



UNIVERSITÀ
DEGLI STUDI
FIRENZE

PhD in
Industrial Engineering

CYCLE XXXVII

Development and characterization of small scale Concentrated Solar Power collector for residential and industrial heat

Academic Discipline (SSD) ING-IND/09

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Years 2023/2024

I may not have gone where I intended to go, but I think I have ended up where I needed to be.

Douglas Adams, The Long Dark Tea-Time of the Soul

*To my family, natural and acquitted
and to Olli*

DECLARATION

I hereby declare that this submission is my own work and, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at University of Florence or any other educational institution, except where due references are provided in the thesis itself.

Any contribution made to the research by others, with whom I have been working at the University of Florence or elsewhere, is explicitly acknowledged in the thesis.

Filippo Cottone
[30/06/2025]

ACKNOWLEDGEMENTS

To my Supervisor, Prof. Maurizio De Lucia, who has believed in my and my capabilities before and during my PhD.

To Giacomo Pierucci, who guided me as a mentor, both technically and personally, in this field.

To my colleagues, who helped me in this journey

To my family and friends, who supported me and endured countless conversations of which they undersand nothing about.

To myself, for the growth and patience in this journey.

ABSTRACT

Decarbonization of emission has been a focus of global and EU policies, with both residential and industrial sector having trouble to reach their goals, both in demand reduction through efficiency gains and increase in renewables share in their energy mix used. Together these two sectors account for two thirds of total energy demand, with heating accounting for 60% of residential needs and 74% of industrial needs, yet renewable direct heat sources account only for 2% and 0.1% share of those demands. Commercially available technologies are focused on low temperature heat production on the small scale with simple yet limited by maximum temperature and efficiency at high end temperatures, while big scale system are complex and necessitate of vast open field installation, which can be difficult to find in high density industrial areas. The objective is to develop and validate a small scale CSP system capable of supplying heat both at lower and higher temperatures, that could be competing with existing technologies while covering also industrial heat needs up to 300 °C. The m-PTC module is characterized by a small dimension ($4.12m^2$), with four mirrors for a net total absorber area of $3,008m^2$, small diameter absorber tubes, high rim angle (100°), short focal length ($83.9mm$), concentrating ratio of 40. The absorber tube is one ended, with both inlet and outlet on the same side, the module has its own tracking system, two motor for the movimentation of the mirrors, which rotate around the fixed absorber tube. Experimental tests were conducted using the Steady State method of ISO 9806:2017 norm to both validate the benchmark and evaluate the performance of the m-PTC module. A benchamrk test was built, with a rotating platform to add another tracking axis to the tested system(s). A python program to aid in the search and selection of valid datapoints was also developed and used. The benchmark was validated comparing tests results on a Evacuated Tube Collector system with its certification values. Tests on the m-PTC module assessed a peak optical efficiency above 72%, with efficiency above 40% for temperatures above 200 °C.

Keywords: Concentrated solar power, small scale PTC, performance evaluation, solar tracking, SHIP

PROPOSITIONS

Motivation (max 2)

- High demand for thermal energy in residential and industrial sector, low renewables share in energy consumption
- Lack of small scale CSP solutions for temperatures up to 300 °C

Original contribution (max 4)

- Benchmark construction and validation for solar heating module testing
- Development of a python program to analyze test data according to ISO 9806:2017 standard
- Review of methodology for Steady State and Quasi Dynamic testing
- Development and performance evaluation of a small scale m-PTC system for heat production up to 300 °C

Open questions (max 4)

- Overlap of oil and water based performance testing
- CFD validation of experimental tests on m-PTC system
- Operation and performance of pilot project using m-PTC modules

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NOMENCLATURE

Acronyms

CFD	Computational Fluid Dynamics
CSP	Concentrating Solar Power
ETC	Evacuated Tube Collector
EU	European Union
HPA	Heat Purchase Agreement
LFR	Linear Fresnel Reflector
MLR	Multiple Linear Regression
NECP	National Energy and Climate Plan
ORC	Organic Rankin Cycle
PCU	Power Conversion Unit
PED	Positive Energy District
PPA	Power Purchase Agreement
PTC	Parabolic Trough Collector
PV	Photo Voltaic
QD	Quasi Dynamic
SHIP	Solar Heat for Industrial Processes
SS	Steady State
TES	Thermal Energy Storage
TFEC	Total Final Energy Consumption
WLS	Weighted Least Square

Greek symbols

α	absorption factor	[-]
ϵ	emissivity factor	[-]

η	efficiency	[-]
$\eta_{hem,0}$	peak optical efficiency	[-]
γ	solar interception factor	
ρ	reflection factor	[-]
τ	transmission factor	[-]
θ	solar incidence angle	

Latin symbols

$\dot{Q}$	power	[W]
A_G	gross area	[m ²]
G	incoming radiation	$\left[\frac{W}{m^2} \right]$
G_b	incoming direct radiation	$\left[\frac{W}{m^2} \right]$
G_d	incoming diffuse radiation	$\left[\frac{W}{m^2} \right]$
K_b		[-]
K_d		[-]

Subscripts

b	direct (beam) radiation
d	diffuse radiation

1. STATE OF THE ART

1.1 Energy demands and production

In the European Union (EU), heating and cooling of buildings represent more than 20% of the final energy demands. This energy is produced mainly from fossil fuel sources, although the share of renewable energy is growing in recent years, reaching 23% [1], but there is still much room for improvement, especially with the goals set with the Paris Agreement and later the Green Deal [2]. With their impact in the sector and overall (space and water heating constitute more than 60% of the European heating and cooling demand and 14% of total energy needs [3]), the decarbonization of this sector has become more important than ever to reach the ambitious goal set.

Energy consumption in residential and service buildings has increased in recent decades [1]: buildings in the EU account for around 40% of total energy use, with 26% from the residential sector. Most of this energy (78%) is used for space heating and hot water. In 2019, fossil fuels provided 75% of heating and cooling energy, with only 22% from renewable sources. In order to reduce fossil fuel consumption and greenhouse gas emissions in the residential sector, the EU is pursuing several strategies, notably: more extensive use of photovoltaic panels and solar thermal collectors by households [4], the electrification of heating through the use of highly-efficient heat pumps, the renovation of existing energy-inefficient buildings and the implementation of district heating networks fed by waste heat and renewable sources . In Figure 1.1 the activities per IP in the Set Plan 2018 are shown, 25 activities are towards Positive Energy Districts, while only 6 are for photovoltaics. Solar thermal collectors are particularly promising due to their scalability, from single-family homes to large-scale plants capable of heating entire towns through district heating networks. Despite the implementation of solar district heating (SDH) systems in recent years[3], their overall impact remains limited; for example, they met only 0.4% of Italy's heating and cooling demand in 2019.

In early 2023, although fossil fuel prices declined, high wholesale electricity prices persisted, impacting energy-consuming sectors[5]. Inflation and high interest rates further hindered investments, especially in emerging markets facing debt and higher capital costs. Simultaneously, substantial fossil fuel subsidies have distorted the market, disadvantaging renewables[6][5][7][8][9].

Renewables nonetheless continued to prove attractive as an affordable and secure energy source in 2023, with a record of USD 623 billion of investments and corporate power purchase agreements reaching a record 46 gigawatts (GW). [10] [11] [12] [13] [14] [15] [16] [17]

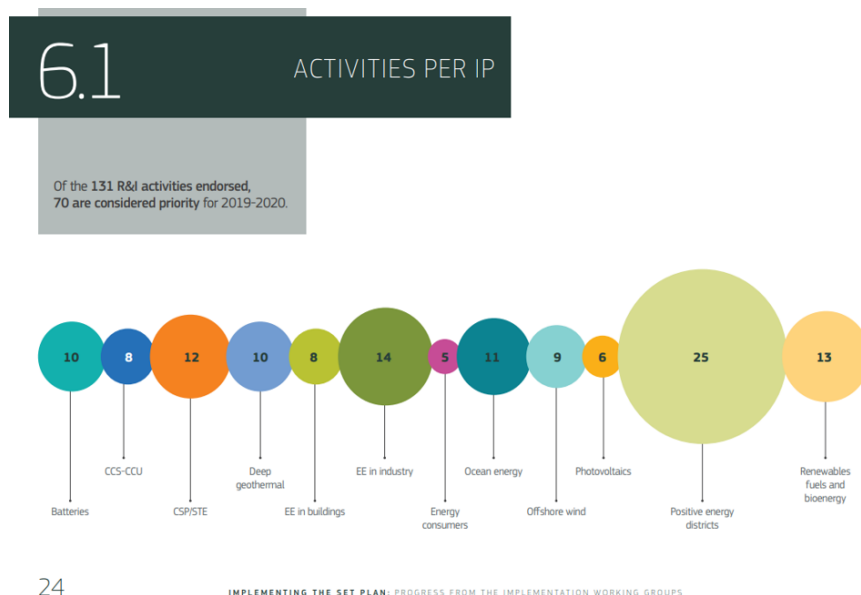


Figure 1.1: Activities distribution in Set Plan 2018[18]

The recovery packages implemented in 2022 led to a significant increase in the deployment of renewable energy; however, this progress has since stalled. To sustain momentum, more ambitious structural and integrated reforms are essential[19][20]. In 2023, signs emerged suggesting that policies supporting the adoption of renewable energy could be rolled back or weakened due to a range of economic and political pressures[21][22][23][24].

By demand sector, the share of renewables in total final energy consumption (TFEC) ranged from as high as 16.8% in industry to as low as 3.9% in transport in 2021 (latest data available)[25], as can be seen in Figure 1.2. These disparities reflect not only the differing characteristics of sectors, but also a lack of integrated policies aimed at increasing the renewable energy share both within and across sectors. Further action is needed to speed the electrification of end-use sectors and to transition to renewable heat and fuels[25][26].

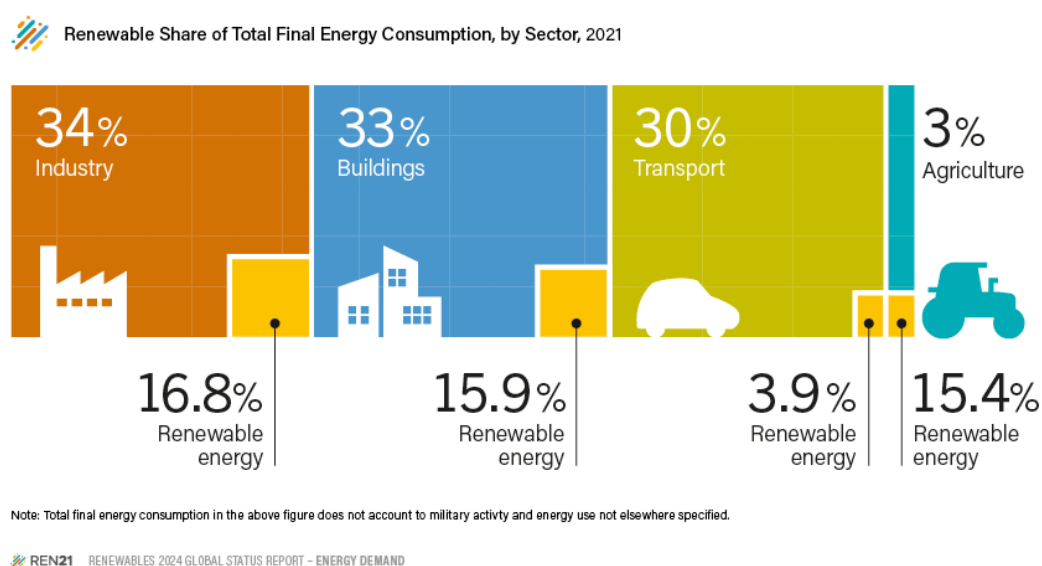


Figure 1.2: Consumption by sector and relative renewables share[19]

1.1.1 Industry sector

Industry is the largest energy consuming sector and the sector with the highest share of renewables, accounting for 34% of the energy consumption in end-use sectors in 2022 with a 16.8% share of renewables[27]. Renewable heat, fuels and electricity are all playing key roles in industrial decarbonisation efforts.

Despite a 5% absolute increase in renewable energy use in 2021, the share of renewables in industrial energy consumption remained relatively steady in 2020 and 2021 as overall energy use also increased. The share of direct energy use for heat in industry was 74% in 2021, of which 12.1% was renewable energy. Energy demand in industry stagnated in 2022 after increasing rapidly in 2021 to surpass the pre-pandemic level by 5%[27]. Due to the diverse processes and temperature requirements of industrial sub-sectors, the share of renewables in energy use varies from 7% in the chemical and petrochemical industry to 44% in paper, pulp and printing. Renewable hydrogen policies for heavy industry expanded in 2023, especially in Europe, with the EU's New Renewable Energy Directive stating that at least 42% of the hydrogen in industry should come from renewable fuels of non-biological origin by 2030.

Two key industries – iron and steel (17.2%) and chemicals (16.7%) – together accounted for

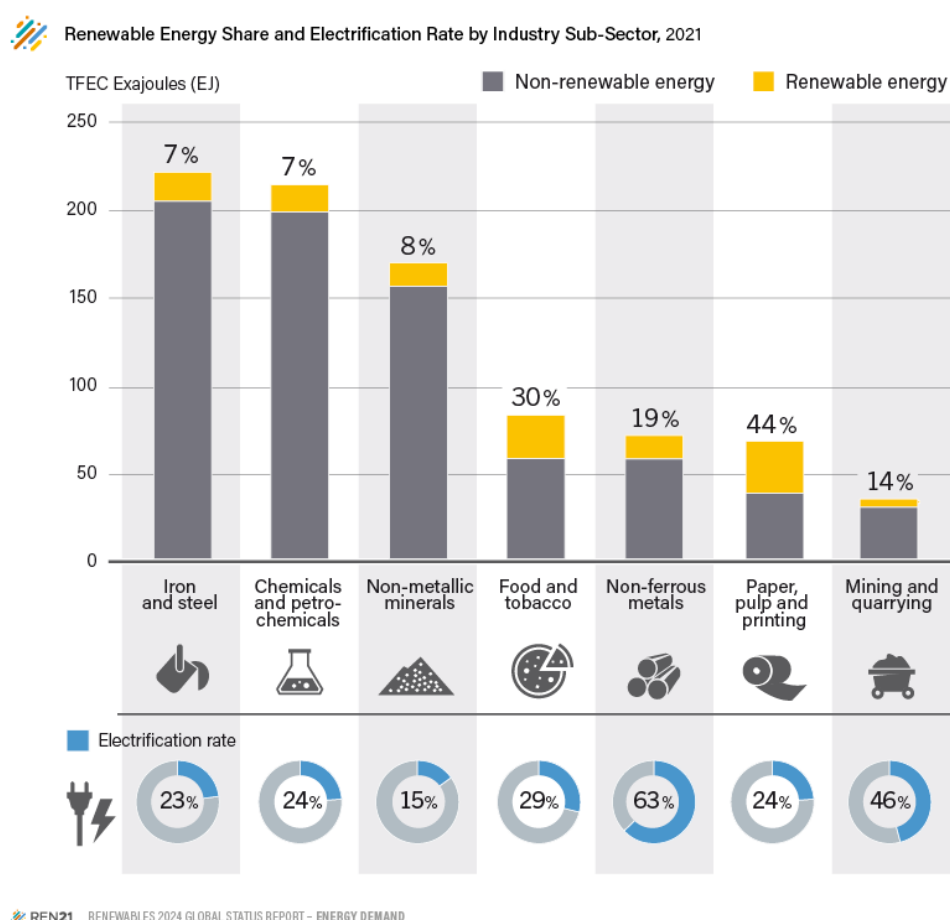


Figure 1.3: Renewable energy share and electrification rate by industry sub-sector, 2021[19]

more than one-third (34%) of the industrial energy demand in 2021, followed by non-metallic minerals (13.2%, including cement and concrete), food and tobacco (6.4%), non-ferrous metals (5.5%), pulp and paper (5.2%) and mining (2.7%), as can be seen in Figure 1.3[27].

Industrial enterprises are very important both in economics and employment, generating 28%

of global GDP in 2022 and 23% of total employment [28][29]. Globally, industrial production underwent significant disruptions in 2022 as a result of the Russian Federation's invasion of Ukraine and a slowdown of the construction sector in China [30], but in 2023 industrial activity produced around 9.37 gigatonnes of CO_2 , an increase of 4.3% from the previous year [31]. Around 71% of direct industrial CO_2 emissions came from three sectors: cement and concrete, iron and steel, and chemicals and petrochemicals [31].

In the European Union (EU), industrial production slowed in 2023 due to high energy prices and interest rates, weak domestic demand and strong international competition [31]. Industrial CO_2 emissions fell by 34 million tonnes in the EU and 26 million tonnes in the United States [31]. In contrast, CO_2 emissions from the sector rose by 32 million tonnes in China, 44 million tonnes in India and 39 million tonnes in Indonesia in 2023 [31].

Since 2010, the energy mix of the industry sector has remained relatively stable, with a heavy reliance on fossil fuels. The share of fossil fuel use in industry declined slightly from 87.2% in 2011 to 82.7% in 2021¹, due mainly to the ongoing electrification of industrial heat combined with the rise of renewable electricity use, which more than doubled during the decade. The renewable energy share in industry in 2021 was 16.8%, split nearly evenly between modern bioenergy and renewable electricity [27], with renewable heat reaching only 0.1% (Figure 1.4). Despite a 5% absolute increase in renewable energy use in 2021, the share of renewables in industrial energy consumption remained steady in 2020 and 2021 because overall energy use also rose [32].

The share of electricity in the industrial sector reached 26% in 2021, up from 22% in 2011[20].

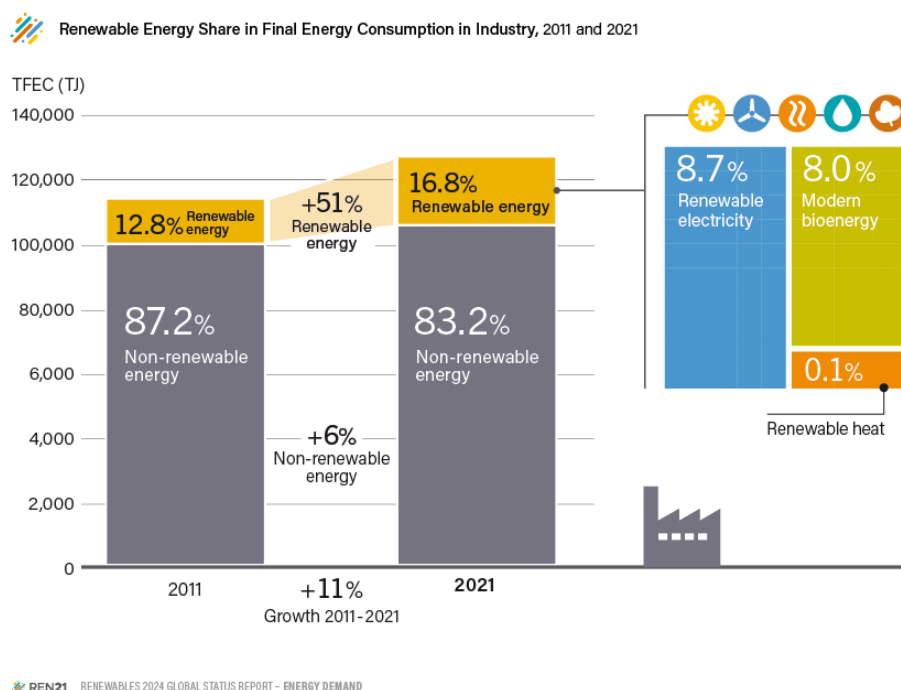


Figure 1.4: Renewable energy share in final energy consumption in industry, 2011 and 2021[19]

Electricity can provide heating across a wide range of temperature levels, including through heat pumps for low-temperature applications and electric arc furnaces for high-temperature applications (such as steel making). Electrical heat also can be provided through resistance, infrared, induction, microwave and plasma heating [33]. Electricity is used to power a range of industrial processes, including alumina electrolysis for aluminium production, and

¹latest complete data available

electrowinning, which produces copper and nickel [34][35].

The share of energy use for heat applications in the industrial sector was 74% in 2021, down from 78% in 2011 [20]. Renewable energy represented 12.1% of the direct use of process heat in 2021 [27]. The majority of this was modern bioheat (89%), followed by renewable electricity (10%) and direct solar thermal and geothermal heat (less than 1%) [27]. Bioenergy use is most common in biomass-based industries that generate energy from their own waste. In the pulp and paper industry, bioenergy (mainly black liquor from pulping) contributed 40% of the total final energy consumption in 2022 [36]. Additional ways to replace fossil fuels for process heat include alternative renewable fuels such as renewable-based hydrogen, which is gaining momentum in steel, ammonia and glass making. Other renewable heat sources, such as geothermal and solar thermal, are used in the food and chemicals industries.

Heat dominates energy consumption in industry. It is used for washing, cooking, sterilizing, drying, preheating boiler feed water and other uses and is essential in refining raw materials, smelting metals and producing chemicals [37][38]. The share of heat in industrial energy use varies by sub-sector, ranging from 32% in machinery production, to 41% in transport equipment manufacturing, to 85% in glass and cement industries and the share of electrification and renewable energy share varies broadly across sub-sectors [39] (See Figure 1.3).

As of 2021, only 12.1% of heat consumption in the industry sector was renewable, and solutions are emerging to increase this share across specific sub-sectors, depending on the required process temperature [27]. Process heat over 750°C remains dependent on fossil fuels, but in some cases resistance, infrared, induction, microwave and plasma heating can provide electric-based solutions up to 1500°C, with renewable hydrogen and biomass also positioned as strong alternatives [33]. Electrothermal energy storage (ETES) technologies have commercially available solutions for heat processes that require temperatures up to 400°C [40]. For processes below 200°C, direct electrification through renewable electricity has gained momentum, with heat pump technology evolving to provide medium-temperature heat [41]. Heat purchase agreements (HPAs) also are on the rise, especially in industries with low and medium temperature requirements.

The use of modern bioenergy in industry increased 46% between 2011 and 2021, rising from 8 exajoules (EJ) to 10.1 EJ. However, the share of bioenergy use relative to total final energy consumption in industry increased only slightly during the decade, from 7% to 8%.

Solar thermal can be an efficient means of providing zero-carbon heat and a cost-effective alternative to the electrification of heat. Although it has been used mainly for low-temperature applications, new solar thermal designs serve applications with temperature requirements of up to 400°C [42]. High initial capital costs, long lead times, and low client awareness have led to limited uptake, even in sectors with significant technical and economic potential, such as textiles and food. However, in 2023 the Dutch packaging and materials manufacturer Avery Dennison commissioned Europe's largest concentrated solar thermal platform and storage unit, with a peak energy yield of 2.7 gigawatt-hours (GWh) of thermal power [43][44]. By the end of 2023, at least 1,209 solar heat for industrial processes (SHIP) installations, totalling more than 951 MWth, were supplying process heat to factories worldwide. At least 116 projects came online in 2023 alone. Projects are getting bigger, and the proportion of systems with temperatures above 100°C is increasing rapidly [45].

High-temperature geothermal energy can be used directly to generate electricity, heat, or both. Direct geothermal use accounted for less than 1% of the total thermal energy use in industry in 2021, mainly in food processing, packaging and transport, and mining. Barriers to wider adoption include resource availability and high upfront costs.

In process heat, renewable electricity (through heat pumps for low-temperature heat), solar thermal heat (boosted by heat pumps) and renewable hydrogen (for higher-temperature processes) are well positioned to provide a stable and secure energy supply.

In Spain, the cement manufacturer Cemex, in partnership with the Swiss-based concentrated solar company Synhelion, achieved industrial production of clinker (the most energy-intensive part of cement manufacturing) in Madrid using only solar heat [46].

