domain	/
0D object	Vertex	Vertex	Boundary	Domain

Further descriptions of how single components have been realized in CM are discussed by the following paragraphs.

Back-plate

The *block* feature is used to define the back-plate of the CPC. This component, as shown by Figure 3.21 provides the plane surface where each one of the aforementioned components is installed.

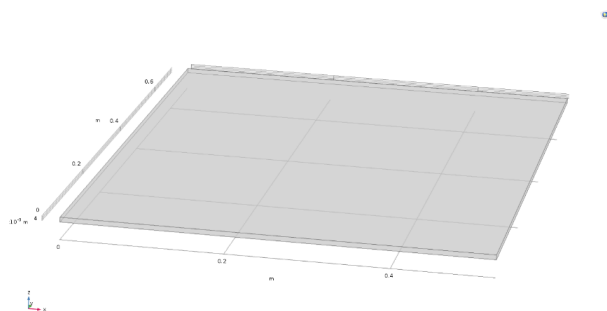


Figure 3.21. Back-plate of the CPC prototype.

Furthermore the back-plate provides an insulation between its upper components and the ground.

Frame structure

The block built-in feature of the CM geometry builder is used to create the whole on-side solid frame. Then, a boolean operation of difference is applied to subtract the slot volume.

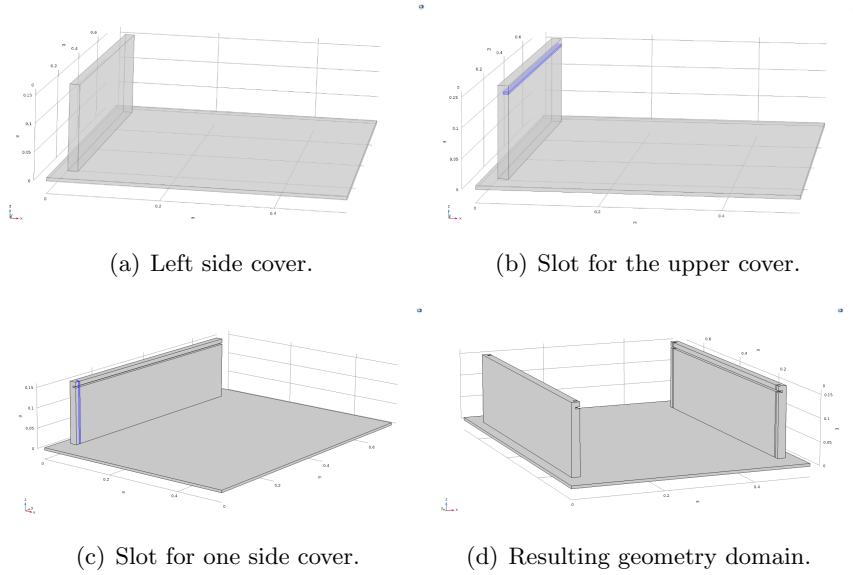


Figure 3.22. Frame structure component of the CPC prototype.

Indeed, boolean operation features of CM have to be considered while direct or reverse extrusion - that is addition or subtraction of volumes, respectively - is required. It allows the user to act easily on solid volumes, defining sectors to be deleted or added. This feature is also particularly suitable once an explicit declaration of zones where atypical mesh parameters are needed. An example of this application could be the local mesh refinement of an air volume around objects to be submitted to CFD analysis of air flows and streamlines. Slots for side covers are obtained by means of *mirror* feature with respect to the half-section xz -plane located at $y = L_y/2$. The same process is applied to the whole one-side frame to be mirrored with respect to the yz -plane located at $x = L_x/2$. The resulting geometrical entities are shown by Figure 3.22.

Foam

The thermal insulation foam on the internal surfaces of both frame structures is realized by means of block feature on one side. Then, the mirror feature is applied like previously discussed for the second solid frame structure. The resulting geometric entities are shown by Figure 3.23.

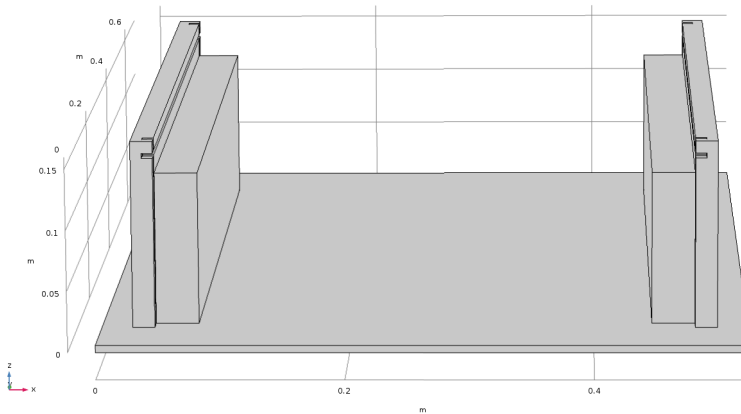
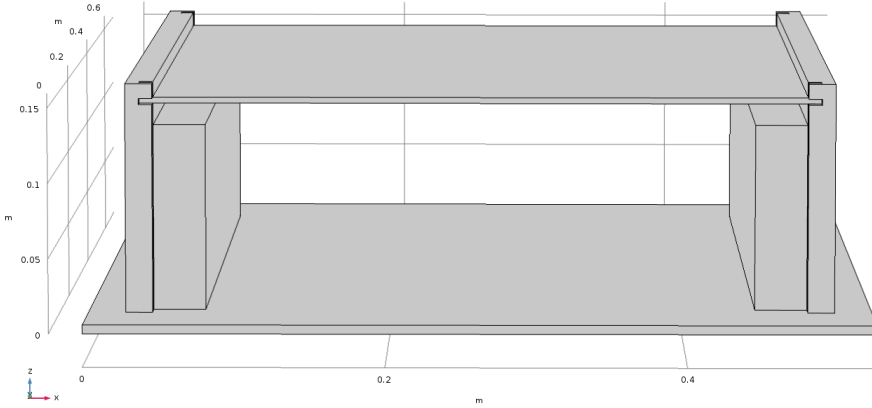


Figure 3.23. Foam component installed for the CPC prototype (for the covered configuration only).

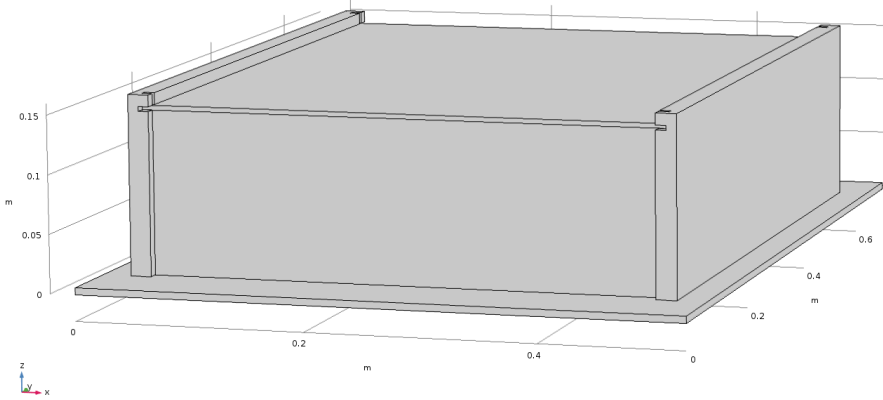
The foam is installed for the only covered configuration of the CPC, since for the uncovered one no air domains remain trapped (none of the covers is installed), reason why the thermal stress frame structures are exposed to by inner surfaces is less relevant. By that, experimental campaign provides no foam for the uncovered CPC configuration. The same assumption is replicated by the numerical simulation scenario implementation.

Side and upper covers

One of the side covers and the upper cover are generated by means of the block features. The other side cover is obtained by means of the mirror feature. Each one of these components is arranged to fit the slot dimensions once positioned as in Figure 3.24, to protect internal components of the CPC (i.e. solar cells, reflectors and reflectors supports).



(a) Upper cover positioned.



(b) All covers positioned.

Figure 3.24. Covers of the CPC prototype (for the covered configuration only).

Reflectors and reflectors supports

All external components of the CPC prototype have been geometrically defined. The reflectors have to be built as one of the inner components. For that reason, the parabolic shape of the reflector surface is defined. The solution to the problem is easy to be found once one point and the

vertex of the parabola defining the shape of the reflector are given. By that, the x-coordinate for the parabola vertex, computed as

$$x_v = -\frac{b}{2a} \quad (3.20)$$

should be replaced within the generic parabola equation:

$$y = ax^2 + bx + c \quad (3.21)$$

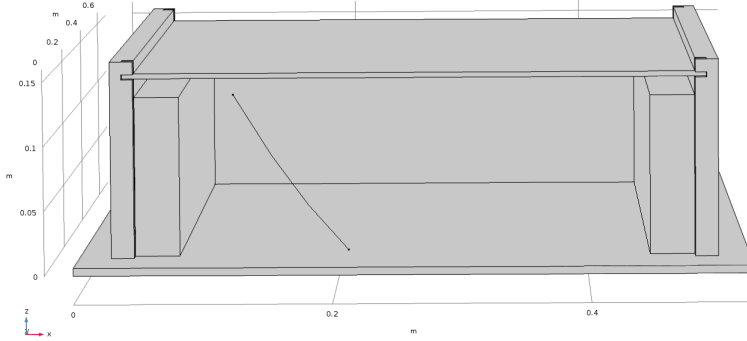
To implement this kind of approach once generating the reflector shape, the *parametric curve* feature is used. The parabolic function is defined as the reference parametric equation, then each one of the parameters is initialized. Geometrically speaking, the vertex is located below the surface of solar cells. The maximum extension of the parabolic arc does not represent a problem since it will be submitted to a cut in correspondence of the inner surface of the upper cover. Initially, the parametric parabola is initialized to fit the following constraints: vertex at (0,0) and existence of the parabola in correspondence of point on xz-plane with coordinates (125;62.5). Following the indications given by the designing and optimization campaign of the CPC prototype, coefficients a , b and c of the parabola will be:

$$a = 0.0041/\text{m}, b = 0 \text{ and } c = 0$$

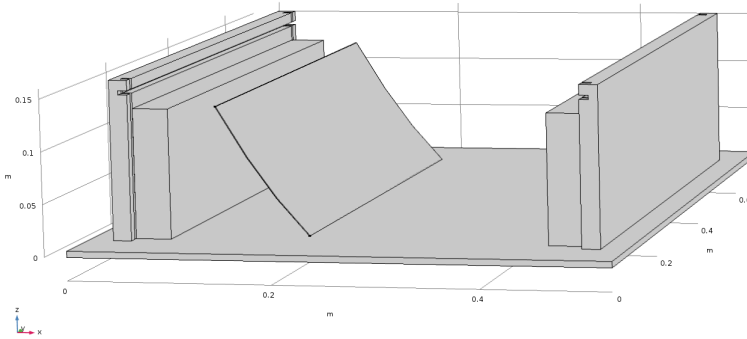
Thus, Equation 3.21 assumes the form:

$$y = 4x^2 \quad [\text{m}] \quad (3.22)$$

Finally, the lower point of the parabolic arc is moved so that it results located on the solar cells upper surfaces. An *offset* is applied to the parabolic arc to constitute the 1-mm thickness of the reflector itself. All these operations are applied on a specific *work plane* (parallel to the xz-plane), available by the *plane geometry* interface. This kind of strategy is particularly suitable once preparing a surface to be submitted to an extrusion operation. Indeed, the *extrusion* feature is applied to extrude the closed surface on the work plane, completing the left-reflector geometry initialization. The resulting geometry is reported by Figure 3.25.



(a) Positioning of the left-side reflector's parabolic arc.

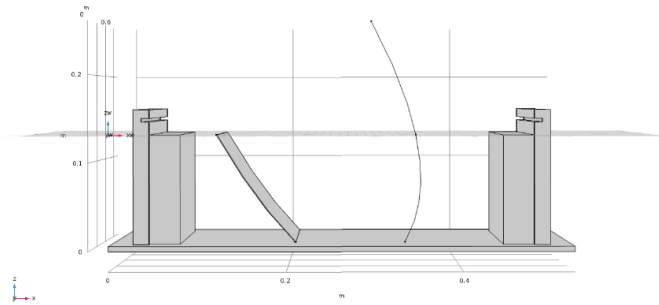


(b) Parabolic-shaped left reflector.

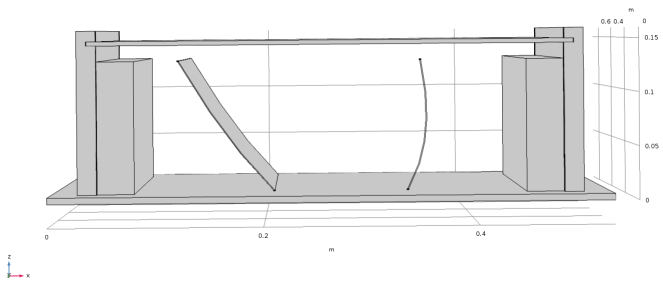
Figure 3.25. Left reflector of the CPC prototype.

To build the left-side reflector an analogue procedure is implemented. The correct CPC design imposes to rotate the second parabola of a 60° angle with respect to the symmetry axis of the first parabola. The parabolic arc defining the right-side reflector is copied on the work plane and rotate with a reference axis, specifically superimposed on the symmetry axis of the right-side parabola. The *rotation* feature allows to rotate of a specific angle (i.e. 60 degrees) the copied parabolic arc. The whole geometry is refined once a cut plane is defined to lie on the upper surface of the foams. The exceeding part of the parabolic arc is deleted by the *delete* feature, once a *partition* of the parabolic arc is defined with respect to the cut

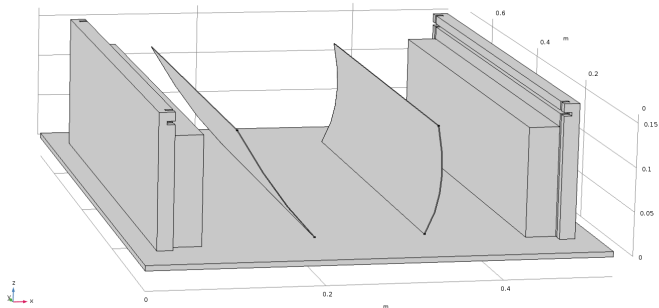
plane, available in Figure 3.26.



(a) Cut plane to delete exceeding parabolic arc.



(b) Right reflector thickness.



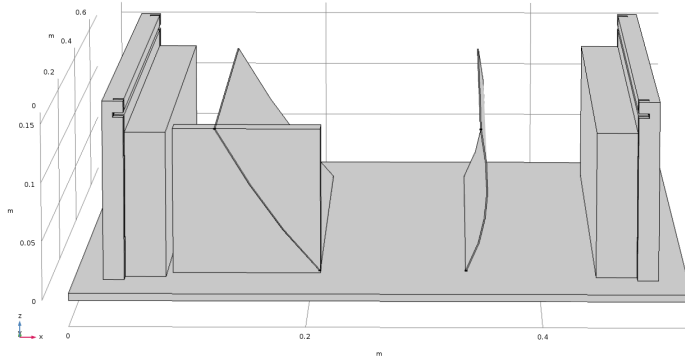
(c) Complete right reflector.

Figure 3.26. Right reflector of the CPC prototype.

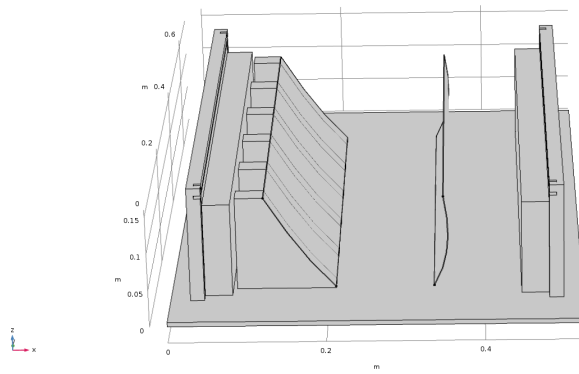
Reflectors supports are built considering both block feature and objects

partition operation. Indeed, a block is generated, the reflector itself is used to create 3 different domains once referring to the initial block⁴: the volume of the block which remains on the left side of the right reflector, the volume of the same block that interpenetrates the right reflector thickness and, finally, the volume on the right side of the reflecting surface. These two parts are deleted so that only the support reflector volume follows the parabolic arc on the opposite side of the reflecting surface. Then, the single support reflector is then copied and repeated by means of *array* features. The same series of operations are implemented on the left side reflector area. The resulting geometrical entities are shown by Figure 3.27.

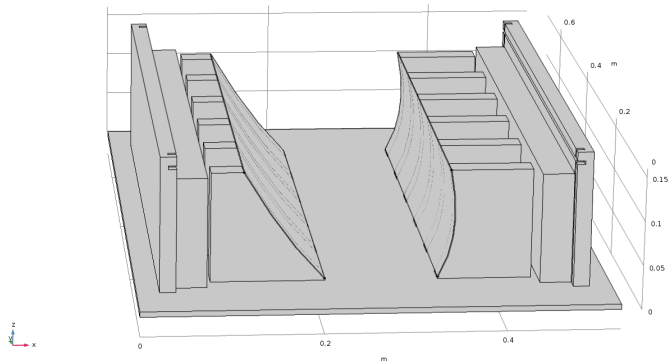
⁴Please note that the right reflector corresponds to the one closest to the origin of the axes.



(a) Initial block for the reflector support volume creation.



(b) Reflectors support for the right reflector.

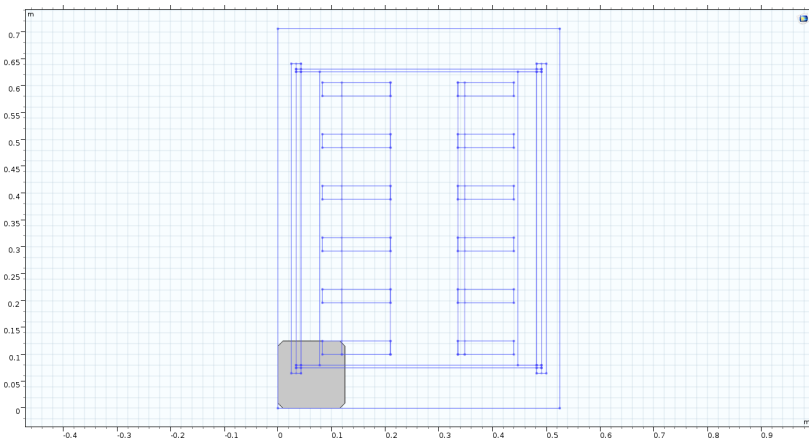


(c) Reflector supports once positioned.

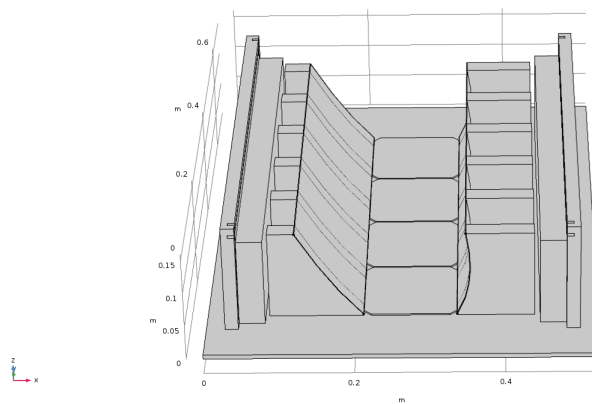
Figure 3.27. Reflector supports of the CPC prototype.

Solar cells and solar cells supports

Referring to the solar cell geometrical definition, a work plane is used to define the upper solar cell surface to be submitted to an extrusion operation to generate the solar cell thickness. Then, the solar cell is positioned on the target zone of the reflectors. Next solar cells are created by means of the copy and move features of CM. The resulting geometrical entities are shown by Figure 3.28.



(a) Initial definition of the first solar cell surface.

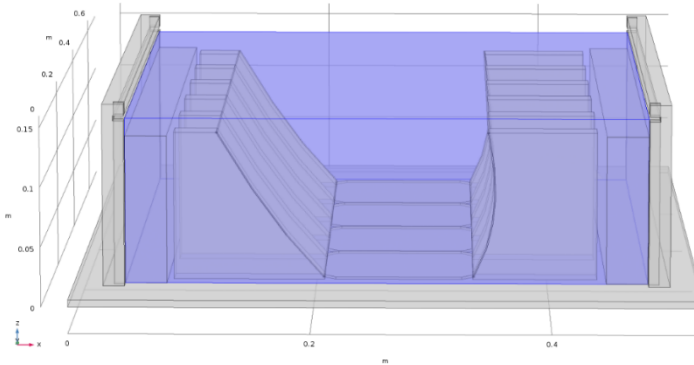


(b) Reflectors support for the right reflector.

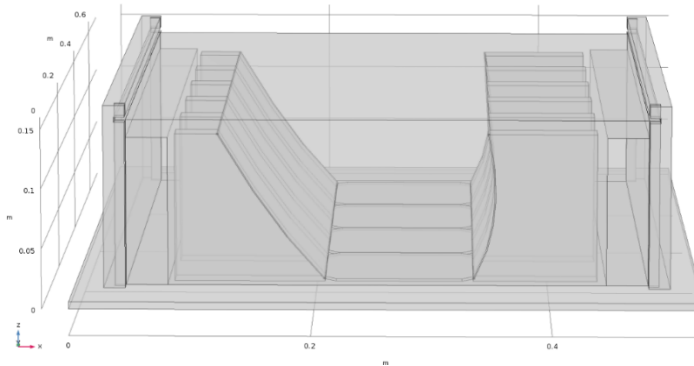
Figure 3.28. Solar cells of the CPC prototype.

Air domain

The air domain is generated once to the block contained by upper and side covers all inner components are subtracted by means of the boolean operation of *difference* applied to volumes. The resulting geometrical entity is shown by Figure 3.29.



(a) Block to be submitted to the boolean operation of difference.



(b) Transparent view of the air domain once trapped by covers.

Figure 3.29. Inner air domain of the CPC prototype (for the covered configuration only).

Resume of geometrical entities

A global overview of each one of the components of the CPC prototype in both configuration is given by Figure 3.30, considering that to simplify

the schematic view of volume entities the inner air domain (for the only covered configuration) is not reported. Colors assignment to components is shown by Table 3.7.

Table 3.7. Color assignment to geometrical entities of the implemented CPC prototype as by Figure 3.30.

Component	Covered	Uncovered	Color
Back plate	✓	✓	Grey
Solar cells	✓	✓	Purple
Solar cells back support	✓	✓	Black
Reflectors	✓	✓	Silver
Support reflectors	✓	✓	Yellow
Foam	✓	✓	Pink
Frame structure	✓	✓	Brown
Side cover	✓	x	Green
Upper cover	✓	x	Blue

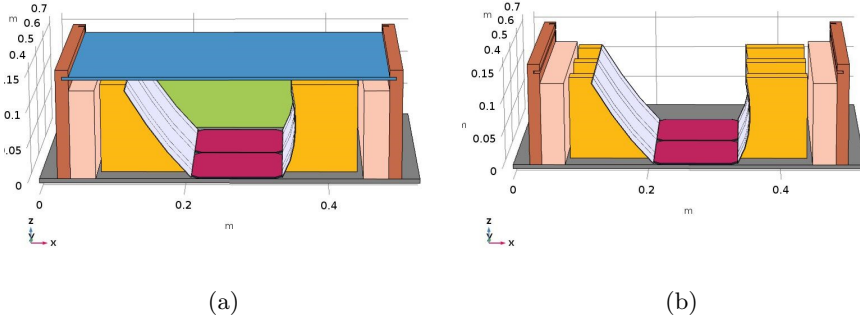


Figure 3.30. Geometrical entities overview for the CPC implemented prototype.

To simplify the comprehension of the sensitivity analysis conducted on half-acceptance angle and parabola coefficient variations, a further schematic view of the reflectors geometry construction is provided by Figure 3.31 and Figure 3.32.

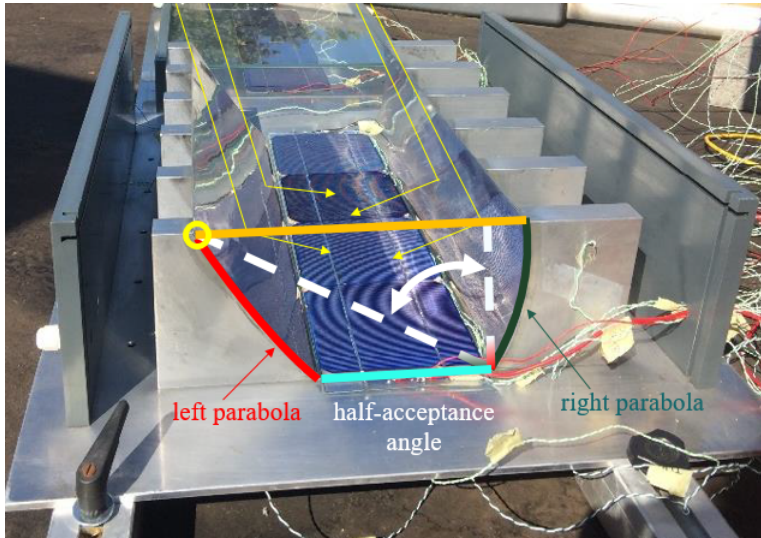


Figure 3.31. Schematic of reflectors shape-defining parameters.

The reflectors are built by a left parabola with a vertical symmetry axis (white dashed line in Figure 3.31, characterized by a coefficient of 4 m^{-1}). By the other hand, the right reflector of the system is built with a right parabola with the same coefficient but rotated like it is possible to see its symmetry axis (white dashed inclined line). The angle between the symmetry axis is the half-acceptance angle: it indicates how much the right parabola is rotated. For this specific prototype, the half-acceptance angle is equal to 60° . The point of intersection between the left parabola and the symmetry axis of the right parabola (the yellow circle in Figure 3.31 determines the height of truncation of the CPC system. In detail, the parabola coefficient a indicates the parabola concavity, appearing in the parabola equation; on the other end, the half-acceptance angle indicates the rotation of the right parabola, as shown by Figure 3.32. However, a visualization of the influence of parabola coefficient and half-acceptance angle variations on the whole CPC geometry is given by Figure 3.33.

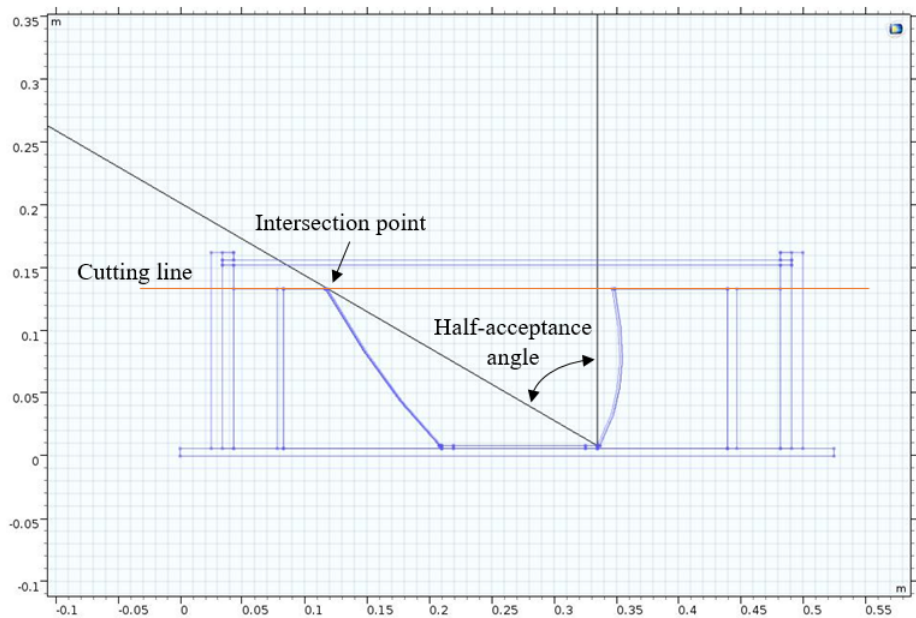


Figure 3.32. Schematic of reflectors shape-defining parameters within COMSOL Multiphysics interface.