Solar thermal heating is another existing solution that is well adapted to low and medium-temperature industrial processes [47].

Operation temperature for industrial process heat is divided into three ranges: low ($T < 100^\circ\text{C}$), medium ($100^\circ\text{C} < T < 250^\circ\text{C}$) and high ($T > 250^\circ\text{C}$). [48]

Less than a third of industrial heat energy consumption is under 150°C , 22% is related to the temperature range of 150°C to 400°C and just under a half (48%) is related to the high temperature (above 400°C) [49][50].

Concentrating collectors could be the right technology to produce heat at medium temperature to provide thermal energy to users that require temperatures between 85 and 250°C . Users with high consumption rates and low-temperature heat demand like domestic hot water and space heating in addition to the industrial process heat applications like ironing, cleaning, drying, sterilization, etc. are the main medium temperature users [51][52][53]. However, IEA reported on December 2015 that 0.3% of total installed solar thermal capacity (about 88MWth) is related to the solar heat for industrial processes[48].

Industrial application		Temperature range [$^\circ\text{C}$]	
Food&beverage	cleaning	80	150
	pasteurization		
	sterilization		
	drying		
	cooking		
Plastic	drying & extrusion	150	200
Chemical	thermal treatment	90	250
	boiling		
	distillation		
	drying		
Paper	whitening & drying	130	180
Textile	Washing	50	150
	Ironing		
	thermal treatment		
	whitening		
Industrial washing	steam washing	100	150

Table 1.1: Distribution of industrial heat demand by sector and temperatures [54]

1.1.2 Residential Sector

The buildings sector is a significant energy consumer, and the adoption of renewable energy sources such as solar panels and energy-efficient systems is contributing to the reduction of carbon emissions.

The share of renewables in the energy demand of buildings increased to 15.9% in 2021, up from 11.3% in 2011. Renewable energy provided 11.5% of the heat consumed in buildings, showing an increase of 0.5%.

The share of electricity in total final energy demand in buildings has risen from 30% in 2010 to 35% in 2022.

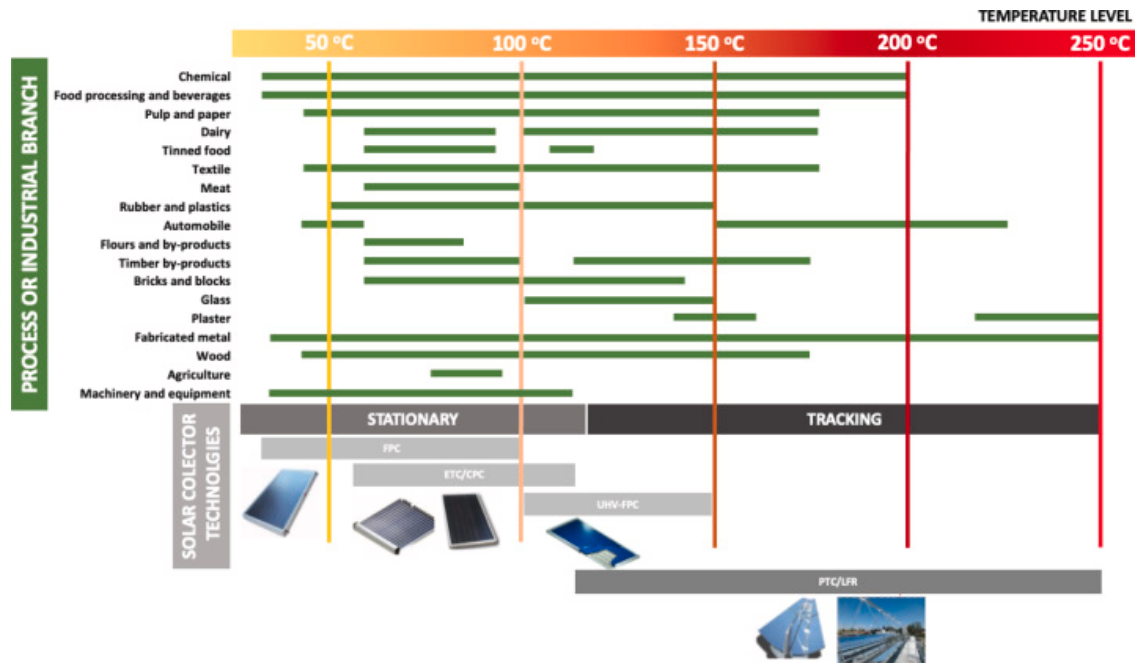


Figure 1.5: Distribution of industrial heat demand by sector and temperatures, solar technologies temperature ranges[55]

Estonia, Ireland, and Poland have launched various subsidy schemes to encourage the adoption of renewable energy heating systems, including heat pumps.

Buildings account for around one-third of global energy demand and carbon emissions, with direct energy consumption in buildings representing 30% of global final energy consumption in 2022. As of 2021, around 15.9% of the energy demand in buildings was met by modern renewable sources (see Figure 1.6), up from 11.3% in 2011. Renewable energy share of heat consumed in buildings stood at 11.5% in 2021, an increase of 0.5%.

Energy consumption in buildings varies greatly around the world, including among the top energy-consuming countries (see Figure 1.7). Energy is consumed in buildings mainly for space and water heating, space cooling, cooking, lighting, and powering of appliances and electronics. This use takes various forms, such as electricity, fuels and direct thermal renewable energy.

Thermal applications accounted for around three-quarters of the final energy consumption in buildings in 2021, with the remaining quarter being electricity used to power appliances. The share of electricity in the total final energy demand of buildings has increased from 30% in 2010 to 35% in 2022, in parallel with a shift towards renewables. Space cooling is the largest growth sector among energy end-uses in buildings, rising more than 5% in 2022. The deployment of heat pumps, electric boilers and other electric heating systems has helped drive a shift towards renewable electricity to heat buildings (see Figure 1.8). This has boosted the use of renewables in the heat sector in China, the European Union (EU), and the United States, although the transition has been gradual.

Improvements in the efficiency of building envelopes and of end-uses within buildings are helping to improve the economics of renewable energy applications, supporting the deployment of adjacent technologies such as heat pumps. Solar PV, wind power and other renewable energy technologies are increasingly competitive with fossil fuels owing to falling technology costs, increased efficiency, and the impetus for strengthening energy security and independence. Innovations in generation technologies and energy storage continue to enhance efficiency and reliability while also bringing down costs, making renewables suitable for a wide range of applications in the built environment.

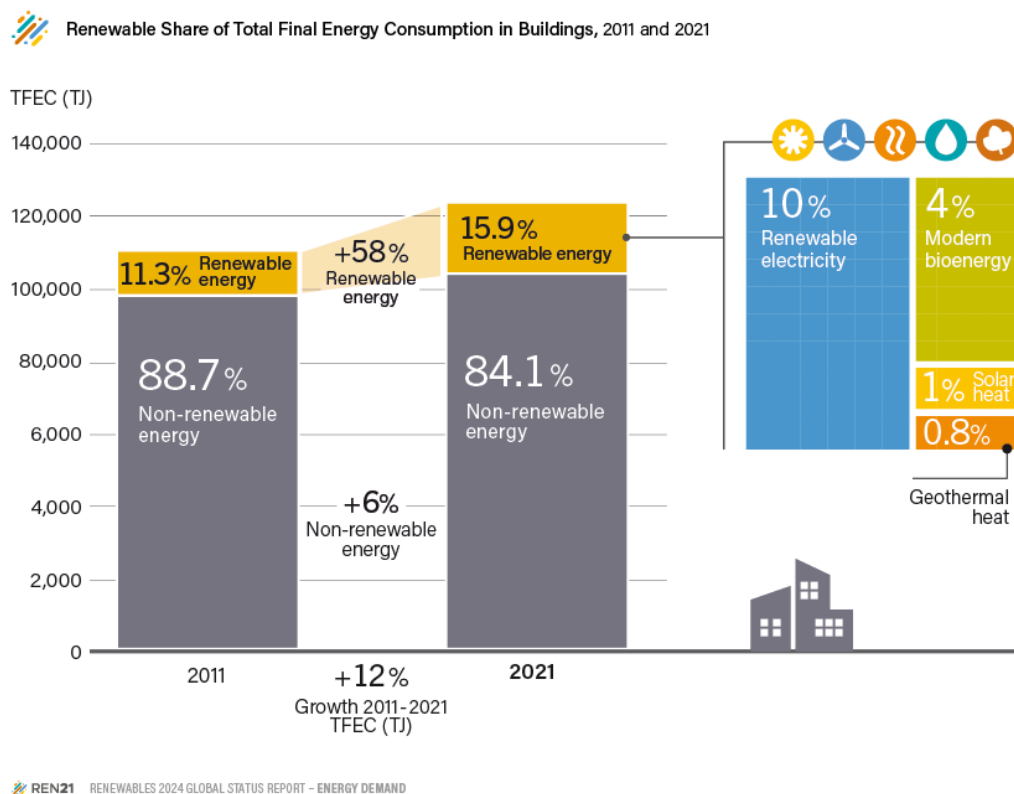


Figure 1.6: Renewables share of total final energy consumption in buildings, 2011 and 2021 [19]

With regard to renewable energy targets for heating, the EU aims to increase the share of renewables used in heating and cooling by 0.8% annually to 2026 and 1.1% annually to 2030. In 2023, several EU Member States submitted draft updates of their energy and climate plans, adopting new 2030 targets for the renewable share of heating in the buildings sector – including Latvia (68%), Cyprus (47.9%), Slovenia (66%) and Italy (42.5%). A few countries have targeted the uptake of renewables in district heating, including Denmark (85% by 2030) and Croatia (1.3% annual increase to 2030).

Heat roadmaps are increasingly being developed to analyse current energy sources, infrastructure, and emissions, and to chart a course to decarbonisation through renewables. These plans aim to guide policy development, foster collaboration and encourage investments. Key strategies in heat roadmaps include promoting the uptake of renewables, such as geothermal, solar thermal and biomass; promoting efficiency; encouraging the deployment of heat pumps; using waste heat; building and improving district heating networks; and developing smart grids that can flexibly combine heat and power infrastructure. The Heat Roadmap Europe initiative has developed strategies for 14 countries.

Policies for increasing on-site and distributed renewable energy generation in buildings also continued to develop, especially for rooftop solar systems (PV and thermal). Türkiye introduced new incentives for rooftop solar power, including net metering for homeowners. Greece is providing grants for households to purchase and install rooftop PV systems at up to 76% of the cost. Bulgaria launched a household solar rebate scheme for PV and thermal systems, totalling USD 133 million (BGN 240 million). India announced a new rooftop PV subsidy scheme for 10 million households and extended its previous solar subsidy scheme to 2026. Kenya updated its draft regulations for solar water heaters, making it mandatory to install the units on all residential and commercial buildings, schools and health centres.

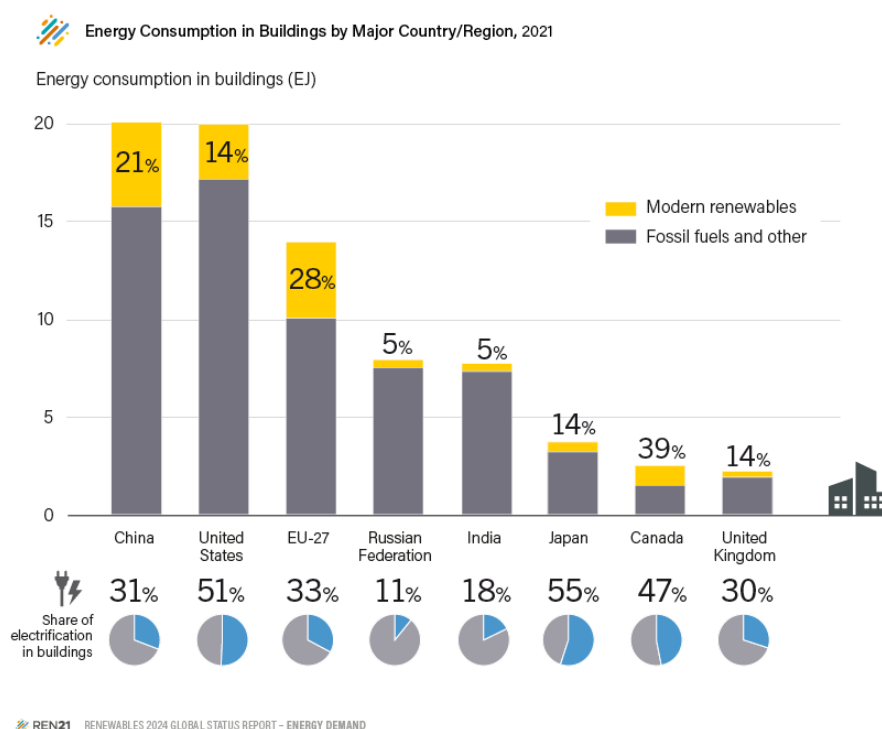


Figure 1.7: Energy consumption in buildings by major country/region, 2021[19]

Challenges

- **High initial costs:** Despite the long-term savings, the initial costs associated with retrofitting buildings with renewable energy systems or constructing new buildings with these systems remain a significant barrier for many stakeholders.
- **Regulatory and policy hurdles:** While many countries have supportive policies, others still face regulatory hurdles that slow the adoption of renewables in buildings. Inconsistencies in regulations across regions and insufficient governmental support can impede progress.
- **Slow growth in renewable heating:** While renewable electricity has seen rapid integration in buildings, renewable thermal technologies such as bioenergy, solar thermal and geothermal have grown more slowly.

Opportunities

- **Government incentives and policy support:** Enhanced government policies, such as subsidies and tax incentives, have greatly bolstered the adoption of renewable technologies in the buildings sector. Policies are also incorporating specific requirements for the integration of renewables and energy efficiency into new building codes and standards.
- **Growing market for net zero buildings:** The market demand for net zero energy buildings is strong and growing, driven by both environmental concerns and long-term economic benefits. This trend is supported by significant increases in certifications and interest in high-performance buildings.
- **Global collaborations and agreements:** International initiatives, such as the Buildings Breakthrough Initiative launched at COP 28, aim to make near-zero emissions and

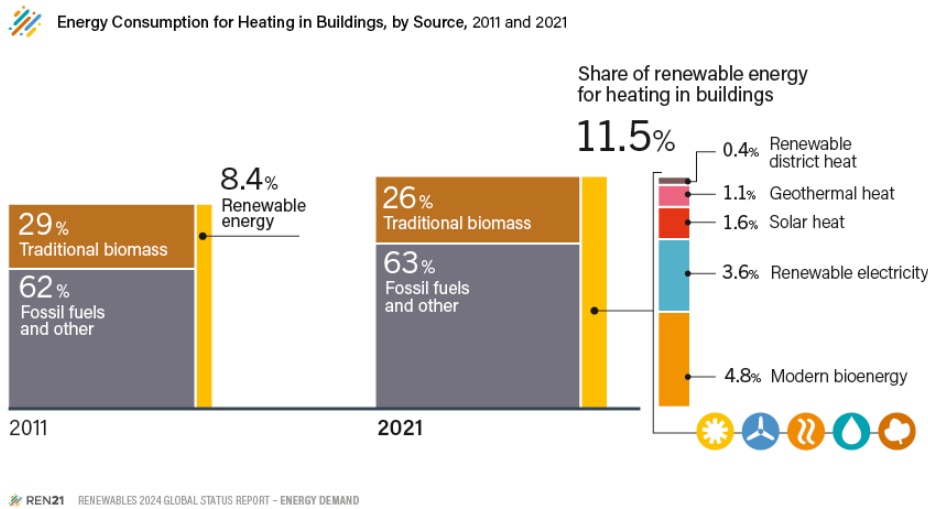


Figure 1.8: Energy consumption for heating in building by source, 2011-2021[19]

climate-resilient buildings the norm by 2030, highlighting a strong commitment to global standards and practices.

1.2 Solar thermal

Between the various renewable sources, sunlight is available almost everywhere in the world, and can be harnessed quite easily. While Photovoltaic (PV) technologies are focused on the direct conversion of sunlight to electrical power, they have generally low efficiency rates of conversion, (from 15% to 25%). Solar thermal technologies, on the other end, are focused on converting the incoming sunlight into heat, which can be used directly or further refined into electric power.

Furthermore, solar thermal technologies can be divided in concentrating and non-concentrating. Non-concentrating technologies include unglazed solar collectors (figure 1.9), Flat Plate (figure 1.10), Evacuated Tube Collectors (ETC) (figure 1.11). In table 1.2 the different characteristics are summarized, both for concentrating and non concentrating technologies.

1.2.1 Non-Concentrating technologies

Non-concentrating technologies are cheap, simple in their construction, don't require any tracking, low maintenance, but have low output temperature and efficiency.

Unglazed Collectors Unglazed solar collectors simply consist in a number of pipes, running from the inlet main pipe to the outlet main pipe, on top of a blackened substrate to increase the absorbed heat. These systems are very simple to build and maintain, but don't reach very high temperatures.

Flat Plate Collectors Flat Plate technology builds over the unglazed type, putting a thermal insulating layer under the piping, and covering it up with some glass layer, to further reduce the heating losses to the ambient temperature, and also to increase the efficiency and temperatures with a little of greenhouse effect (solar radiation can enter, but irradiation due

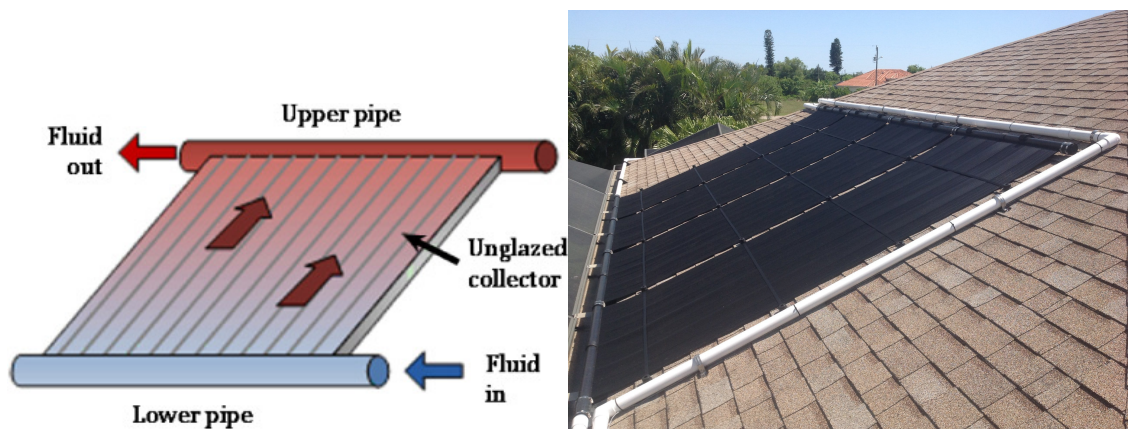


Figure 1.9: Unglazed solar collectors

to the pipe temperature is reflected back by the glass). Still, having no vacuum insulating, is exposed to heat loss with convection and conduction.

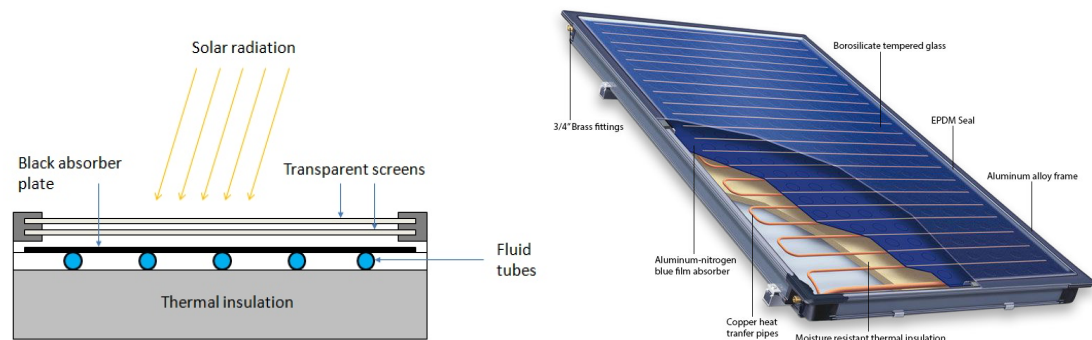


Figure 1.10: Flat Plate Collectors

Evacuated Tube Collectors As the names suggests, this type of collectors implements an evacuated tube over the piping, to reduce the conduction and convection heat losses, as well as radiative ones. A common setup comprises of some U shaped pipes, running from the main inlet to the main outlet (usually both at the top of the collector), sometimes connected to a thin flat surface to increase their area, which is placed inside a double glass tube, with some vacuum in between the glass layers.

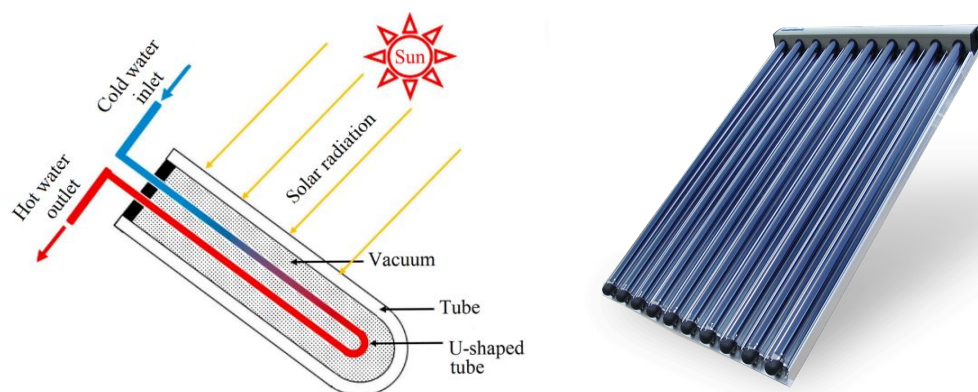


Figure 1.11: Evacuated Tube Collectors

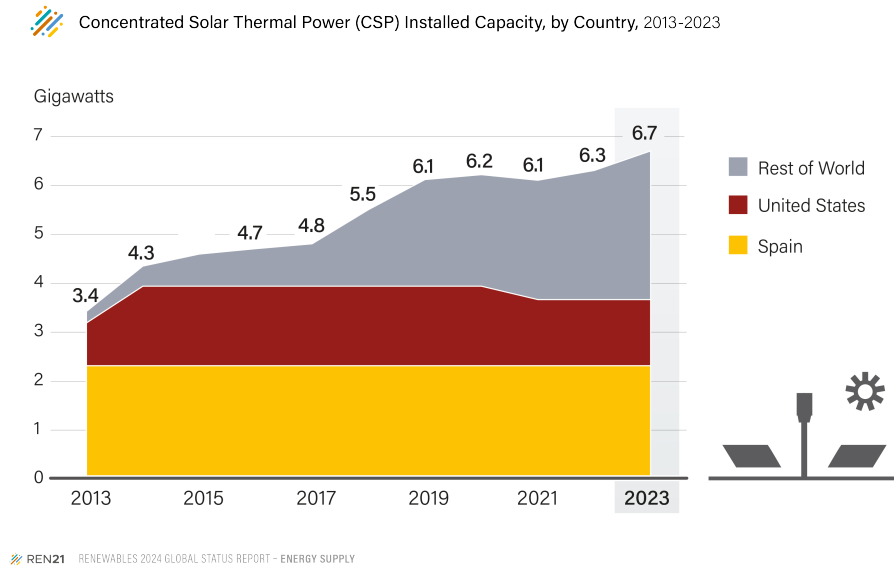


Figure 1.12: Concentrating solar thermal power installed capacity by country (2013-2023) [20]

1.2.2 Concentrating Technologies

On the other spectrum, we find Concentrating technologies, which working principle relies on capturing the sun's light rays on a wide surface, and concentrating them on a smaller area, multiplying the effective incoming radiation, and thus achieving higher temperatures and efficiency thanks to limited heat losses surfaces, among other things.

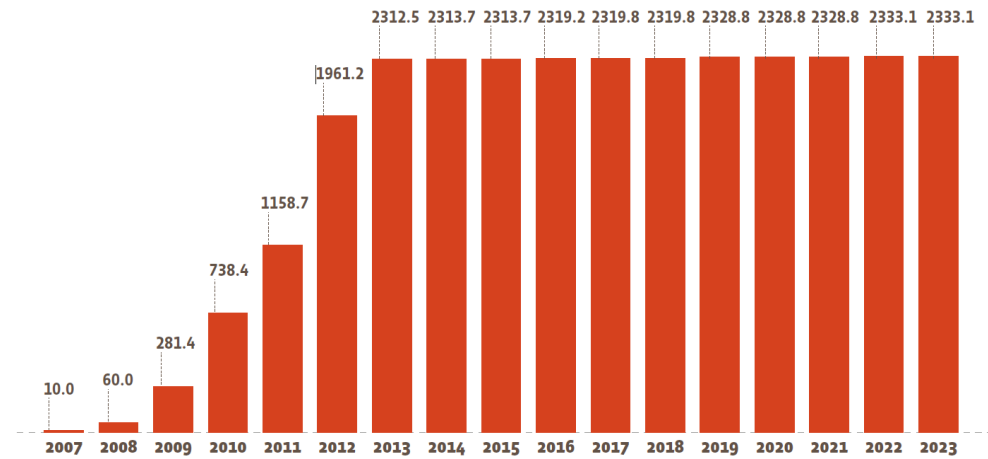
In order to be able to constantly focus the sunlight on their targets, they need precise ways to keep track and follow the sun position, as very precise optics, reflection surface and targeting are involved. These are referred to as Solar Tracking Systems, which can vary from the use of various type of sensors to infer the position of the sun, to theoretical calculation of its angle relative to the collector and the movement of the reflective or concentrating part to accommodate for its movement. They will be discussed in depth in section 1.2.3.

In 2023, the total installed capacity of concentrated solar thermal power (CSP) grew 400 megawatts (MW) to reach 6.7 GW (see Figures 1.12 for world and 1.13 for EU). CSP with thermal energy storage is increasingly valued as a variable renewable energy technology that can provide storage and night-time power in synergy with solar PV and wind energy. Although first-generation parabolic trough plants remain the most proven and reliable CSP technology, second-generation CSP plants using molten-salt towers are increasingly being deployed, primarily in China.

Concentrating Solar technologies are promising and expected to have an important role in the energy transition, as we can see in figure 1.14 for the European Union.

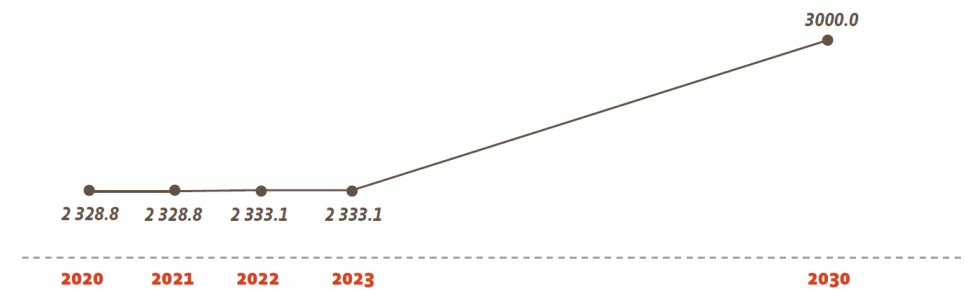
The global CSP market has shown signs of a renewed dynamic. In 2023, the Noor Energy 1 project, a 950 MW hybrid PV-CSP plant, was inaugurated during the United Nations Climate Change Conference (COP 28) in Dubai, United Arab Emirates. Additionally, China initiated several new projects, expanding the pipeline of Chinese CSP plants to more than 1 GW under construction and 3 GW in development. Spain and the United States continued to lead in cumulative CSP installed capacity in 2023, followed closely by the United Arab Emirates and China. If current patterns hold, China is positioned to take the lead in both CSP deployment and supply chain capabilities by the end of the decade.

In 2023, the remaining 400 MW of a 600 MW parabolic trough field came online at the Noor Energy 1 project in the United Arab Emirates. The plant is now the world's largest CSP



Source: EurObserv'ER 2024

Figure 1.13: European Union concentrated solar power capacity trend (MW) [56]



Source: EurObserv'ER 2024

Figure 1.14: EurObserv'ER projection of the evolution of CSP capacity installed in the EU 27 (in MW) [56]

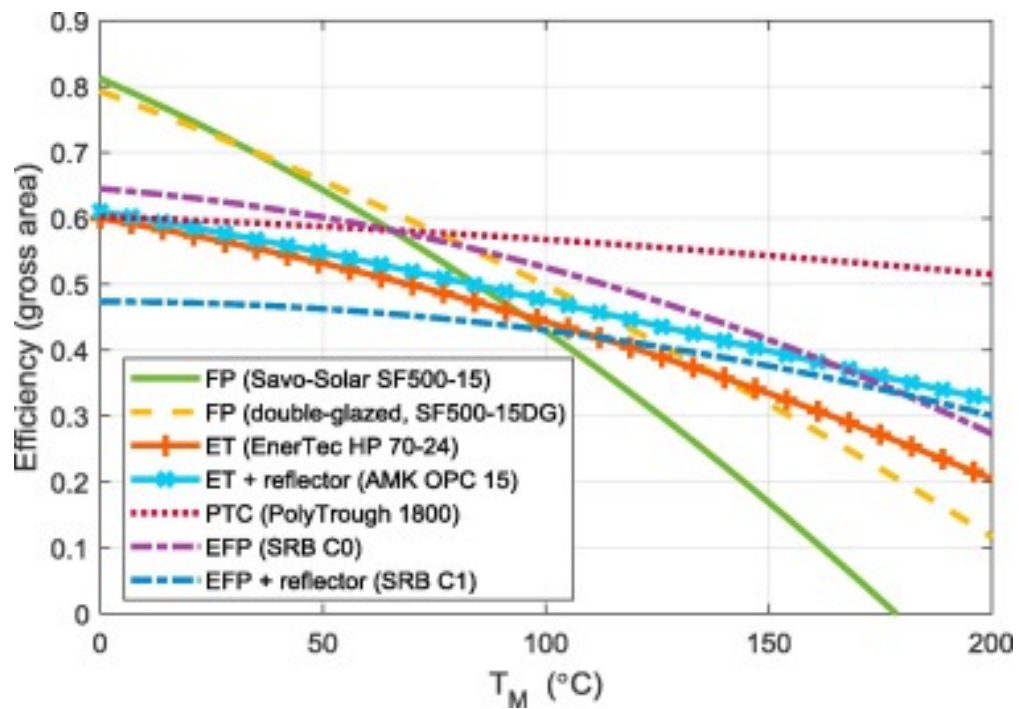


Figure 1.15: Performance comparison of different solar technologies [57]

facility, with 700 MW of CSP capacity (including a previously completed 100 MW central receiver tower). It showcases the synergistic deployment of CSP alongside large-scale solar PV installations to deliver solar power through the night. The project uses state-of-the-art US and European second-generation CSP technologies, including large-aperture parabolic troughs and the latest molten-salt towers (with more than 10 hours of thermal energy storage in hot and cold tanks). Noor Energy 1 has a total power storage capacity of 5.9 gigawatt-hours (GWh), making it the largest thermal battery in the world.

In China, several key policies related to CSP were implemented at the national and provincial levels during 2023, helping to clarify technical prescriptions and the role of CSP as a peak-shaving resource. The country's total installed CSP capacity remained at 588 MW, the same level as in 2020, as no new capacity was connected to the grid. The first plants of China's "CSP+" projects were expected in 2024 and include mostly 100 MW towers, as well as some troughs and Fresnel plants, co-located with solar PV and wind power capacity. A typical configuration is Cosin Solar's Jinta project, which finished Heliostat assembly at the end of 2023 and deploys a 100 MW molten-salt tower with eight hours of storage alongside 600 MW of solar PV. China announced some 13 additional plants with a combined capacity of 1.35 GW, 5 of which will be located in the high altitudes of the Tibet Autonomous Region. Italy was the only country in Europe with a CSP plant under construction as of 2023. The CSP 3 Bilancia project in Sicily is the country's third 4 MW Fresnel plant, with 16 hours of storage, and is slated for completion in 2024. The plant is expected to contribute to Italy's goal of 873 MW of CSP capacity by 2030, as outlined in the updated National Energy and Climate Plan (NECP).

Spain had the largest installed CSP capacity globally, at 2.3 GW, and in 2023 CSP plants delivered around 5 TWh, or 2% of the country's electricity needs, to the grid. However, no new activity occurred during the year, challenging Spain's efforts to deliver on its goal of 4.8 GW of CSP by 2025, set out in the 2020 NECP. After the disappointing first-ever 220 MW CSP auction held in 2022, which did not award any projects, no additional or adapted auctions occurred in 2023. Instead, Spain updated its NECP to shift its target year for the 4.8 GW of CSP capacity from 2025 to 2030.

Elsewhere in the world, no new CSP plants broke ground in 2023. In South Africa, the Redstone project was expected to connect to the grid in 2024. No further projects are in sight in the country, as CSP has been excluded from capacity expansions in South Africa's Integrated Resource Plan since 2019.

In Morocco, the Noor Midelt project had not started construction as of 2023, despite having been awarded a power purchase agreement (PPA). Several stakeholders view the technology as too expensive and error prone – pointing to the patchy record and high power generation cost of the country's Noor Ouarzazate project – and have recommended instead substituting CSP with solar PV and batteries.

Several countries announced their intentions to tender new CSP plants. India was actively preparing a CSP tender for 2024, which would end a ten-year hiatus and build on the operational experience of several CSP plants completed during the country's National Solar Mission. Kuwait launched a request for proposals for 200 MW of CSP for the long-awaited Shagaya project, and Egypt has explored using CSP heat and power for desalination. Botswana was working on a 200 MW tender for CSP.

CSP costs remain challenging to assess, in part because few successful tenders have occurred, and the new plants being built lack transparent information on cost and financing. Because of its size and its recent completion, Noor 1 is widely regarded as the current CSP cost reference, with a PPA of USD 7.3 cents per kilowatt-hour; however, the project's financing conditions and concessional financing make it likely that CSP is still more expensive elsewhere. In general, it is increasingly difficult to isolate the cost of electricity from CSP, given the

trends towards dispatchable generation during only a few hours, and hybridisation with other generators. As with Noor 1, PPAs are usually awarded for all co-located technologies. Moreover, the investment cost for CSP may only be reported for the whole project: for example, China's hybrid CSP plants rarely report the CSP investment cost, although the known investment cost is much lower than in the demonstration plants completed during 2016-2020.

Thanks to their ability to focus and concentrate the sunlight, as mentioned, this typology of solar collector are able to reach higher temperatures - up to 800 degree C **cit needed**, and are often used in electric power production, with and without coupling conventional thermal electric production systems, as well in some direct use of the heat produced for steam use in industrial processes. In figure 1.16 are illustrated the most used concentrating technologies and their share in the mix. From the top left, clockwise, they are the Parabolic Dish, Linear Fresnel, Parabolic Trough, Solar Tower. These are also known as CSP, Concentrated Solar Panels technologies.

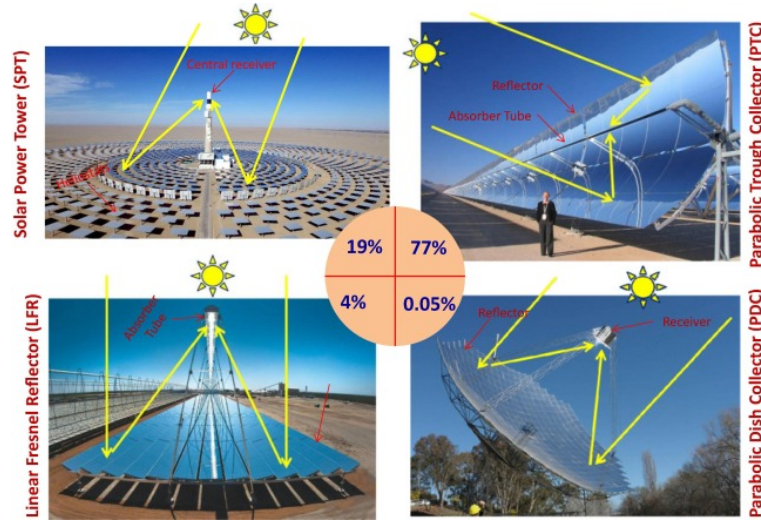


Figure 1.16: CSP technology distribution in 2003 [58]

Collector type	Tracking system	Absorber	T_{max} [$^{\circ}C$]
Flat plate	Stationary	Flat	80
Evacuated tube	Stationary	Flat	200
Compound parabolic	Stationary/one-axis	Flat/tubular	250
Parabolic trough	One-axis	Tubular	450
Linear Fresnel	One-axis	Tubular	250
Parabolic dish	Two-axis	Point	1500
Heliostat field	Two-axis	Point	2000

Table 1.2: Summary of solar technologies tracking systems and maximum operation temperatures [59]

Parabolic Dishes A typical SDSS system is composed of a parabolic concentrator connected to a power conversion unit (PCU) as shown in Fig.1.17 (a) and (b). The latter consists of

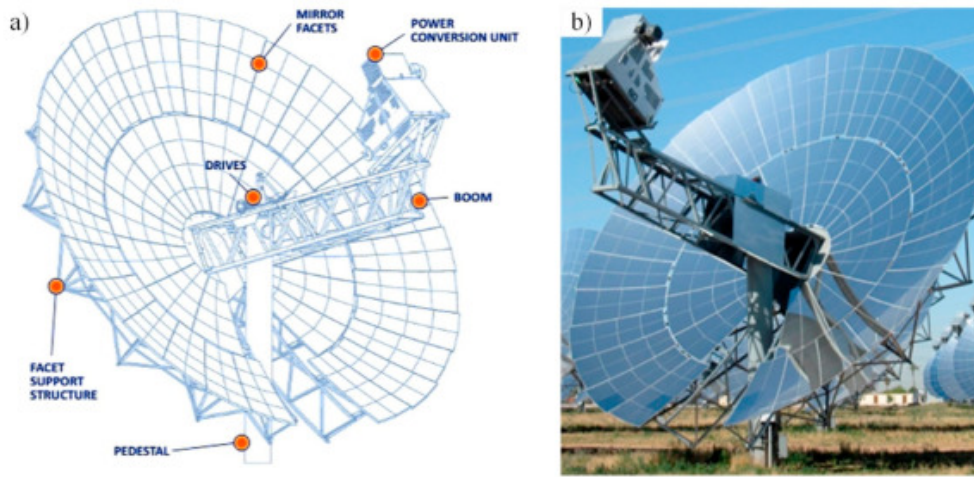


Figure 1.17: Solar dish schematic and example[69]

a Stirling engine, a spiral cavity receiver, and an alternator. The incident solar radiation is collected using the parabolic concentrator and concentrated on its focal point where a receiver is fixed (Singh et al., 2018[60]; Zayed et al., 2021[61]). The receiver surface received a huge amount of concentrated solar energy and consequently its temperature increases to very high levels (Hafez et al., 2016[62]; Shouman and Khattab, 2015[63]). This absorbed heat is used to heat up hydrogen or helium gases, which are used as working gases (WG) (Pitot de la Beaujardiere and Reuter, 2018[64]; Sharaf Eldean et al., 2017[65]). The temperature of the WG is elevated and may reach high values of 650–750 °C (Malali et al., 2019[66]). The WG is utilized to operate the Stirling engine in which the thermal energy is converted into mechanical energy through expansion/compression cycles (Ahmadi et al., 2017[67]; Kaldehi et al., 2017[68]). The boom allows for PCU mounting such that the PCU is in the correct position relative to the mirror facets. An electrical generator is then used to convert this produced mechanical energy into electrical power.

Linear Fresnel Linear Fresnel Reflector (LFR) is similar to parabolic trough collectors, but use a series of long flat, or slightly curved mirrors placed at different angles to concentrate the sunlight on either side of a fixed receiver which is located several meters above the primary mirror field (see Fig. 1.18). Each line of mirrors is equipped with a single-axis tracking system (either in the South-North direction or East-West direction) and is optimized individually to ensure that sunlight is always concentrated on the fixed receiver. The receiver consists of a long, selectively-coated absorber tube. LFRs are so-named due to their use of the Fresnel lens effect, which allows a mirror with short focal length and a large aperture therefore reducing the volume of reflector material. For LFR systems, there are a large number of parameters (Montes et al., 2017[70]) to consider when designing the collector field. These design variable include such as the number of collectors, the spacing (Zhu et al., 2016[71]), individual mirror widths, the curvature of the primary mirrors (Zhu et al., 2017[72]), and the height and the position of the receiver (Abbas and Martínez-Val, 2017[73]). Therefore, there is a high degree of freedom in the geometric design, which can be optimized based on Levelized Cost of Electricity (LCOE) minimization (Martinez-Val et al., 2015[74]).

Solar Towers The Solar power tower consists of a field of thousands of mirrors (heliostats) surrounding a tower which holds a heat transfer fluid to concentrate light on a central receiver atop a tower[75] (Fig. 1c). Each heliostat has its own tracking mechanism to keep it focused on the tower to heat the transfer fluid, which is then used to run a turbine. Power towers

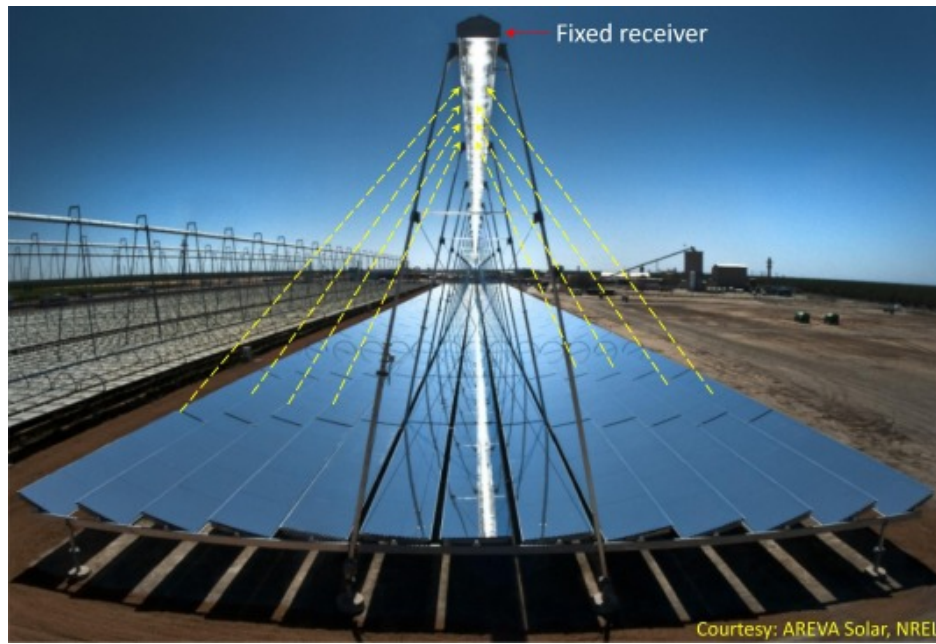


Figure 1.18: Schematic of a typical Linear Fresnel Reflector (LFR) with fixed receiver[58]



Figure 1.19: Gemasolar Concentrated solar power tower near Sevilla, Spain[58]

are more cost effective, offer higher efficiency and better energy storage capability among CSP technologies. The Solar Two in Barstow, California and the Planta Solar 10 in Sanlúcar la Mayor, Spain are representatives of this technology [76]. Table 1 shows the world largest concentrating solar thermal power stations. Although the applications mentioned here are concerned with the generation of electricity, the essential product of each system is heat, which could potentially be used to provide process heat for industrial applications. A solar updraft tower (also known as a solar chimney or solar tower) consists of a large greenhouse that funnels into a central tower. As sunlight shines on the greenhouse, the air inside is heated, and expands. The expanding air flows toward the central tower, where a turbine converts the air flow into electricity. A 50 kW prototype was constructed in Ciudad Real, Spain and operated for eight years before decommissioning in 1989 [77].

Parabolic Trough Collectors - PTC Parabolic trough collector (PTC) is the most widely used system among the concentrated solar thermal technologies due to its technical maturity and performance stability. Currently PTC occupies more than 77% of the global

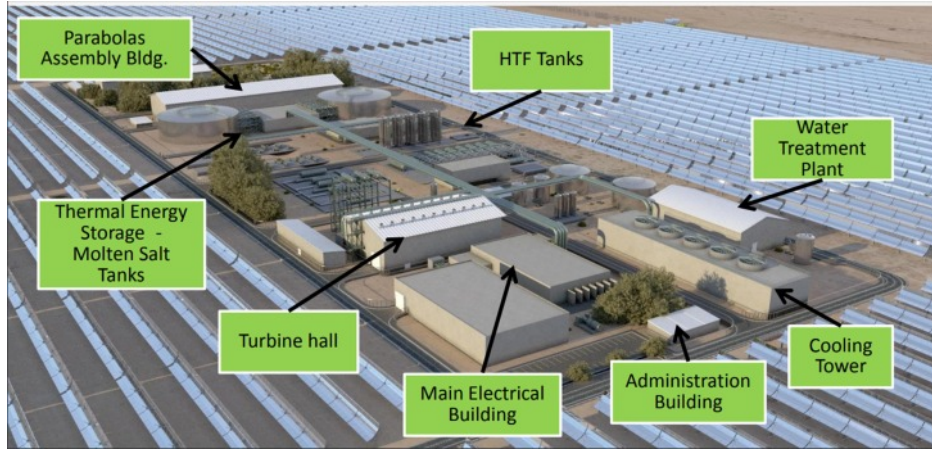


Figure 1.20: Major component and Layout of a 110 MW Ashalim (Plot A) Parabolic Trough Plant

CSP installations[58]. Fig. 1.20 illustrate the layout of a large commercial PTC based CSP plant. Major components and their design requirements for a PTC based CSP plant are discussed below.

1.2.3 Solar Tracking

Depending on the technology used, different types and number of axis of tracking are used. In table 1.2 we can see how as the concentrating factor (and thus the maximum temperature) increase, more fine and complex tracking system are needed, going from no tracking system at all (stationary systems), to one axis tracking systems (PTC and Fresnel systems), to two axis tracking systems (Parabolic Dishes and Solar Towers).

Most large scale Concentrated Solar systems rely on a theoretical tracking system, usually with an open loop control. Tracking systems relying on sensor are more common on small scale systems, and are often based on a closed loop control.

Theoretically, one axis systems (such as PTC and Fresnel) disposed in the solar field of a CSP plant can have any horizontal orientation. Sun tracking is always possible. However, there is a preferred orientation, which is the north-south alignment with the respective east-west tracking (figure 1.21 left). East-west alignment with the respective north-south tracking (figure 1.21 right) was applied only for experimental purposes.