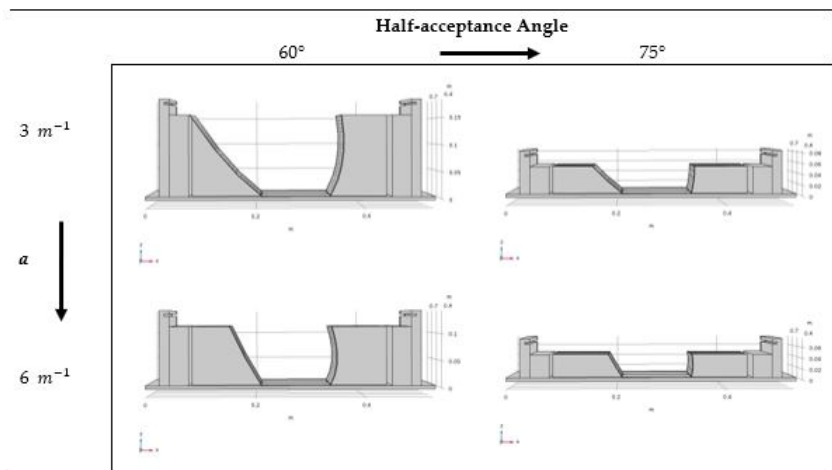


Figure 3.33. Parabola coefficient and half-acceptance angle influence on CPC geometry.

3.4.4 Materials assignment

The theoretical background defining the involved physical phenomena requires the assignment of specific characteristics and properties to the materials of each CPC component. More in detail, the heat transfer solving procedure needs the thermal properties (density, heat capacity and thermal conductivity) to be defined by the user. Moreover, the surface-to-surface radiation phenomena depends strictly on the emissivity of each material once the incoming radiation falls into a certain spectral band. For the implemented scenario, as previously discussed, both solar and ambient spectral bands are considered. Therefore, two kinds of emissivity are required to be defined for each material: solar spectral band emissivity (ε_{B1}) and ambient spectral band emissivity (ε_{B2}). The first is related to the emission spectrum of the solar radiation, while the second is referred to the radiation spectrum once the incoming radiation is reflected by a generic surface. The assigned properties are given by Table 3.8 for each one of the scenario components. So far as no emissivity value is defined, the relative component has to be considered as transparent.

Table 3.8. Assignment of materials properties for each one of the scenario components [41, 54–57].

Component	Availability in CPC		Thermal properties				Emissivity	
	Covered	Uncovered	Material	ρ [kg/m ³]	c_p [J/(kg · K)]	k [W/(m · K)]	ε_{B1} [1]	ε_{B2} [1]
Back plate	✓	✓	Aluminium sheet	2700	900	238	0.14	0.14
Frame Structure	✓	✓	PVC (40% pl.)	1400	900	0.19	0.60	0.92
Foam	✓	✓	PUR	33	2200	0.08	0.20	0.80
Cover	✓	x	Silica glass	2203	703	1.38	/	/
Side covers	✓	x	PMMA (solid)	1190	1470	0.18	/	/
Reflectors	✓	✓	Aluminium (foil)	2700	900	238	0.04	0.04
Support reflectors	✓	✓	Aluminium (sheet)	2700	900	238	0.14	0.14
Solar cells supports	✓	✓	Glass (quartz)	2210	730	1.40	0.90	0.90
Solar cells	✓	✓	Silicon	2329	700	130	0.70	0.70
Air domain	✓	x	Air	$\rho(p, T)$	$c_p(T)$	$k(T)$	/	/

3.5 Thermal field within a CPC prototype

3.5.1 Geometry model components

The schematic view of the implemented uncovered CPC is given by Figure 3.34. Every component reported by the aforementioned schematic is shared by both uncovered and covered CPCs.

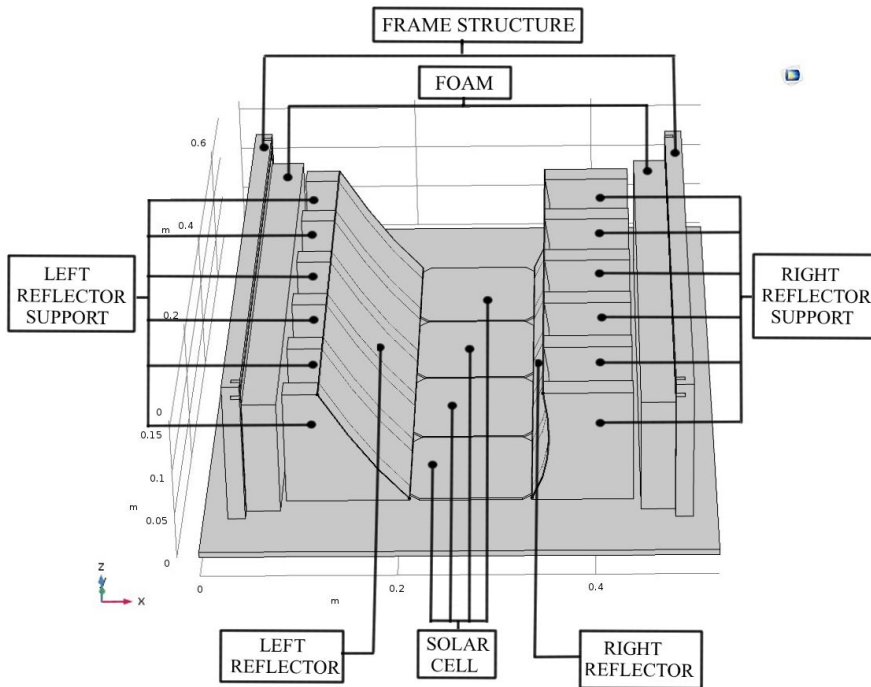
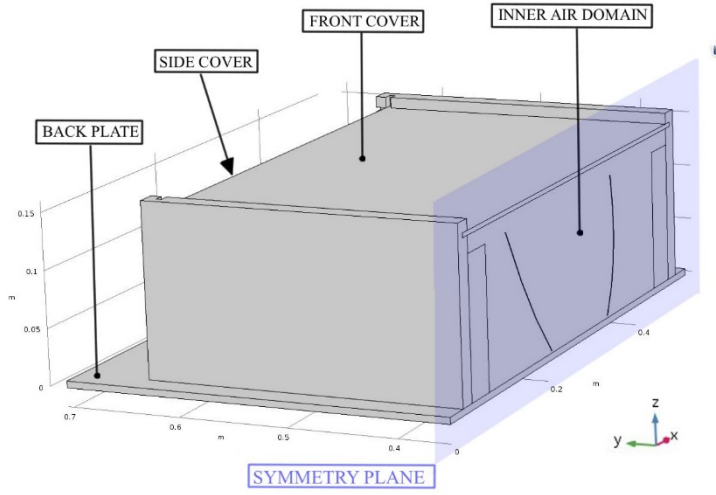


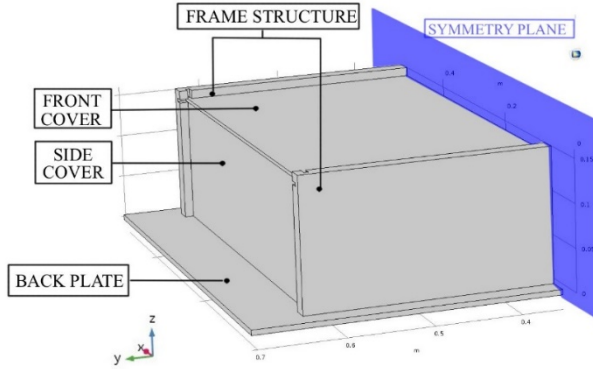
Figure 3.34. Components of the uncovered CPC as submitted to the study [46].

Left and right reflector supports are shaped to fit the curvature radius of left and right reflector, respectively. Solar cells are placed on the center zone where incoming solar radiation is focused by the reflectors. A thermal insulation foam thick layer is installed above each one of the frame structures exposed to the inner part of the CPCs. This is to avoid an extreme thermal stress caused by residual reflections on the frame structures that should be critical once side and upper covers are installed on the covered configuration. To reduce required computational resources, a symmetry approach is implemented, considering a symmetry xz -plane at

$y = L/2$, as given by Figure 3.35.



(a) Front view.



(b) Rear view.

Figure 3.35. Geometry model for the covered CPC [46].

3.5.2 Parametrization of geometric entities

Geometrical values and general purpose parameters assignment are listed by Table 3.9 and Table 3.10, respectively, as defined in CM. Those values are in common for both configurations.

Table 3.9. Parameters of both covered and uncovered configurations scenarios (geometrical entities definition).

Name	Expression	Value	Description
d_back	706 [mm]	0.706 m	Back-plate length
w_back	525 [mm]	0.525 m	Back-plate width
h_back	6 [mm]	0.006 m	Back-plate height
d_cell	125 [mm]	0.125 m	Solar cell length
w_cell	125 [mm]	0.125 m	Solar cell width
h_cell	2.2 [mm]	0.0022 m	Solar cell height
center_cell	210 [mm]	0.21 m	Solar cell center (short-side)
center_cell_L	100 [mm]	0.1 m	Solar cell center (long-side)
w_foam	35 [mm]	0.035 m	Foam width
d_foam	546 [mm]	0.546 m	Foam thickness
h_foam	125 [mm]	0.125 m	Foam height
x_frame	25 [mm]	0.025 m	Frame-origin x-distance
y_frame	65 [mm]	0.065 m	Frame-origin y-distance
w_frame	18 [mm]	0.018 m	Frame width
d_frame	576 [mm]	0.576 m	Frame depth
h_frame	154 [mm]	0.154 m	Frame height
w_cover	457 [mm]	0.457 m	Cover width
d_cover	556 [mm]	0.556 m	Cover depth
h_cover	4 [mm]	0.004 m	Cover height
d_s_cover	5 [mm]	0.005 m	Side cover depth
w_s_cover	457 [mm]	0.457 m	Side cover width
h_s_cover	140 [mm]	0.14 m	Side cover height
w_l_ref	127 [mm]	0.127 m	Left reflector width
h_l_ref	125 [mm]	0.125 m	Left reflector height
d_l_ref	25 [mm]	0.025 m	Left reflector depth
x_l_ref	5 [mm]	0.005 m	Distance left reflector - foam
d_r_ref	25 [mm]	0.025 m	Right reflector thickness
h_r_ref	125 [mm]	0.125 m	Right reflector height
w_r_ref	104.5 [mm]	0.1045 m	Right reflector width
h_back_cell	2 [mm]	0.002 m	Solar cell back height

Table 3.10. Parameters of both covered and uncovered configurations scenarios (general simulation assignments).

Name	Expression	Value	Description
t_start	5 [h]	18000 s	Initial time step
t_step	10 [min]	600 s	Time step
t_end	18 [h]	64800 s	Final time step
perc_diff_beam	0.15	0.15	Ratio of DHI
A_cell	d_cell*w_cell	0.0156 m ²	Solar cell area
I_mpp	5.4 [A]	5.4 A	Current at maximum power point
V_mpp	0.53 [V]	0.53 V	Voltage at maximum power point
eta_Tref	0.175	0.175	Solar cell efficiency
gamma	0.12	0.12	Coefficient of efficiency eq.
beta	0.0045 [1/K]	0.0045 1/K	Coefficient of efficiency eq.
T_ref	25 [°C]	298.15 K	Reference ambient temperature

3.5.3 Boundary and initial conditions

To replicate the environmental conditions and the whole physical phenomena influencing the thermal response of the CPC system, the numerical scenario implementation requires the initialization of specific boundary conditions. In addition, initial conditions (at t_0) needs to be assigned because of the time-dependent analysis. The applied boundary conditions should be listed as

- **surface-to-surface radiation** condition: this is the primary node of the model tree of the *Heat Transfer with Surface-to-Surface Radiation* in CM, a particularly suitable built-in interface while implementing thermal fluxes due to conduction, convection and radiation, taking into account the exposure of radiative fluxes between exposed surfaces. Some additional features to define the optical behavior of each surface once exposed to radiation are automatically enabled to be implemented by the user, as discussed below (refer to *Diffuse mirror* and *Diffuse Surface* conditions). The ambient settings node is filled with the trends exposed by subsection 3.4.2.
- **external radiation source** condition: the node related to this global boundary conditions gives the opportunity to initialize any radiation source also in terms in its relative position all over the simulation time frame. In this case, the solar radiation has to be

considered as the main external radiation source, reason why it is necessary to know the geographical position (latitude, longitude and time zone) of the simulated object. As specified in section 3.2, the location is that of TCD Simon Perry's Building in Dublin (Ireland) and the dates are July 17 and 18, 2017 for covered and uncovered experimental configurations, respectively. The solar irradiance is required by the *external radiation source* settings interface which has been chosen to be the user-defined clear sky noon beam normal irradiance. Once the date has been initialized, the local time to be used to define the external radiation source position (i.e. Sun's position in the sky) is updated with the solver time step automatically. It is important to notice that the assigned irradiance contributes to the incident radiative heat flux on all spectral bands, that is solar and ambient ones⁵. Indeed, the contribution of the source is equal to the product between the view factor of the same source and its radiosity [33]:

$$G_{extDir,Bi} = F_{ext,Bi}(i_s) \cdot q_{0,s} \cdot FEP_{Bi}(T_{sun}) \quad (3.23)$$

where $FEP_{Bi}(T_{sun})$ is the fractional black-body emissivity power, $q_{0,s}$ is the external radiation source, $F_{ext,Bi}$ is the external view factor where the subscript Bi is referred to i -th spectral band and T_{sun} is the temperature of the solar source;

- **initial values**, that is the unknown values (i.e. temperature field) to be computed over the entire simulated time frame;
- **solid domain** condition, that is the way the user is able to define a solid volume where related phenomena (e.g. heat conduction by conduction) take place, as analytically reported by Equation 3.4. All CPC internal components (i.e. foam, support reflectors, reflectors, frame, solar cells and solar cells supports) are implemented as opaque elements (as by Figure 3.36), except for the trapped air volume and both covers volumes which are implemented as full-transparent domains (Figure 3.37);

⁵It happens because of the automatic interaction between the declared irradiance and both *Diffuse surface* and *Diffuse mirror* conditions [33].

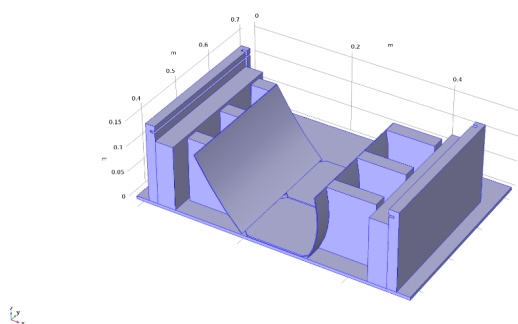
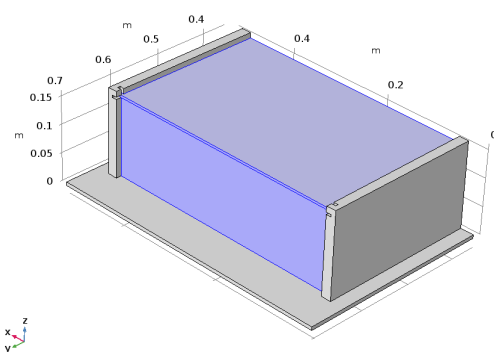
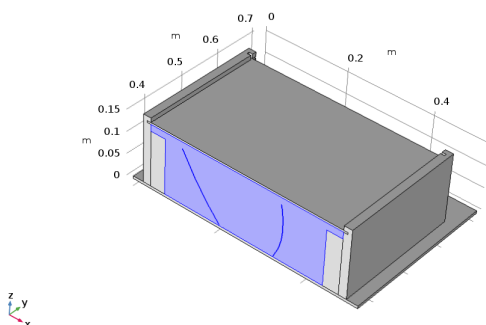


Figure 3.36. Opaque solid domains of the CPC prototype (half-section xz -plane applied).



(a) Side and upper covers.



(b) Inner air domain.

Figure 3.37. Fully transparent domains of the CPC prototype (half-section xz -plane applied).

- **fluid domain** condition: that is the way the user is able to define a fluid volume where related phenomena (e.g. heat conduction by convection) take place, as analytically reported by Equation 3.5. In this case, the fluid domain condition is applied to the trapped air domain once the covers are positioned,
- **diffuse surface** condition: while implementing the whole surface-to-surface radiation phenomena, this kind of condition needs to be added in the scenario to allow the computation of the irradiation reflections by surfaces. Effectively, the incoming radiation at the boundary surface is defined as [33]:

$$q = \varepsilon (G - e_b(T)) \quad (3.24)$$

In addition to that, the initial value of the surface radiosity has to be set by the same interface of the diffuse surface condition:

$$J_{B,init} = \varepsilon_{Bi,u} e_b(T_{init}) + (1 - \varepsilon_{Bi}) e_b(T_{amb}) \quad (3.25)$$

where the subscript Bi is referred to i -th spectral band (i.e. solar spectral band and ambient spectral band). The assignment of materials emissivity is conducted by means of the *material property* nodes as specified by subsection 3.4.4. The time-dependent trend of external temperature initialization as reported by subsection 3.4.2 is guaranteed by the same boundary condition settings node, as for the surface-to-surface radiation one. It has to be noticed that for the internal surfaces the assignment of the aforementioned daily temperature trend is not consistent. It follows that the temperature trend, to which interior boundaries are exposed to, is the one calculated at each time step by the heat transfer module interface. To do that by the software, the unknown temperature field variable name (T) as taken by the variables name-space of CM routine is initialized. The diffuse irradiance is also included once its values are obtained by [52]. Thus, diffuse surfaces are those directly exposed to the external environment, without considering the upper and side covers in addition to the trapped air domain for the covered configuration, for which a full transparency condition is applied (emissivity equals to 1);

- **diffuse mirror** condition: by assuming an ideal scenario, the reflectors provide a full reflection of the incident radiation, conveying sun

rays on the solar cells, directly. Then, the diffuse mirror condition is applied to the reflector surfaces on the interior zone of the CPC (refer to Figure 3.38), where solar cells are placed. Theoretically, it allows to define a surface characterized by an emissivity that is equal to zero. This condition is implemented for both covered and uncovered configurations;

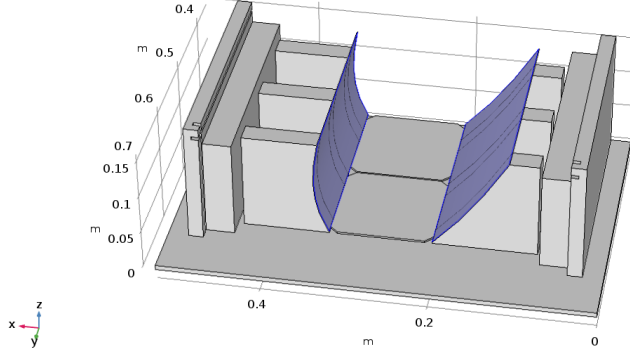


Figure 3.38. Diffuse mirror condition application on the interior reflectors surfaces of the CPC prototype (half-section xz-plane applied).

- **thermal insulation** condition: the assumption of a thermal insulation between the roof ground level and the back-plate rear surface on which the CPC is placed is implemented by means of the following condition:

$$-\hat{n} \cdot q = 0 \quad (3.26)$$

- **symmetry** condition: to significantly reduce the time and computing resources required by the scenario resolution procedure, a symmetry approach is applied once the xz-plane at $y = L_y/2$ represents the symmetry plane;
- **symmetry for surface-to-surface radiation** condition: the implemented interfaces within CM require to define a symmetry plane also for the *surface-to-surface radiation module*. Actually, the symmetry approach as by single symmetry condition neglects view factors computation and incident solar radiation direction as defined by the *external radiation source* condition. The symmetry plane is coincident with the one at $y = L_y/2$;

- **thin layer** condition: once a thin layer needs to be studied to compute the temperature field, many problems in terms of mesh application on those thin regions could arise. The main issue is related to the fact that the isotropic characteristic of the spatial discretization elements may be difficult to guarantee. COMSOL Multiphysics allows the user to implement the *thin layer* condition to avoid this drawback: by applying the thin layer boundary condition it is possible to bypass the direct computation of the desired value distribution within the target region. However, the software gives the opportunity to visualize it by means of the post-processing section. Roughly speaking, the numerical solution process approximates the distribution of the target variable (e.g. the temperature field) across the thin layer, neglecting its geometrical footprint within the whole geometry model. The thin layer condition could be applied to 2D surfaces in 3D coordinate systems, to make them interact with the software as if the third dimension existed. To learn more about these concepts, refer to the COMSOL simulation manuals [31–33]. The basic formulation of the thin layer condition is the following:

$$\rho_{s_i} c_{p,s_i} \frac{\partial T_s}{\partial t} + \nabla_t \cdot q_{s_i} = Q_{s_i} \quad (3.27)$$

where ρ_{s_i} , c_{p,s_i} , T_s , q_{s_i} and Q_{s_i} are the density, the heat capacity, the dependent variable, the conductive heat flux and the applied heat source of the i -th layer, respectively. Geometrically, the thin layer condition is applied to the upper solar cell supports surfaces, to define the incident radiation target solar cells, as given by Figure 3.39;

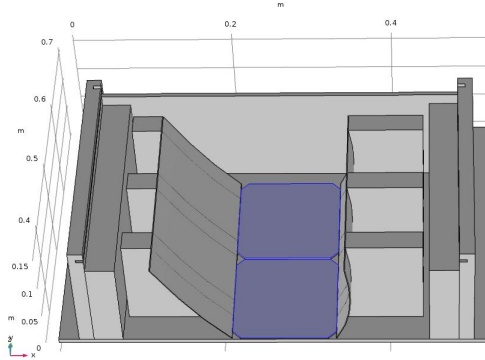
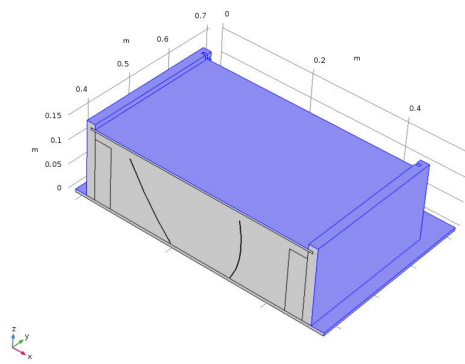


Figure 3.39. Thin layer condition to define solar cells of the CPC prototype (half-section xz-plane applied).

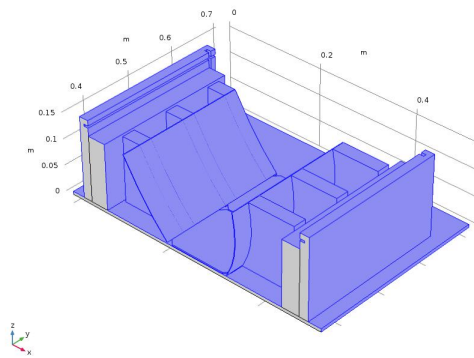
- **heat flux** condition: this is a fundamental condition while implementing any kind of cooling phenomena acting on the CPC prototype. For this specific case, in accordance with the research staff, a constant convective flux due to a 0.5 m/s wind speed is assumed. Obviously, the external temperature setting node is initialized by means of the daily trend temperature. The governing equation is the following:

$$q_0 = h \cdot (T_{ext} - T) \quad (3.28)$$

where h is the convective heat transfer coefficient, T_{ext} is the external temperature of the environment and T is the computed temperature. Boundary condition assignment to surface entities is reported by Figure 3.40.



(a) Covered configuration.



(b) Uncovered configuration.

Figure 3.40. Assignment of heat flux condition to the external surfaces of the CPC prototype (half-section xz-plane applied).

Then, the external forced convection condition is imposed. All inner components are exposed to the external convection once an uncovered CPC configuration is considered; on the other hand, for the covered CPC configuration every external surface of the frame structure and covers in addition to the most external back-plate regions are exposed to the external convection. Referring to the 0.5 m/s wind speed value, it was chosen once a sensitivity analysis has been conducted on a preliminary scenario setup. This approach led to results as reported by Figure 3.41.

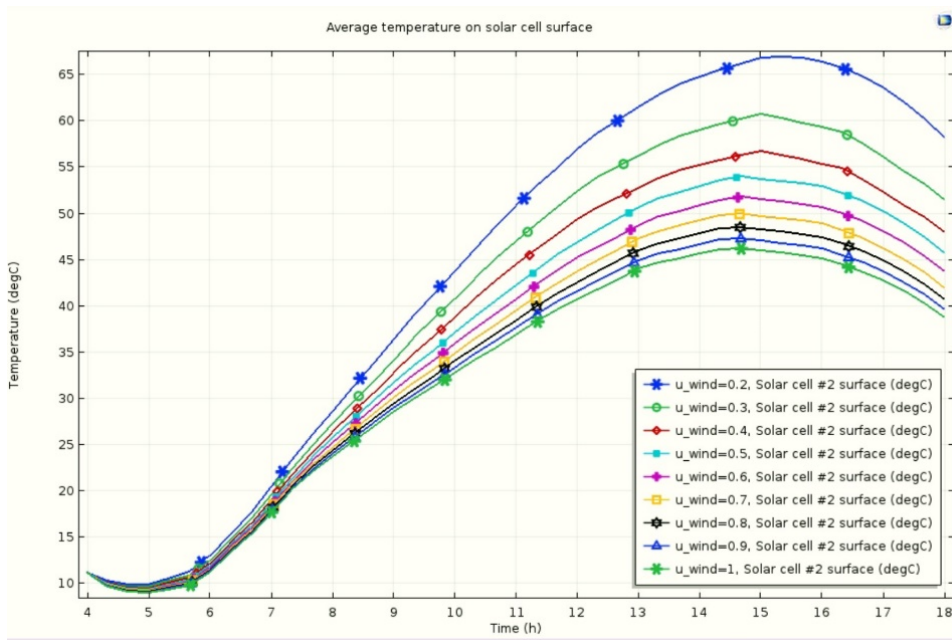


Figure 3.41. Wind speed influence on the solar cells temperature by preliminary scenario setup.

Considering experimental data, the most suitable wind velocity to be considered to ensure the consistence of the simulation scenario while solving the external convection is 0.5 m/s. For this specific purpose, the reference data set came from the uncovered CPC prototype experimental measurements.