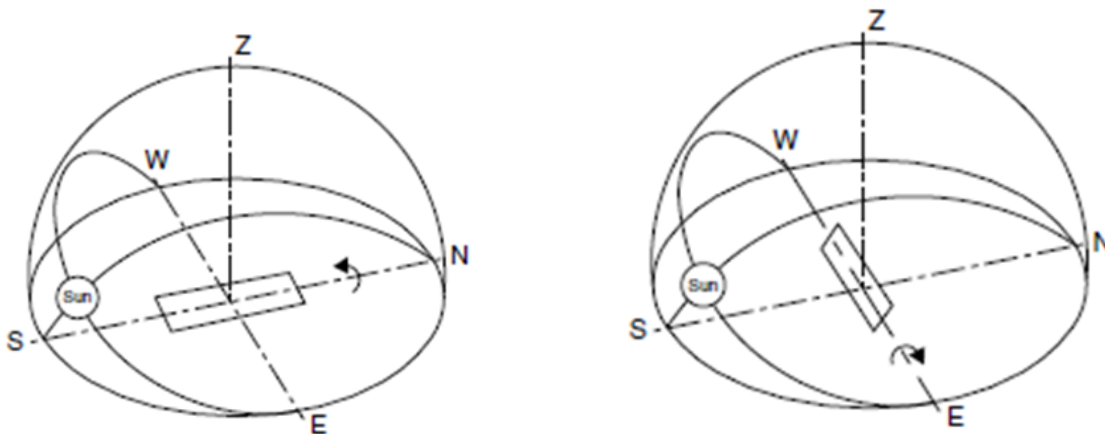


Figure 1.21: Orientation and tracking. On the left North-South orientation with East-West tracking, on the right East-West orientation with North-South tracking

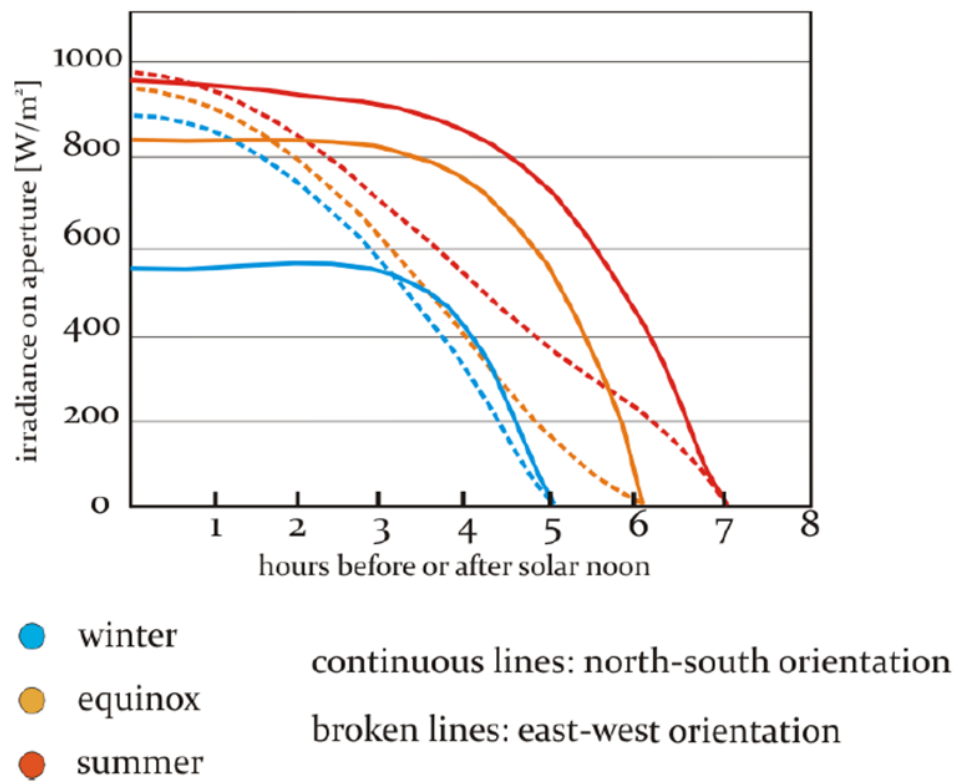


Figure 1.22: Irradiance comparison N-S orientation vs E-W orientation due to cosine effects on the incidence angle for a PTC (or any one axis tracking system). Different curves for summer solstice, winter solstice and equinox(es), for a 30° latitude location.

Depending on the latitude where the power plant is installed, different orientations have different effects on the energy yield of the power plant. For Sun Belt locations, i.e. at latitudes below 40° and, generally, not too close to the equator (not below 15°), the following holds:

East-West orientation:

- The collector performance over the day is quite uneven. Due to large incidence angles, the collector performance is reduced considerably in the hours after sunrise and the hours before sunset. At noon, the full aperture always faces the Sun, i.e. the incidence angle is zero. This means that the highest possible thermal peak power of the solar field at a given direct irradiance is always reached if it has east-west alignment (but not necessarily if it has a north-south alignment).
- Energy yield differences between summer and winter are smaller than for north-south alignment. Contrary to north-south alignment, incidence angles on the collector are not larger in winter than in summer.
- Quite small tracking movements are required during the day.
- The annual energy yield is lower than for north-south alignment.

North-South orientation:

- The collector performance over the day is quite even. Generally, the cosine loss is higher at noon than in the morning and evening and tends to compensate, hence, the different DNI conditions.
- Due to incidence angle differences between summer and winter, the seasonal energy yield differences are larger than for east-west alignment.
- The annual energy yield is higher than for east-west alignment

1.2.3.1 Theoretical Tracking

It is possible to mathematically evaluate the sun's position, relative to a location on earth's surface, through the knowledge of the day of the year, the hour of the day and the location's coordinates.

The apparent motion of the sun in the sky is opposite of the real one of Earth's rotation around its axis, which proceeds with a constant angular velocity of $\omega_a = \frac{15^\circ}{\text{hour}} = \frac{0.25^\circ}{\text{minute}} = \frac{360^\circ}{\text{day}}$. Taking a local cartesian system of reference (x,y,z) , such as the z axis is parallel to Earth's

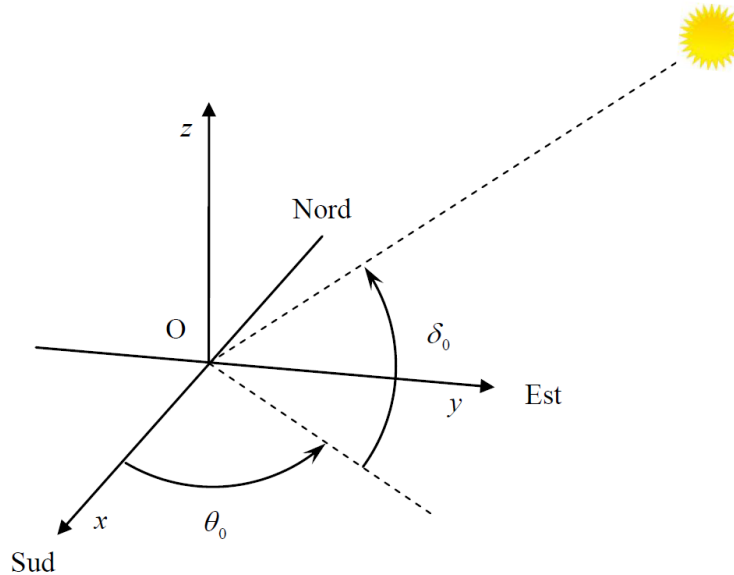


Figure 1.23: Definition of angles used to evaluate the sun's position through theoretical calculations

rotation axis, the x-y plane is perpendicular to it and such as the x axis is pointing from North to South and the y axis is pointing from West to East, the sun's position can be expressed with coordinates: the declination angle δ_0 and the hour rotation angle θ_0 , which are shown in Figure 1.23.

The declination angle δ_0 is defined as the angle between the x-y plane and the vector going from the origin of the reference system to the sun's center. The hour rotation angle θ_0 is defined as the rotational angle of the sun around the z axis, measuring from 0° to $+180^\circ$ from the South cardinal point in West direction, and from 0° to -180° from South to the East direction. This θ_0 angle will be negative in the morning (as the sun rises from the East) and then positive in the afternoon (as the sun sets in the West).

The hour rotation angle θ_0 is linked to the Real Local Time (RLT) which is the time of the

day in which the sun is exactly in the South (or North, if in the boreal emisphere) direction, assumed to be 12:00, from the equation 1.1 below

$$\theta_0 = (RLT - 12) \omega_a \quad 1.1$$

where RLT is expressed in hours and fraction of hour.

The Real Local Time differs (Equation 1.2) from the Mean Time (which is the time reported on clocks) by a fixed amount due to the distance from the meridian of the refereed Time Zone and of a variable quantity, called Time Equation (TE), linked to the variability of the Earth velocity in its rotation around the sun due to its elliptical orbit and Earth's rotational axis inclination. Since the longitude is defined to the Greenwich meridian, the relation between RLT and MT takes a simpler form if we consider the Mean Greenwich Time, which is the mean time for the Greenwich time zone:

$$RLT = MGT + TE + \frac{\text{longitude}}{\omega_a} \quad 1.2$$

The Time Equation can be derived from Keplero's Law, and its final forms is:

$$TEg(t) = TEog(t) + TEag(t) = 2\varepsilon \sin(\omega_M t) + \frac{5}{4}\varepsilon^2 \sin(2\omega_M t) + \arctan \left[\frac{\tan(\alpha(t))}{\cos(\delta_T)} \right] - \alpha(t) \quad 1.3$$

where $\omega_M = \frac{2\pi}{T}$ is the angular velocity for a circular orbit, $\varepsilon = \sqrt{1 - \frac{b^2}{a^2}}$ is the eccentricity of Earth's orbit, $T = 365^d : 5^h : 48' : 47'' : 33'''$ is one year tropic length (the time between two consecutive spring equinoxes), $\delta_T = 23^\circ : 26' : 20''$ is the inclination angle of Earth's axis to the plane of its orbit, $\alpha(t)$ is the angular position of earth to the sun (starting from the winter solstice).

A representation of the Time Equation is shown in Figure 1.24 below:

The TE values changes from -15° to $+15^\circ$ during the year, so its effect on RLT is not negligible.

The sun's declination can be evaluated as:

$$\delta_0(t) = -\arcsin[\sin(\delta_T) \cos(\alpha(t))] \quad 1.4$$

while θ_0 can be deducted from:

$$\frac{d\theta}{dt} = \omega_M \frac{a^3}{b^3} [1 + \varepsilon \cos(\theta(t))]^2 \quad 1.5$$

which doesn't have an analytical solution, but it can be numerically resolved. The formulas used to derive the angular position are shown in equations 1.6 and 1.7.

$$\alpha = \sin^{-1}(\sin \delta \cdot \sin \phi + \cos \delta \cdot \cos \omega \cdot \cos \phi) \quad 1.6$$

$$A' = \cos^{-1} \left(\frac{\sin \delta \cdot \cos \phi - \cos \delta \cdot \cos \omega \cdot \sin \phi}{\cos \alpha} \right) \quad 1.7$$

$$\begin{aligned} \text{if : } \sin \omega > 0 & \rightarrow A = 360^\circ - A' \\ \text{if : } \sin \omega \leq 0 & \rightarrow A = A' \end{aligned} \quad 1.8$$

where θ_z is the zenith angle (the angle between the vertical of the observer and the sun's position), α is the altitude angle (complementary to the the zenith angle, defined between the horizon and the sun's position), A is the azimuth angle (angle difference between the

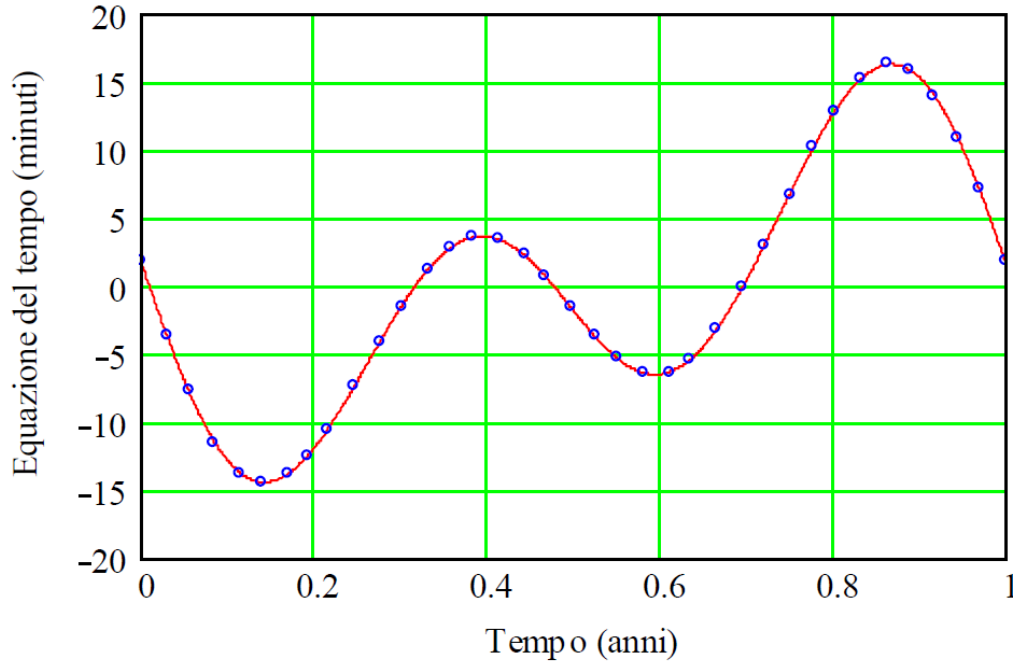


Figure 1.24: Time Equation (year 1941)

projection of the solar position on the horizontal plane and the north direction, with positive values to the East and negative values to the West), ϕ is the latitude angle, δ is the declination angle and ω is the hour angle (angle difference respect to the local sun's noon position, every hour equals to 15° , with negative values in the morning and positive values in the afternoon), as which are also shown in figure 1.25.

Through the 1.6 equation is possible to evaluate the sun height α , while the azimuth angle A can be evaluated with equation 1.8, with A' calculated as in 1.7.

In this evaluation the sun's tracing, its rays were considered parallel, as it was a punctual source at an infinite distance, but it is necessary to be more precise, and take into account both the sun's dimension and the actual earth-sun distance, which contribute to the sun's divergence angle (figure 1.26), which is calculated as:

$$\theta = \arcsin \frac{R_{sun}}{D_{earth-sun}} = \arcsin \frac{6.9599 \cdot 10^8 m}{1.505 \cdot 10^{11} m} \cong 16' \cong 0.266^\circ \quad 1.9$$

The divergence θ is also known as Sun's Image.

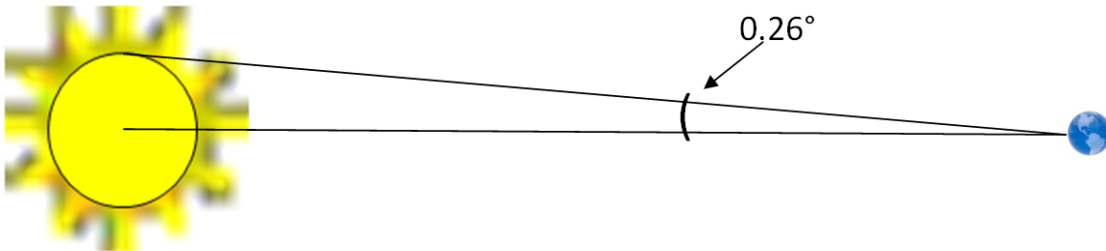


Figure 1.26: Representation (not to scale) of Earth-Sun distance and solar radius for the evaluation of the Solar Image

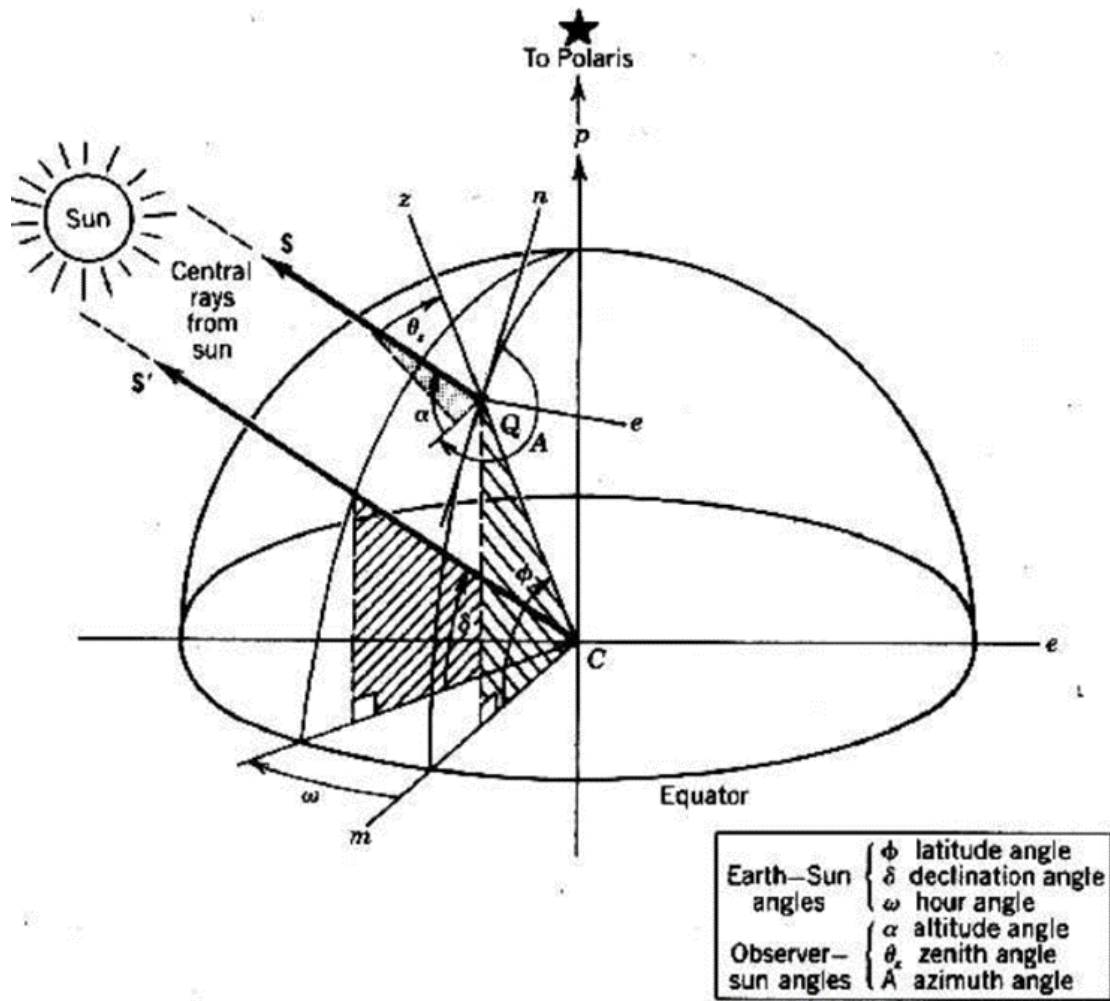


Figure 1.25: Definition of angles used to evaluate the sun's position through theoretical calculations

1.2.3.2 Sensor Tracking

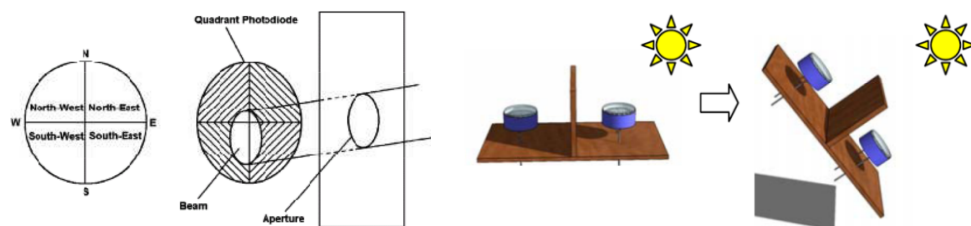


Figure 1.27: Sensors used for solar tracking. On the left, a pin-hole sensor [78]; on the right a LDR (Light Dependent Resistor) [79]

Common solar tracking technologies for one axis and dual axis tracking are shown in figure 1.27, such as LDR and Pin-Hole. The LDR, also called flag sensor, is comprised of two light sensitive elements, which are divided by a tall barrier (the flag). When the sun is right above the flag, the flag itself doesn't cast any shadow on the light sensitive elements (figure 1.27 left of the two LDR images), which are mounted right adjacent to it on opposite sides,

and the output signal from both the elements is the same. Whenever the sun has a different inclination to the flag (figure 1.27 right of the two LDR images), a shadow is cast, so that one element will have light on it while the other is within said shadow, thus creating a difference in the output signal that can be interpreted as the direction of the sun's position relative to the flag. The Pin hole sensor uses photo sensible elements too, but instead of having a flag dividing them, they are set near each other, and a small circle of sunlight hits them, passing through a small hole in the top of the sensor. When the sensor is aligned with the sun, the sun spot hits all four elements equally, generating the same output from them, while otherwise some elements will have a stronger signal than others, and from this difference is possible to evaluate the direction of the sun. Generally the pin hole sensors are used with four sensible elements, been able to track the sun in two directions, thus enabling its use for two axis tracking.

Single-axis trackers are simpler and cheaper to install than dual-axis trackers. They are widely used in parabolic trough systems and linear Fresnel reflectors, where large rows of mirrors need to adjust in a single direction to focus sunlight onto a fixed receiver.

Using a one axis tracking can improve solar collection efficiency by up to 20-30% compared to fixed non tracking systems like PV.

Dual-axis trackers allow for optimal solar alignment throughout the day and across seasons. They are primarily used in solar power tower systems, where heliostats must constantly adjust to reflect sunlight to a single point on the central tower receiver, as well in Solar dishes, which too need to focus the light into one single point. This set up is the most accurate and maximizes sunlight capture, enhancing system efficiency by up to 40% compared to fixed or single-axis systems.

1.3 Parabolic Trough Collectors - PTC

Parabolic Trough Collectors are characterized by the use of parabolic mirrors to focus the solar radiation onto the absorber tube. This shape is chosen for its geometrical proprieties, as all lines parallel to the parabola's axis are reflected and sent back all into the focus point (Figure 1.28).

The main part of the PTC system is a trough collector. It's characterized by geometrical parameters such as aperture width, rim angle, trough length and focus length. These dimensional parameters are shown in figure 1.29.

- Trough length l is the linear length of the mirror. Usually the absorber tube has the same length
- Focal length f is the distance from the focal point to the vertex of the parabola, which can be expressed analytically as a simple function of f as $y = \frac{1}{4f}x^2$
- Aperture width a is the distance from one edge of the linear mirror to the other
- Rim angle Ψ is the angle between the optical axes of the parabola and the line going from the focal point to the edge of the mirror.

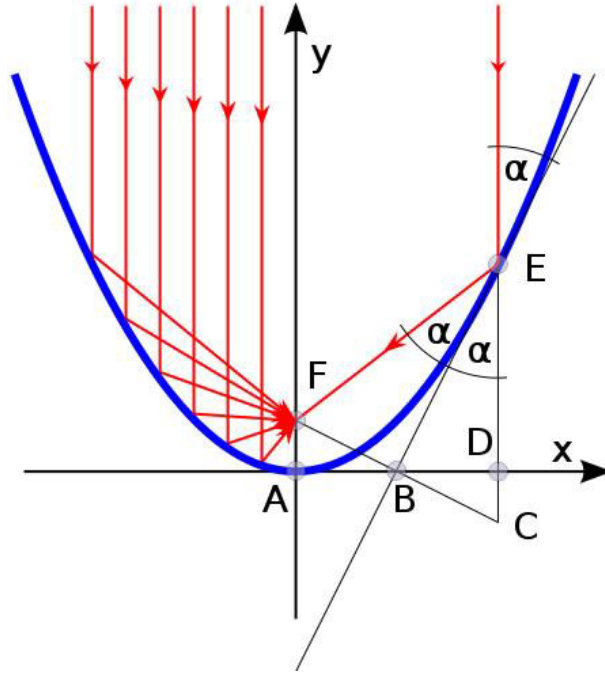


Figure 1.28: Path of parallel rays at a parabolic mirror

The last three parameters are not independent from each other, as they are tied by the equation² 1.10, so once two of them are decided, the last is also determined.

$$\tan \Psi = \frac{\frac{a}{f}}{2 - \frac{1}{8} \cdot \left(\frac{a}{f}\right)^2} \quad 1.10$$

The rim angle influences how much and how solar radiation reach the absorber tube, which is located around the focus point. On a perfect mirror, for same aperture length, the lower the rim angle, the wider and further apart the mirror is in respect to the absorber tube, increasing the focal length and also the dispersion of the solar image. In figure 1.30 a is shown how the focal distance changes depending on the rim angle (and vice versa), with a fixed aperture.