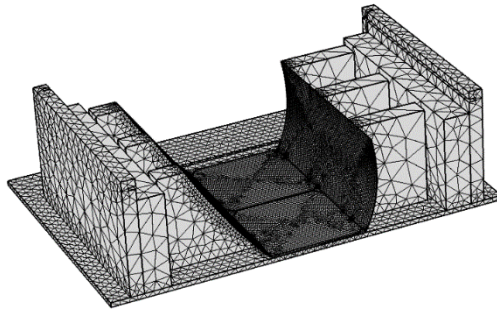
3.5.4 Mesh settings

The geometric domain discretization is one of the main issues to solve once simulating. The convergence of the FEM iterative solver should be deeply influenced by the number of elements used to mesh each volume, edge and boundary of the whole geometry. Hardware resources and time required by the scenario to compute a possible solution are strictly related to the resolution of the chosen mesh criteria. Every one of the CPC configurations (covered and uncovered) reported by Figure 3.34 have been submitted to the mesh generator, which was setup to apply high resolution meshing elements to the reflectors and the solar cells. Obviously, covers and the inner air volume have been also submitted to the mesh procedure for the covered CPC configuration. The relevant geometry gradients that could be identify in both parabolic reflectors and solar cells – due to the curvature radius and to the thin layer condition for the semiconductor layer, respectively – have to be taken into account to minimize the losses in terms of accuracy. The meshing procedure has to consider the following points:

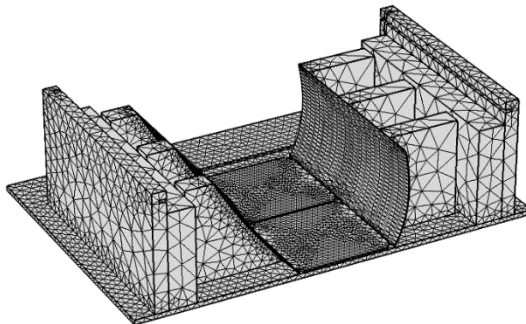
- each parabolic reflector is characterized by a different curvature radius, so they have to be meshed separately;
- solar cells exposed surfaces need a high-resolution mesh since a thin layer condition is applied to them because of the thermal resistance of 0.2 mm-thickness semiconductor (silicon-based) layer;
- the back-plate does not need a high-resolution mesh because of the imposed thermal insulation boundary condition at its bottom surface. Moreover, the heat transfer is mainly due to conduction, even if a part of convection is considered on the outside;
- the foam is meshed considering the thermal contact with the frame structure and the lower importance in terms of results resolution over its volume;
- side and upper covers are meshed considering the transparency condition by the radiation point of view, so no high-resolution mesh across the thickness is needed;
- the remaining components of the CPC system (see e.g. the frame structure and the reflector support) have been meshed with a physics-

induced sequence of elements, by implementing the built-in feature of COMSOL.

The setting-up procedure of the mesh generator has been checked step-by-step by ad-hoc implemented scenarios. Indeed, the element size has been submitted to a parametric sweep that highlighted the need of an increasing resolution of the mesh on certain narrow regions. Therefore, referring to the only uncovered CPC as a reference to discuss, some tests on the mesh influence on the numerical solution have been conducted: assuming the average temperature on solar cells as a reference validation parameter and two kind of suitable meshes for the computing purpose (refer to Figure 3.42), a sensitivity analysis is reported by Figure 3.43.



(a) High resolution mesh.



(b) Low resolution mesh.

Figure 3.42. Preliminary geometry domain discretization (mesh).

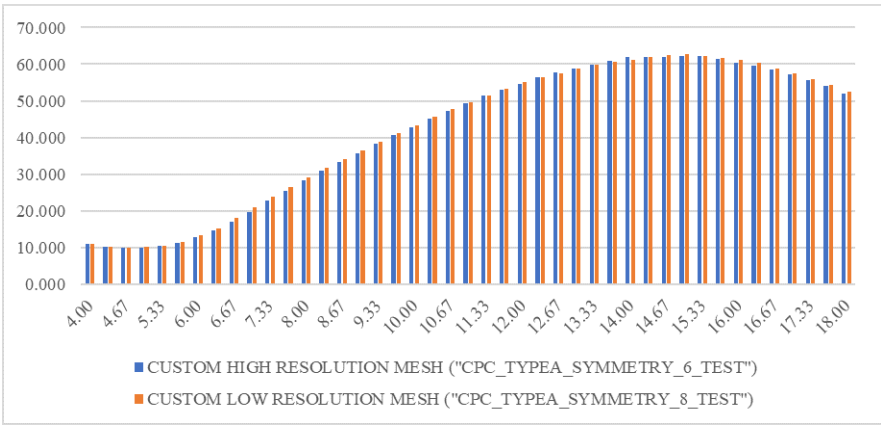


Figure 3.43. Sensitivity analysis applied to the mesh procedure (x axis: time in hours, y axis: computed temperature in Celsius).

Referring to the implemented scenario, the characteristics for each kind of mesh, that is the one with a major number of elements (high-resolution mesh, available in Figure 3.42(a)) and the one characterized by a smaller number of elements (low-resolution mesh, available in Figure 3.42(b)) are given by Table 3.11.

	High-resolution	Low-resolution
Mesh vertices	18581	9151
Tetrahedral elements	68335	31887
Triangular elements	35279	17721
Edge elements	2751	2234
Vertex elements	198	198
Estimated required RAM	80 GB (approx)	17 GB (approx)

Table 3.11. Mesh characteristics for both high-resolution and low-resolution geometrical domains discretization.

As reported by Figure 3.44, the iterative procedure once related to the mesh constitution requires that the number of elements no longer affects the final solution, reaching a certain asymptotic trend.

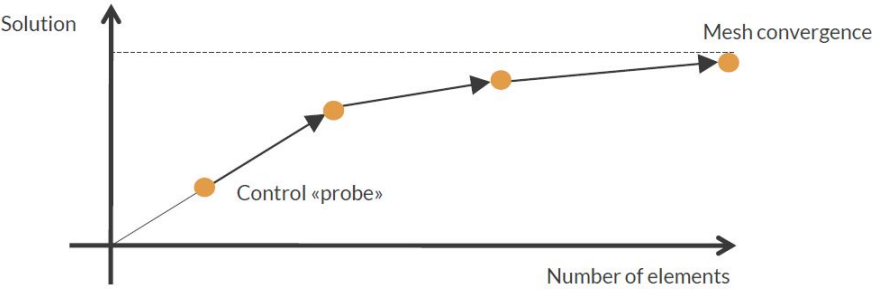


Figure 3.44. Generic mesh refinement concept in terms of solution-based mesh convergence [53].

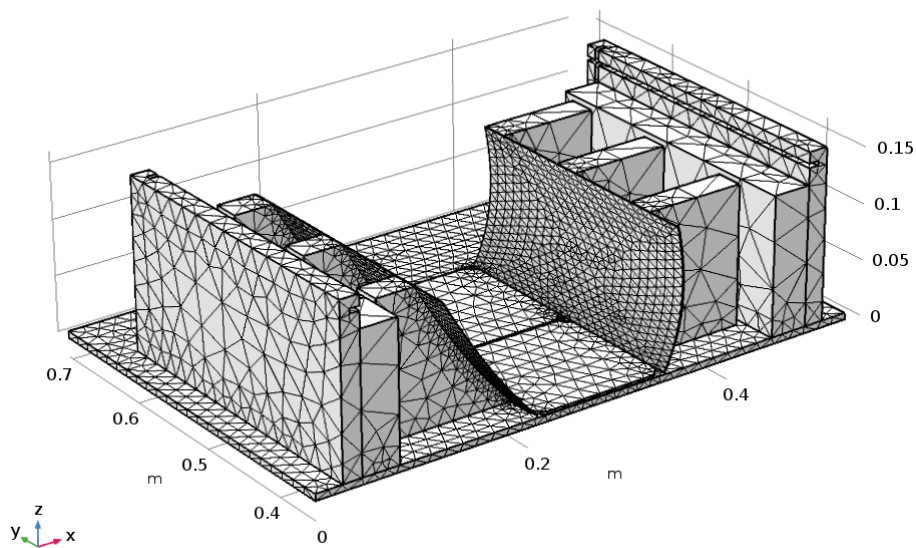
Working on the mesh refinement, following the indications from the preliminary simulations and from [58], the discretization shown in Figg. 3.45(a) and 3.45(b) has been adopted for the uncovered and covered CPC, respectively. Due to the presence of an air volume for the covered configuration, some additional details for the interior elements mesh are given by Figure 3.46. Details about the implemented mesh characteristics for both CPC configurations are listed in Table 3.12. Referring to the mean skewness value of the whole geometry model, which is defined as the difference between the shape of the cell and the shape of an equilateral cell of equivalent volume, it is possible to consider ranges as reported by Table 3.13. Meshing procedure as previously discussed led to a 0.46 and 0.44 mean skewness values for the covered and uncovered configuration of CPC, respectively. It allows to assert how the mesh should be considered as very good.

	Uncovered CPC	Covered CPC
Mesh vertices	7517	11630
Tetrahedral elements	25949	59194
Triangular elements	14787	19226
Edge elements	1889	2123
Vertex elements	198	198
Estimated required RAM	11 GB (approx)	13 GB (approx)

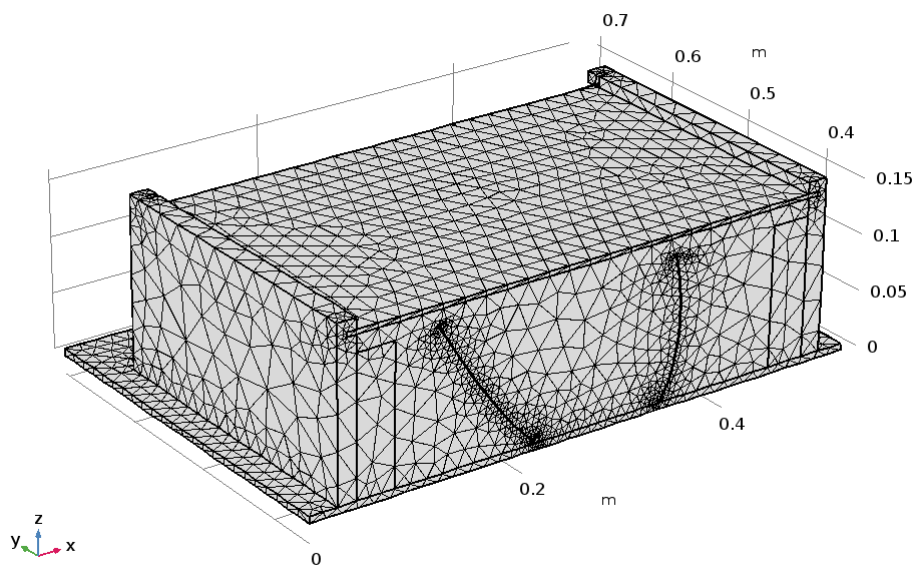
Table 3.12. Final mesh characteristics for both CPC configurations.

Skewness value	Mesh evaluation
$0 \div 0.25$	Excellent
$0.25 \div 0.50$	Very good
$0.50 \div 0.80$	Good
$0.80 \div 0.95$	Acceptable
$0.95 \div 0.97$	Bad
$0.98 \div 1.00$	Unacceptable

Table 3.13. Reference skewness mean value for geometrical volumes meshing.

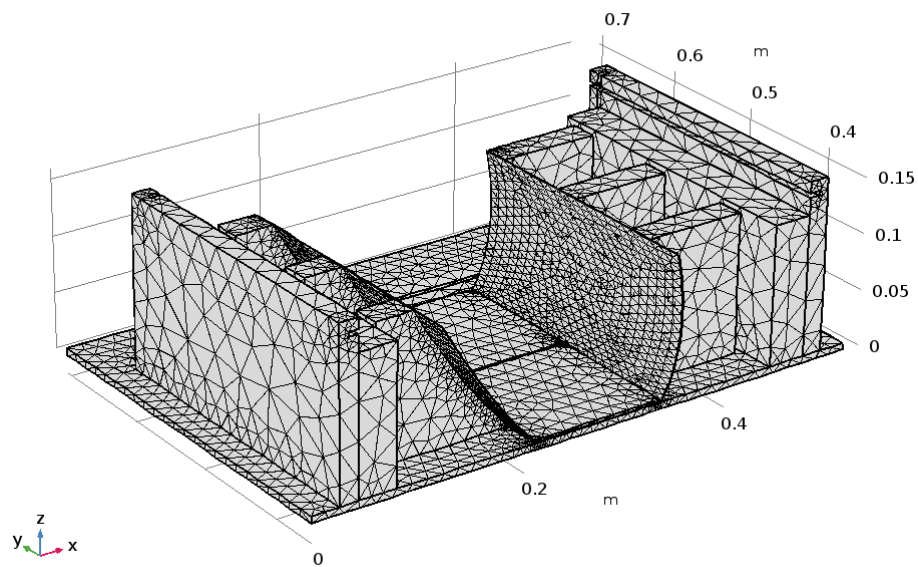


(a) Covered CPC.

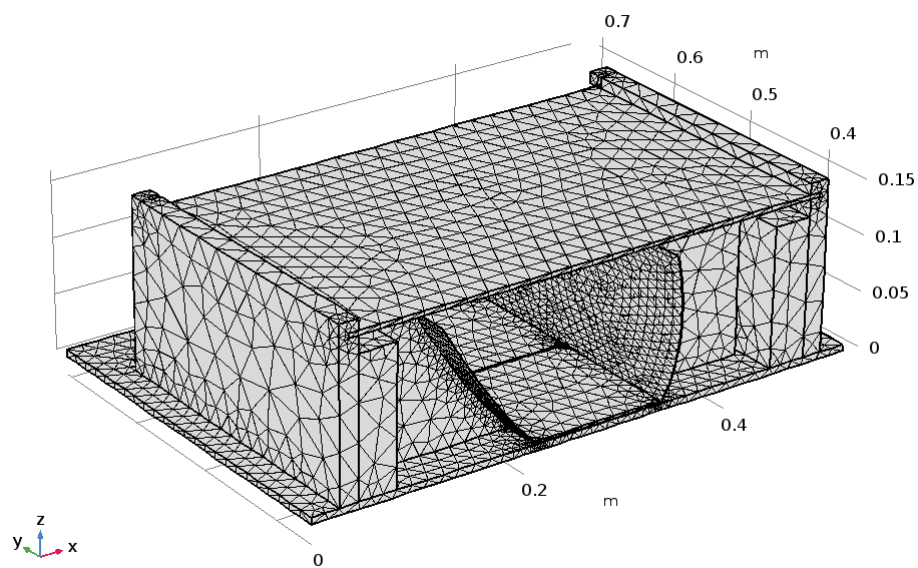


(b) Uncovered CPC.

Figure 3.45. Final geometry domain discretization (mesh).



(a)



(b)

Figure 3.46. Details of the final mesh adopted for the covered configuration of the model.

3.5.5 Study settings

To reduce the risk of non-convergence, a stationary study is passed as initial condition to the time-dependent study. This helps the simulation once the initial conditions are difficult to be identified on the whole domain. The time-steps are also chosen to allow a suitable time-related resolution (or time sampling) of the transient numerical solver. Increasing the time stepping could result in a reduced accuracy, leading to a non-consistency of the simulation scenario.

3.5.6 Results and discussion

The simulation scenario computation leads to the definition of the temperature field within the CPC prototype, once daily environmental conditions are influencing the thermal response of the system. As previously discussed, the whole implementation aims to replicate the real conditions the CPC prototype of the experimental campaign was submitted to. Obviously, some assumptions need to be made once in order to simplify the setting-up of the numerical approach.

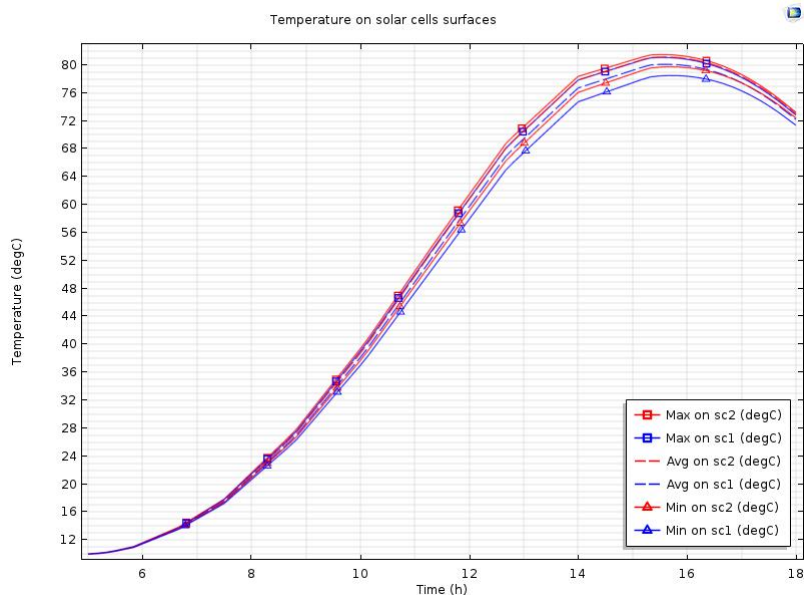
The following discussion refers to the results from the numerical approach, validating each of them with data from experimental campaigns (if available).

Thermal field determination

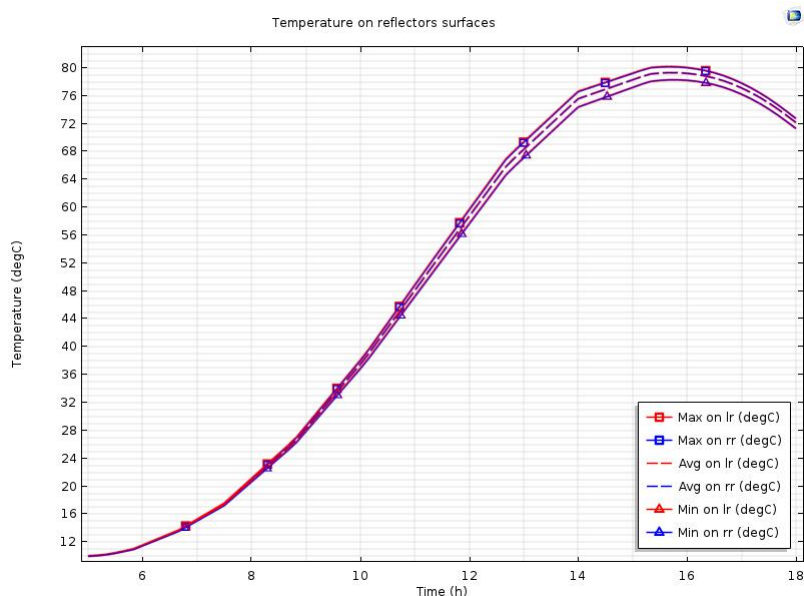
Due to the complexity of the geometry, the visualization of data resulting from numerical simulation computing is provided as:

- time-dependent trends of maximum, minimum and average temperature value on solar cells surfaces;
- surface plots of temperature distribution all over the geometry entities at fixed time steps;
- instantaneous focus on temperature distribution all over the solar cells and reflectors surfaces to identify the hot-spot exact location, being the critical components of the CPC by a thermal point of view;
- cut-plane views at different coordinates to visualize the temperature distribution within solid and fluid domains.

Covered CPC configuration. The solving procedure led to the thermal field determination within the CPC prototype. As previously discussed, the most critical parts in terms of influence on the whole system efficiency are the reflectors and the solar cells. Acting external conditions are those exposed by subsection 3.4.2 and subsection 3.5.3, obviously referring to the only covered CPC configuration (experimental campaign of July 17, 2017). Due to that, the temperature trend on both components' surfaces are reported by Figure 3.47. Since the symmetry approach is implemented, only the results for solar cells #1 (SC1) and #2 (SC2) are reported.



(a) Solar cells

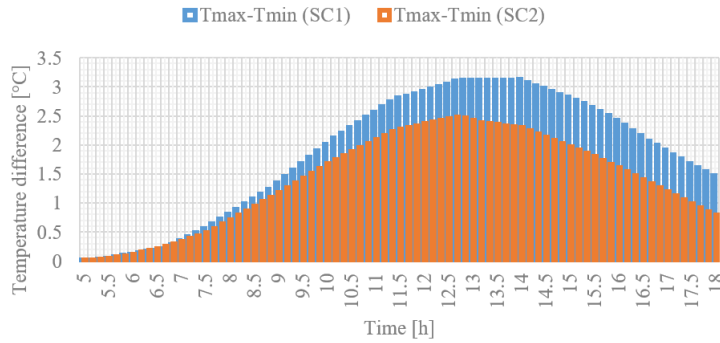


(b) Reflectors

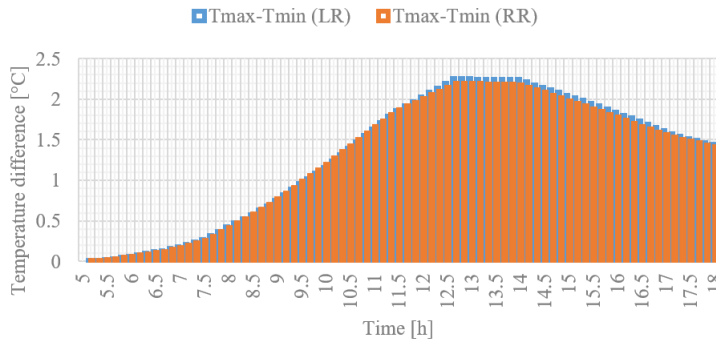
Figure 3.47. Temperature trends on the critical components surfaces over the day (covered CPC).

The preliminary analysis of trends in Figure 3.47 highlights a notice-

ably small difference between each one of the curves. Indeed, the maximum, the average and the minimum temperature on the solar cells surfaces could be considered as overlapped by an engineering point of view. The goal to achieve by means of the simulation campaign is the identification of a suitable strategy to characterize the thermal response of the system. To reduce the number of variables to consider and therefore to reduce the complexity of the post-processing analysis, only one representative temperature value is chosen. To do that, a graphic approach as the one given by Figure 3.48 is used to visualize the difference between maximum and minimum temperature values over the simulated time frame.



(a) Solar cells



(b) Reflectors

Figure 3.48. Difference between maximum and minimum temperature values on the critical components surfaces over the day (covered CPC).

The higher discrepancy between maximum and minimum surface temperature on the critical components is:

- less than 3.1°C and 2.6°C for SC1 and SC2, respectively;
- less than 2.3°C for both reflectors.

It follows that the average surface temperature of any critical component (SC1, SC2, LR and RR) is a convenient choice while assuming a components reference temperature for further analysis implementation.

Considering the average surface temperature on each of the critical components to uniquely identify their thermal response is a suitable choice once the degrees of freedom (and so on the complexity) while developing the post-processing analysis have to be reduced⁶.

Then, transient scenario results are plotted at different time steps, considering 1-hour-long sampling from hour 10:00 up to hour 15:00. The temperature distribution all over the covered CPC configuration external surfaces is reported by Figure 3.49. It is important to notice how the resulting data-set from the scenario solving (i.e. the temperature field) is mirrored by a specific built-in feature of CM software. In fact, it allows to visualize the whole domain even if only a part has been simulated.

The presence of covers prevents the display of the temperature distribution inside the assembly, reason why multiple cut-plane views for each one of the planes (see e.g. Figure 3.50, Figure 3.51 and Figure 3.52) have been applied to the computed domain.

⁶By that, the solar cell electrical performance analysis is discussed considering the only average temperature.

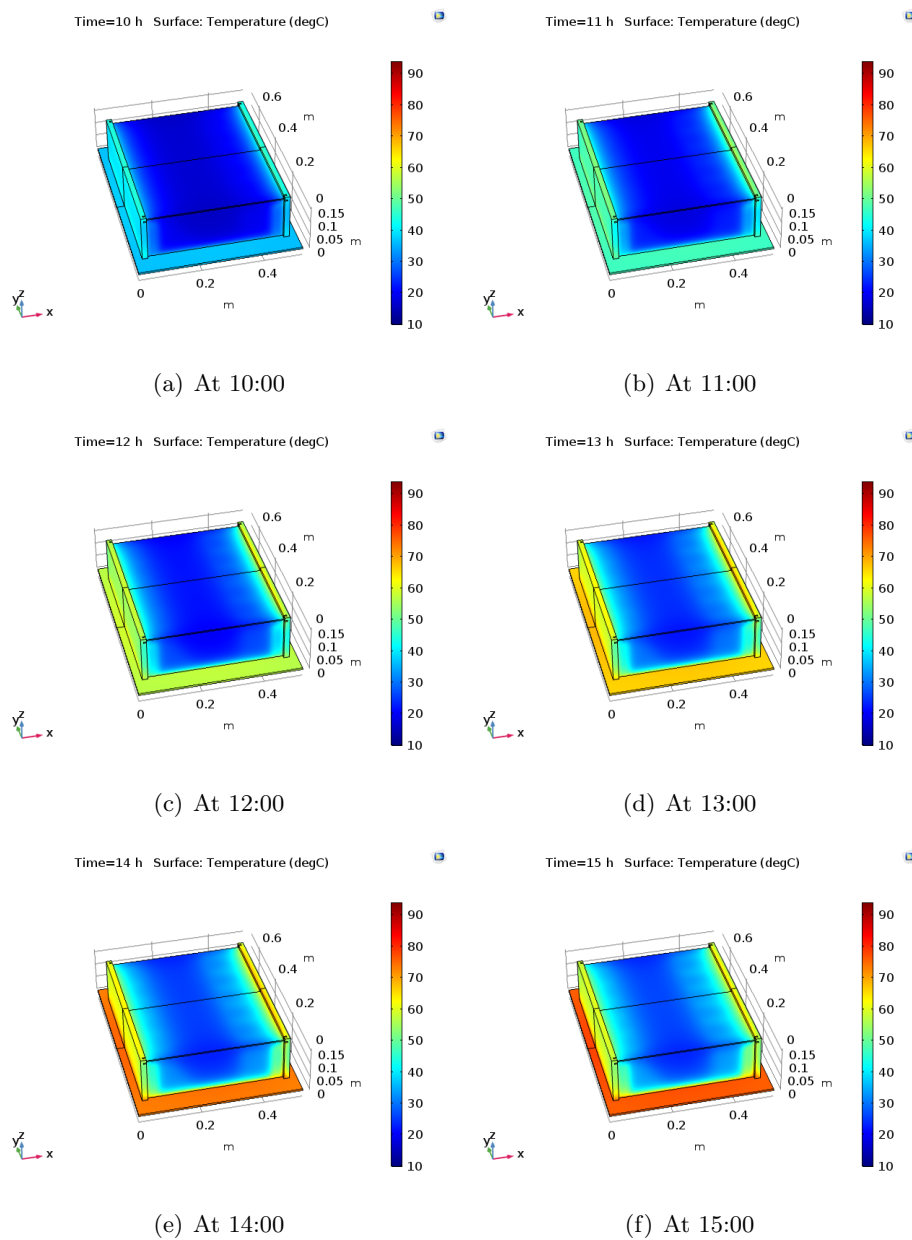


Figure 3.49. Temperature distribution on the external surfaces of the assembly over the day (covered CPC).