More over, considering real mirrors, with some imperfections in their surfaces and reflecting factors, the path of the solar radiation from the mirror to the absorber tube should be kept as lower as possible, in order to intercept the most of the radiation and not to lose it, as optical defects are amplified by distance (figure 1.30 b). This means that collectors with higher rim angle collectors need smaller absorber tubes, compared to the aperture width of the collector. There is also an argument against increasing rim angle, as it uses more materials and so can be more costly and provide smaller and smaller benefits.

Another important parameter is the Concentrating Ratio, which compares the number of times the surface of the absorber tube is reached by sunlight. This can be calculated from the geometry, dividing the aperture area ($A_{ap,c}$) of the collector by the surface of the receiving absorber tube (A_r). In case of evacuated tubes, the surface of the fluid tube is used, not the encasing glass one.

$$C_G = \frac{A_{ap,c}}{A_r} \quad 1.11$$

²this can also be written as $\frac{a}{f} = -\frac{4}{\tan \psi} + \sqrt{\frac{16}{\tan^2 \psi} + 16}$

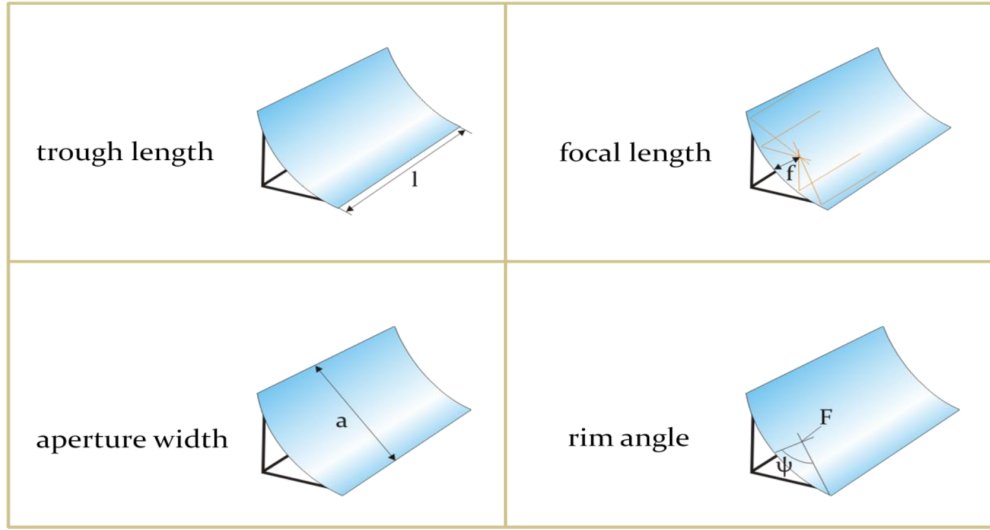


Figure 1.29: Dimensional parameters of a PTC

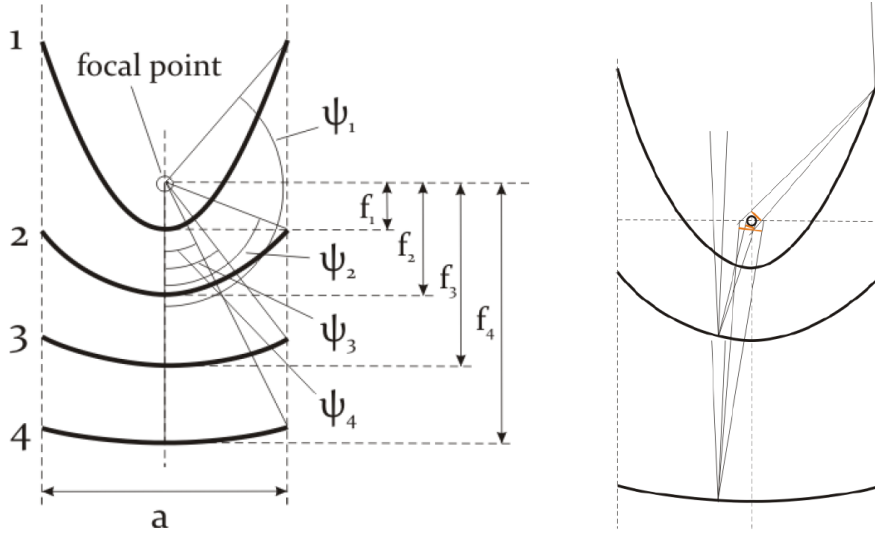


Figure 1.30: Focal length and rim angle influence on parabolic collectors

The aperture area can be easily calculated as $A_{ap,c} = a \cdot l$, while the receiving collector's surface is often intended as its projected area ($diam_{receiver} \cdot l$), while it can be argued that most of its surface is used, so it would be better to express it as $\pi \cdot diam_{receiver} \cdot l$. This argument is beyond the scope of this work, and the first formula will be used. With these consideration equation 1.11 can also be expressed as:

$$C_G = \frac{a \cdot l}{diam_{receiver} \cdot l} = \frac{a}{diam_{receiver}} \quad 1.12$$

1.3.1 Notable PTC applications

Parabolic Trough Collectors (PTC) are one of the most widely deployed CSP technologies due to their scalability, efficiency, and relatively lower cost. Some of the most famous and largest PTC installations are located in Spain and the United States, where solar resources and government incentives have enabled the development of large-scale solar thermal plants. New and wide markets are represented by countries in North Africa, India, and China. These are some of the current installations that work using this technology.

SEGS (Solar Energy Generating Systems) - California, USA Capacity: 354 MW
SEGS is one of the largest PTC installations in the world, located in the Mojave Desert in California. It consists of nine plants and was one of the pioneering projects in large-scale CSP technology, starting operations as early as the 1980s. The SEGS plants use single-axis tracking parabolic trough collectors, where sunlight is concentrated onto a receiver pipe containing synthetic oil, which then generates steam to drive turbines. SEGS has been a cornerstone for CSP development and remains the world's largest operational parabolic trough installation.

Solaben Solar Power Station - Extremadura, Spain Capacity: 200 MW

Description: This complex is made up of four parabolic trough plants, Solaben 1, 2, 3, and 6, located in the sunny region of Extremadura. The plants have contributed significantly to Spain's leadership in CSP. The Solaben plants use single-axis tracking parabolic troughs, similar to SEGS, with molten salts used as a heat transfer fluid for increased efficiency and thermal storage capabilities. The project is a key example of how Spain has leveraged its solar resources to become a global leader in solar thermal technology.

Noor Energy 1 (part of Noor Complex) - Morocco Capacity: 160 MW (PTC contribution to a hybrid system)

Noor Energy 1 is part of the massive Noor Solar Complex near Ouarzazate, Morocco, which combines both parabolic trough and solar power tower technologies. Noor 1 and Noor 2 are based on parabolic troughs, while Noor 3 uses a solar tower. The PTC systems at Noor use molten salt for energy storage, enabling the plant to generate electricity even when the sun is not shining. This installation has positioned Morocco as a leader in renewable energy, aiming to reduce dependence on fossil fuels.

Andasol Solar Power Station - Andalusia, Spain Capacity: 150 MW

Andasol consists of three 50 MW PTC plants (Andasol 1, 2, and 3) located in the Tabernas Desert. Andasol was the first CSP plant in Europe to integrate thermal energy storage with molten salts, allowing it to provide power during cloudy periods and after sunset. Parabolic trough collectors with molten salt storage to extend the operating hours of the plant. The thermal storage capability and strategic location have made Andasol a model for future CSP projects in Europe and around the world.

Shams 1 - Abu Dhabi, UAE Capacity: 100 MW

Located in the UAE desert, Shams 1 was one of the largest CSP projects in the Middle East when it was commissioned. It represents the region's push towards renewable energy development and diversification away from oil dependency. Shams 1 uses parabolic trough technology combined with a natural gas backup system to ensure continuous power generation. Shams 1 underscores the potential for CSP technology in arid and sunny regions like the Middle East.

2. M-PTC AND ITS SUB-SYSTEMS

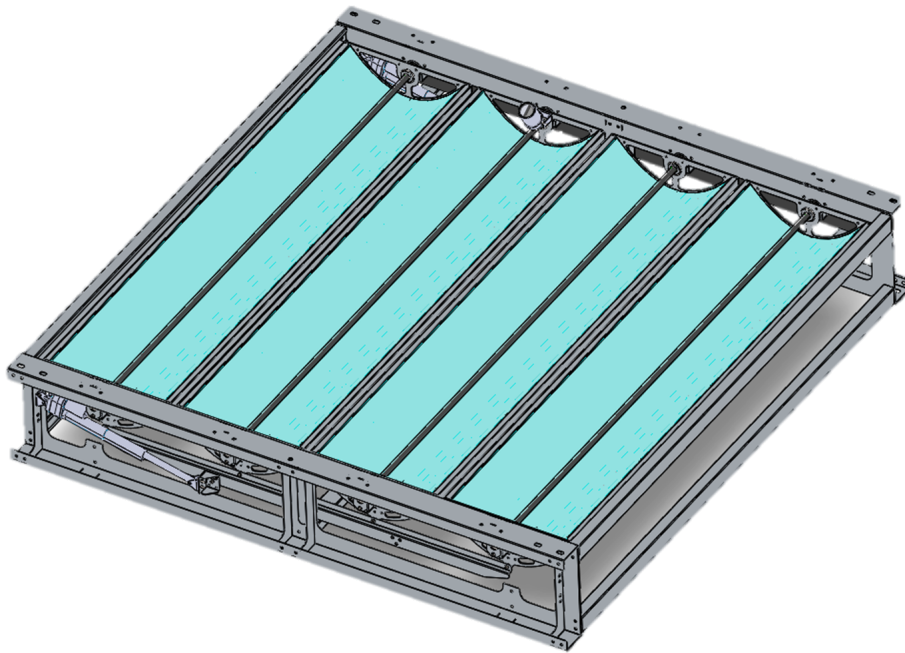


Figure 2.1: CAD drawing of the m-PTC

2.1 Description

The m-PTC is a small scale PTC system, with each module measuring roughly 2 meters per side, each of which can be positioned independently of each other. Each module contains four linear parabolic mirrors (each with its absorber tube), one inlet and one outlet pipe (which fed the inlets and outlets of the absorber tubes), two linear motors for the movement of the mirrors, one flag sensor and one control unit, all housed inside the mechanical structure. In figure 2.1 we can see a CAD drawing with all the components.

Geometrical Specs		
Aperture width	400	[mm]
Focal length	83,9	[mm]
Rim angle	100	[°]
Absorber external diameter	10	[mm]
Glass external diameter	30	[mm]
Length	1880	[mm]
Concentrating ratio	40	[-]

Table 2.1: Geometric specs of the m-PTC

The parabolic mirrors have a small aperture (400 mm), with a short focal length of 83,9 mm, which brings the rim angle to 100°. For all geometrical data, see Table 2.1. The rim angle over 90° also means that the absorber tube is below the aperture line, for added protection (figure 2.2).

The focal point is also used as the center of rotation of the mirrors, so that the absorber tube

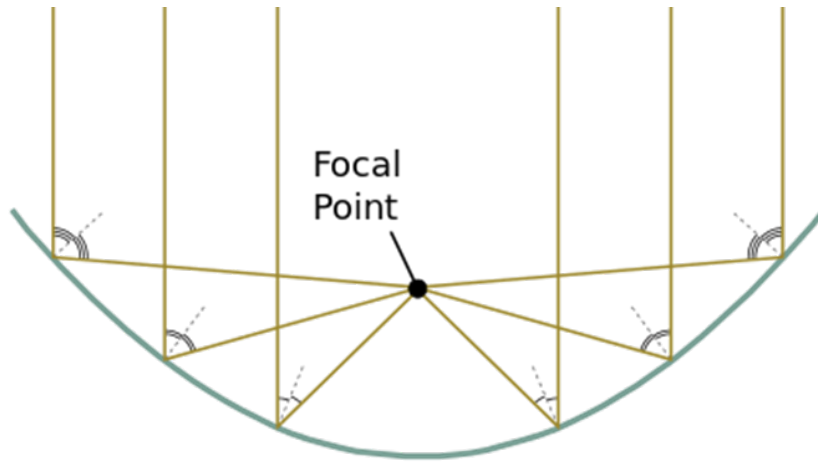


Figure 2.2: Schematic section of a m-PTC like system (not to scale)

can be maintained stationary during operation, removing the need for costly and delicate flexible joints or piping. This is a notable advantage respect to big scale PTC systems, which usually have very big and heavy mirrors, so the center of their rotation is closer to their center of mass rather than on the focus line, and the use of flexible pipe joints introduce sensible moving parts.

The short focal length also means that a small diameter tube can be used for the absorber, due to the reduced dispersion of the sun's rays. The smaller tube allows for a smaller glass envelope, responsible for the vacuum isolation, which further lowers the heat dissipation losses through both vacuum insulation and smaller contact area with the ambient. The high concentrating ratio is also critical to reach higher temperatures and has the double advantage of reducing the number of receiver tubes per solar acceptance area, which can significantly reduce the cost of the system, since the receiver tube is often one of the most expensive components.

The absorber tube has both the inlet and the outlet on the same side (with tube in tube configuration) to facilitate accessibility in assembly and maintenance. This configuration means that the inner circle and outer ring of fluid are basically in a counter-flow pipe heat

Technical operational specs		
Net Area	3.008	$[m^2]$
Gross Area	4, 12	$[m^2]$
ρ	88%	$[-]$
τ	95%	$[-]$
α	95%	$[-]$
Max temperature	300 ¹	$[^{\circ}C]$
Max pressure	16	$[bar]$
Mass Flow rate	0, 08	$\left[\frac{kg}{s}\right]$

Table 2.2: Operational specification for m-PTC

exchanger, which affects only the evolution of temperatures from inlet to outlet, but not the total heat received and thus the outlet temperature.

The mirrors are linked together through a solid bar on each side, joining them together so that all of them can be moved/rotated at the same time, at the same angle, with a single motor on each side. Two motors are used for added precision, preventing skewing angles from side to side (which would affect the parabola geometry and intercepting factor), especially with vertical and semi-vertical installation with azimuth tracking, that would put more friction on one of the rotating joint of the mirror than the other. Linear motors are vastly available, cheap and trustworthy, they also can house embedded encoders, to be able to read their position/extension length.

Each module has its own solar tracking sensor, which allows to very precise tracking of the sun during operation, with a closed loop control system. There is also a dedicated control card, which is responsible for reading the solar sensor and also powering and commanding the electric linear motors. Both the tracking and command system are further detailed below (section 2.2). This way every module is autonomous, can be deployed stand alone, needing only 24V power supply.

The module is quite compact, measuring roughly 2 m per side, yet achieving a net capturing area of 3 m², with little to no shadow losses in its operation, thanks to the short aperture width. This is quite good, compared to bigger systems, which can have a better net to gross area ratio for each module, but wider spaces between modules or rows are needed to avoid shadowing losses, which led to a lower efficiency of space utilization, which corresponds to more space needed for the same radiation captured, or less power for surface available, not to mention the shale scale of the space needed (for 75 m length modules, that means more than its length in open, non shaded, flat land, and wouldn't fit on top of roofs).

2.2 Tracking system

Most PTC systems use theoretical tracking, meaning the control board calculate the sun position, its angle relative to the installation location, the direction the collector surface should be facing, then it commands the motor(s) to point the collectors in that direction. This method doesn't require any sensor, except of the motor position, is quite accurate, but is an open control loop, meaning it has no way to validate itself and if configured incorrectly will insure a constant error in tracking, even not allowing the system to produce heat at all. With a solar sensor, the tracking accuracy is constantly monitored in a closed loop, allowing a more precise and trusty tracking of the sun.

For the m-PTC both system were implemented, with the command board able to calculate sun position based on timestamp and location, in order to point in that direction for the start up procedure, or in case the sun was covered by clouds and thus the sensor was blind, allowing the mirrors to remain in position for when the sun shines again. It also features a flag sensor, which gains priority over the theoretical tracking when it receive enough light, meaning it is facing the right direction and the sun is shining. The sensor consists in two light-reactive elements, separated by a small flag, such as when the sun light is on top of the flag and parallel to it, the reactive elements should receive the same amount of light and thus provide the same output. Figure 2.3 shows a simple representation of its working principle. The flag, also called shadow element, is positioned in the middle of the two sensors, perpendicular to their surface, so that when the sun moves across, it casts a shadow on one of the elements, while the other remains in light. By measuring the light received by both elements, is it possible to evaluate if it is aligned to the sun or not, and in which direction the sun is (opposite to the shadowed sensor). By also measuring the amount of light/shadow on the sensors, it is also possible to evaluate how much far away from the correct alignment the sensor is.

Photodiodes were used for the light reactive elements, each paired with a tension multiplier

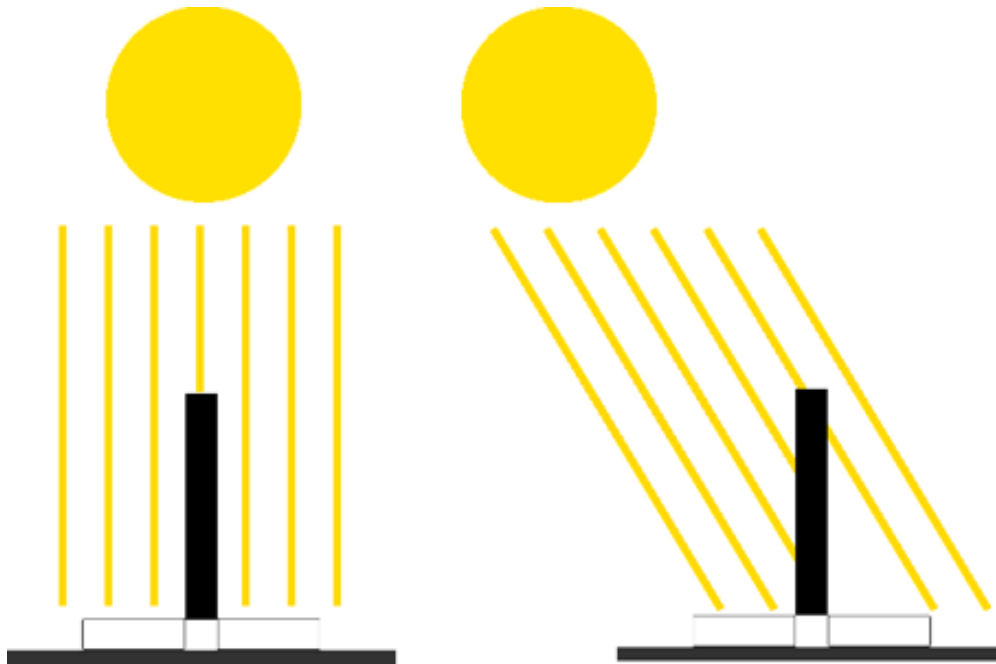


Figure 2.3: Working principle of "flag" solar tracking sensor

to be able to appreciate more subtle variation of the light absorbed. The tension multipliers need to be regulated by hand, setting them to the point where, under direct sunlight, they give close to their maximum value, and the same amount on both sides. In figure 2.4 we can see the two diodes on the sensor circuit board while been tested outside in the sunlight, without the flag. After this procedure, the flag was installed on the the sensor board with two screws, and the sensor was checked again to be sure the correct flag mounting, checking if the diodes were to give the same signal when there wasn't any visible shade on neither of them.

The sensor's signal is interpreted by the control board and then a command issued to the motors or the movement system used, making the collector move in the direction of the sun, thus creating a very effective closed loop control.

This sensor is very simple in principle, yet very effective, and its sensibility can be easily

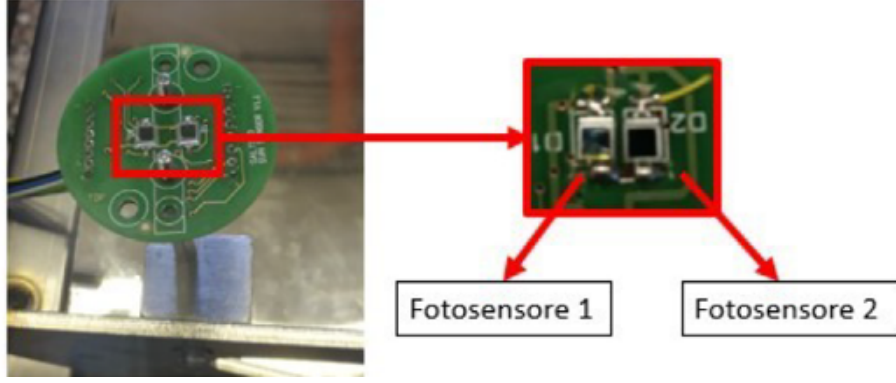


Figure 2.4: Circuit board of the solar tracking sensor with photodiodes zoom

improved just by elongating the height of the flag, thus reducing the angle for which its shadow is casted on the sensors. Its simple construction do not require complex electronics, nor powerful chips for the calculation of the theoretical position of the sun, making them also energy-efficient. It is as much effective on the tracking in the direction perpendicular to the flag, as it is *blind* to tracking/movement in the direction of the flag itself. This is still a favorable characteristic, as it continues to track the sun in the desired direction regardless of the position of the sun in the other direction, avoiding the need for seasonal mounting change or a more complex mounting and movement system for the sensor itself.

2.2.1 Calibration of the sensors and setting up of thresholds

Some of my PhD work and research went into developing a reliable and effective methodology to calibrate the sensors, as well as finding the best parameters values on the control board to operate them. The sensor were calibrated in our laboratory, following the previously described procedure: setting a first time the potentiometers so that in bright sunlight the would give almost maximum response (2,5V in our case), then mounting the flag and checking again the signal were no visible shadows were cast by the flag on the sensors.

We then needed to set a proper threshold to decide when to move the mirrors more towards the sun and when it was acceptable to stay put, as the position was within the acceptance angle of the receiver system. In order to evaluate this threshold we set a sensor so that one of the photodiodes was in total shadow of the flag, position the flag perpendicular to the movement of the sun, so that the sun will gradually illuminate the shadowed photodiodes, pass over the perfect alignment position and over to cast the flag shadow over the other sensor. In figure 2.5 is shown an example of such tests, along with the elaborated signal, calculated with equation 2.1, so that when the two signal are the same, the signal is 0, while the sign of the elaborated signal tells about which photodiode receive more light, thus inferring in which direction the sun is.

$$elab\ signal = \log \left(\frac{signal_{sensor\ 1}}{signal_{sensor\ 2}} \right) \quad 2.1$$

By measuring the time elapsed, time of the day (and consequentially the angular velocity of movement of the sun) we were able to evaluate the effect of said threshold on the sensor precision. In the table 2.3 we can see some results of these tests.

The threshold values are 1000 times the elaborated signal of equation 2.1, so a threshold of 100 corresponds to 0.1 of the elaborated signal.

The threshold value is a compromise between needing a precise tracking and avoiding a

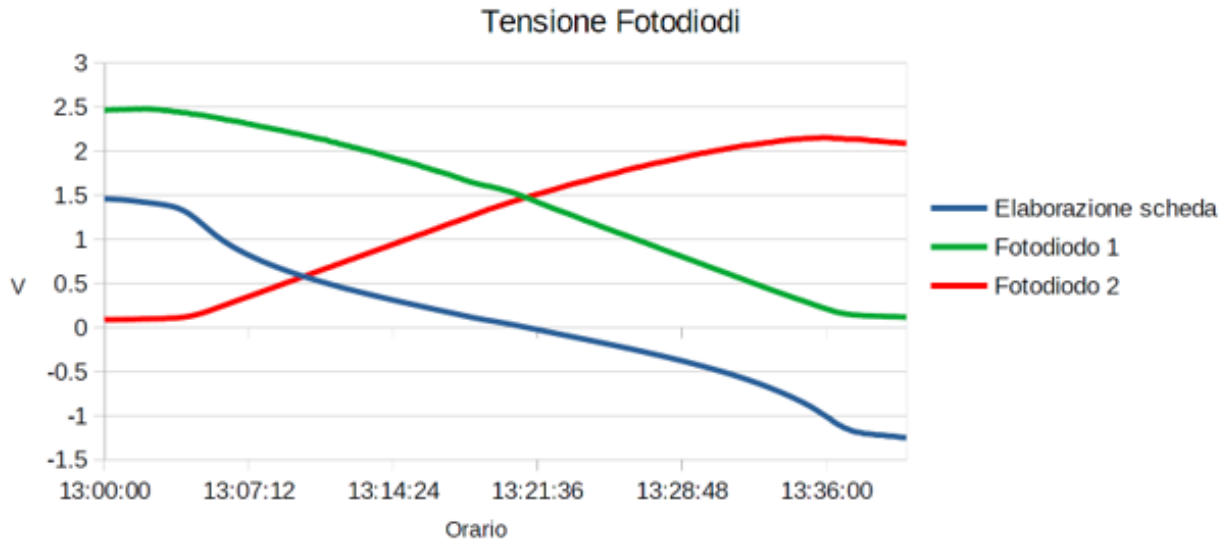


Figure 2.5: Graph of the sun passing over the solar sensor, with the elaborated signal

Flag sensors		Threshold values			
		25	50	75	100
sensor 1	time of passing [mm:ss]	1:06	2:15	3:22	4:33
	degrees of view [°]	0.28	0.57	0.84	1.14
sensor 2	time of passing [mm:ss]	1:10	2:25	3:40	4:55
	degrees of view [°]	0.30	0.61	0.92	1.23
sensor 3	time of passing [mm:ss]	1:11	2:20	3:33	4:38
	degrees of view [°]	0.30	0.59	0.89	1.16
sensor 4	time of passing [mm:ss]	1:00	2:10	3:33	4:22
	degrees of view [°]	0.25	0.55	0.89	1.10
sensor 5	time of passing [mm:ss]	1:09	2:19	3:29	4:41
	degrees of view [°]	0.29	0.58	0.87	1.16

Table 2.3: Passing over tests and relative degrees of solar view

constant power and movement to the motor, between a small enough threshold so the tracking would be accurate and the reflecting sunlight would hit the absorber tube, and wide enough so the motor would work in a step by step mode, instead of constantly feeling the need to move backward and forward, thus preventing the system to ever rest and reach some stable conditions.

2.3 Control and movement system

The control board (figure 2.6), and its system, was developed to work autonomously, managing both the power to the motors, the reading of sensors and motor encoders, as well as provide an interface that could be accessible for controlling the operation of the modules, as well to ease its configuration phase. It also features a digital input, which is configured to be a fail safe operation mode, meaning that when the contact is on the closed status, the system goes to safety mode and position, and will not go into focus mode until the contact is opened.

It has internal chip-set, relays, clock, and build in 232 and 485 protocols communication, as well as connections for the solar sensor, power supply and the motors (independent power

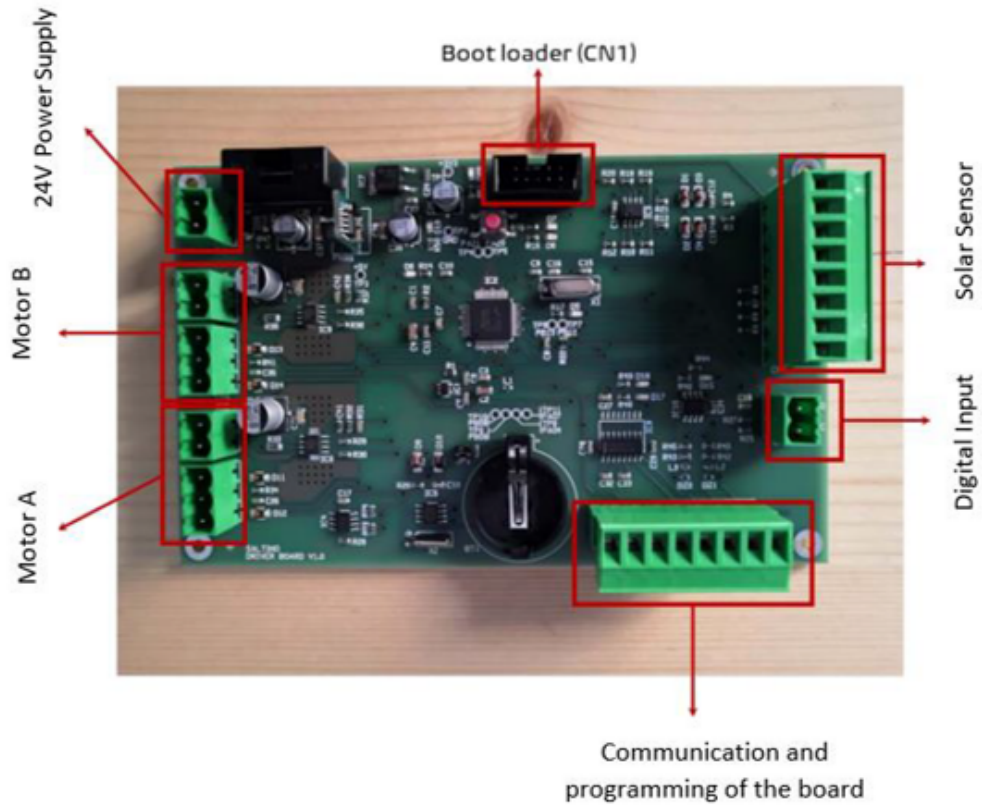


Figure 2.6: Control board with main connections highlighted

lines and encoder reading).

In order to convert the encoder reading to an angle value, it has to know some information of the cinematism involved (figure 2.7), on top of the calibration of the encoders relative to the extension length of the motors. This is crucial for its operation. Some of these information come from the design geometry of the system, while the encoder association to the length of the linear motor has to be measured and fed into the board setting on each board, since each motor may differ slightly, but crucially, from each other. During my PhD, methodology to evaluate the motors' length to encoder relation were studied, as well as refining the logic implemented on the board to control them.

While in operation, the angular position of each side of the mirrors is monitored, especially during the start up or powering down of the system, which features the biggest movements. In order not to over skew or bend the mirrors, which may affect their concentrating ability and even cause metal fatigue, if the board senses that the two sides are not moving at the same speed, or are too far apart from each other, it will stop one motor in order to let the second one catch up. Once they are within a threshold of angular distance from each other, they both resume the movement together.

2.3.1 Modbus communication

During the PhD, the 485 (or MODBUS) protocol was also implemented both on the board side, and as stand alone programming on an external PC. This is a one-to-many communication protocol, which allows a single "master" computer to address, read and control many "slave" control boards, and to do so remotely, through a single connection. In figure 2.8 is shown the web interface developed to monitor, configure and command multiple control board.

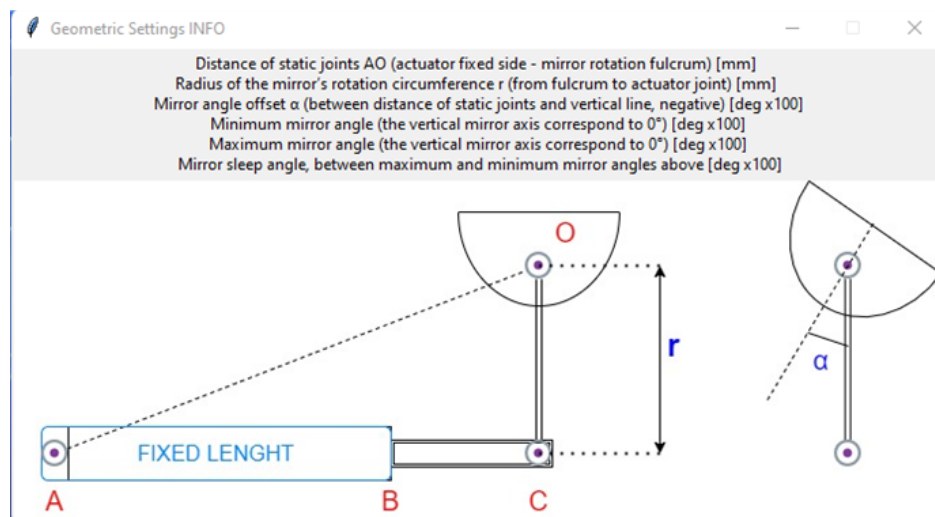


Figure 2.7: Linear motor cinematism and length parameters

This is very handy for multiple modules configuration, monitoring and control, allowing to set up parameters and changing operational mode remotely, without the necessity to reach each board, connect to it with a 232 connection and a PC, on field. It also allows for problem diagnosis thank to the error flags reading, which can also be addressed and resolved remotely. The error flags raising, reading and management was also developed during the PhD.

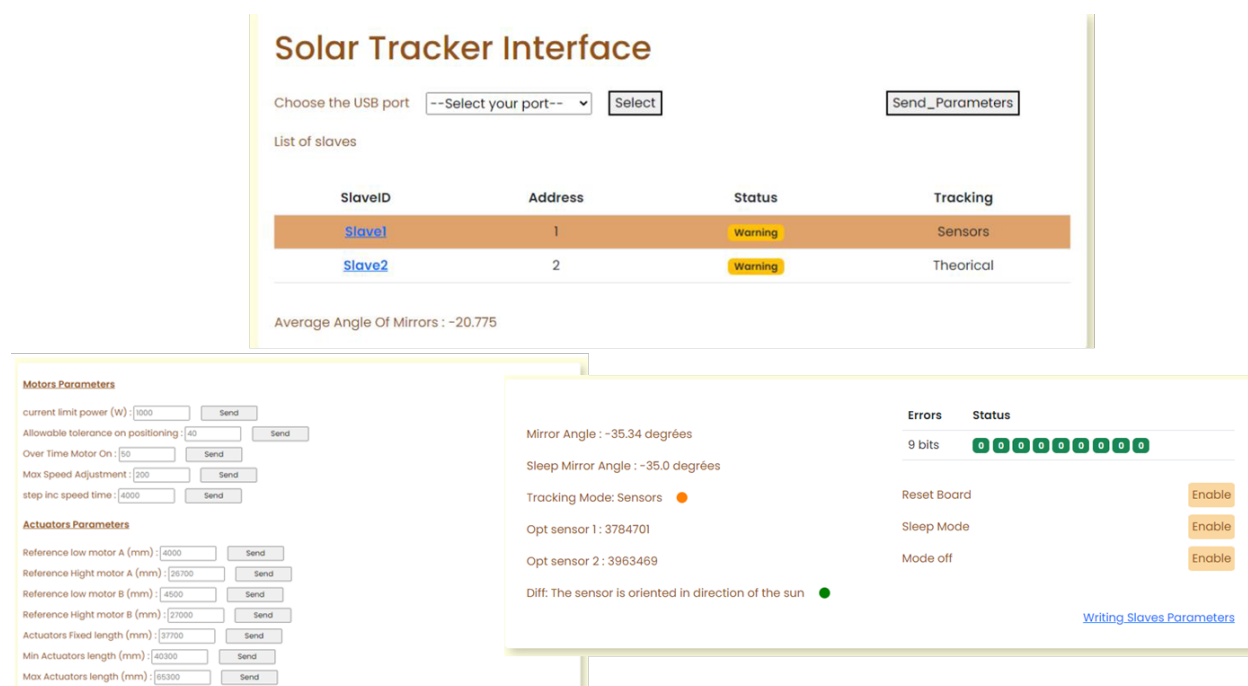


Figure 2.8: Screenshots of 485 MODBUS browser interface, with parameters management and errors monitoring

2.4 Absorber tube

The absorber tube used was specifically developed and tested for the m-PTC system. It features one side supply, with both inlet and outlet piping running one inside the other, as it can be seen in Figure 2.9.

The tube is vacuum insulated thanks to an external glass tube, which is secured to the metal receiver tube through a kovar joint. This also ease the problems with glass/metal joining, due to their different heat expansion coefficients, as having the joint only on one side allows the other one to expand freely. This also facilitates the vacuum creation inside the tube, which can be executed after the glass/metal joint, on the glass end with glass forming supplies, instead of necessitating complex and bulky machines that need to do both procedures at the same time. These design choices are done to make the absorber tube efficient and simple to produce, lowering both the initial and running costs of the module.

The outside of the metal receiver tube, which is made of steel, is coated with Cermet selective coating ($\alpha = 0.94$ for $\lambda < 2.5\mu m$ and $\epsilon = 0.12$ for $\lambda > 2.5\mu m$ at ambient temperature), which has been selected to reduce the emission in infrared range and increase the energy absorption in solar spectral range. The absorber tube is covered by a glass envelope with AR layer to prevent reflection of solar radiation by the glass surface. Inside, a vacuum level is fixed at $10^{-4}mbar$ to reduce the radiative heat losses.

The absorber tube performance in regards to the heat losses was previously tested in indoor

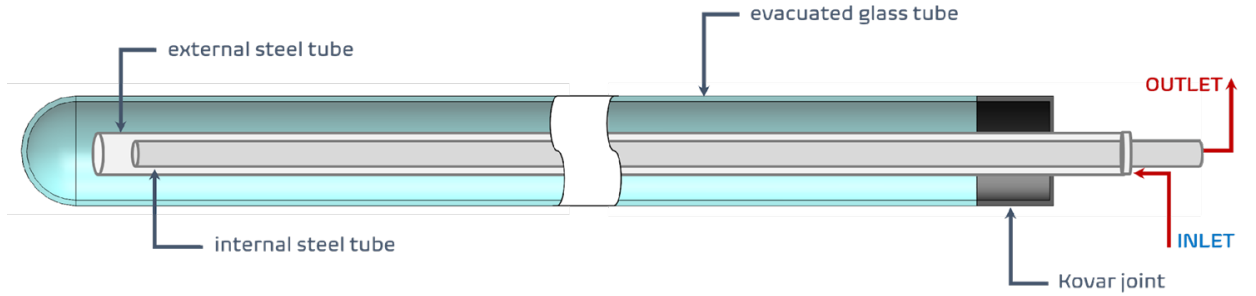


Figure 2.9: Schematics and features of the m-PTC absorber tube, not to scale

environment [80]. The electrical power needed to maintain the inside of the tube at target temperature was compared to the difference between internal and ambient temperature, characterizing its behavior up to $200^{\circ}C$ with and without vacuum (see Figure 2.10). Its emissivity ϵ is shown to be linearly growing with the internal temperature. Thanks to Kirchoff's Law total emisferic emissivity of a body is the same as its total emisferic absorbance, $\epsilon(T) = \alpha(T)$. The optical peak efficiency can be expressed as

$$\eta_{opt,0^{\circ}} = \alpha \cdot \rho_{total} \cdot \tau \cdot \gamma \quad 2.2$$

where α is the absorption factor (which can be substituted with ϵ), ρ_{total} is the total reflection factor, τ is the transmission factor and γ is the interception factor (which from previous design analysis [80] was valued at 1).

Further research and development is undergoing in order to improve the absorption in the visible and near infrared range, while decreasing its emissivity at higher temperatures. This will increase the overall performance, as potentially it will absorb more sunlight and emit less heat due to its temperature.

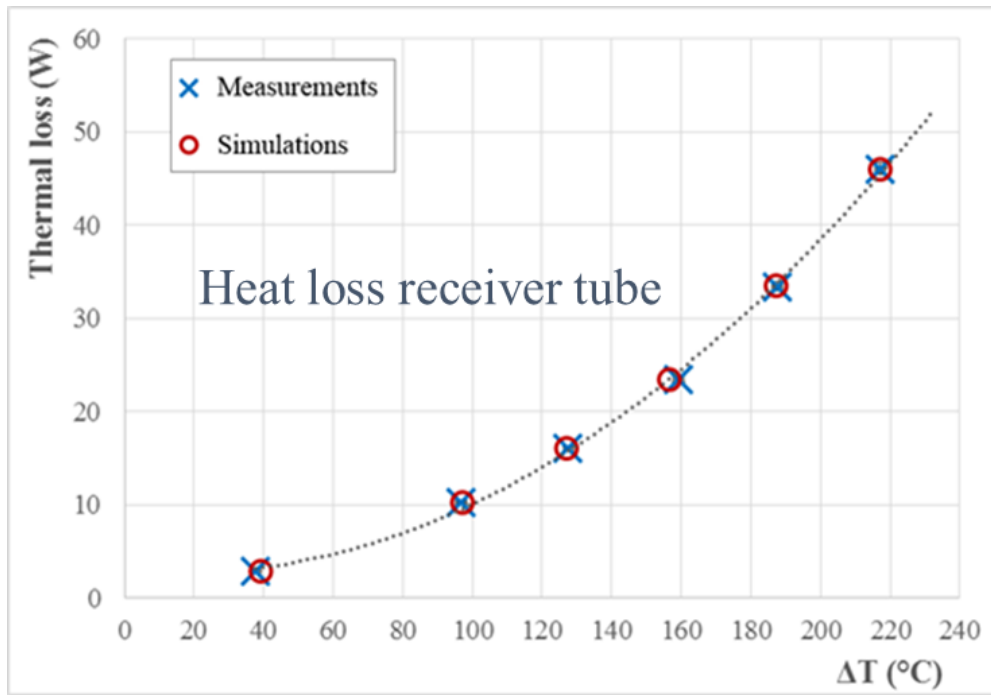


Figure 2.10: Results of the indoor testing of the m-PTC absorber tube

2.5 Heat production and performance

Thanks to the concentrating ratio of 40, the m-PTC is capable of reaching quite high temperature, especially if compared with similar dimension systems that are commercially available (such as Absolicon T160 [81], Greenetica EOSth [82], Trivelli SolarWingEvo 2 [83], data comparison shown in Table 2.4).

Due to the space limitation in industrial environments, design and development of compact solar thermal energy systems is important. Over recent years, few small size parabolic trough collectors have been developed [84]. A small size PTC collector was developed during the CAPSOL project in collaboration with the University of Almeria. Aperture width and total length are 1 and 2 m, respectively. Maximum operation temperature for this system is 250°C. The dimension of this system are compatible for domestic and industrial application [85]. O. A. Jaramillo et al. [86] studied performance of parabolic trough solar collectors named PTC 45 and PTC 90. Reported thermal efficiency in an open loop and in a closed loop form of the mentioned PTC system are 29% and 43%, respectively. J. Macedo-Valencia et al. [87], studied a PTC system with the parabolic aperture of 0.95m long and 0.5m wide. The efficiency during clear and partly cloudy weather condition is 50.7% and 36.49%, respectively. J.-L. Bouvier et al. [88], reported small size PTC ($46.5m^2$) with two axis tracking system for direct steam generation as a Micosol project (Micro solar CHP). Obtained thermal efficiency for this system with steam is around 50% and suitable for coupling with the steam engine. I. H. Yilmaz et al. [89], studied thermal performance of the parabolic trough collector array for a small-scale process heat application in agreement with ASHRAE 93-1986 standard and the maximum efficiency is 57%. G.Q. Chaudhary et al. [90], studied small size PTC system with aperture area of $2.077m^2$ integrated with a solid desiccant dehumidifier (SDD) for solar air-conditioning applications. Maximum thermal energy gain and peak efficiency for this system on a sunny day are 3.07 kW and 62%.

M. Yang et al. [91], designed a micro-parabolic trough solar collector for building integration. Optical and thermal performance of proposed collector were determined theoretically,

		m-PTC	Absolicon T160	Greenetica EOSth	Trivelli So- lar Wing Evo 2
Aperture width	[mm]	400	1594	1206	1140
Length	[mm]	1800	5508	3203	2100
net area	[m ²]	2.88	5.5	3.86	1.88
gross area	[m ²]	4.12	8.78	4.56	2.28
operational temperature	[°]	0-300	60-160	0-100	0-200
max pressure	[bar]	16	8		16
η_0	[-]		0.766	0.77	0.636
a_1	$\left[\frac{W}{m^2 \cdot ^\circ C} \right]$		0.368	0.47	0.70
a_2	$\left[\frac{W}{m^2 \cdot ^\circ C^2} \right]$		0.00322	0.03	-
K_d	[-]		0.859	0.85	
Tracking		one axis	one axis	dual axis	one axis

Table 2.4: Comparison of m-PTC and commercially available small scale PTC specs

experimentally and the incident angle modifier and normalized thermal efficiency curve were reported. Reported annual optical efficiency is 67% and the instant thermal efficiency is 59% at 200°C. However, installed micro PTC on building's facade (31° latitude) shows thermal efficiency of 37.5% at 200°C.

Comparing the specifics of these parabolic trough collectors, the commercial available models have quite bigger surfaces, for a single module, and the spacing between one module (or row of modules) is not specified nor accounted for. The operational temperatures also are not that high, limiting their integration with industrial uses and the fields of use (see figure 1.5 for comparison).

Since these are heat generating systems, they are affected by heat losses that depend on their working temperature relative to the ambient one. Their efficiency varies accordingly, and it's expressed with the coefficients η_0 , a_1 and a_2 , their evaluation is used to compare different systems. In order to be able to fully compare the m-PTC with other systems, it is necessary to evaluate its performance curve. The methodology used is further explained in section 3.1.

2.6 Torre degli Agli installation

A pilot project, using 38 m-PTC modules, located on the rooftop of a six stores Positive Energy Building in via Torre degli Agli in Florence, has completed the construction phase and is going into test and operation phase. A part of the PhD work and research evolved around this plant, its assembly, configuration and management, as the studied parts and methodology of the m-PTC systems were applied. In figure 2.11 is shown an early render of the buildings, the PV was moved on the roof of the second building, and in its place was constructed the m-PTC solar field, which can be seen in figure 2.12.

The system comprises of two rows of 19 modules, each divided in 3 block of 6 or 7 modules.



Figure 2.11: Early render of Torre Agli building

The blocks are linked in series, while the modules inside each block are linked in parallel, to achieve both a sustained flow rate and high temperature gain through the solar field. It uses pressurized water as working fluid, being able to produce heat up to 180 °C. The solar field is connected via heat exchanger with a Thermal Energy Storage (TES) of 30 m^3 situated underground adjacent to the building and to an Organic Rankin Cycle (ORC) machine to convert excess heat into electricity. The objective of the solar field is to cover the demand for sanitary hot water and eventually contribute to the space heating demand. A simplified scheme of the plant layout is shown in figure 2.13.

The system is expected to work autonomously, in synergy with the automation of the rest of the building, which features shading facades, photo voltaic systems, with centralized management of the heat and cooling supply.