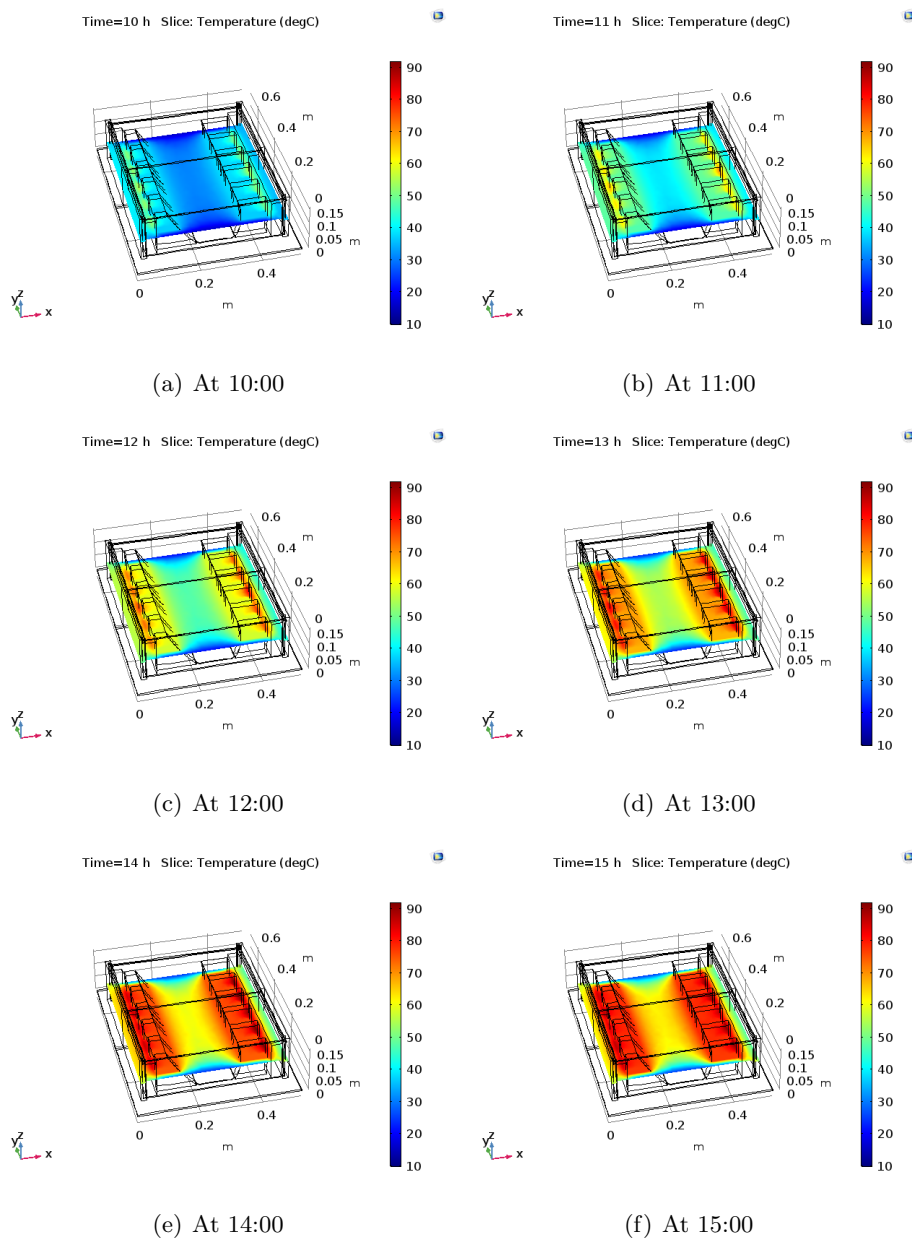


Figure 3.50. Temperature distribution over the day once multiple XY-cut-planes have been applied (covered CPC).

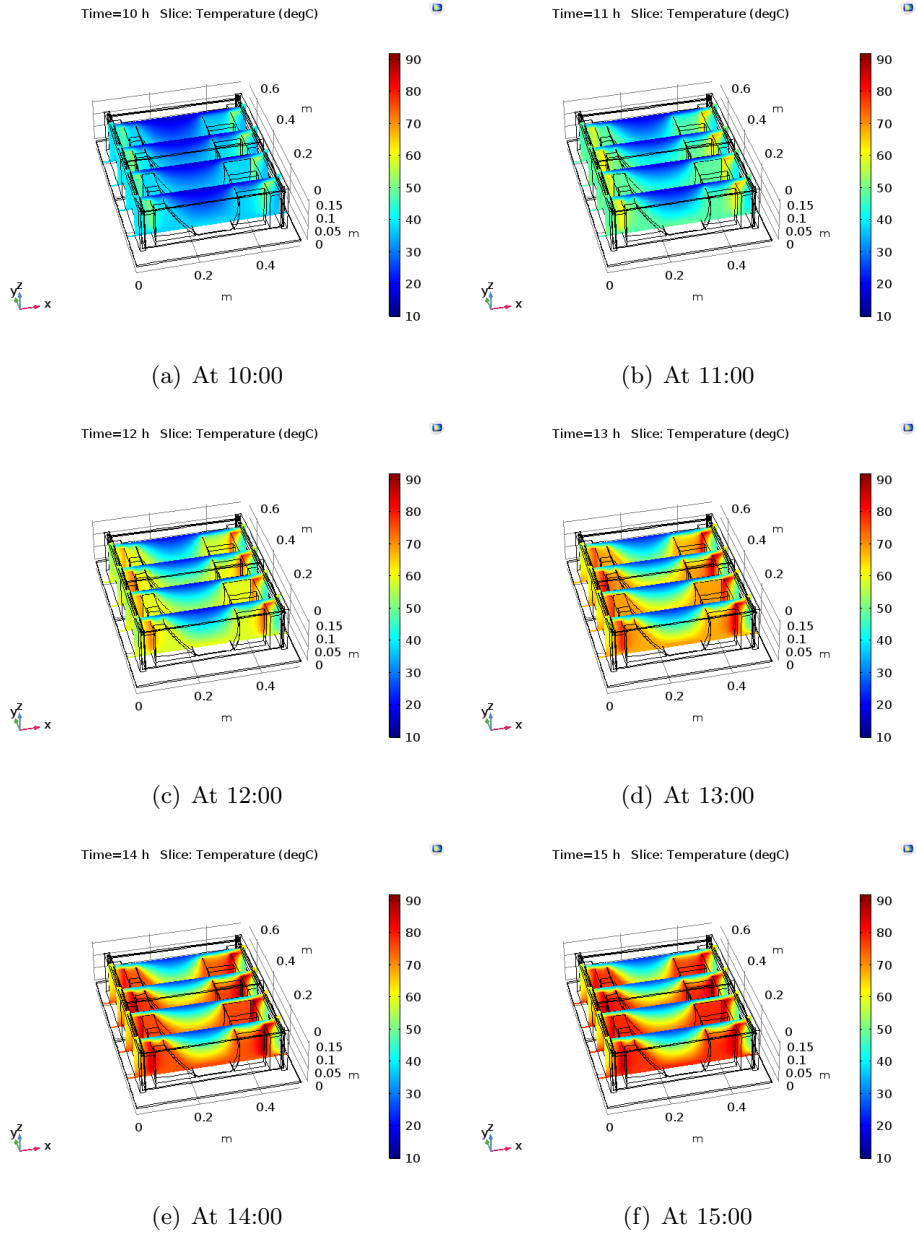


Figure 3.51. Temperature distribution over the day once multiple XZ-cut-planes have been applied (covered CPC).

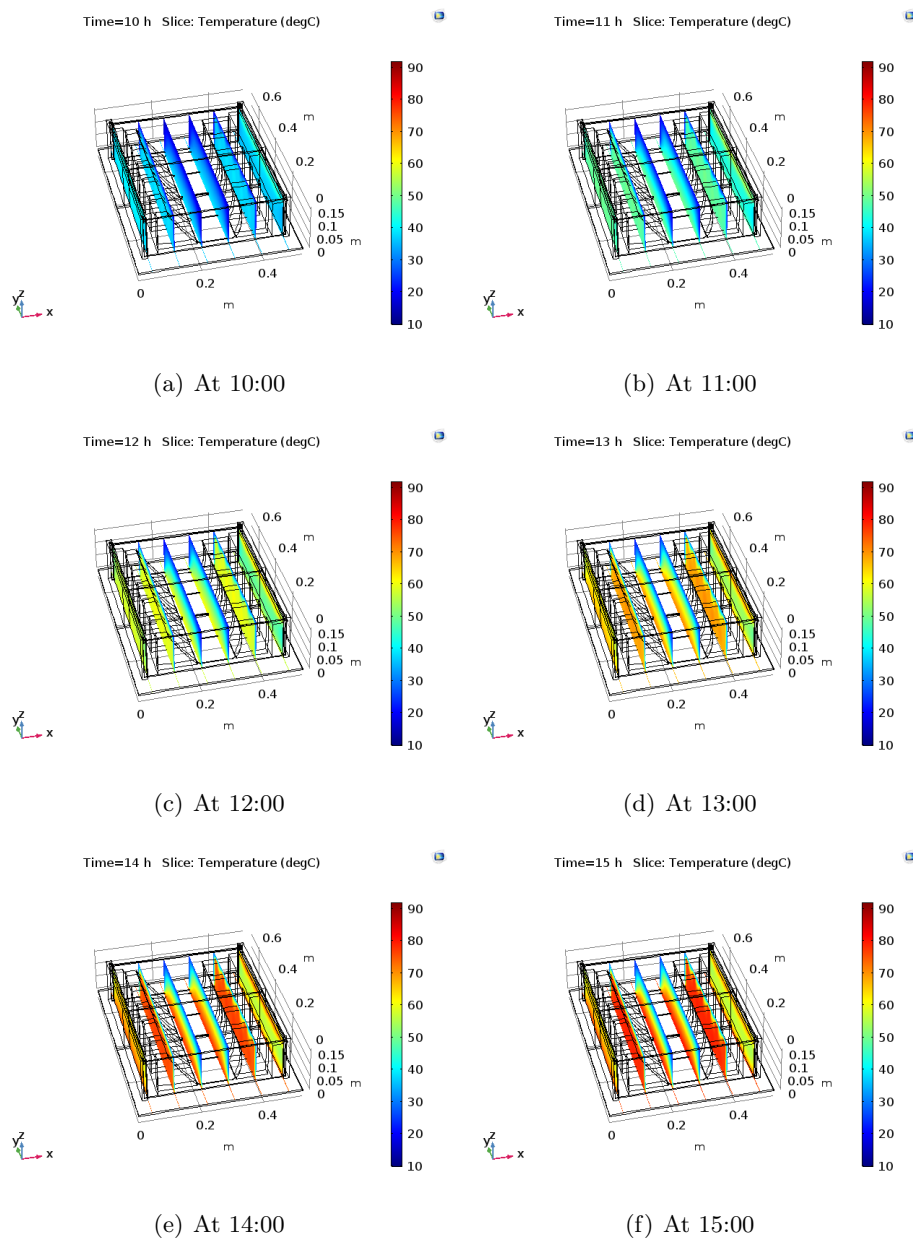


Figure 3.52. Temperature distribution over the day once multiple YZ-cut-planes have been applied (covered CPC).

The heating process of each one of the inner components is then visible. The higher temperature is reached by the zone between the reflectors supports and the foam. This is due to high radiation reflection rate because of the low emissivity (which corresponds to high reflectivity) of the aluminum sheet reflectors supports are made of. So, the radiation is made incident on the inner foam surface, which traps the heat energy becoming a sort of additional heat source within the assembly (when high temperatures are reached). At the same time, the inner air domain increasing temperature is prominent while it remains trapped by the side and upper covers.

Focusing on the critical components, the colored plot scale of Figure 3.53 has been fixed to better appreciate the variation in critical components temperatures during the day. However, a non-fixed scale plot is reported by Figure 3.54 to visualize the temperature hot-spot zone mostly due to the reflection of both LR and RR. For each one of the temperature surface plots both air domain and covers are hidden.

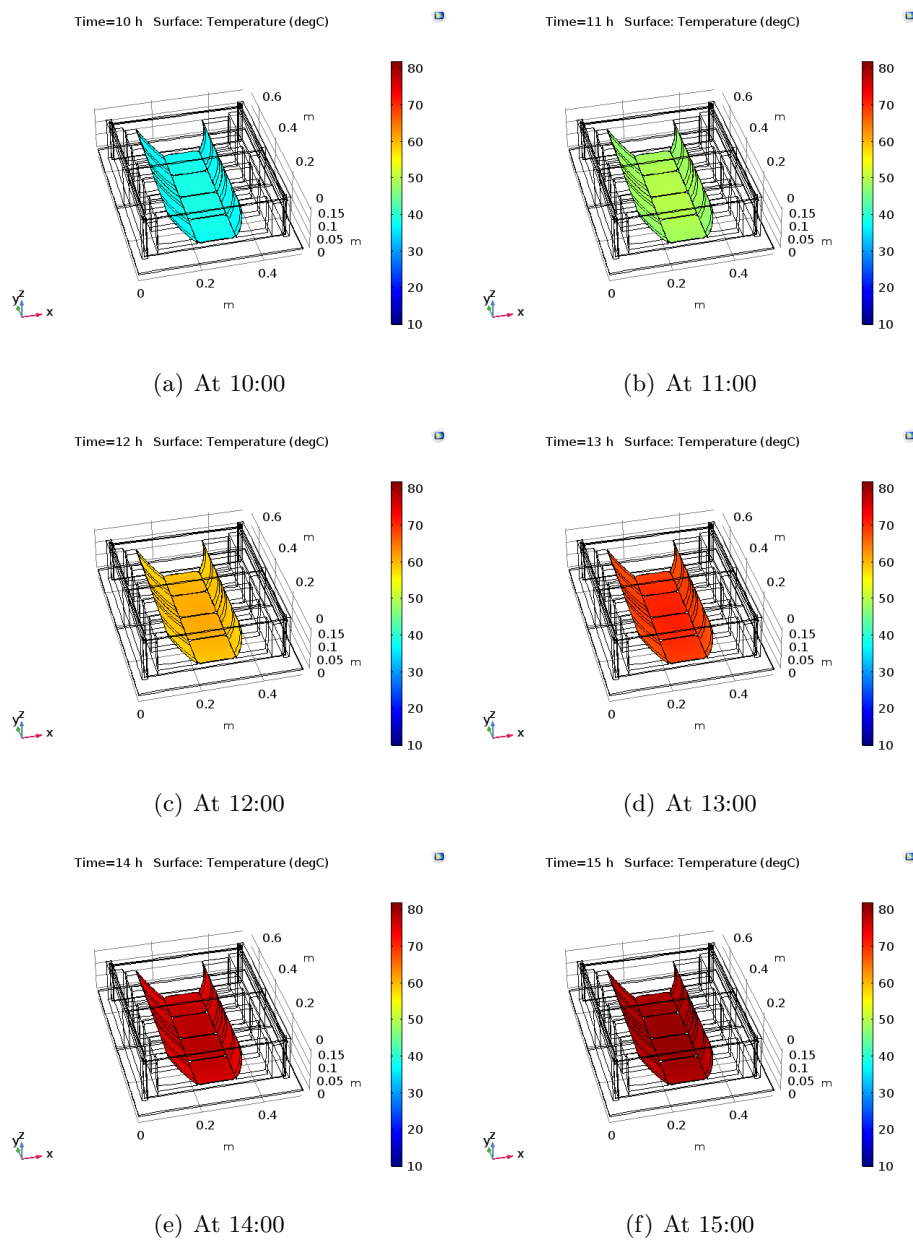


Figure 3.53. Solar cells and reflectors surfaces temperature over the day (covered CPC).

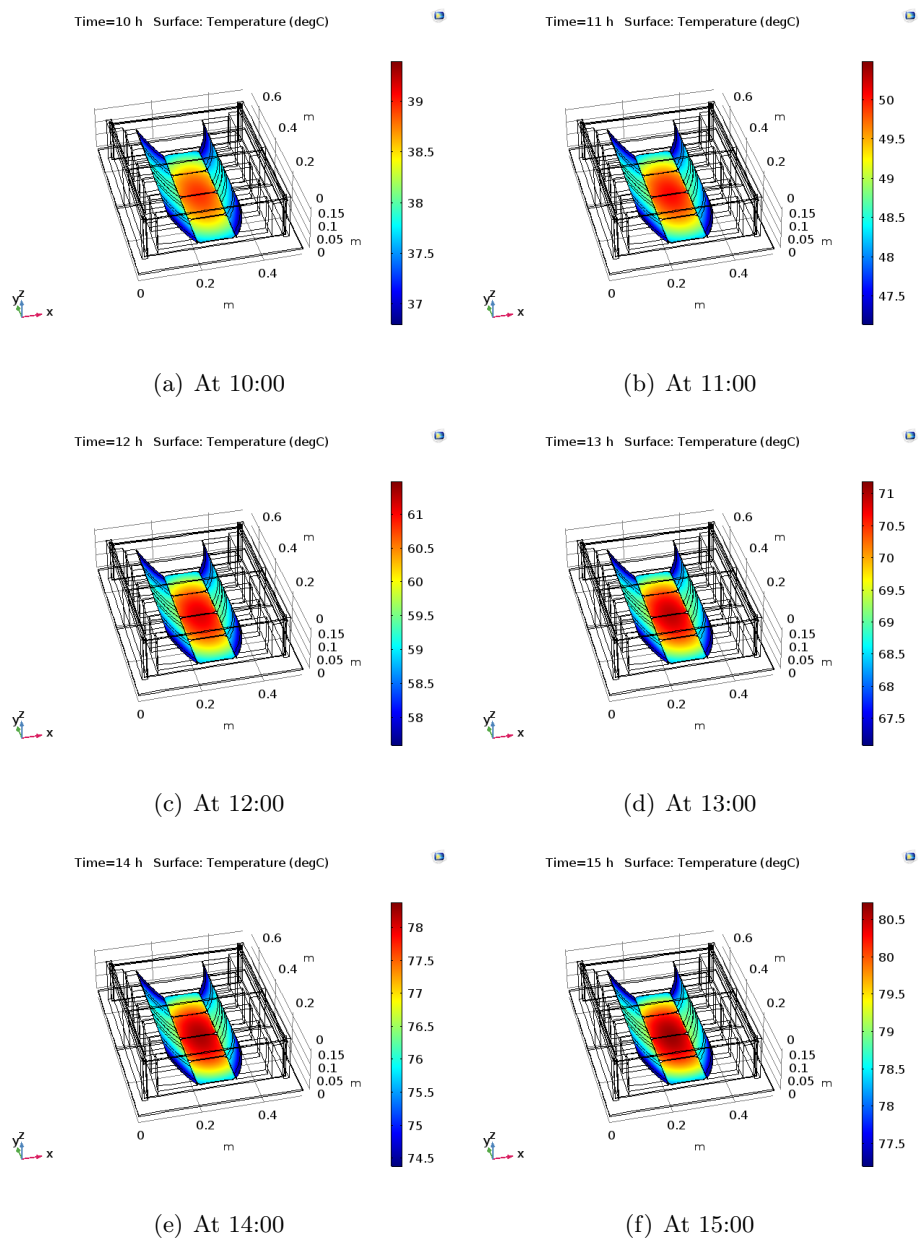
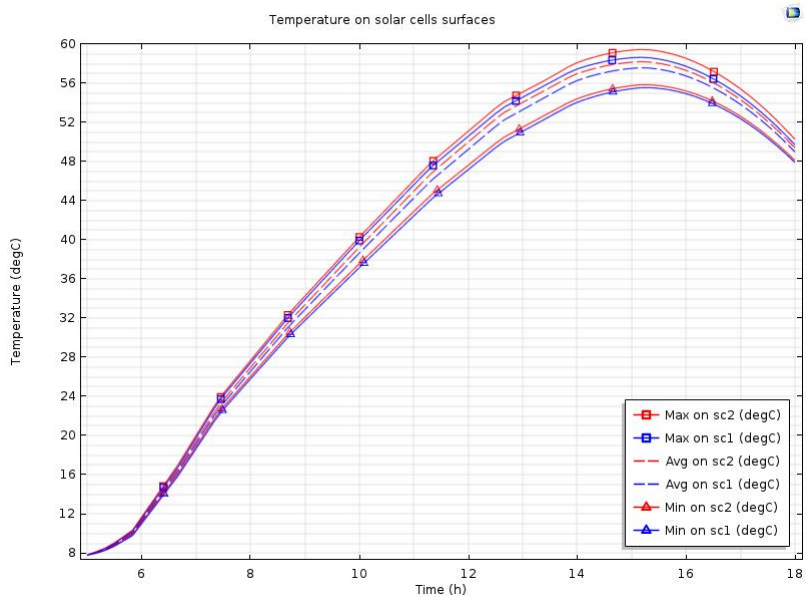
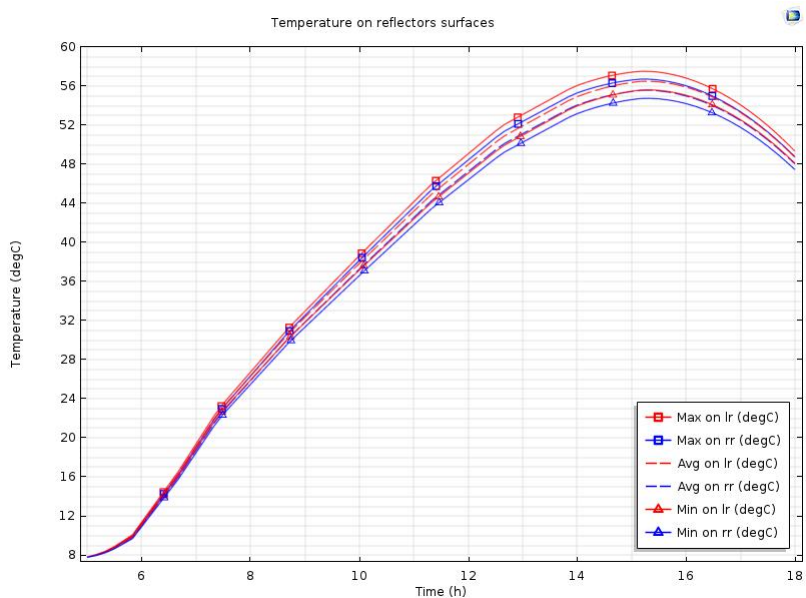


Figure 3.54. Hot-spot zone on the solar cell surfaces due to the reflectors action (covered CPC).

Uncovered CPC configuration. Similarly to what is provided for the covered configuration of the CPC, the results relating to the temperature field and distribution for the uncovered configuration are shown below. Initialized external conditions are those exposed by subsection 3.4.2 and subsection 3.5.3, obviously referring to the only uncovered CPC configuration (experimental campaign of July 18, 2017). The inner air domain is not initialized since no cover is installed (so no fluid remains trapped). Following the indications by the experimental campaign setup, no foam is provided for the uncovered CPC. As already done before, SC1 and SC2 surfaces temperature trends are plotted, considering the symmetry approach. The resulting data-set of temperature values all over the computational domain is then mirrored to allow the complete visualization of the geometry model for the temperature surface plots. As for the covered configuration, the solar cells surfaces temperature trend over the day for uncovered CPC scenario highlights the almost overlapping trends. In particular, the difference between minimum and maximum temperature values on each one of the solar cells and reflectors surfaces is graphically reported by Figure 3.56. The peak discrepancy between the maximum and minimum temperature on solar cells and reflector surfaces is equal to 3.6°C and 2.2°C , respectively. By an engineering point of view, as noticed for the covered configuration, it is possible to assert that the average value of surface temperature could be assumed to be the representative parameter to define the single component-related temperature field. The whole temperature distribution on components surfaces are reported by Figure 3.57 for the uncovered CPC. Referring to the critical components of the CPC, i.e. reflectors and solar cells, a focus on their surfaces related temperature field is given by Figure 3.58. The color legend has been fixed to appreciate the temperature distribution globally all over the day. However, the hot-spot should be identified by an instantaneous plotting of the temperature field all over the solar cells and reflector surfaces, as by Figure 3.59. This kind of visualization should be very useful while analyzing the thermal consequences of the reflectors action on the solar cells radiation-exposed surfaces.

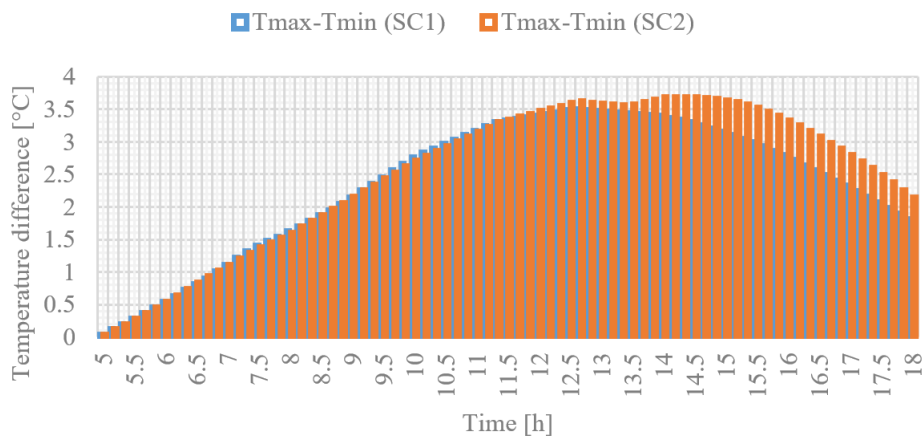


(a) Solar cells

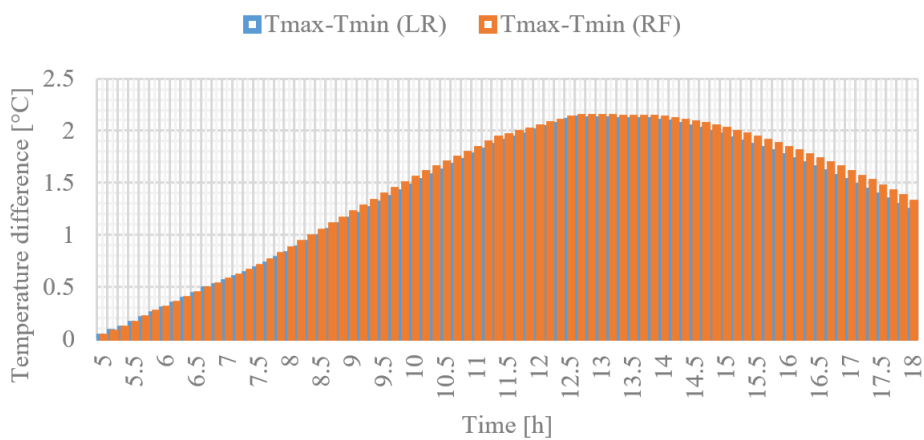


(b) Reflectors

Figure 3.55. Temperature trends on the critical components surfaces over the day (uncovered CPC).



(a) Solar cells



(b) Reflectors

Figure 3.56. Difference between maximum and minimum temperature values on the critical components surfaces over the day (uncovered CPC).