At the time of writing, the construction phase for the building and hydraulic circuit of the plant are finished, as well as the installation of the modules and their assembly. The control



Figure 2.12: m-PTC field of Torre degli Agli pilot project

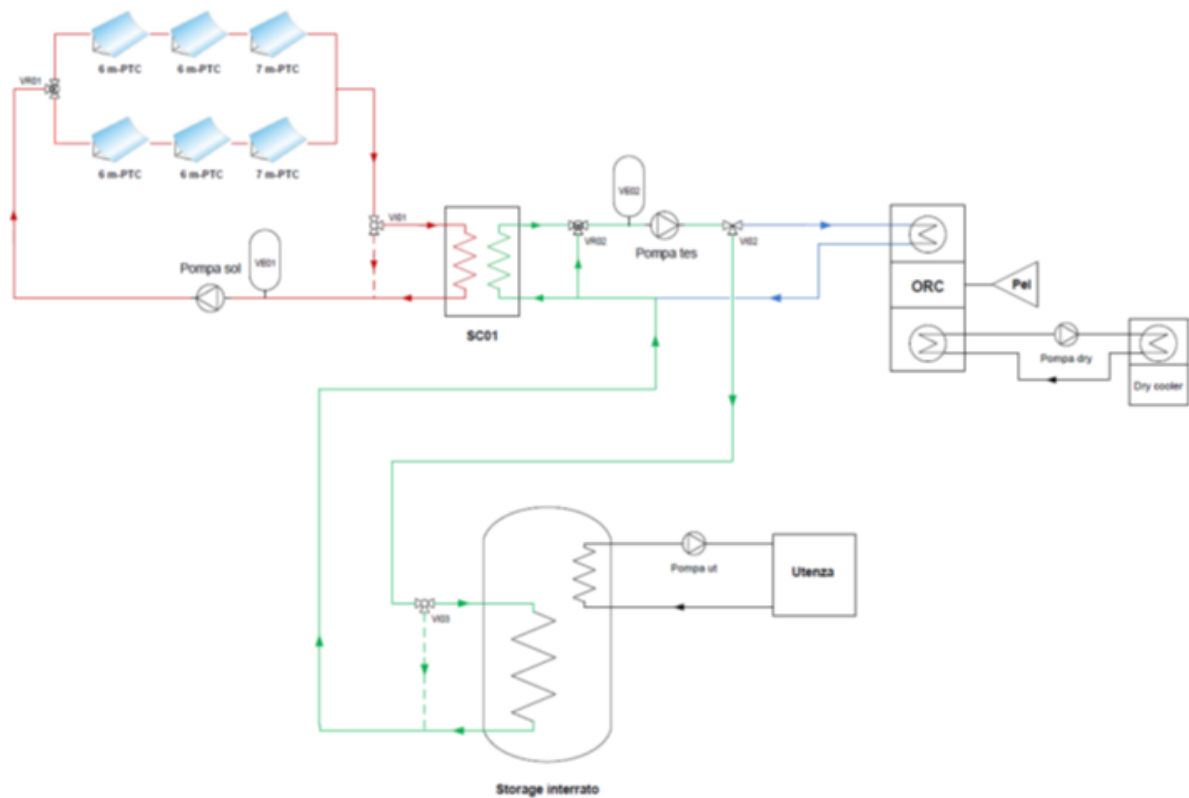


Figure 2.13: Torre Agli plant schematic



Figure 2.14: m-PTC field of Torre degli Agli pilot project

and management of the pilot plant, the building and their connection are going on, developed by an firm contracted by the builders, following our instructions for the plant part. The plant is expected to start operations in the year 2025, after a start up period needed to refine the parameters of the logic of control, as well assist and test its working capacity.

3. METHODOLOGY

The efficiency of PTC systems, and all solar heating systems in general, depends on the operating temperature as well as environment conditions, such as solar radiation and ambient temperature, also wind velocity influences the thermal losses for non concentrating systems. For concentrating systems, their capacity to harvest the solar radiation, directing it towards the absorber tube also affects their performance. To better estimate this influences and to be able to confront systems with very different characteristics between each other, many methodologies and norms have been developed.

In figure 3.1 is shown the typical efficiency profile for a concentrating system, which varies

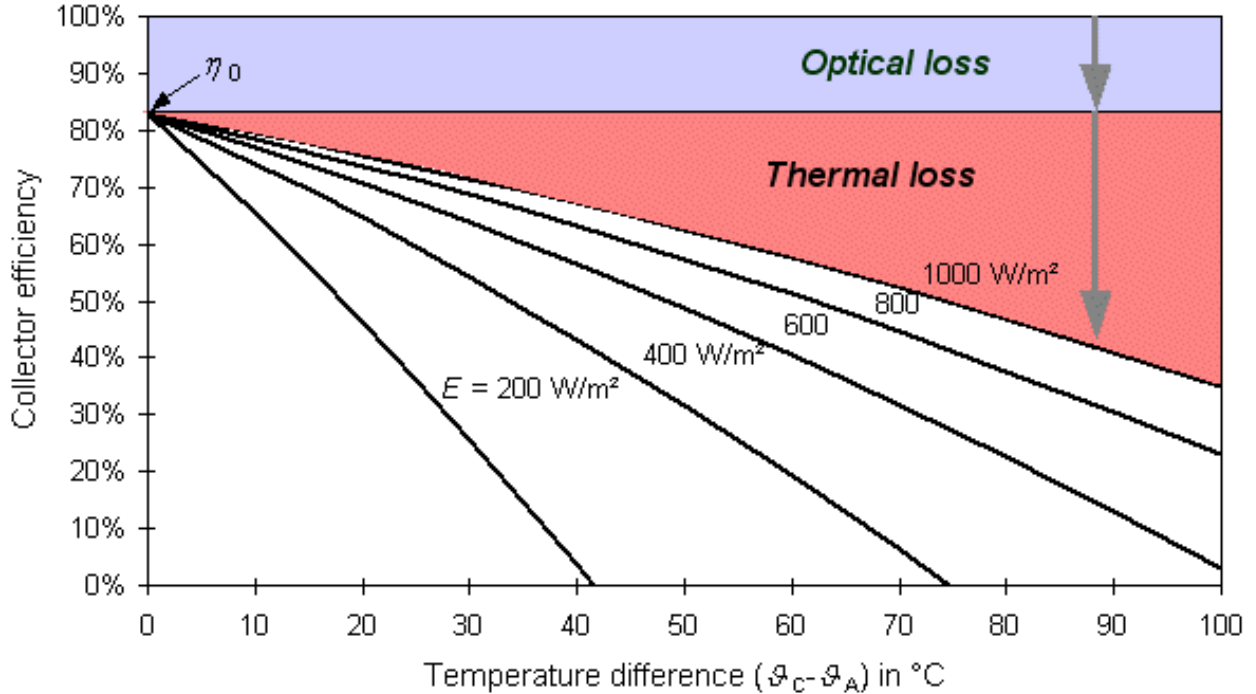


Figure 3.1: Efficiency curve, with optical and heat losses highlighted

both with the difference of temperature to ambient and with radiation intensity, as those affect the heat losses and input power, respectively.

The optical losses are usually independent of the working and ambient temperature or input power (but they may affect the system geometry, such as the focal distance, and

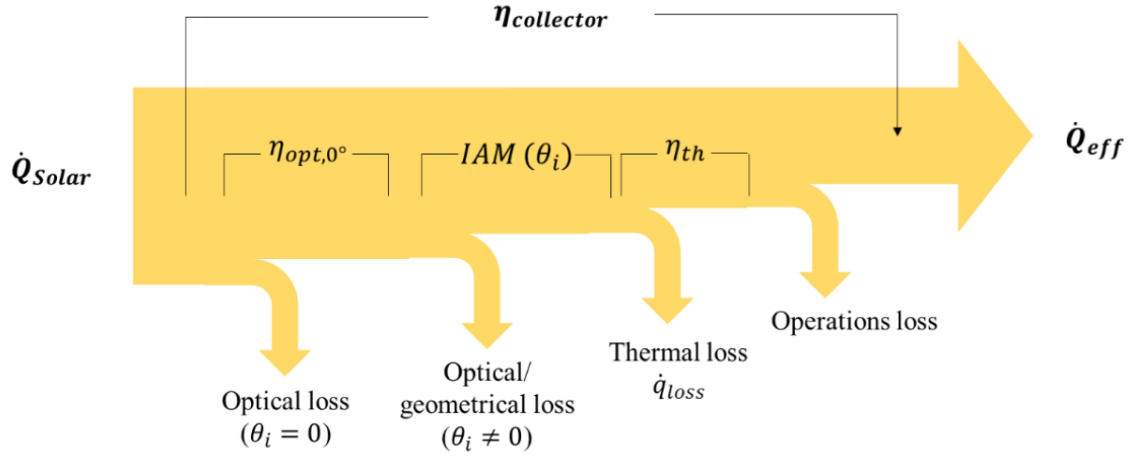


Figure 3.2: Calculation of the effective thermal energy in a PTC

thus its efficiency, depending on the system and its configuration), affect the constantly the performance and are related to the geometry of the system, the characteristics of mirrors, absorber tube, etc (for example intercept coefficient, absorbing factor α , reflecting factor ρ , transmission factor τ). The thermal losses increase with the difference between the operating mean temperature and ambient temperature, subtracting output power until no more power can be extracted (efficiency = 0) of the system reaches its maximum operating temperature. Depending on the incoming solar radiation, we have different curves, because with less input power the heat losses are going to weight more, the lesser the solar radiation, the lower the curve is and sooner the system can no longer produce useful power.

The information on the thermal performance of a solar thermal collector is important for the prediction of the energy output of any solar thermal system. Several standards are presented for test procedure on concentrating solar collector, such as ASHRAE 93 [92], EN 12975-2 [93], ISO 9806:2017 [94], ASTM E905-87:2013 [95] and SRCC 600 2014-07 [96]. However, the SRCC 600 2014-07 standard refers to ISO 9806 standard in relatively high similarity. Mentioned standards propose two different test approaches for characterizing the thermal performance of solar thermal collectors: The steady state test (SS) and the quasi-dynamic test (QD) [97]. In SS, all important variables for the thermal performance evaluation remain constant (in the range of permitted value by the standard) during the test period and test has to be performed under clear sky condition (low percentage of diffuse radiation). As a result, in obtained model by SS method there is no correction term for the diffuse radiation. However, obtained model in QD method is more detailed about the description of collector and drives from SS model by adding some correction terms (wind speed and radiation of long wavelength incident on the collector should be considered). In this method, test has to be performed under varying sky conditions for at least 3 h. Both methods are inspired by same principles. Therefore, there are no arguments to choose between these methods [97].

For this study the ISO 9806:2017 was used, and it is detailed below.

3.1 ISO 9806:2017

INTERNATIONAL
STANDARDISO
9806Second edition
2017-09**Solar energy — Solar thermal
collectors — Test methods***Énergie solaire — Capteurs thermiques solaires — Méthodes d'essai*

The ISO 9806:2017 [94] norm follows the previous ISO 9806:2013. The norm addresses the methodology for the analysis and thermal evaluation of all solar thermal systems, whether they use air, water or another fluid, be concentrating or not concentrating, all kind of sizes and types of technology, for indoor and outdoor testing. It is the referenced methodology for the certification and characterization of many studies. [98] [99] [100] [101]

It also contain methods for mechanical resistance, pressure drop, freezing resistance, leakage tests and many more.

3.1.1 Efficiency evaluation

In order to evaluate the performance of a system, we need to measure the power produced by it (such as with formula 3.1), so a proper measurement and estimation of those variables is needed.

$$\dot{Q} = \dot{m} \cdot c_f \cdot \Delta T = A_G \cdot G \cdot \eta \quad 3.1$$

where ΔT is the difference between the outlet and the inlet of the system (eq. 3.2); c_f is the specific heat of the operating fluid at constant pressure; A_G is the gross area of the system;

$$\Delta T = T_{outlet} - T_{inlet} \quad 3.2$$

$\dot{m}$ is the mass flow (obtained with 3.3 if volume flow is measured instead);

$$\dot{m} = \dot{v} \cdot \rho \quad 3.3$$

G is the incoming radiation on the system, and its evaluation changes based on the system considered. For dual axis concentrating systems, it is simply the direct component, G_b ; for

one axis concentrating systems, it can be evaluated with equation 3.4:

$$G_b = DNI \cdot \cos\theta \quad 3.4$$

For non concentrating systems, that rely on both direct and diffuse component of sunlight, the best option would be to measure the global component on a plane parallel to the collector itself. Another option, is to evaluate it from the global component measured on the horizontal plane, then projecting it on the plane of the collector, with equation:

$$G_{collector} = G_{global, horizontal plane} \frac{\cos \theta_{collector}}{\cos \theta_{zenith}} \quad 3.5$$

where $\theta_{collector}$ can be the zenith or elevation angle, the azimuth angle, or the combination of both, depending on whether the system has one axis tracking system (and its orientation), or is fixed.

The massflow rate shall be set at approximately $0.02 \frac{kg}{s}$ per squared meter of collector gross area.

The surrounding air temperature is to be monitored and registered, as well as wind velocity, although the last is not necessary per glazed and high concentrating collectors, as its effect can be neglected. For high concentrating systems with at least 1 axis tracking, the diffuse radiation can also be neglected.

The norm offer two different methodologies to perform tests and collect data: Steady State and Quasi Dynamic.

The Steady State method tries to recreate fixed points of working conditions, equally spaced in the operation range of working temperatures of the system, with a more compact formula due to the stability of tests and so the lack of need to further introduce other coefficients to account for dynamic effects.

The Quasi Dynamic method is more flexible on the test condition, more suitable and with conditions easier to meet for outdoor testing. It uses an additional term, the a_5 coefficient, which should be linked to the evolving temperature in the system.

The norm also provides methods for analyzing the experimental data and presenting the results. To analyze the data is recommended a least squared regression, or any other regression that minimizes the errors.

Conditions and requirements for both SS and QD methodology are presented, as well as formula used, which will be later incorporated in a Python program to analyze tests data.

3.1.2 Steady State (SS)

This method is trying to measure and isolate steady working points to use for the evaluation of performance of the studied system. To establish that a steady-state exists,

Name	Affected variable	Condition
Global test solar irradiance	G_d	$\pm 50 \frac{W}{m^2}$
Net Solar radiance	G_d	$> 650 \frac{W}{m^2}$
Surrounding air temperature	T_{amb}	$\pm 1.5K$
Fluid mass flow rate	$\dot{m}$	$\pm 1\%$
Fluid temperature at collector inlet	T_{in}	$\pm 0.1K$
Fluid temperature at collector outlet	T_{out}	$\pm 0.5K$
Fluid temperature gain	ΔT	> 0

Table 3.1: Steady State conditions

average values of each parameter taken over successive periods of 30 seconds shall be compared with the mean value over the measurement period. The following values in the table 3.1 show the requirements for the tests to be included.

The general formula used is:

$$\begin{aligned} \frac{\dot{Q}}{A_G} = & \eta_{0,hem} G_{hem} - a_1(T_m - T_a) - a_2(T_m - T_a)^2 - a_3 u(T_m - T_a) \\ & + a_4(E_L - \sigma T_a^4) - a_6 u G_{hem} - a_7 u(E_L - T_a^4) - a_8(T_m - T_a)^4 \end{aligned} \quad 3.6$$

where $a_4 = \eta_{0,hem} \frac{\epsilon}{\alpha}$ and $a_6 = \eta_{0,hem} \cdot b_u$ and $a_7 = \eta_{0,hem} \cdot b_u \frac{\epsilon}{\alpha}$ and $T_m = \frac{T_{out} + T_{in}}{2}$.

For concentrating and tracking systems, the wind and diffuse radiation can be neglected, and thus the linked term set to 0 ($a_3 = 0$, $a_4 = 0$, $a_6 = 0$, and $a_7 = 0$), so the equation 3.6 can be written as:

$$\frac{\dot{Q}}{A_G} = \eta_{0,hem} G_b - a_1(T_m - T_a) - a_2(T_m - T_a)^2 - a_8(T_m - T_a)^4 \quad 3.7$$

of which the use of both terms a_2 and a_8 has no sense, since they're correlated. Only one of the two shall be used.

The instantaneous efficiency for concentrating systems and one axis tracking¹ is valued as:

$$\eta = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A_G \cdot G} \quad 3.8$$

The equation 3.7, using the a_2 coefficient and not the a_8 , can also be written as:

$$\eta_{hem} = \eta_{0,hem} - a_1 \frac{T_m - T_{amb}}{G} - a_2 \cdot \frac{(T_m - T_{amb})^2}{G} \quad 3.9$$

Sometimes the temperature terms are written as

$$T^*_1 = \frac{T_m - T_{amb}}{G} \quad 3.10$$

¹if two axis tracking is used, the formula is simplified to $\eta = \frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A_G \cdot G_b}$

and

$$T^*_2 = \frac{(T_m - T_{amb})^2}{G} \quad 3.11$$

so Equation 3.9 can so be written as

$$\eta_{hem} = \eta_{0,hem} - a_1 \cdot T^*_1 - a_2 \cdot G \cdot T^*_1{}^2 \quad 3.12$$

or

$$\eta_{hem} = \eta_{0,hem} - a_1 \cdot T^*_1 - a_2 \cdot T^*_2 \quad 3.13$$

In equations from 3.8 to 3.12 G is intended as G_b , or as expressed in equation 3.4, or equation 3.5 depending whether a concentrated collector with dual axis tracking, concentrated one axis tracking and non concentrating systems, is studied, respectively.

The a_1 coefficient is representative of linear heat losses due to convention and conduction, while the a_2 is related to the radiative losses, although is a second power instead of a fourth power term, and the a_8 coefficient is also related to radiative heat losses.

Normally a second-order curve shall be used which can be achieved by least squares regression. A second order fit shall not be used if the value deduced for a_2 is negative or has no statistical significance (i.e. if $\tau = \left[\frac{\text{parameter value}}{\text{standard deviation of parameter value}} \right]$ is less than 3), and the regression shall be evaluated again without including that coefficient.

3.1.3 Quasi Dynamic (QD)

This methodology evaluates the performance of a system based on the evolving output power during various conditions, and requires multiple days of testing under clear sky, cloudy sky, as well as increasing and decreasing temperature at the inlet. For this methodology every row of data counts as a independent entry in its performance evaluation.

The formula used with this method is the equation 3.14 below:

$$\begin{aligned} \frac{\dot{Q}}{A_G} = & \eta_{0,b} \cdot K_b(\theta_L, \theta_T) \cdot G_b + \eta_{0,b} \cdot K_d \cdot G_d - a_1 \cdot (T_m - T_a) \\ & - a_2 \cdot (T_m - T_a)^2 - a_3 \cdot u \cdot (T_m - T_a) + a_4 \cdot (E_L - \sigma T_a^4) - a_5 \frac{dT_m}{dt} \\ & - a_6 \cdot u \cdot G - a_7 \cdot u \cdot (E_L - \sigma T_a^4) - a_8 \cdot (T_m - T_a)^4 \end{aligned} \quad 3.14$$

For collectors with high concentrating ratio (>20) and tracking system, K_d is not always significant and can be omitted. Under the same conditions, the wind dependency can be neglected, so $a_3 = 0$, $a_6 = 0$ and a_7 may be set to 0. The a_2 and a_4 parameters may also be set to 0.

The formula is therefore:

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} \cdot K_b(\theta_L, \theta_T) \cdot G_b - a_1 \cdot (T_m - T_a) - a_5 \frac{dT_m}{dt} - a_8 \cdot (T_m - T_a)^4 \quad 3.15$$

With one axis tracking², the $K(\theta_L, \theta_T)$ term is depending on only one angle, becoming $K(\theta)$. Its dependency on that angle is usually expressed as:

$$K_\theta(\theta) = \cos(\theta) + b_1 \cdot |\theta| + c_1 \cdot \theta^2 \quad 3.16$$

²with two axis tracking this term is set equal to 1

The evaluation formula is therefore:

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} \cdot (\cos(\theta) + b_1 \cdot |\theta| + c_1 \cdot \theta^2) \cdot G_b - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2 - a_5 \frac{dT_m}{dt} - a_8 \cdot (T_m - T_a)^4 \quad 3.17$$

The a_2 and the a_8 are strongly correlated, as the latter is the square of the first, so only one of them should be considered.

This method allows for a wider variability of measured data, such as the inlet temperature ($\pm 1K$). It also features a term to factor in the change in temperature, with the a_5 coefficient:

$$\frac{dT_m}{dt} = \frac{T_{m,new} - T_{m,old}}{\text{sampling interval}} \quad 3.18$$

There are guidelines to evaluate the suitability of the data recorded. they are the following:

$$T_{out} - T_{in} > 0 \text{ K} \quad 3.19$$

$$T_{in} \text{ stable within } \pm 1 \text{ K} \quad 3.20$$

The first part of each test day, at least 4 times the time constant of the collector or at least 15 minutes, with the correct fluid temperature at the inlet shall be skipped to ensure that the initial state of the collectors fades away and does not influence the result of the parameter identification.

3.1.4 Performance curve extraction

Even in its simplest form (Steady State), T^*_1 and T^*_2 are independent variables, and even more so in Quasi Dynamic, the norm suggests to use a Multi Linear Regression (MLR) approach with Least Squares Fitting (LSF). The general description is in appendix A.

To evaluate the performance of the collector the coefficients η_0 , a_1 and a_2 are to be calculated (here written for SS, from Equation 3.13, but can be easy adapted for QD with Equation 3.17). Its matrix form is:

$$\begin{bmatrix} IAM_{test\ 1} & T^*_{1\ test\ 1} & T^*_{2\ test\ 1} \\ IAM_{test\ 2} & T^*_{1\ test\ 2} & T^*_{2\ test\ 2} \\ \vdots & \vdots & \vdots \\ IAM_{test\ n} & T^*_{1\ test\ n} & T^*_{2\ test\ n} \end{bmatrix} \begin{bmatrix} \eta_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \eta_{test\ 1} \\ \eta_{test\ 2} \\ \vdots \\ \eta_{test\ n} \end{bmatrix} \quad 3.21$$

For dual axis tracking systems, IAM is always 1, and equation 3.21 can be simplified in:

$$\begin{bmatrix} 1 & T^*_{1\ test\ 1} & T^*_{2\ test\ 1} \\ 1 & T^*_{1\ test\ 2} & T^*_{2\ test\ 2} \\ \vdots & \vdots & \vdots \\ 1 & T^*_{1\ test\ n} & T^*_{2\ test\ n} \end{bmatrix} \begin{bmatrix} \eta_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \eta_{test\ 1} \\ \eta_{test\ 2} \\ \vdots \\ \eta_{test\ n} \end{bmatrix} \quad 3.22$$

In order to factor in the uncertainties of the experimental data, the matrixes are weighted as:

$$\begin{bmatrix} 1 & T^*_{1\ test\ 1} & T^*_{2\ test\ 1} \\ 1 & T^*_{1\ test\ 2} & T^*_{2\ test\ 2} \\ \vdots & \vdots & \vdots \\ 1 & T^*_{1\ test\ n} & T^*_{2\ test\ n} \end{bmatrix} \begin{bmatrix} err_{test\ 1} \\ err_{test\ 2} \\ \vdots \\ err_{test\ n} \end{bmatrix} \begin{bmatrix} \eta_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \eta_{test\ 1} \\ \eta_{test\ 2} \\ \vdots \\ \eta_{test\ n} \end{bmatrix} \begin{bmatrix} err_{test\ 1} \\ err_{test\ 2} \\ \vdots \\ err_{test\ n} \end{bmatrix} \quad 3.23$$

For ease of calculation, η is evaluated as a sum of positive terms, and as such the $-$ sign before the a coefficient in equation 3.13 is not explicit, and shall come from the evaluation. This treats the regression with $c = -a$ coefficient, so the coefficient should be negative as these terms represent heat losses. If one of the c coefficient should come out as positive, the parameter should be set to 0 and the regression evaluated again without it. This should also be applied if the uncertainty for the parameter has no statistical significance such as if

$$\tau = \left[\frac{\text{parameter value}}{\text{standard deviation of parameter value}} \right] \text{ is less than } 3.$$

3.1.5 Data reports and data representation

The ISO 9806:2017 also sets standards regarding the results reporting, with detailed examples and forms for all considered tests. Regarding the performance evaluation, in particular, it uses the $\eta - T^*_1$ plane for reference, for its ease to extrapolate functional operational data: simply multiply the y values for the area of the system to read the output power, and the x axis can be scaled to the typical radiation and offset with average local temperature to be the average working fluid temperature. A value of $\eta = 0.5$ at $T^*_1 = 0.1$ can be 4 kW of heat power for a 10 m^2 system, working at $800 \frac{\text{W}}{\text{m}^2}$ and operating at $100 \text{ }^\circ\text{C}$ in a $20 \text{ }^\circ\text{C}$ ambient, but also 5 kW under $1000 \frac{\text{W}}{\text{m}^2}$, working at $130 \text{ }^\circ\text{C}$ in a $30 \text{ }^\circ\text{C}$ ambient, it can even be 1,5 kW under $300 \frac{\text{W}}{\text{m}^2}$, working at $30 \text{ }^\circ\text{C}$ in a $0 \text{ }^\circ\text{C}$ ambient. Since the radiation, working and ambient temperatures can greatly vary the output, the $\eta - T^*_1$ normalization is really useful to report results in a more objective way, to be able to compare different systems tested in totally different condition, and also to be able to evaluate every possible scenario of use.