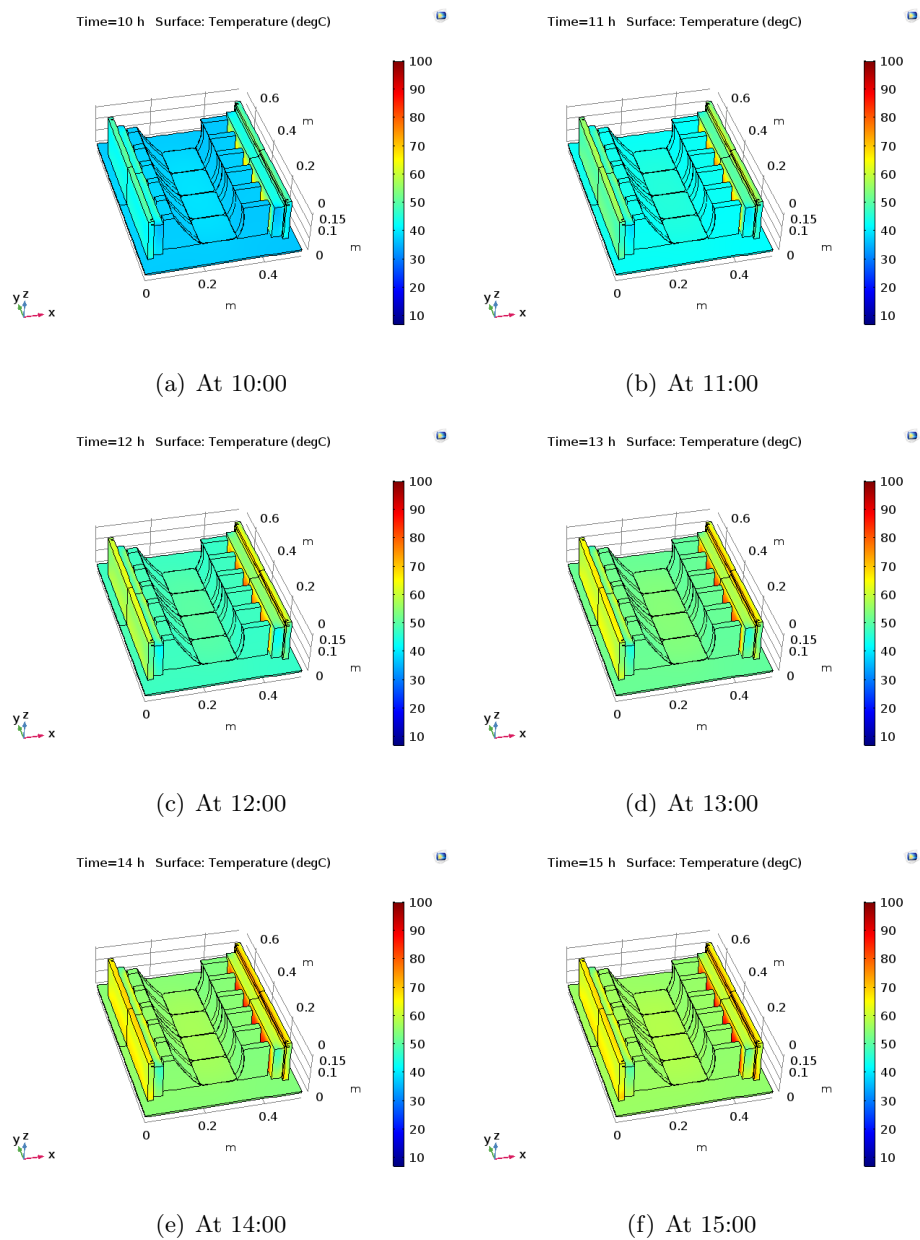


Figure 3.57. Temperature distribution on the external surfaces of the assembly over the day (uncovered CPC).

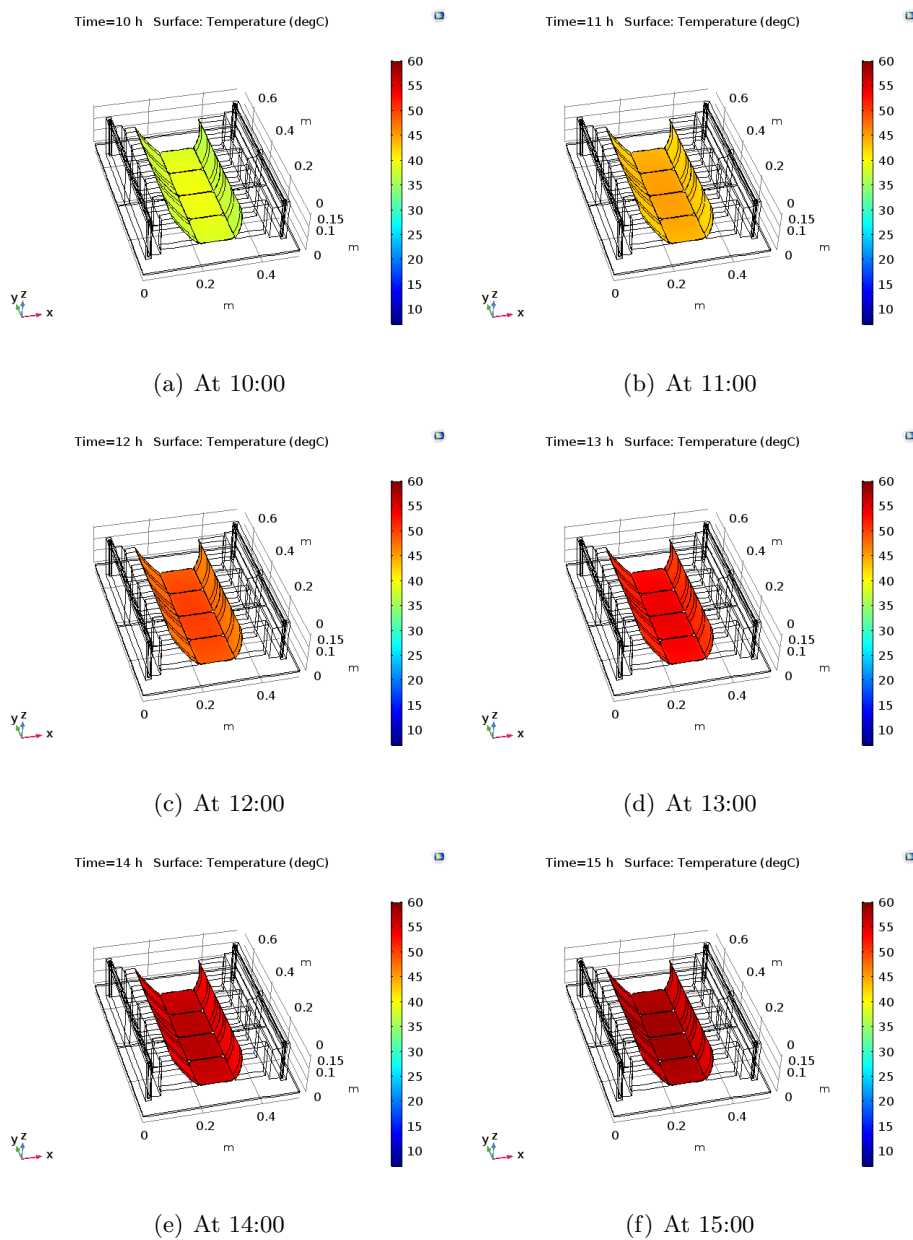


Figure 3.58. Solar cells and reflectors surfaces temperature over the day (uncovered CPC).

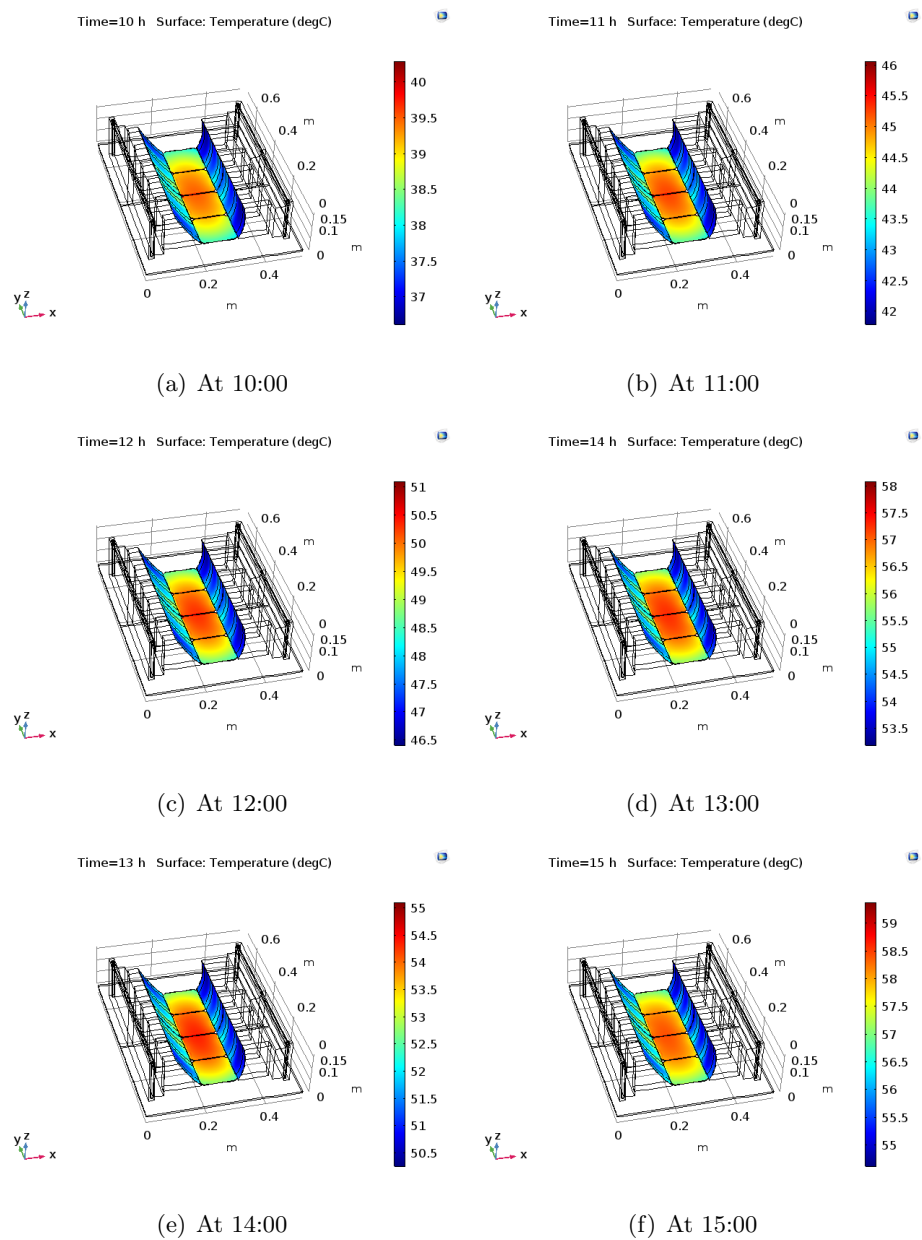


Figure 3.59. Hot-spot zone on the solar cell surfaces due to the reflectors action (uncovered CPC).

Post-processing analysis: efficiency and power

The post-processing analysis of computed data is conducted once temperature distribution across the whole geometry has been solved, for both covered and uncovered configurations. The efficiency of solar cells depends strictly on the temperature, reason why the simulation campaign plan aims also to define the $\eta_{sc}(T_{sc}, Q_{irr})$ distribution. However, the peak temperature is chosen as the reference temperature once computing the solar cells efficiency trend. The radiative total heat flux through the solar cells is also used to obtain the efficiency of the whole system. Correlations between temperature, passing-through radiative heat flux and efficiency is provided by experimental equations as discussed by authors in [59–61]:

$$\eta(T_{sc}, Q_{irr}) = \eta_{ref} \cdot [1 - \beta(T_{sc}(t) - T_{ref}) + \gamma \log_{10} Q_{irr}(t)] \quad (3.29)$$

Values for reference efficiency ($\eta_{ref} = \eta(T_{ref})$), temperature coefficient (β) and solar radiation coefficient (γ) are taken by literature, being equal to 17.5%, $4.5 \cdot 10^{-3} \text{ K}^{-1}$ and 0.12, respectively. Due to the implemented symmetry approach, the temperature distribution is given for solar cells #1 and #2 only. However, in accordance with the simulation campaign plan, the only solar cell #2 is considered since it is focused on the peak values⁷. The same assumption is made for the efficiency distribution computation. The sampling frequency is set to visualize results every hour; the studied time frame goes from 10:00 to 15:00, because of the higher relevance of the solar irradiance than the one of the very first hours of the day. The final goal is to define the obtainable electric energy production by the most suitable configuration (covered or uncovered). An equation has been deduced by experimental data about power once referred to the CPC prototype: the efficiency is directly proportional to the power multiplied by a constant value, determinable as discussed in [46], experimentally. Then, for this specific purpose, the following correlation should be considered:

$$\eta_{sys} = 0.02055 \frac{1}{W} \cdot P \quad (3.30)$$

where P is the power of the solar cell. Further details are discussed next.

Covered configuration. The efficiency of each solar cell is computed by means of Equation 3.29. This operation leads to the efficiency trends

⁷The peak value of temperature on solar cells surfaces is reached on the solar cell #2 (and so also on the solar cell #3 following the symmetric approach).

as exposed by Figure 3.60. SC2 is chosen as a reference while conducting post-processing analysis, due to the fact that critical factor acts much on SC2 surface (lower temperatures are reached on SC1 than SC2, so the research team preferred to investigate the thermal response of the critical components of CPC system while heavy-duty operating conditions are reached). Moreover, efficiency trends are almost overlapped so that an unique curve is assumed to be consistent for the analysis purposes by an engineering point of view.

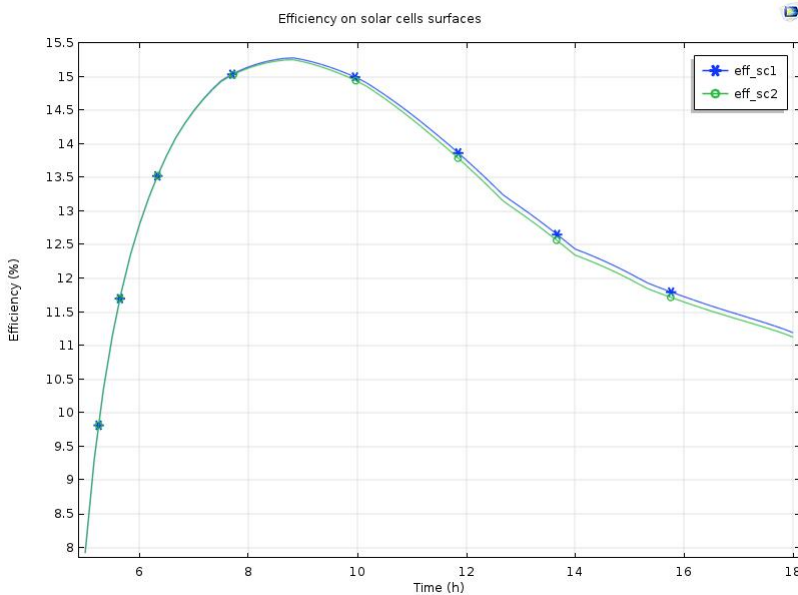


Figure 3.60. Efficiency of solar cells for simulated conditions (covered configuration - July 17, 2017).

Following the previous assumptions, the temperature distribution is passed through Equation 3.29 to define the efficiency trend while both temperature and incident solar radiation change. A 3D surface plot is then obtained by importing CM data into MATLAB, as shown by Figure 3.61.

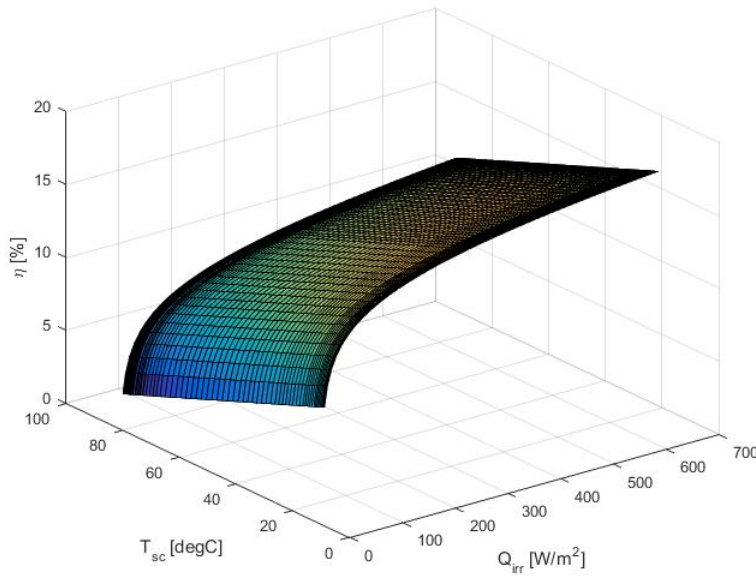


Figure 3.61. Influence of temperature and incoming solar radiation on SC2 efficiency (value range limits are taken by covered CPC scenario).

Axis of the graph in Figure 3.61 reports the temperature, the solar irradiance (both diffuse and direct components) and the efficiency of SC2. The simulated conditions lead to the efficiency on SC2 as given by Figure 3.60. This visualization should be very useful to identify the peak of each solar cell efficiency in typical operating conditions. A further analysis is related to the radiative heat flux through SC2. The surface integration CM's feature is initialized to obtain an average value of the heat flux through the semiconducting layer, influencing the photo-generation of free charge carriers within the P-N junction. The total power is computed and reported by Figure 3.62. As observed by experimental data, the graphical report of the correlation between whole CPC efficiency and measured power (i.e. Equation 3.30) lead to the curve by Figure 3.63.

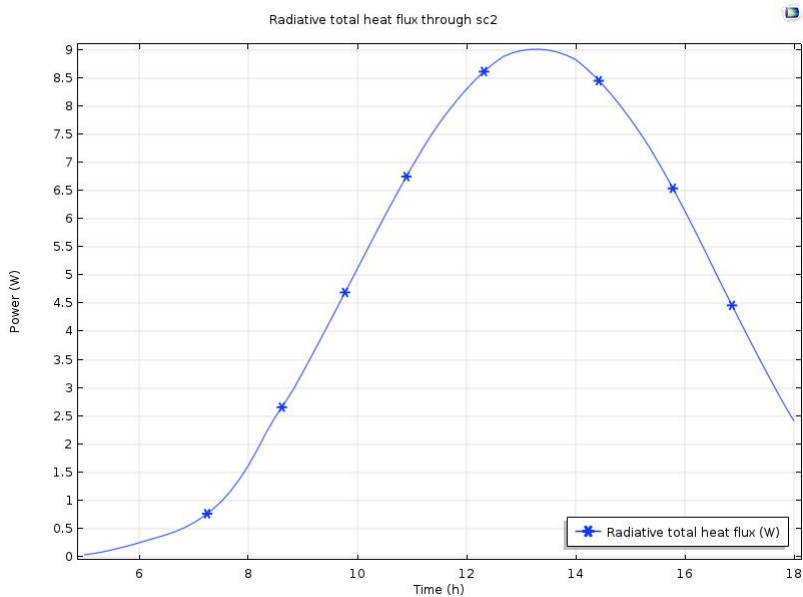


Figure 3.62. Radiative heat flux through SC2 for simulated conditions (covered configuration - July 17, 2017).

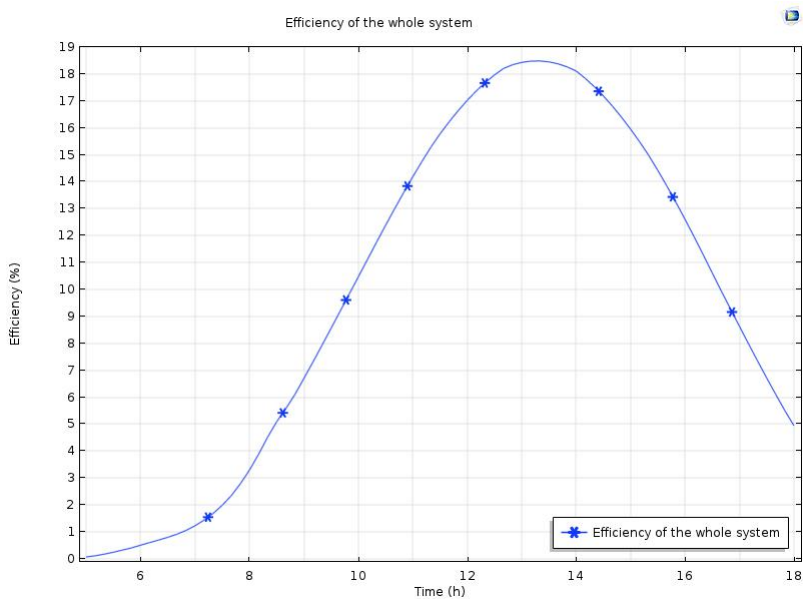


Figure 3.63. Efficiency of whole CPC system for simulated conditions (covered configuration - July 17, 2017).

Peaks are reached in correspondence of the higher incoming solar radiation, around hour 13:00. A comparison between the solar cells efficiency trend (Figure 3.60) and the one of the whole CPC system (Figure 3.63) highlights that even respective peaks do not correspond, the CPC system guarantees the best performance when the higher incident and reflected radiation is provided. It confirms the non-overlapping of trends. However, in case of a lower temperature on SC surface during the day could provoke an increase of the CPC system efficiency.

Uncovered configuration. The previous kind of approach is applied also to the uncovered CPC configuration. In this case, the efficiency of each solar cell is given by Figure 3.64. The influence of both incoming radiation and surface temperature on SC2 (reference solar cell) is reported by Figure 3.65. The total power, that is the total heat flux passing through the SC2 surface multiplied by the solar cell area in square meters, is visualized by Figure 3.66. Equation 3.30 application leads to the whole uncovered CPC system efficiency trend in Figure 3.67.

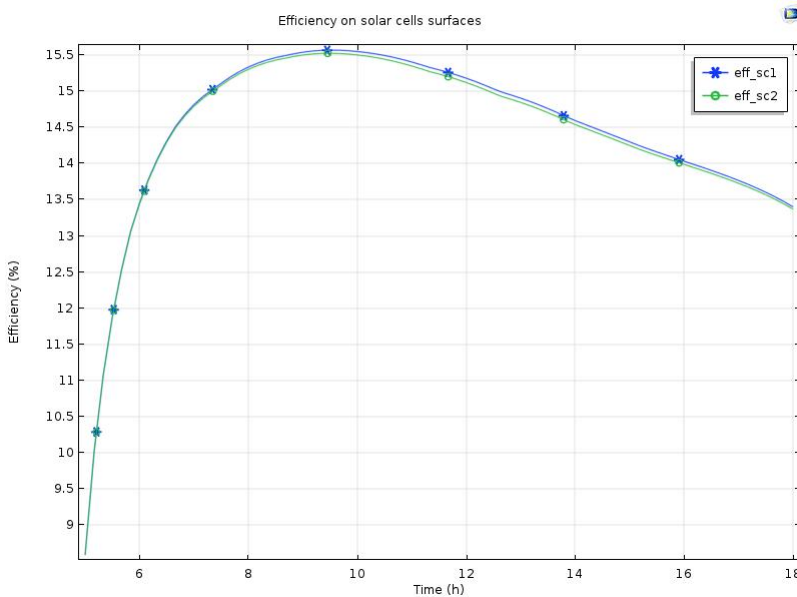


Figure 3.64. Efficiency of solar cells for simulated conditions (uncovered configuration - July 18, 2017).

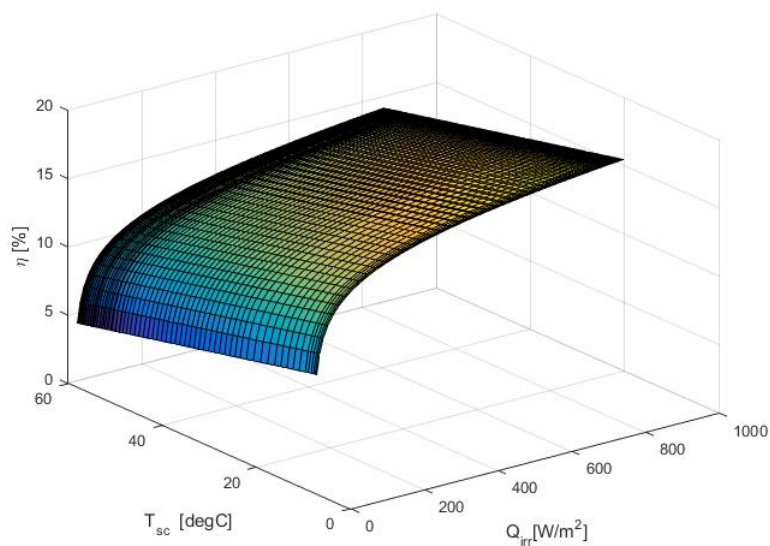


Figure 3.65. Influence of temperature and incoming solar radiation on SC2 efficiency (value range limits are taken by uncovered CPC scenario).

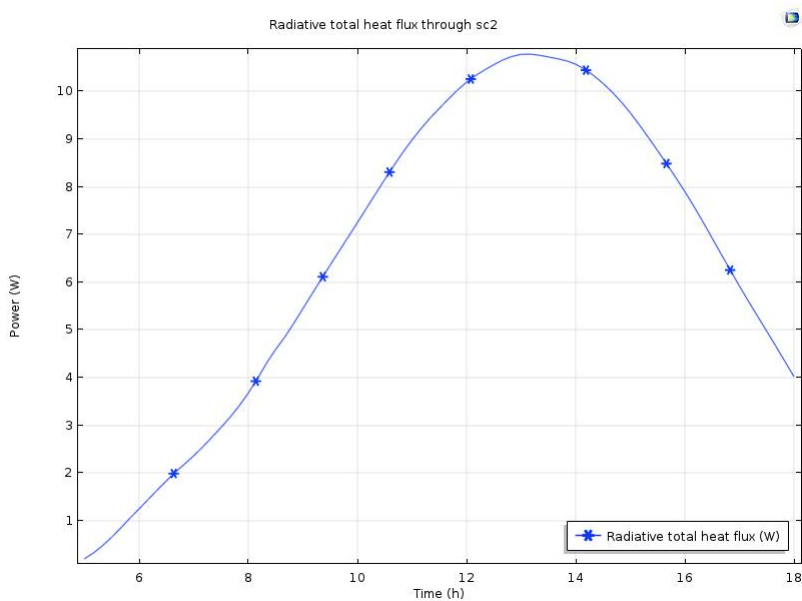


Figure 3.66. Radiative heat flux through SC2 for simulated conditions (covered configuration - July 18, 2017).

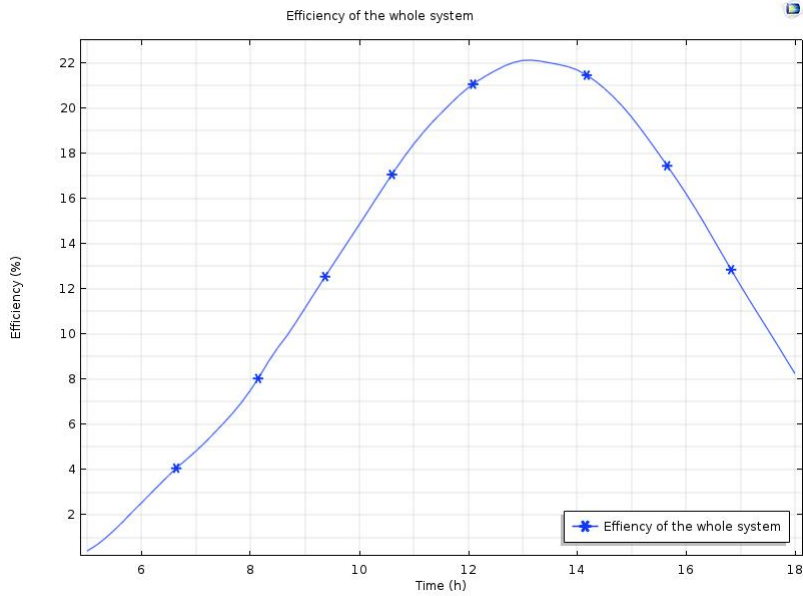


Figure 3.67. Efficiency of whole CPC system for simulated conditions (uncovered configuration - July 18, 2017).

3.5.7 Validation of computed scenarios

The validation of numerical scenarios is conducted by comparing simulation results with available experimental acquisitions. To quantify the consistence of simulation approach the percentage discrepancy D_x is considered between samples (numerical vs experimental), as by Equation 3.31:

$$D_x = \left| \frac{x_{exp} - x_{sim}}{x_{exp}} \right| \cdot 100 \quad (3.31)$$

where x_{exp} and x_{sim} are the experimental value and the simulation result, respectively. Then, each measurement is compared with its relative simulation output. Finally, the global discrepancy D_{gl} is evaluated by defining the average of samples discrepancies:

$$D_{gl} = \frac{\sum D_{x,i}}{N} \quad (3.32)$$

where N is the number of considered samples. Aa limit value of D_{gl} is set to 12% in accordance with the research team. Such value is assumed to be consistent with the needs of the simulation campaign in terms of accuracy. In effect, the implementation difficulties while exactly defining the variability of time dependent external conditions justify this assumption.

Then, considering the covered CPC scenario, the temperature values are compared with experimental ones as reported by Table 3.14. In these terms, the global discrepancy is equal to 10.4% so that the covered CPC thermal simulation scenario is validated.

	Measured at								
	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
TCD	46°C	59°C	68°C	76°C	81°C	79°C	75°C	71°C	62°C
CM	39°C	49°C	58°C	66°C	76°C	78°C	77°C	76°C	72°C
D [%]	15.2	16.9	14.7	13.2	6.2	1.3	2.7	7.0	16.1

Table 3.14. Average surface temperatures comparison between experimental (TCD) and simulation values for the covered CPC configuration (July 17, 2017).

Similarly, to validate the uncovered CPC scenario refer to comparison of numerical and experimental data as by Table 3.15. In this case, the global discrepancy is reduced up to 7.7%, confirming the validation of the

uncovered CPC simulation scenario also. This approach is applied to the only covered configuration of the CPC prototype because of experimental data availability [41, 46].

	Measured at					
	10:00	11:00	12:00	13:00	14:00	15:00
TCD	49°C	48°C	51°C	55°C	56°C	57°C
CM	39°C	44°C	45°C	52°C	56°C	57°C
D [%]	20.4	8.3	11.8	5.4	0.0	0.0

Table 3.15. Average surface temperatures comparison between experimental (TCD) and simulation values for the uncovered CPC configuration (July 18, 2017).

3.5.8 Reflectors shape influence on performance

Following the validation of simulated scenarios with experimental data, a further study is conducted on the geometrical parameters of the CPC prototype reflectors. Effectively, its optical performance in terms of solar radiation concentration by reflection is basically related to the reflectors shape. The investigation of the parabola-shaped reflectors geometry on CPC performance is the main goal of the simulation campaign, since no experimental campaigns and prototypes are required. Parabola equation is discussed by subsection 3.4.3 and the parametrization of geometrical entities within the simulation scenario allows the modification of values, also by means of a parametric sweep in CM. Left reflector parabola shape is rebuilt by passing different coefficients to its equation. Then, right parabola is also defined. However, some controls and conditions are imposed to avoid any error in geometry reconstruction process. Regarding the right reflector, one of the main parameters which defines the shape and then the optical performance of the CPC system is the half-acceptance angle. Moreover, it depends on the location the CPC is installed on. Due to the truncated parabolic concentrators design principles, it is possible to assert that the right parabola is assumed to be identical to the left one, but rotated of a certain angle (i.e. the half acceptance angle itself). The intersection point between the left parabola arc and the symmetry axis of the right one defines the cutting line, a horizontal line to cut the vertical extension of the structure, as by Figure 3.32. In accordance with the research team, the half-acceptance angle is varied, modifying the CPC structure, automatically. Limit values for the half-acceptance angle variation range are fixed to fit back-plate dimensions (which represent a bound on width) and length, avoiding an extreme increase of costs and installation surface requirements. Therefore, a parametric analysis is implemented in CM by modifying both parabola coefficient (a) and half-acceptance angle (θ_c). The influence of those kinds of variations on the whole geometry is summarized by Figure 3.33 [46] and Figure 3.68. A multi-parametric sweep is conducted in CM to generate a combined data-sets of a (parabola concavity) and θ_c (rotation angle of the right parabolic arc) values, evaluating for each couple of values the average surface temperature for the reference solar cell (i.e. SC2), the power and efficiency. Initialized ranges are given by Table 3.16. It follows that the number of scenarios to be computed is $4 \cdot 4 = 16$, as by Table 3.17. The multi-parametric analysis is implemented

for both scenarios (covered and uncovered CPC).

	Initialized range
Parabola coefficient (a) [m^{-1}]	3:1:6
Half-acceptance angle (θ_c) [$^\circ$]	60:5:75

Table 3.16. Parametric sweep values ranges for parabola coefficient and half-acceptance angle.

Data-set ID	a [m^{-1}]	θ_c [$^\circ$]
PS_1	3	60
PS_2	3	65
PS_3	3	70
PS_4	3	75
PS_5	4	60
PS_6	4	65
PS_7	4	70
PS_8	4	75
PS_9	5	60
PS_10	5	65
PS_11	5	70
PS_12	5	75
PS_13	6	60
PS_14	6	65
PS_15	6	70
PS_16	6	75

Table 3.17. Parametric sweep scenarios: parameters combinations initialization.

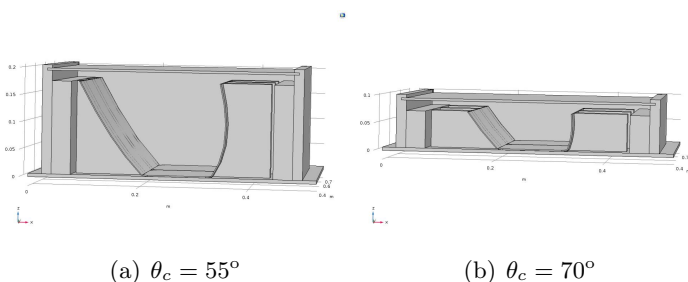


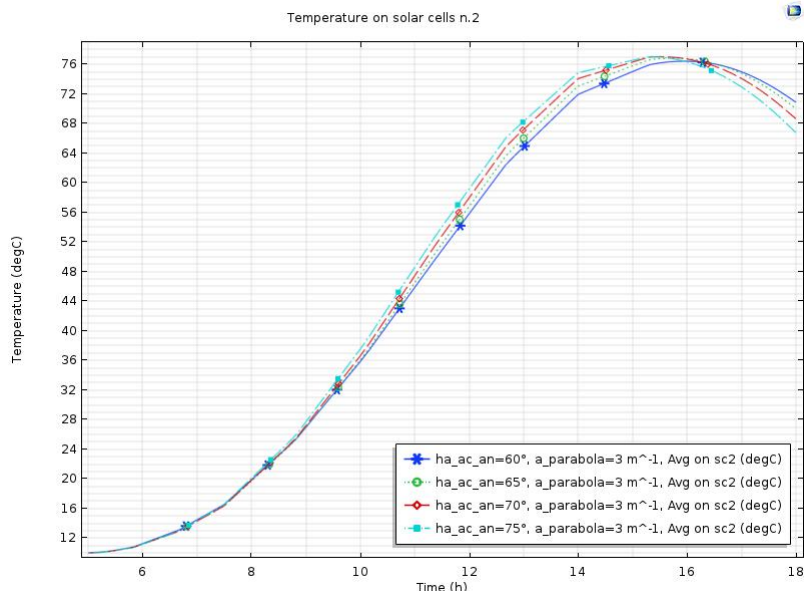
Figure 3.68. Half-acceptance angle variation influence on CPC vertical dimension (once back-plate dimensions have been fixed).

Covered CPC configuration

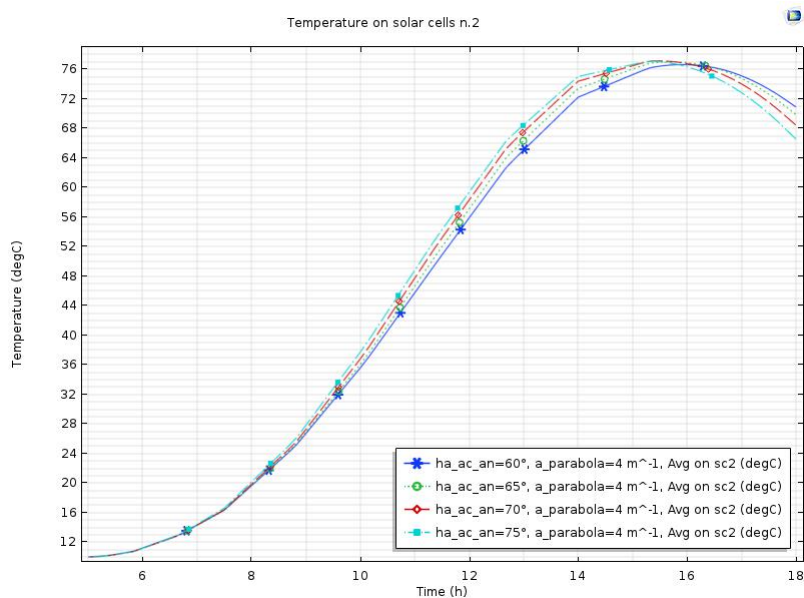
Referring to the covered CPC, Figure 3.69 and Figure 3.70 report the average surface temperature on SC2 for different parabola coefficients and half-acceptance angles. Boundary conditions and simulated environmental parameters are those exposed for the thermal field numerical analysis. On one hand, computed trends highlight a weak influence of parabola concavity on the solar cell average surface temperature; on the other hand, the variation of half-acceptance angle seems to influence much more the temperature field, even if the maximum difference between temperature trends (around 2°C) is provided by Figure 3.69(b). However, even if geometrical shape doesn't affect to much the temperature distribution, once environmental conditions such as the ones of 17th and 18th of July 2017 are imposed, the parametric sweep makes possible to notice a and θ_c influence in terms of heat flux enhancement in correspondence of the solar cell. Effectively, the incoming radiative heat flux which passes through SC2 increases while parabola coefficient and half-acceptance angle decrease. In fact, considering for each computed data-set the total heat flux over time peak, the power (and so the whole CPC system efficiency, by using Equation 3.30) could be defined as explained by the previous section. Results of such operation are given by Figure 3.71.

Uncovered CPC configuration

The previous approach is applied also to the uncovered CPC configuration in order to highlight reflectors geometry influence on thermal field. Acting boundary conditions are related to the experimental campaign as conducted on July 18, 2020. Once external conditions have been fixed, the resulting exposed-to-radiation-surface average temperature trend of SC2 is given by Figure 3.72 and Figure 3.73, considering a variation in terms of both parabola coefficient and half-acceptance angle. The whole CPC system performance in terms of power and efficiency trends is provided by Figure 3.74.



(a) $a = 3 \text{ m}^{-1}$



(b) $a = 4 \text{ m}^{-1}$

Figure 3.69. Influence of the parabola coefficient and half-acceptance angle variation on average surface temperature on reference solar cell (part 1, covered CPC).

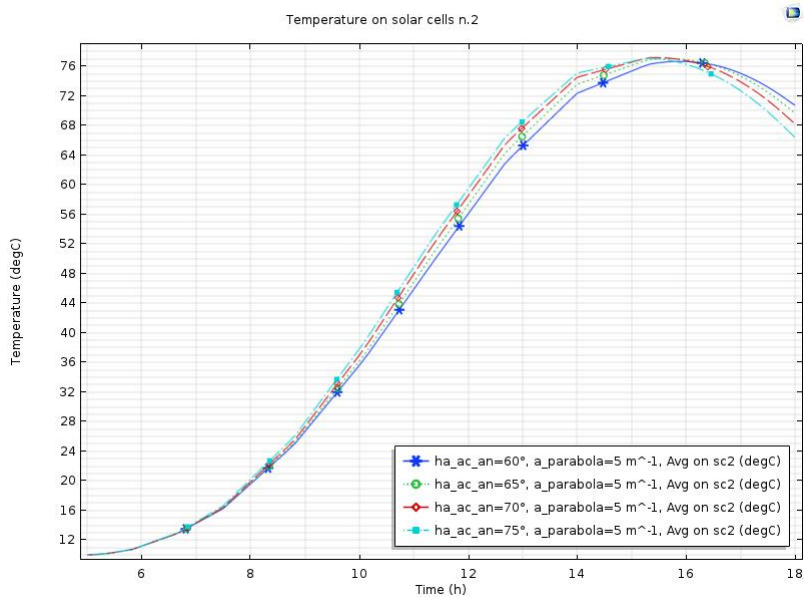
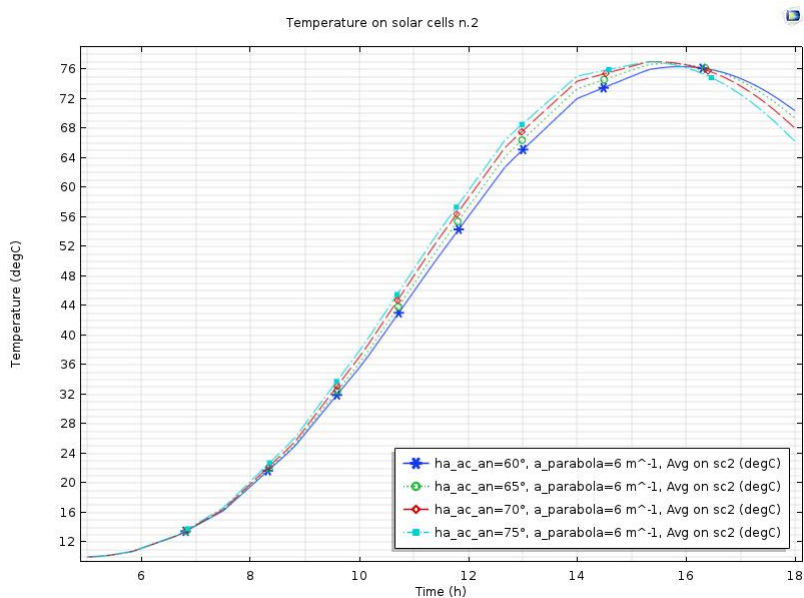
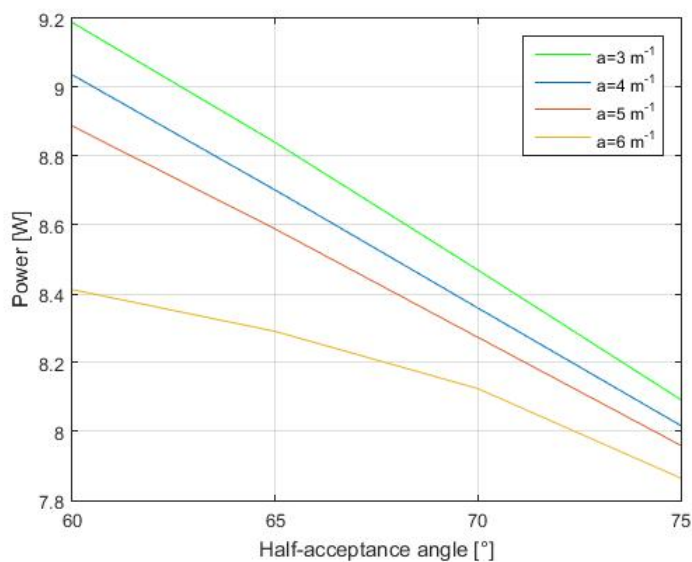
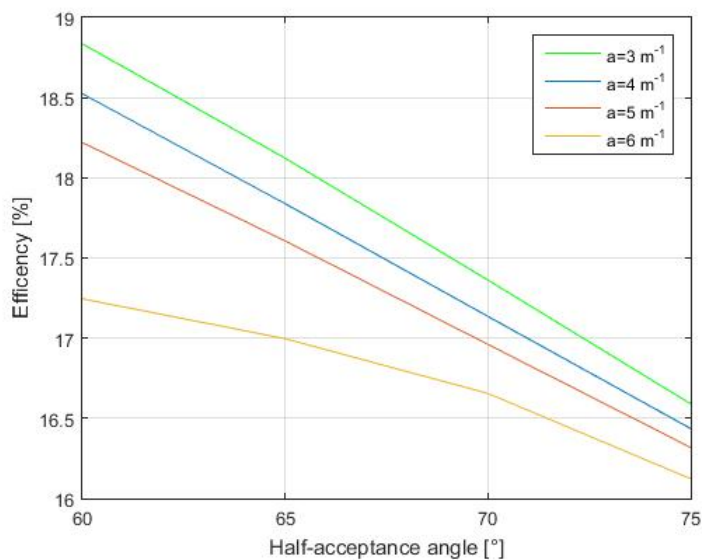
(a) $a = 5 \text{ m}^{-1}$ (b) $a = 6 \text{ m}^{-1}$

Figure 3.70. Influence of the parabola coefficient and half-acceptance angle variation on average surface temperature on reference solar cell (part 2, covered CPC).



(a) Radiative total heat flux.



(b) Whole system efficiency.

Figure 3.71. Performance of the covered CPC system while considering total heat flux peaks for each one of the parabola coefficient and half-acceptance angle combinations.

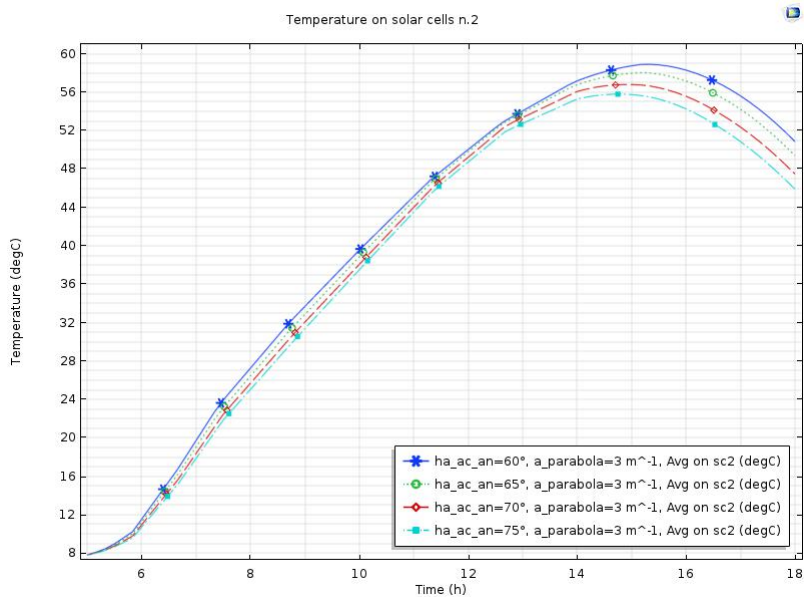
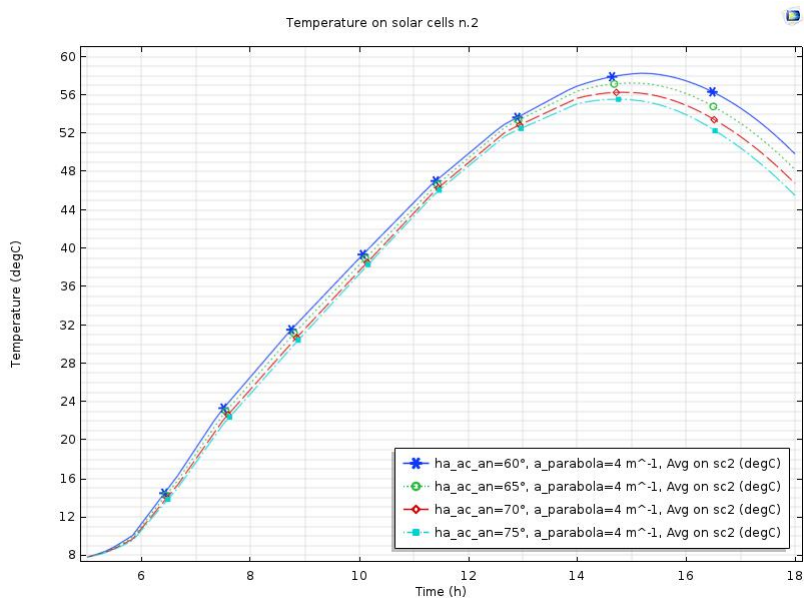
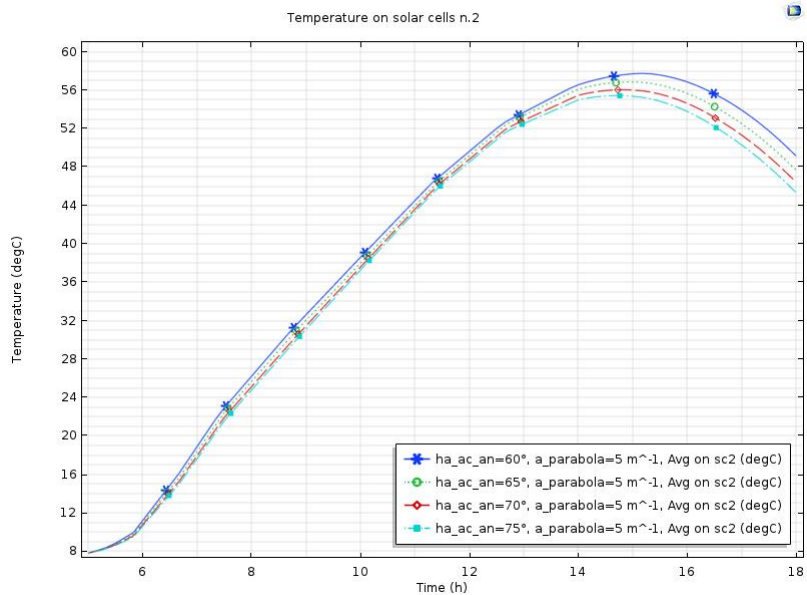
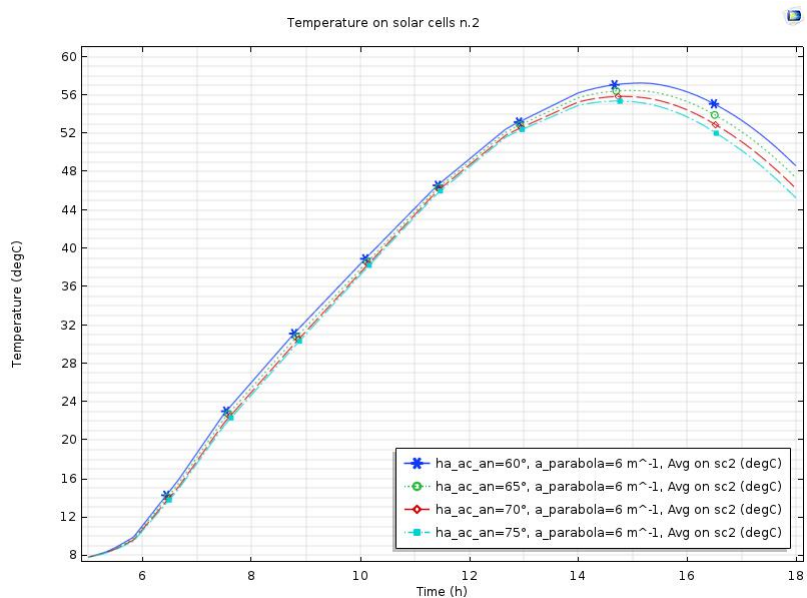
(a) $a = 3 \text{ m}^{-1}$ (b) $a = 4 \text{ m}^{-1}$

Figure 3.72. Influence of the parabola coefficient and half-acceptance angle variation on average surface temperature on reference solar cell (part 1, uncovered CPC).

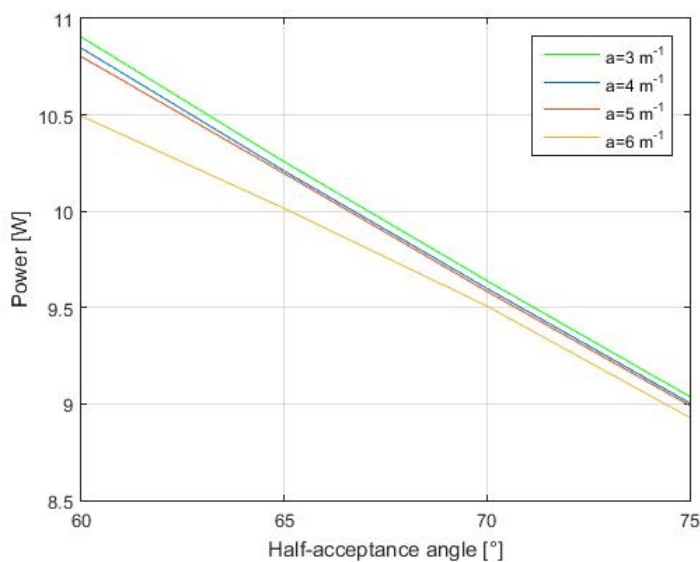


(a) $a = 5 \text{ m}^{-1}$

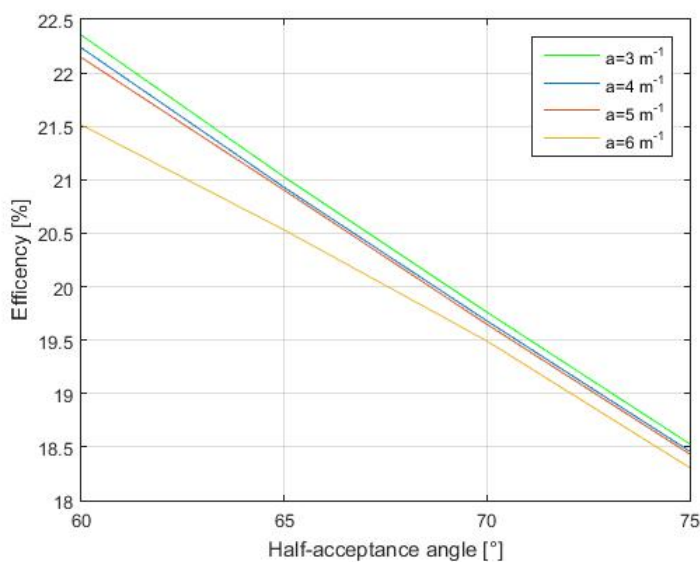


(b) $a = 6 \text{ m}^{-1}$

Figure 3.73. Influence of the parabola coefficient and half-acceptance angle variation on average surface temperature on reference solar cell (part 2, uncovered CPC).



(a) Radiative total heat flux.



(b) Whole system efficiency.

Figure 3.74. Performance of the uncovered CPC system while considering total heat flux peaks for each one of the parabola coefficient and half-acceptance angle combinations.

Parametric sweep results discussion. For the covered CPC configuration, the presence of the trapped-by-covers air volume influences the thermal response of the system. An increase in terms of half-acceptance angle (once the parabola coefficient has been fixed) results in a decrease of the CPC height, as graphically reported by Figure 3.68. Effectively, the intersection point z-coordinate showed by Figure 3.32 is located much near to the solar cells for high θ_c angles. It follows that a reduced air volume remains trapped and exposed directly to the solar cells surfaces. The air domain should be considered as a heat storage: less air volume, due to the thermal inertia, requires a lower time to reach a certain temperature. This is consistently confirmed by temperature trends as by both Figure 3.69 and Figure 3.70. A half-acceptance angle of 60 degrees provides a bigger air volume than the covered CPC configuration with a θ_c which equals 75 degrees. By that, the heating process requires much time for the largest trapped air volume. Once a specific time step is fixed, it is possible to notice how the highest temperature value is reached by the maximum half-acceptance-angle-provided covered CPC configuration. In addition to that, it is possible to discuss the interception point between trends, since it is related to the longest cooling time required by increasing air volumes. Thus, a low half-acceptance angle for the covered CPC configuration provides a major air volume which remains trapped: Figure 3.69 and Figure 3.70 highlight a decreasing required time to reach a certain temperature during the heating-up process while the half-acceptance angle increases (being much lower the trapped air volume dimension); however, bigger air volumes require a major time to decrease their temperatures. The uncovered CPC configuration temperature trends (as given by Figure 3.72 and Figure 3.73) show that the thermal response is reversed if compared to the one of the covered CPC. Internal components of the uncovered CPC are exposed to the external environment, directly. Due to that, it is possible to assert that a CPC characterized by a lower height (and so by a higher semi-acceptance angle) is easier to cool for the imposed external convection conditions. More than referring to the surface/volume ratio, in this case it has to be considered how the lower height of the CPC prevents the transmission of a large amount of solar rays onto the surface of the solar cells. A reduction in terms of CPC height results in a reduction of the reflectors surface as a consequence (see e.g. Figure 3.68). This concept is confirmed by a lower CPC power once low half-acceptance angle has been implemented. The consistency of the scenario is then supported.

3.5.9 Design and development of a standalone software tool

To fit experimental campaigns requirements, avoiding any loss in terms of time and economical resources to extend the set of CPC prototypes, a standalone tool has been developed by means of the COMSOL Multiphysics *Application Builder* interface. Considering the implemented model as a starting point, concerning the simulation structure by which physical phenomena are numerically replicated, it is possible to design and realize a specific tool, characterized by an ad hoc graphical user interface that should be useful once the influence of different geometrical and environmental conditions need to be investigated.

The *Application Builder* built-in feature allows the user to extend the usability of implemented scenarios. Following the indications and needs as by experimental campaign, the main features, that a *virtual laboratory* has to provide, should be summarized as:

- geometrical parameters modification to investigate the influence of CPC shape on its performance;
- environmental conditions variation on time-dependent trends (e.g. incoming solar radiation, external convection and temperature);
- materials' characteristics (e.g. emissivity, heat capacity, thermal conductivity, density) assignment to each one of the geometry entities and domains;
- CPC installation locality and time variability (e.g. daytime, longitude and latitude).

To do that, the GUI has been designed to allow the modification of previously discussed parameters, constituting the final virtual experimental environment or laboratory. As reported by Figure 3.75 and Figure 3.76 two different tools are given, each of which is dedicated to the simulation of a specific CPC configuration between those previously investigated (i.e. covered and uncovered CPC). Entry spaces should be initialized by the user to set each one of the desired conditions, avoiding any loss of time to implement the whole simulation model tree. In effect, this application is also accessible by those who have no previous experience with the COMSOL Multiphysics. Moreover, the validation issues should be neglected while launching a simulation by this tool, because of previous checks and comparison with experimental data.

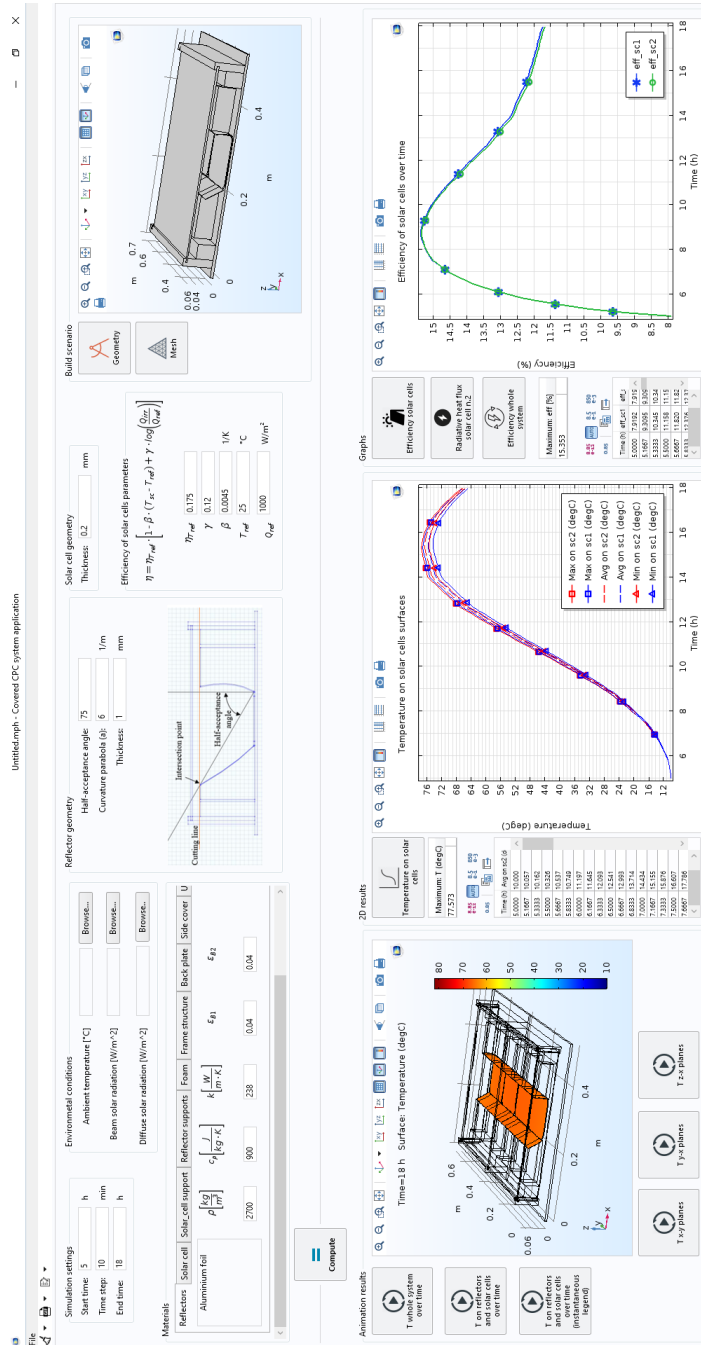


Figure 3.75. Standalone application GUI for covered CPC virtual testing and simulation.

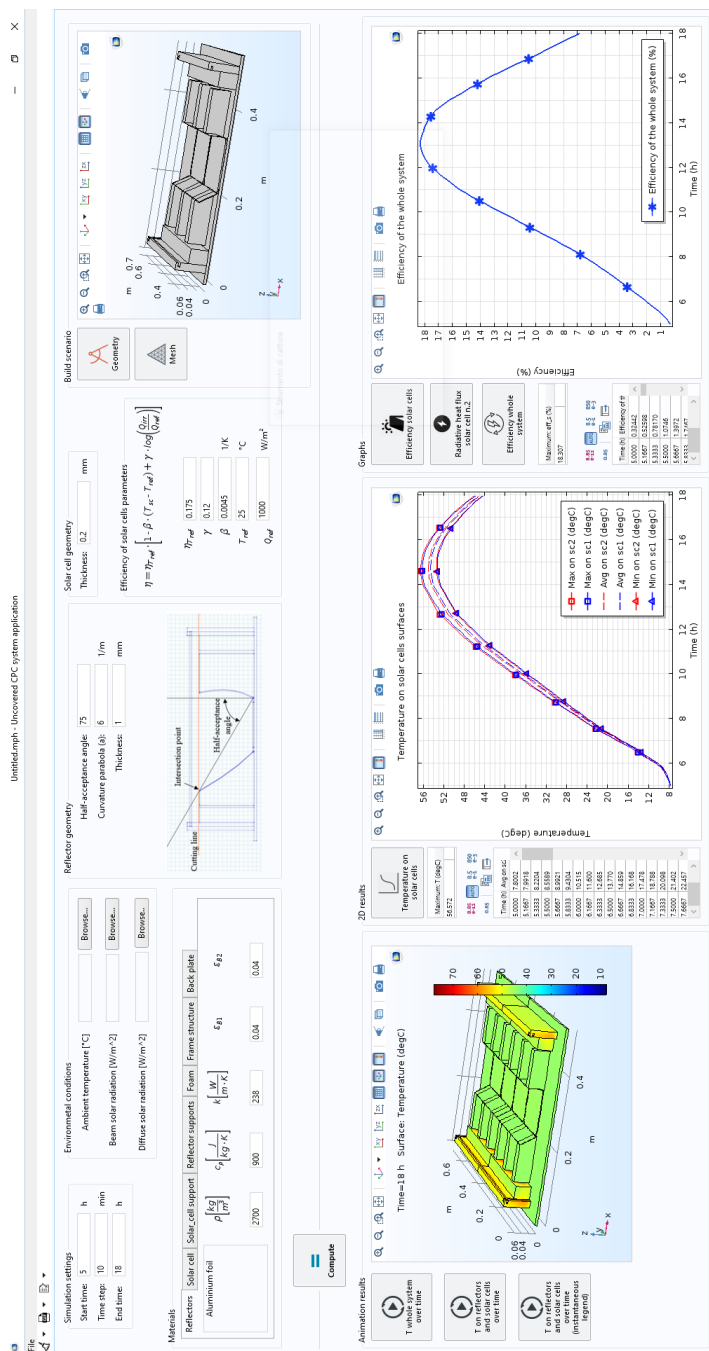


Figure 3.76. Standalone application GUI for uncovered CPC virtual testing and simulation.

Two main sectors within the GUI could be identified: on one hand, the user is allowed by the top frames to provide specific parameter assignment to the main influence parameters, building up the mesh; on the other hand, the results visualization and post processing operations are also available on the bottom frame of the interface. The top half section of the interface provides many frames or forms, such as

- *Simulation settings* form, by which transient simulation parameters (i.e. start time, time step and end time) could be managed by the user;
- *Materials* form, by which it is possible to assign required materials properties (i.e. density, heat capacity, thermal conductivity and both solar and ambient spectral bands emissivities) once related to the each one of the CPC components (i.e. reflectors, solar cells, solar cells' supports, reflector supports, foam, frame structure, back plate, upper and side covers);
- *Environmental conditions* form, by which time dependent trends of ambient temperature and solar radiation components (i.e. beam and diffuse radiation) could be imported by external files (.csv, .xls, .txt)
- *Reflector geometry* form, by which the user should manage reflectors shape, in terms of half-acceptance angle, parabola curvature and thickness. An illustration of geometrical parameters is also provided to simplify their meaning and influence on the CPC structure;
- *Solar cell geometry* form, by which solar cell thickness should be initialized. In addition to that, the user is also allowed to set efficiency trend equation coefficients for post-processing visualization of solar cells efficiency over time;
- *Build scenario* form, by which the user is allowed to update the geometry and generate the automatically-managed mesh and visualize its application on the whole geometry domains. The discretization procedure of geometrical entities follows specific rules and criteria, as imposed by the simulation scenario model tree. The user is not allowed to access those mesh settings in order to reduce possible causes of errors and non convergence of computed scenarios.

Once the user has implemented and defined all required data, the *Compute bottom* is then enabled to compute the simulation scenario. Once the

results data-set has been computed, an automatic generation of graphical results within the bottom half section of the interface is also guaranteed, in particular:

- *Animation results* form visualizes the time dependent trend of temperature field. Three different kinds of visualization could be selected: temperature fields associated with the whole CPC system or with specific components such as reflectors and solar cells, providing both fixed and instantaneously updating color legend. Furthermore, it is possible to select the visualization on each one of the 3D planes (i.e. x-y plane, y-z plane and z-x plane);
- *2D results* form report the temperature trends over time. Maximum, average and minimum temperature values trends are visualized and reported by a specific table on the left-side of the form. Peak temperature value is also directly highlighted. The data export feature is enabled;
- *Graphs* form allows the user to choose between the visualization of solar cells efficiency, radiative heat flux through solar cells and the whole CPC system efficiency. The peak value of the chosen parameter is also reported, in addition to the table which highlights instantaneous values over time. As done for the 2D results form, a data export feature is also provided.

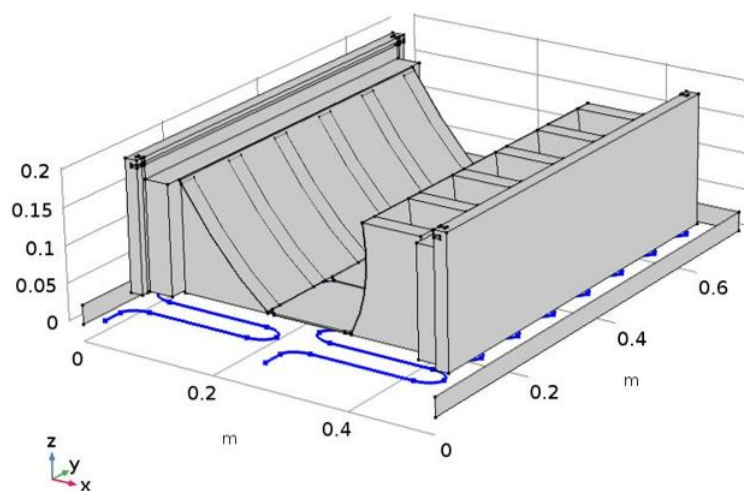
3.6 Thermal field within a coil-cooling-system-provided CPC prototype

Due to the influence of the temperature on the efficiency of the system, the following study aims to define the temperature field within a Compound Solar Concentrator (CPC) with a cooling system built by coils, as discussed in [62]. The target is to decrease the temperature of the solar cells, observed by solving a sequence of 3D transient Finite Element Method simulation scenarios. Post-processing analysis is conducted to check the behaviour, mostly in terms of efficiency, of the whole system. More in detail, the target is to implement a cooling system in a CPC model to decrease the temperature on the solar cells surfaces, increasing the whole system efficiency once recovering the heated water for different options.

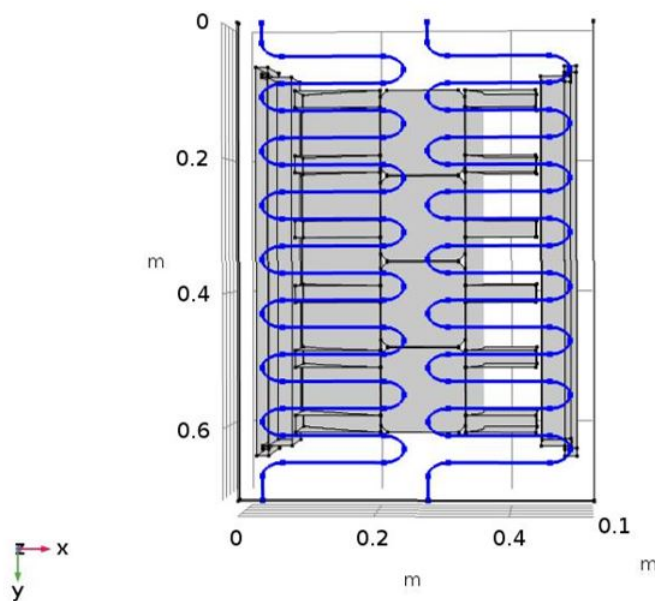
3.6.1 Scenario definition

The considered day has been the 18th of July 2017 and the environmental conditions (the temperature, the beam and diffuse solar radiation) are referred to the Trinity College Dublin (Ireland) location. Others input parameters are the material properties of the whole model that influence the heat exchange in the system, as discussed in subsection 3.4.4.

The strategy of the simulation campaign is based on the previously validated uncovered CPC system, where some cooling coils have been added to increase the efficiency of the whole system while decreasing their temperature. Then the heated water will be used for external plants applications. Multiple CPC simulation scenarios will be solved to observe the response of the systems since the real goal is to install series of CPC. Therefore, the simulation scenario remains the same of by [46] for the heat transfer module where the pipe flow module will be added. Obviously, the first step is to change the geometry while inserting the cooling system. The chosen position is located at the middle of the back plate (thickness has been increased up to 26 mm), defining a pair of coils to increase the heat exchange surface. The coils are drawn with two polylines so that the diameter could be assigned consequently. The geometric configuration of the cooling system is shown in Figure 3.77.



(a) Side view of the back plate (hiding some faces).

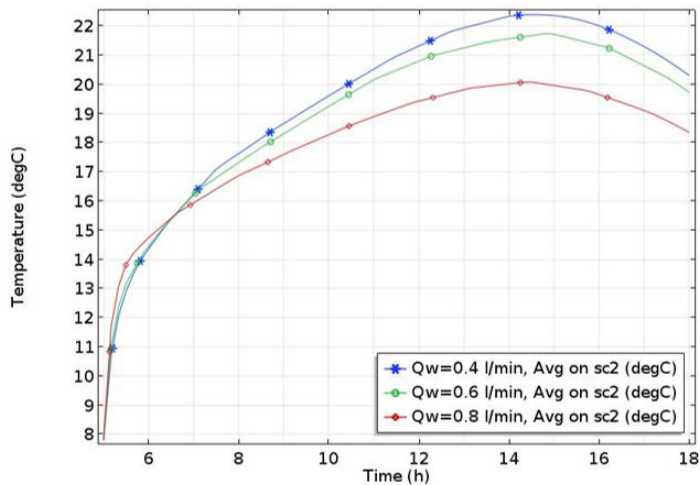


(b) Bottom view of the back plate.

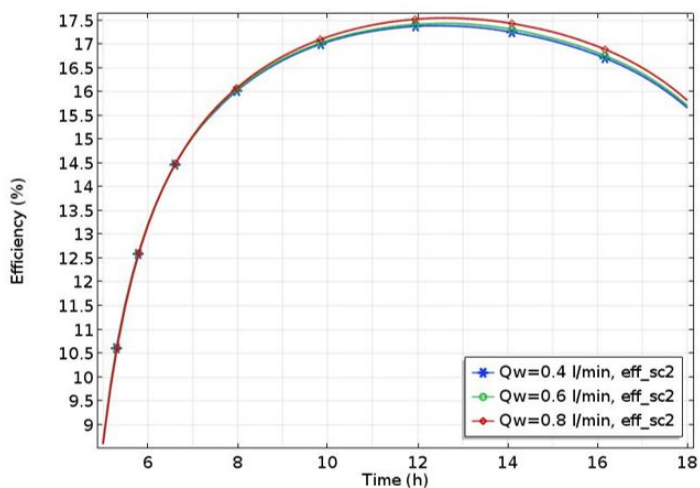
Figure 3.77. Geometry definition of the coils.

The required environmental conditions are the temperature and the solar radiation for the reference day (18 July 2017) from 0:00 to 23:30,

as the one reported for the first CPC modelling approach. The fluid that flows and fills the pipes is water, which properties (density, heat capacity and thermal conductivity) are defined as a function of temperature. The boundary conditions as imposed in the scenario are needed to solve the heat transfer and pipe flow module, concurrently. For the heat transfer phenomena which led to the temperature field definition, refer to the conditions exposed and validated in [46], while the pipe flow module critical conditions are related to the inlet and outlet definition. The water temperature of inlet changes for each one of the simulated CPCs, since the outlet water temperature is considered as the inlet water temperature for the next CPC. However, the first CPC is characterized by an inlet water temperature of 15°C, fed by a water source (e.g. a water well) with a constant temperature. Following this approach, the daily temperature trend at the next CPC inlet corresponds to the daily temperature trend at the previous CPC outlet. The inner diameter of the pipe is set at 0.01 m, and the flow resistance characteristics are chosen, with a surface roughness typical of a commercial steel (0.046 mm). The Navier-Stokes equations govern the motion of fluids and can be seen as Newton's second law of motion for fluids. This equation is always solved together with the continuity equation. In fact, the Navier-Stokes equations is the hearth of fluid flow modeling. By solving them, for a particular set of boundary conditions (such as inlets, outlets, and walls), it is possible to predict the fluid velocity and its pressure in a given geometry. In order to solve Navier-Stokes equations, the pressure constraint (imposed at 1 bar at outlet) is required. Another boundary condition to be chosen is the flow rate inside the coils, because of its influence on the heat flux within the system. The choice of the flow rate value is determined by a preliminary sweep parametrization between three possible values: 0.4 l/min, 0.6 l/min and 0.8 l/min. The results of the average temperature on the SC2 and the post-processing analysis of the efficiency of the solar cells are reported by Figure 3.78.



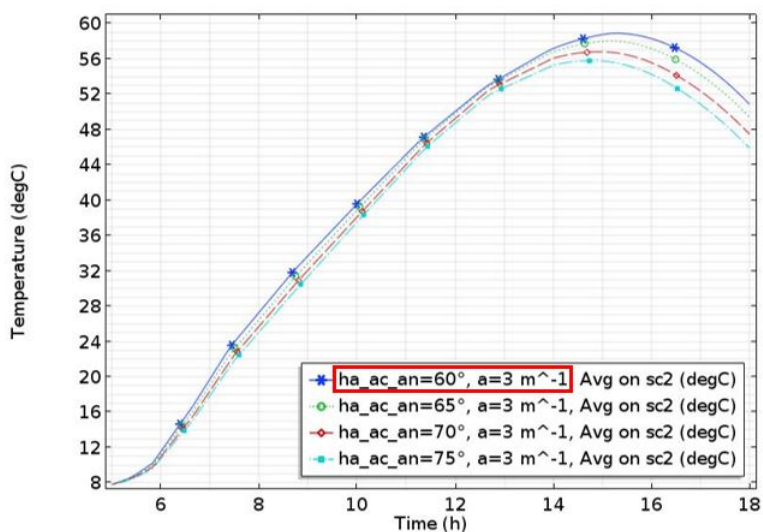
(a) Average temperature on the solar cell SC2.



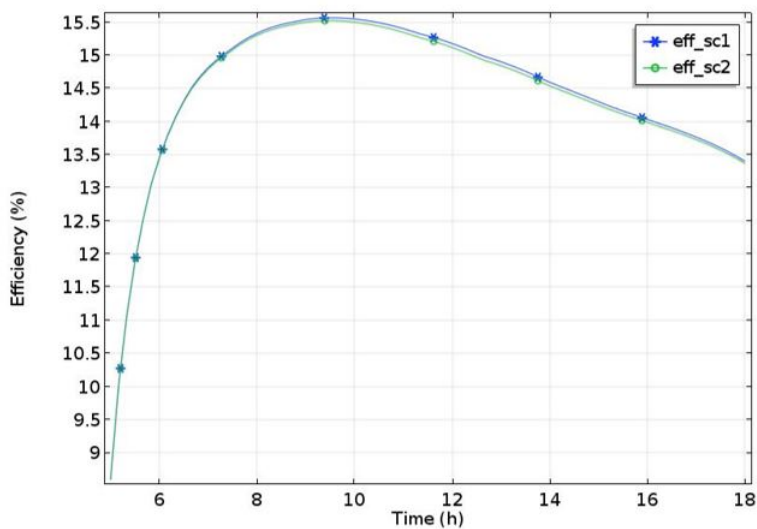
(b) Efficiency of the SC2.

Figure 3.78. Sweep parametrization of the flow rate.

Observing the temperature trends in Figure 3.78(a), it highlights that the temperature decreases while flow rate increases flow, since the feeding water is at 15°C, constantly. Furthermore, comparing the systems powered (as by Figure 3.78) and not (as reported by Figure 3.79) with a cooling system it is possible to notice a significant decrease of temperature, causing an increase of conversion efficiency of the solar cells, as it is shown in Figure 3.78(b).



(a) Temperature on SC2.



(b) Efficiency of the SC2.

Figure 3.79. CPC analysis for the best performing configuration in terms of half-acceptance angle and parabola coefficient (60 degrees and 3 m^{-1} , respectively).

The choice of the flow rate falls on 0.6 l/min because it allows to decrease the temperature on the solar cells but meanwhile a good increase of

water temperature inside the coils through the heating could be observed, as shown by Figure 3.80.

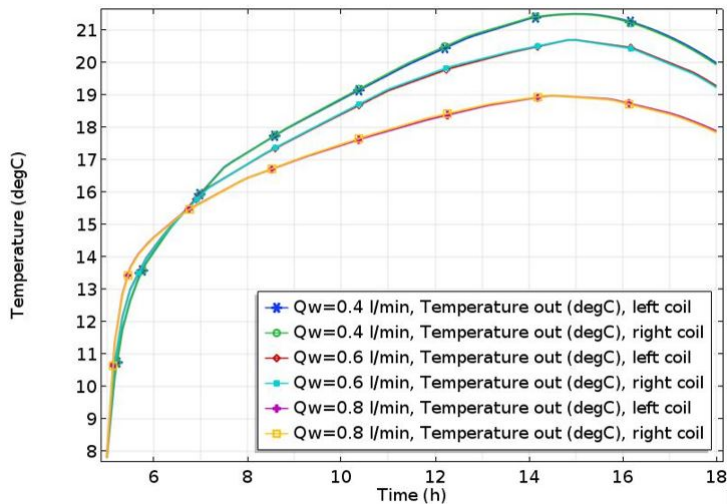


Figure 3.80. Temperature of the outlet water inside the coils for different flow rates.

The discretization for the single CPC model is shown in Figure 3.81.

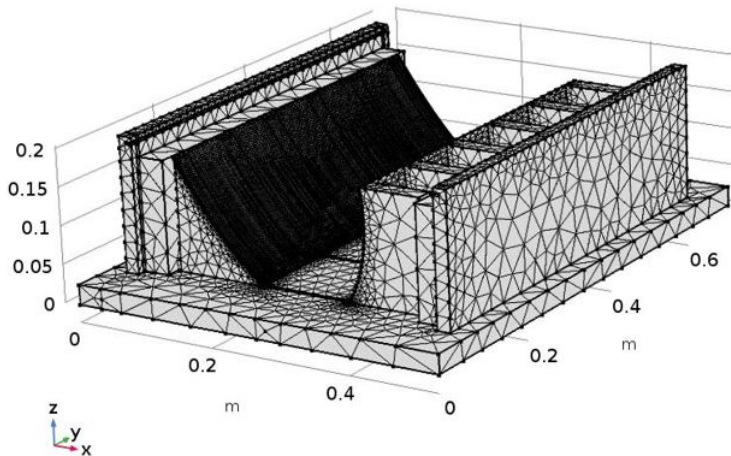


Figure 3.81. Mesh applied to the computational domain.

The discretization is a tetrahedral mesh implemented to guarantee in increasing resolution on the reflector domains, in the solar cells and on

the back plate. The setting-up procedure has been checked step-by-step by ad-hoc implemented scenario for the presence of the relevant geometry gradients that could be identify in both parabolic reflectors and solar cells, due to the curvature radius and to the thin layer condition for the semiconductor layer. Details about the implemented mesh characteristics are given in Table 3.18.

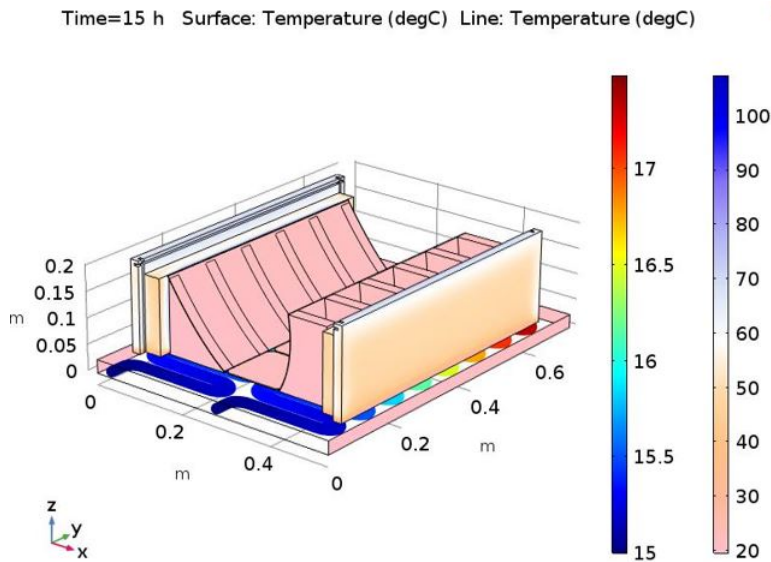
Mesh vertices	20456
Tetrahedral elements	75754
Triangular elements	36942
Edge elements	4069
Vertex elements	420
Estimated required RAM	80 GB (approx)

Table 3.18. Mesh details for the cooling-system-provided CPC.

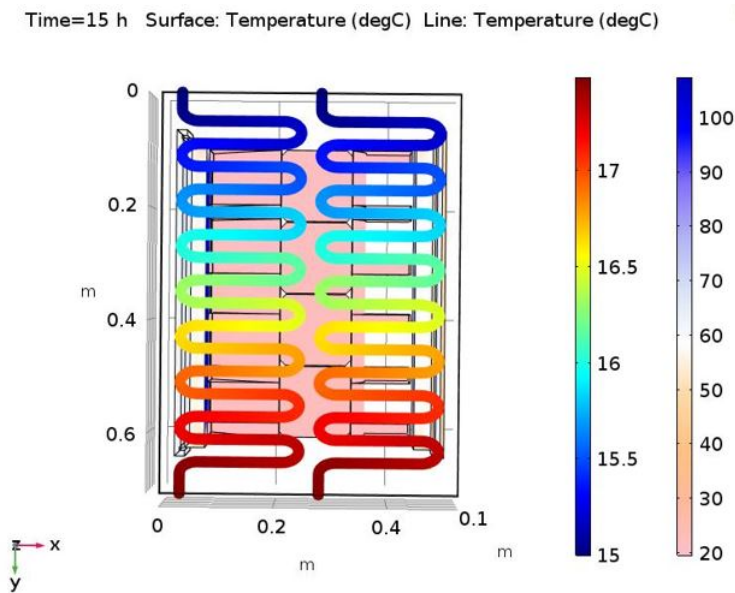
Each simulation analyzes only a single CPC model, therefore there will be different scenarios to solve a whole CPC plant (composed by series of CPC): the output flow of the previous one is the input of the next one, as discussed before. The aim of the simulations is to analyze the transient thermal field in output by every CPC, solving the coupling between heat exchange and pipe flow module. As aforementioned, the output values of temperature from the coils has to be considered as the flow temperature at inlet for the next CPC simulation.

3.6.2 Simulation results

The first step is to simulate different CPC scenarios to consider them in an installation as series. The obtained results are the temperature fields of the whole system. The temperature field on the surfaces for the first CPC exposed to the heat exchange is reported in Figure 3.82.



(a) Side view of the back plate (hiding some faces).

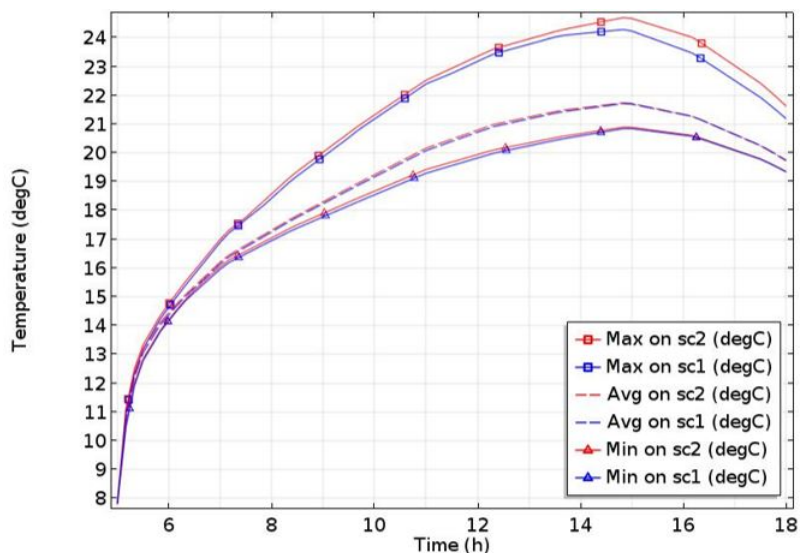


(b) Bottom view of the back plate.

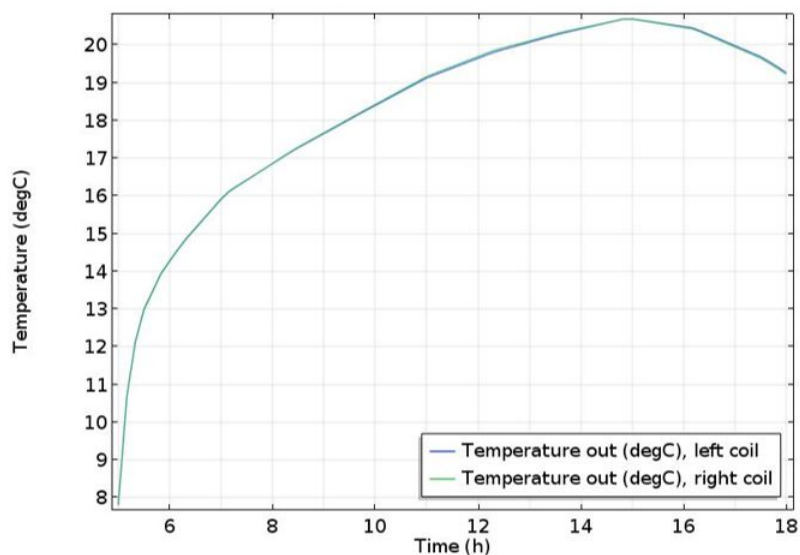
Figure 3.82. Temperature field on the first CPC of the cooling system provided plant.

Considering the aim of this work, it is necessary a specific focus on

the temperature distribution on the solar cell surfaces and inside the coils. For each simulation these temperature daily trends are available, as it is shown only for the first CPC in Figure 3.83.



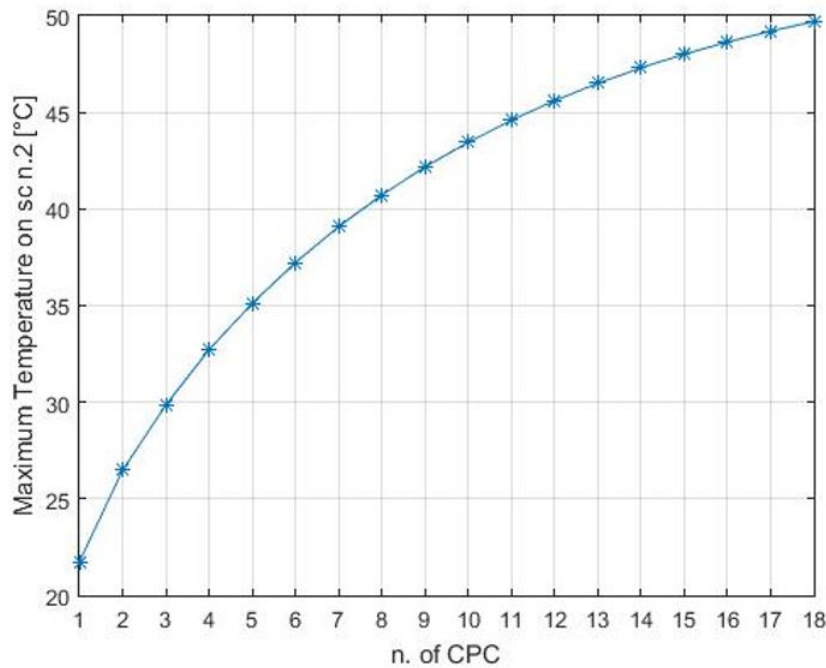
(a) Temperatures of SC2 exposed surface.



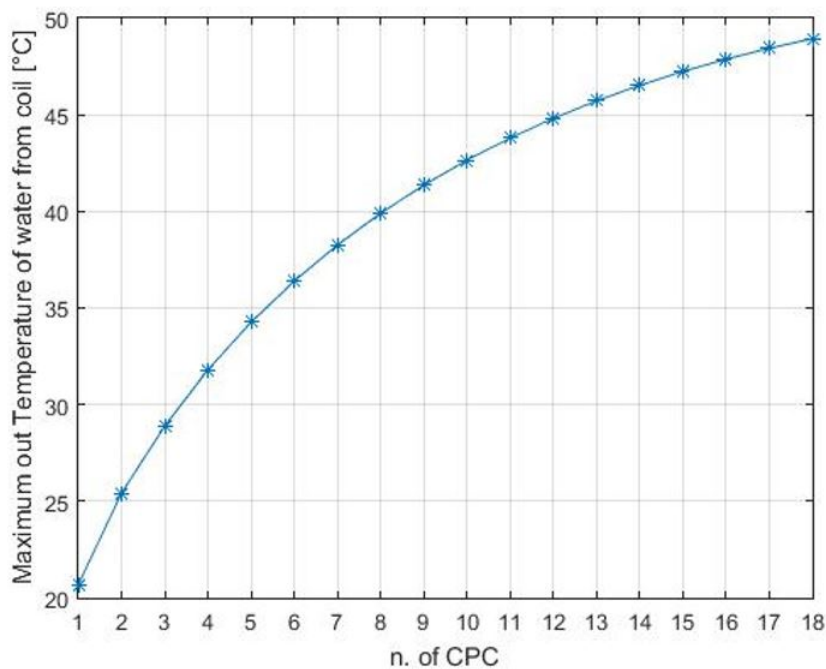
(b) Temperatures of water flow at outlet.

Figure 3.83. Thermal response relevant data for the first CPC of the cooled plant.

The maximum, average and minimum values of the surface temperature over time in Figure 3.83(a) shows that it is possible to consider the average temperature on the SC2 as a representative thermal parameter of the whole system. The difference between maximum and minimum temperature values over time is less than 3°C which indicates a uniform temperature distribution along the solar cell surfaces. However, the difference between the solar cells is neglectable by an engineering point of view, therefore the SC2 is the only one considered because is the one positioned in the middle and softly more critical. The reached peak is about 22°C at 15:00. In Figure 3.83(b) the outlet water temperature from the cooling system is reported, showing the trend over time from both coils. The difference between the out temperature of coils is graphically imperceptible and the peak of about 21°C is reached at 15:00. The outlet temperature of water from the first CPC will be considered as the inlet for the next CPC simulation: the same approach has been applied to the next n.17 CPCs. Referring to the temperature trends, the values are summarized in one graph only, reporting the maximum temperature for each simulation and the relative CPC number, both for the temperature on the solar cells and for the outlet water temperature from coils. In other words, Figure 3.83 reports the maximum daily temperature trend (at 15:00, Figure 3.83(a)) on each CPC's SC2 and the outlet water temperature (at 15:00, Figure 3.83(b)). The trend reported by Figure 3.83(a) is quite useful to identify the efficiency trend of solar cells indirectly.



(a) Temperature on SC2.



(b) Output water temperature from coils.

Figure 3.84. Thermal response relevant data for a n.18 cooled-provided CPC-composed plant.

Considering an increasing number of CPCs, the temperature difference between the first CPC and the last one increases, as quantified by Figure 3.84(a), because of the heat exchanging dynamics. The water flowing inside the coils increases its temperature along the whole extension of the CPC plant Figure 3.84(b). By means of the post-processing analysis it is possible to characterize the efficiency of the solar cells, calculated by means of Equation 3.29. Referring to the temperature fields exposed by the previous discussion, it is possible to define the efficiency trend over the number of CPCs, as reported by Fig. 15.

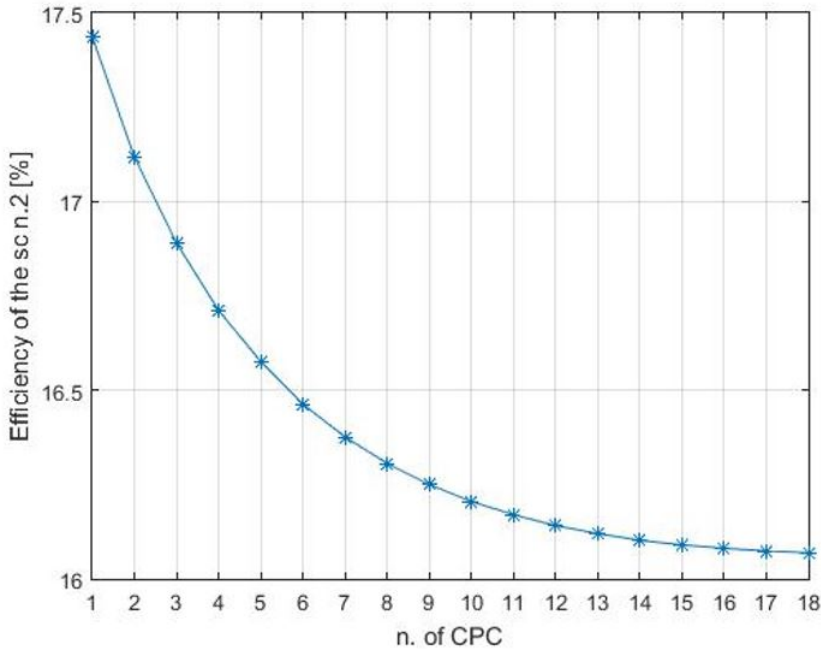
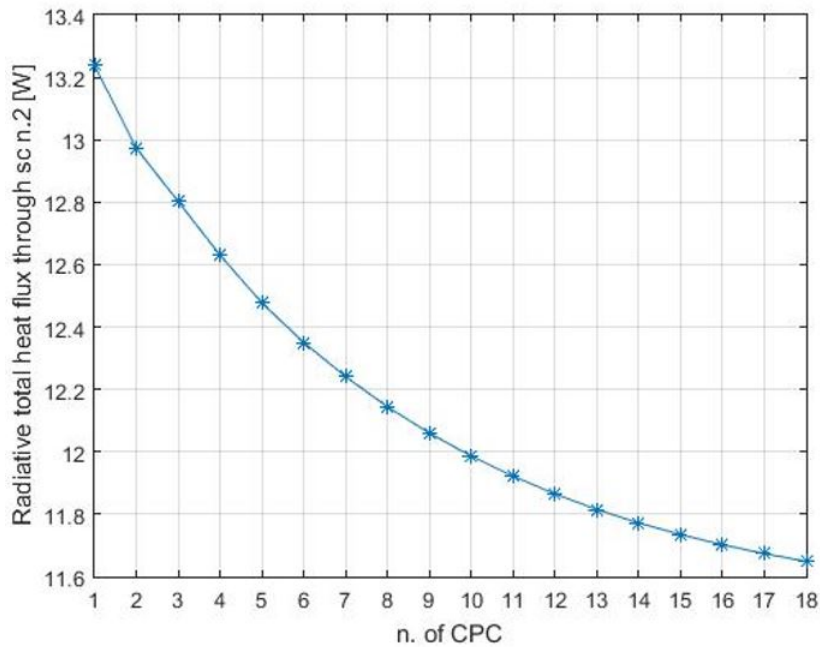
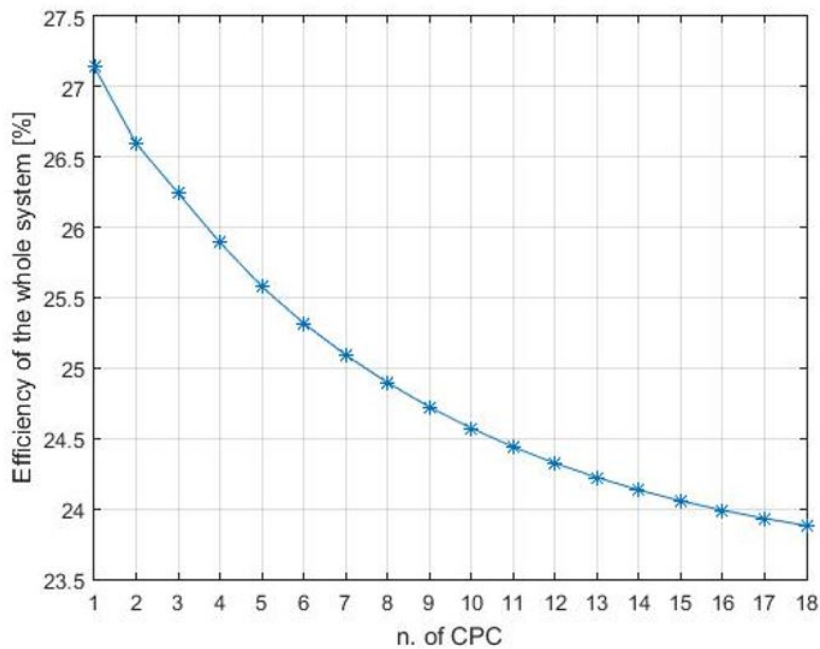


Figure 3.85. Efficiency of SC2 over the CPC cooled plant.

By this case, the efficiency of the solar cell decreases with the number of CPCs since the temperature on the solar cell increases due to the heat exchange phenomena. The maximum difference of efficiency of the solar cell between the 1st and the 18th CPC is 1.3%. By means of (3.30), it is possible to calculate the efficiency of the whole system, referring to the portion of energy as the sun's incident radiation that can be converted by means of PV phenomena into electricity. The trends in Figure 3.86 represent the maximum values of the radiative total heat flux and the efficiency of the whole system in different CPCs.



(a) Radiative total heat flux through SC2.



(b) Efficiency of the whole system.

Figure 3.86. Performance of the whole CPC cooled plant system.

The radiative total heat flux through the solar cell and consequently the efficiency of the whole system decreases with the number of CPCs, since the temperature of the solar cells increases.

3.6.3 Discussion

The simulated scenarios of n.18 CPCs, defined as CPC plant, lead to the definition of temperature fields for each system. In those terms, Figure 3.84(a) shows the maximum temperature on SC2 (defined as a reference) for each CPCs, where it could be noticed that its temperature increases with the number of CPCs, because of the increasing cooling fluid temperature while approaching the CPC plant cooling pipe outlet. The following discussion refers to the most relevant radiation condition, which occurs at 15:00: the first CPC is characterized by a temperature of about 22°C on the reference solar cell, less than the peak temperature of 59°C of an analogue system without cooling pipes, as discussed by author in by [46]. It is a consistent gap of temperature that affects the behavior of the CPC system in the radiative total heat flux and the efficiency of the whole system. Referring to the last CPC of the series composed by n. 18 systems, the reached temperature on the reference solar cell is about 50°C, less than the peak temperature of 59°C of the CPC without cooling system. The other important parameter to check is the outlet water temperature from coils. The increasing of the temperature in the water offers the possibility to use it in different applications to exploit the obtained thermal gap. The outlet water temperature from coils has a similar trend to the one on the reference solar cell, increasing its value with the number of CPCs and reaching a peak at the 18th CPC of 48°C. The efficiency of the reference solar cell for the first cooled CPC of the series is about 17.4%, while its value for a not cooled CPC system is 15.5%. By this way, the presence of the coils allows to increment the efficiency of about 2%. At the 18th CPC the reached efficiency is 16.1%, which is higher than the peak efficiency of the solar cell of 15.5% in an analogue system without cooling pipes. The radiative total heat power on the reference solar cell of the first CPC without and with cooling system is 10.9 W and 13.2 W, respectively. The difference is about 17% due to the cooling of the solar cells. At the 18th CPC the radiative total heat power on the reference solar cell is about 11.7 W, higher than the first CPC without cooling system. Similarly, the efficiency of the whole system is affected

by the total heat power through the solar cells, deriving from capacity to convey the sun rays on the cells. The efficiency of the whole system for the first CPC without and with coils is about 22.4% and 27.2%, respectively. At the 18th CPC the efficiency of the whole system of the cooled CPC decreases up to 24% due to a decreasing efficiency of the cooling coils which target is to remove heat from the PV system. Therefore, as highlighted by the results, the insertion of a cooling system improves the characteristics of the CPC technology, decreasing the temperature of the solar cells and increasing the efficiency of the whole system. Furthermore, for the effect of the cooling system, there is an increase in terms of temperature of the cooling fluid (water) which could be used in external applications, where no high temperatures are required (e.g. ORC plants). However, it is shown that at the same instant (see e.g. Figure 3.84(a)), that is at hour 15:00, solar cells of contiguous CPCs are exposed to different temperature fields, which corresponds to different PV efficiencies. This results in an unbalanced CPC plant by an efficiency point of view. It follows the necessity to identify an alternative solution to reach a higher level of uniformity in terms of solar cells temperature for contiguous CPCs. A suitable way could be the implementation of a countercurrent flow, to establish a minor temperature gradient between the first CPC and the last one.

3.7 Conclusions

A FEM-based thermal analysis has been applied to an innovative compound parabolic concentrator (CPC) for solar photovoltaic applications. In particular, COMSOL Multiphysics software is used to define the temperature distribution all over a CPC prototype. Numerical scenarios have been implemented to fit the consistence of the simulated physical phenomena in accordance with data from an experimental campaign. Indeed, the CPC prototype has been tested in standard operational conditions on the Simon Perry's building at TCD in Dublin, Ireland. However, the whole experimental approach aimed to investigate the electrical power production enhancement with respect to a standard photovoltaic system for which no solar radiation concentrator is installed. Two different configurations of CPC have been considered: a transparent-covers-provided CPC (covered configuration) and a CPC for which each one of the components is exposed to external environment conditions. The same prototype has been adapted to allow the installation and removing of upper and side covers. Due to that, the experimental campaign has required two days for which radiation conditions should be considered almost identical. In detail, the 17th and 18th of July 2017 has been chosen by TCD staff to conduct the measurement campaign, for the covered and uncovered configuration of the CPC, respectively. Therefore, the available experimental data is considered to re-create within a numerical simulation framework the real external environment conditions, as similarly as possible. Obviously, the implementation of external convection conditions is one of the most discussed and critical topics in thermal and fluid dynamics numerical analysis. Due to that, it was expected from the beginning the need of fixing a suitable validation tolerance for the numerical simulation scenario once compared with the experimental measurements. This limit has been fixed to 12% in terms of average global discrepancy on each single sample discrepancy. The resolution of thermal analysis leads to the temperature field distribution across each one of the CPC components surfaces. The visualization of the thermal behavior, while standard operational conditions are acting, is one of the main goals of this work. After all, the temperature deeply affects the efficiency of photovoltaic cells, as an increase in terms of temperature means a decrease in terms of output voltage. This issue pushes to quantify this dependence of solar cells efficiency by temperature within the CPC context. However, it is important to highlight how an

increase in terms of incident radiation as provided by the optical performance of the CPC means a higher output power. By knowing the relation which express the mutual dependence of aforementioned parameters, a post-processing of simulation results could provide a relevant support in those terms.

While discussing the consistence of simulation data-sets, the influence of the geometrical domain discretization on the accuracy of computed temperature distributions has been also checked, choosing a suitable mesh to reduce required computational resources. The convergence is strictly affected both by the kind of mesh and by the imposed boundary conditions. The mesh-sizing and application have been conducted on each one of the domains, focusing on what have been called *critical components*, namely solar cells and reflectors. The geometry scale of the model imposes a careful tuning of the discretization procedure: details such as the reflectors thickness and shape in addition to the solar cell surfaces required a separate management. The convergence analysis on the mesh led to the definition of a suitable mesh to reduce as much as possible the required allocation space for computed matrices. It follows that the efficiency of the simulation has been checked, compatibly with the available calculation resources. Two scenarios have been then evaluated to replicate covered and uncovered CPC prototype conditions, numerically. Besides that, some assumptions about concerning the de-featuring of external convection condition have been also made, in accordance with experimental data. A constant convection condition was implemented, considering a constant wind speed that should guarantee the consistence of preliminary scenarios with acquired temperature in some points of the CPC prototype. The thermal consequences of the optical reflection of radiation were accounted by enabling a specific feature of CM, that is the surface-to-surface radiation interface. Sun movement over the day was modeled too, influencing the incident radiation angle. View factors were computed within the software, to reach a higher level of fidelity while reproducing optical phenomena. Specific materials were assigned to each one of the CPC geometric components, assigning thermal properties and emissivity factor in both ambient and spectral bands. The diffuse mirror condition allowed the modelling of full reflection by reflectors surfaces to divert the incoming sun radiation, being focused towards the semiconductor layer of the solar cells. Due to the symmetry of the prototype, the complexity of the

solving procedure has been reduced up to a half of the original structure. Besides that, the symmetry boundary condition allows to assert that the whole data-set is related to the complete geometry model. Resulting temperature data-set is then compared to the experimental one, determining samples percentage discrepancy: global discrepancy is then computed as the average of all samples discrepancies, leading to the validation of both simulation scenarios. Thus, referring to the only thermal simulation, covered and uncovered CPC scenarios were characterized by a 10.4% and 7.7% of average global discrepancy, respectively.

To understand and quantify the CPC performance as an enhanced electric energy production system, the efficiency should be considered as a suitable choice. Both configurations have been investigated: peaks in terms of power are reached at around 13:00, when the incident solar radiation is higher, obtaining 9.2 W and 10.9 W from the covered CPC and from the uncovered one, respectively. It has been noticed that the reason why CPC reaches an higher power than the covered one is because of installed covers, that reduce incident radiative heat flux through solar cells surfaces. A part of solar radiation is lost and *wasted* to increase trapped air volume temperature within the covered CPC. A validation of the simulated scenario and model has been also conducted, comparing numerical data with available experimental measurement for the covered CPC.

Efforts made by both research groups (SEAG and CIRDER) while developing the innovative CPC were integrated by the availability of a standalone application as a virtual laboratory, which allows the user to test different operating conditions on a parameterized CPC prototype. As previously discussed, multi-parametric sensitivity analysis could be conducted by means of this software tool, providing a fundamental contribution to the CPC research and optimization field.

The use of the Compound Solar Concentrators improves the characteristics and mostly the efficiency of the full system. A further improvement could be implemented by installing cooling systems fed by water, which flows to decrease the temperature of the solar cells increasing the efficiency. The simulations of n.18 cooling CPCs shows that for the first CPC, fed by water at 15°C, the maximum temperatures of the solar cells decrease if compared to the ones of an analogue non-cooled CPC plant. By positioning n.18 CPCs in series to build the CPC-powered PV plant,

the water which flows along the coils increases its temperature due to the heat inflow. Obtained trends could be used to extrapolate the temperature, efficiency and heat flux values for CPC plant with more than 18 CPC in series. However, the output water temperature gradient between CPC does not justify the addition of other concentrators. More in detail, depending on the cooling system configuration, a limit condition in terms of temperature on solar cell surfaces should be identified: in fact, by considering the proposed coil-based cooling system, a horizontally asymptotic trend is reached. Extrapolation of data from the discussed trends highlights that a cooled CPC plant provided with n.50 concentrators reaches a 60°C output water temperature from coils. It follows that an increase of the number concentrators (passing from 18 up to 50) allows a reduced benefit in terms of output water temperature increasing. Besides that, a suitable solution could be the installation of multiple series of n.18 CPC, each one provided with its own cooling system. The advantage of such kind of solution is the increase in terms of output flow rate to face external exploitation systems requirements, such as Organic Rankine Cycles plants functioning parameters.

Further works will be related to the influence of non-uniform efficiencies of solar cells along the CPC plant, due to the presence of cooling systems which should not provide a uniform temperature on semi-conductive layers of contiguous CPCs. At the same time, the implementation of optimized cooling systems in those terms will be also investigated.

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