3.1.6 Summary

The methodology should be chosen before the tests, as it determines how to do them, however, a SS dataset may be analyzed as QD, maybe augmenting the number and quality of data available.

It should be noted that in SS, to find the data ranges that match the conditions, should be only considered the continuous ranges that satisfy them all, with the effect that if there are outliers, it acts as a breaker for all possible ranges, which shall finish before or start after them. In QD, the outliers can just be removed without any further considerations.

Both the SS and the QD methodologies use data collected at the same time to evaluate the thermal efficiency, which means that, especially with bigger systems, with some variables, as inlet and outlet temperature for example, are compared between measurements on different fluid elements.

For the SS method this should not be influential, as a stable condition should be achieved, with little to no difference between the various variables measured, so it doesn't matter which fluid element we are considering, as all the variables should remain constant (mass flow should be constant, as well as the inlet temperature, the outlet temperature is allowed to fluctuate a bit more, following the variable natural radiation). Also the data at the beginning of each test (4 time constants or 15 minutes) are discarded, to be sure not to include transient regimes.

For big full-scale systems, using the QD method, we are not evaluating the same element of fluid as it evolves through the system, subjected to changing conditions from the inlet to the outlet. This would transfer the natural delay of the effect of a small change in the regime (a higher variance in the inlet temperature or a variability in the radiation) to the coefficient a_5 ,

as well as other coefficients, since there is no methodology to take that into account. This will be taken into account during the work of this Phd, and its effect studied in details in Chapter 4, while a description of the working of a Python program developed during the PhD is also described in Section 3.2 and later in Chapter 4.

All formulas in the norm are trying to take into account various physical effects that can lower the efficiency (such as various heat exchange modes) and effects that may reduce the effective area of the collector (such as incident angles). For this reason, all coefficients should have a negative effect on the power/efficiency.

3.2 Analysis methodology

The following informations were not provided in the ISO 9806:2017 itself, but were derived from the experience with the tests and data analysis during the PhD period, such as the initial logic of the Python analysis program.

3.2.1 Pre processing

The pre processing of data consists of its preparation for later analysis. All data sets should be in the same format, with recognizable data columns, gathering all the sensor types to which the analysis is sensible to. This includes the associating data saved in different logs to one database, as well as removing from the dataset non test data, such as starting up procedures and other control related periods, like changing operating values (temperature inlet, massflow, tracking mode, etc).

Dataset assembly Radiation sensors are situated near the test site to provide accurate measurements, but often they may serve multiple scopes and different tests, so they might be logged and saved on a common but independent system. This also means that they need to be aligned with the tests' data. In order to achieve this, both logs should have timestamps, so that they can be used for alignment.

A simple and effective, yet manually-set way to achieve this is to use the *VLOOKUP* formula on Excel, which can correlate different datasets rows based on the value of its first columns, containing the timestamp in this case. The dataset should then be saved again as value format, instead of a formula based one, to be used in other analysis environments, different from Excel, such as Python. A common and light format used is the Comma Separated Values (.CSV).

This creates a complete data set of the whole set, containing all the variables of interest, such as inlet and outlet temperatures, ambient temperature, massflows, pressures, solar radiation and its components (global, direct, and diffuse), as well as other control variables, such as timestamp, control sensors, and so on.

Non conforming data removal Thanks to an operation journal and the complete extent of variables measured and stored in the dataset, periods of setting up, reaching temperatures, and other non useful and/or erroneous data are excluded from the database, which is then cleaned and passed on to the next analysis phase.

3.2.2 Data processing

The datasets are fed to Python program, written specifically to help in this analysis. The methodology differ depending on the type of analysis (SS or QD), but the first steps are

mostly the same.

The first step consists in reading the dataset, checking if the single rows of data satisfy the requirements (minimum solar radiation, massflow is not 0, ΔT is positive), then it calculates every other variable, such as the solar deviation θ (depending on the tracking system, timestamp and location) if was not logged, c_p of water (the formula provided in the ISO 9806[94] was used), punctual input and output power (equation 3.1), punctual efficiency η . Another optional check on $\eta < 1$ was also implemented to clear the data of transition period data which may have unreal temperature gains.

Steady State With this analysis approach, the datasets are scanned in search of valid tests periods. The program starts with a small subset of data, checks whether the 30 seconds mean points of this subset respect the conditions reported in Table 3.1. If this check is positive, it will add a further row of data at the bottom of the dataset, otherwise it will remove the first one and continues its checking. Once the minimum length is reached, it stores the initial row of data and the length of this subset, continuing to update it to its maximum length until this no longer satisfies the condition of Table 3.1.

Thanks to the Python program, all possible subsets are saved, and summary of the average values of all variable of interest and the standard deviation of its 30 seconds subpoints, as well as time stamp and full duration, are saved and displayed. Due to the logic of this search method, if multiple subsets share the same rows of data, are still considered valid and stored. The selection process of the subsets to be used still necessitate a human screening and choice, before going into the regression portion of the analysis.

Quasi Dynamic In Quasi Dynamic methodology, all rows are considered independent entry to the evaluation process, and are evaluated all together. The screening in this case is focusing on monitoring the whole dataset, to check that the full range of conditions suggested in the ISO 9806, to be able to fully characterize correctly every needed coefficient, as well as finding and removing unintentional (transitional) or unreal ($\eta > 1$) data in the dataset.

3.2.3 Post Processing

After the processing phase, all data must still be screened, to further exclude any outliers values, which could pass other checks. This is still a minor volume screening, respect to a full analysis of all raw data.

Then the python program compute all the terms needed for the performance evaluation, such as the punctual efficiency, the reduced temperature, in order to have all the values to evaluate equation 3.12.

The analysis then proceeds with error and performance coefficients evaluation via the MLR.

3.2.4 Errors

After the selection and preparation of data, it is time to factor in the measurement and statistical errors (Type A and B), and few option for the error on η are considered below (Errors propagation).

Type A

These are the errors that derives from condensing a series of different measures in one value. For n repeated measurements in the same conditions, the best evaluation of the

expected value of the measured quantity is its arithmetic mean x_i :

$$x_i = \bar{x}_i = \frac{1}{n} \sum_{k=1}^N x_{i,k} \quad 3.24$$

while the best estimate for its probability distribution is the experimental variance of the observed measurements:

$$s^2(x_i) = \frac{1}{n-1} \sum_{k=1}^N (x_{i,k} - \bar{x}_i)^2 \quad 3.25$$

with the experimental variance of the mean being the best estimate of its variance:

$$s^2(\bar{x}_i) = \frac{s^2(x_i)}{n} \Rightarrow s(\bar{x}_i) = \frac{s(x_i)}{\sqrt{n}} \quad 3.26$$

resulting in an uncertainty of:

$$u(x_i) = s(\bar{x}_i) = \frac{s(x_i)}{\sqrt{n}} \quad 3.27$$

Type B

Errors associated with instrument characteristics and equipment uncertainty are the most common examples of this type of errors. For the first one, producers and/or certification companies often state resulting uncertainties either in terms of standard deviations or ranges about the measurement values. If there is no additional information about the frequency distribution of values within the stated bounds (a_- ; a_+), the most suitable way of including all available information is by describing it with a rectangular distribution, as illustrated in Figure 3.3.

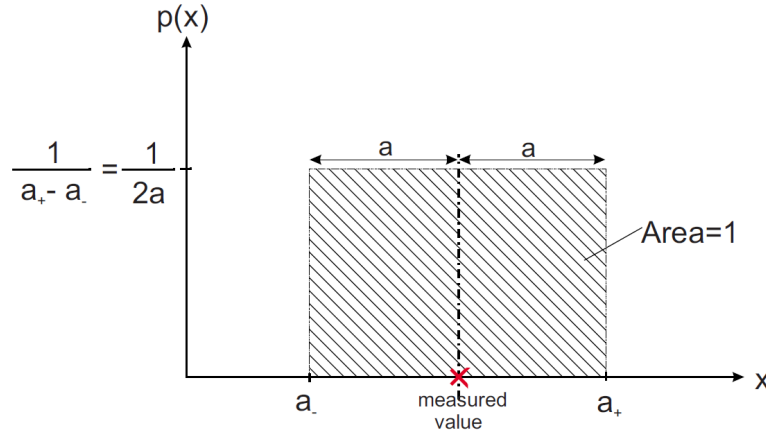


Figure 3.3: Rectangular error distribution (Type B)

For this kind of distribution the best approximation of the expected value is expressed as:

$$x_i = X_i = \int_{-\infty}^{+\infty} x \cdot f(x) dx = \frac{1}{a_+ + a_-} \int_{a_-}^{a_+} x dx = \frac{a_- + a_+}{2} \quad 3.28$$

while the associated error and standard variation is:

$$u^2(x_i) = \sigma^2(x) = E((x - E(X))^2) = E(x^2) - E(X)^2 = \frac{(a_+ - a_-)^2}{12} \quad 3.29$$

When both a_+ and a_- have the same value, equation 3.29 can be simplified as:

$$u^2(x_i) = \frac{(2a)^2}{12} = \frac{a^2}{3} \quad 3.30$$

so that

$$u(x_i) = \sqrt{\frac{a^2}{3}} = \frac{a}{\sqrt{3}} \quad 3.31$$

Sensor errors and data acquisition system (DAS) errors are combined with

$$u_b(x_i) = \sqrt{u_{sensor}(x_i)^2 + u_{DAS}^2} \quad 3.32$$

Error type A and B combination

Errors of type A and type B are combined in one absolute error, with

$$u(x_i) = \sqrt{u_a(x_i)^2 + u_b(x_i)^2} \quad 3.33$$

Errors propagation

Different formulas of error propagation were evaluate to compute the final error on η , through the errors of the variables that contributes to its calculation, such as massflow $\dot{m}$, temperature difference ΔT , solar radiation G .

Simple derivation Is based on the formula 3.34, where δ represents the absolute error:

$$\delta f = \sqrt{\sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \cdot \delta x_i \right)^2} \quad 3.34$$

which, applied to our η formula (equation 3.8) becomes³:

$$\delta \eta = \sqrt{\left(\frac{\partial \eta}{\partial \dot{m}} \delta \dot{m} \right)^2 + \left(\frac{\partial \eta}{\partial \Delta T} \delta \Delta T \right)^2 + \left(\frac{\partial \eta}{\partial G} \delta G \right)^2} \quad 3.35$$

³No error was hypothesised on c_p , as its value, especially for water, is well known and varies very little in the range of analysis. Similarly no error was included for the surface A , as it will not vary between different measurements on the same system.

We divide everything for the equation 3.8, making use of the relative error instead of the absolute one, we get:

$$\frac{\delta\eta}{\eta} = \frac{\sqrt{\left(\frac{c_p \cdot \Delta T}{A \cdot G} \delta\dot{m}\right)^2 + \left(\frac{\dot{m} \cdot c_p}{A \cdot G} \delta\Delta T\right)^2 + \left(\frac{\dot{m} \cdot c_p \cdot \Delta T}{A \cdot G \cdot G} \delta G\right)^2}}{\frac{\dot{m} \cdot c_p \cdot \Delta T}{A \cdot G}} = \quad 3.36$$

$$= \frac{\frac{c_p}{A \cdot G} \sqrt{(\Delta T \cdot \delta\dot{m})^2 + (\dot{m} \cdot \delta\Delta T)^2 + \left(\frac{\dot{m} \cdot \Delta T}{G} \delta G\right)^2}}{\frac{\dot{m} \cdot c_p \cdot \Delta T}{A \cdot G}} = \quad 3.37$$

$$= \frac{\sqrt{(\Delta T \cdot \delta\dot{m})^2 + (\dot{m} \cdot \delta\Delta T)^2 + \left(\frac{\dot{m} \cdot \Delta T}{G} \delta G\right)^2}}{\dot{m} \cdot \Delta T} = \quad 3.38$$

$$= \sqrt{\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta G}{G}\right)^2} \quad 3.39$$

which is simply the squared sum of the relative errors⁴.

Multiple derivation In order to better evaluate the reciprocal influence of the variables on each other, seconds and following derivate were calculated using the general formula in equation 3.40.

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i) + \sum_{i=1}^N \sum_{j=1}^N \left[\frac{1}{2} \left(\frac{\partial^2 f}{\partial x_i \partial x_j}\right)^2 + \frac{\partial f}{\partial x_i} \frac{\partial^3 f}{\partial x_i \partial x_j^2} \right] \cdot u^2(x_i) \cdot u^2(x_j) \quad 3.40$$

In our cases, when $i = j$ both term between square brackets are null for $\dot{m}$ and ΔT , as their second order derivate is 0, since they have exponent 1. When these two variables are j the

⁴in this case G is intend as whatever radiation is used. If also diffuse radiation G_d must be included, the equation 3.39 becomes $\sqrt{\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta G_b}{G_b}\right)^2 + \left(\frac{\delta G_d}{G_d}\right)^2}$

second term is 0. Expanding the formula and applying our η equation, we get:

$$\begin{aligned}
 u_c^2(\eta) = & \left(\frac{\partial \eta}{\partial \dot{m}} \right)^2 \cdot u^2(\dot{m}) + \left(\frac{\partial \eta}{\partial \Delta T} \right)^2 \cdot u^2(\Delta T) + \left(\frac{\partial \eta}{\partial G} \right)^2 \cdot u^2(G) + \\
 & + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial \dot{m} \partial \Delta T} \right)^2 \right] \cdot u^2(\dot{m}) \cdot u^2(\Delta T) + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial \dot{m} \partial G} \right)^2 + \frac{\partial \eta}{\partial \dot{m}} \frac{\partial^3 \eta}{\partial \dot{m} \partial G^2} \right] \cdot u^2(\dot{m}) \cdot u^2(G) + \\
 & + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial \Delta T \partial \dot{m}} \right)^2 \right] \cdot u^2(\Delta T) \cdot u^2(\dot{m}) + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial \Delta T \partial G} \right)^2 + \frac{\partial \eta}{\partial \Delta T} \frac{\partial^3 \eta}{\partial \Delta T \partial G^2} \right] \cdot u^2(\Delta T) \cdot u^2(G) + \\
 & + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial G \partial \dot{m}} \right)^2 \right] \cdot u^2(G) \cdot u^2(\dot{m}) + \left[\frac{1}{2} \left(\frac{\partial^2 \eta}{\partial G \partial \Delta T} \right)^2 \right] \cdot u^2(G) \cdot u^2(\Delta T)
 \end{aligned} \tag{3.41}$$

We can group term between squared brackets which are preceded by $\frac{1}{2}$, followed by the remaining higher order derivatives (only in $\partial^2 G$, as all other ∂^2 are 0):

$$\begin{aligned}
 u_c^2(\eta) = & \left(\frac{\partial \eta}{\partial \dot{m}} \right)^2 \cdot u^2(\dot{m}) + \left(\frac{\partial \eta}{\partial \Delta T} \right)^2 \cdot u^2(\Delta T) + \left(\frac{\partial \eta}{\partial G} \right)^2 \cdot u^2(G) + \\
 & + \left(\frac{\partial^2 \eta}{\partial \dot{m} \partial \Delta T} \right)^2 \cdot u^2(\dot{m}) \cdot u^2(\Delta T) + \left(\frac{\partial^2 \eta}{\partial \dot{m} \partial G} \right)^2 \cdot u^2(\dot{m}) \cdot u^2(G) + \\
 & + \left(\frac{\partial^2 \eta}{\partial \Delta T \partial G} \right)^2 \cdot u^2(\Delta T) \cdot u^2(G) + \\
 & + \left(\frac{\partial \eta}{\partial \dot{m}} \frac{\partial^3 \eta}{\partial \dot{m} \partial G^2} \right) \cdot u^2(\dot{m}) \cdot u^2(G) + \left(\frac{\partial \eta}{\partial \Delta T} \frac{\partial^3 \eta}{\partial \Delta T \partial G^2} \right) \cdot u^2(\Delta T) \cdot u^2(G)
 \end{aligned} \tag{3.42}$$

Formula used

Error evaluation with both equation 3.39 and equation 3.42 show no significant difference (ranging from 10^{-6} to 10^{-10}) between each other, so the first one was used.

4. METHODOLOGY REVIEW

The period abroad was spent at the Solar Plataforma Solar de Almeria (PSA) in Almeria, Spain. During the three month period the Python program was implemented to be able to analyze data with the Quasi Dynamic methodology. Data from EUROTrough and URSSATrough tests were analyzed with a new approach.

4.1 Study cases

Both the EUROTrough and the URSSATrough were tested some years ago with different methodologies. The collectors' specifics and the methodologies used are described below.

4.1.1 EUROTrough

The EUROTrough collector was tested at the Plataforma Solar de Almería "HTF test loop" facility (Almería Province, Spain, located at latitude 37.0927N and longitude 2.3564W) in 2015-2016. An extended report on its performance was published in 2017 ([99]).

It is a large PTC (length 75 m), composed of four first-generation and two second-generation modules at the time of testing, designed and built under the European EUROTrough Project ([98]). It has an aperture width of 5.76 m, for a total cross-area of 432 m^2 .

The collector tracking axis was oriented East-West (EW) and the tracker was based on a solar position algorithm (time/date based, open loop control). The tests were conducted only from 200°C to 400°C to avoid a variability in the geometry of the receiver assembly due to the expansion of the receiver tube with increasing temperature, collecting data only in the operating range defined for the nominal operating condition of the CSP plant.

The tests were made using the Quasi Dynamic method of the ISO 9806: 2017 method, with the correction of the cleanliness factor (F_c).

4.1.2 URSSATrough

The URSSATrough was tested in 2011-2012, also at the Plataforma Solar de Almería "HTF test loop" facility, using the Steady State method.

Similarly to the EUROTrough, it has a 5.76 m aperture and a 75 m length.



Figure 4.1: EURO-Trough collector [98]



Figure 4.2: URSSATrough [102]

The results of the optical and thermal performance were published in 2014 ([102]). These results were obtained with a Steady State methodology.

4.1.3 Summary

Both systems are very similar to each other, as we can see from the parameters in Table 4.1. The main difference resides in the absorber tubes and the analysis method used.

4.2 Modelling and programming

In order to aid in the data analysis and the extrapolation of the optical and thermal efficiency coefficients, the Python code was implemented.

Parameter	EUROTrough	URSSATrough
Tube length	75 m	75 m
Aperture	5.76 m	5.76 m
Total area	409.908 m	409.908 m
Inner diameter	66 mm	66 mm
Fluid used	Syltherm [®] 800	Syltherm [®] 800
Tracking system	1 axis	1 axis
Analysis Method	QD	SS

Table 4.1: Summary of parabolic trough collectors characteristics

In addition to standard operations such as reading and extracting relevant data¹ from raw files, methods to analyze them both with SS and QD methodology were included. The code can also work with either a column number or the channel name per each variable. This was made to be able to analyze the data stored in different ways more easily (and also because at least one of the data sets changed column's order during the tests).

The routine starts by reading all the data in the specified files, then, because many files

Variable Name	Variable	Method
Timestamp	<i>Date_time</i>	read only
Inlet Temperature	T_{in}	read only
Outlet Temperature	T_{out}	read only
Ambient Temperature	T_{amb}	read only
Direct Radiation	G_b	read only
Diffuse Radiation	G_d	read only (if needed)
Wind Velocity	u	read only (if needed)
Inclination	θ	read if available, or calculated from position and timestamp ²
Specific heat capacity	c_p	calculated at T_m
Density	ρ	calculated at T_m if needed
Mass flow	$\dot{m}$	read or calculated from volflow
Volume Flow	$\dot{V}$	read or calculated from massflow

Table 4.2: Read/needed variables, method (read or calculate)

were captured for whole 24 hours periods, it has a first screening process in order to identify and exclude data ranges where there would be no radiation (the night times). Then, to find the beginnings and ends of the testing periods, it is looking for high variability in the outlet temperatures, as it was identified as a good indicator of the test periods, due to the focus/defocus process. After this first screening procedure, the algorithm of data analysis differs for the two methodologies (SS and QD), to converge again in the linear regression part at the end.

¹Table 4.2 summarizes the data read and evaluated as needed, using the Python code

4.2.1 For Quasi Dynamic

In this case we have a constraint on the minimum solar radiation, a larger range of acceptance of the variability of the inlet temperature (with a term for the derivate of the medium temperature with time), and positive difference between inlet and outlet temperature. A very large value of the derivative term also implies a transition in the operating condition, so restrain on this term is also helpful. In Table 4.3 are summarized the condition evaluated (they can be set to different values as pleased).

With this method, each line of data counts as an independent entry for the performance

Variable Name	Variable	acceptance range	range used
Solar Radiation	G	$G > 700 \frac{W}{m^2}$	$G > 700 \frac{W}{m^2}$
Inlet Temperature	T_{in}	T_{in} stable $\pm 1K$	T_{in} stable $\pm 1K$
Mean Temperature derivate	$\frac{dT_m}{dt}$		$-0.25 < \frac{dT_m}{dt} < 0.25$
Power produced	$\dot{Q}$	$\dot{Q} > 0$	$\dot{Q} > 0$

Table 4.3: Acceptance conditions for QD method

evaluation, so each row that respects the conditions is taken into account for the evaluation. The formula used is:

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} \cdot (\cos(\theta) + b_1 \cdot |\theta| + c_1 \cdot \theta^2) \cdot G_b + a_1 \cdot (T_m - T_a) + a_2 \cdot (T_m - T_a)^2 + a_5 \frac{dT_m}{dt} + a_8 \cdot (T_m - T_a)^4 \quad 4.1$$

it differs from equation 3.17 by having all positive terms, so the value of each coefficient is expected to be negative.

For each entry, all the variables are computed as values to feed the linear regression, in order to have something like:

$$\frac{\dot{Q}}{A} = \sum p_i x_i \quad 4.2$$

where p_i are the coefficients to be extracted, and x_i are the calculated variables.

For high concentrating solar systems, with no diffuse radiation and wind dependency, they are shown in table 4.4 below:

Term	Coef p_i	Var x_i	Abbr
$\frac{\dot{Q}}{A_G}$	-	$\frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A_G}$	y
$\eta_0 \cdot \cos(\theta) \cdot G$	η_0	$\cos(\theta) \cdot G$	a
$(\eta_0 \cdot b_1) \cdot \theta \cdot G$	$\eta_0 \cdot b_1$	$ \theta \cdot G$	b
$(\eta_0 \cdot c_1) \cdot \theta^2 \cdot G$	$\eta_0 \cdot c_1$	$\theta^2 \cdot G$	c
$a_1 \cdot (T_m - T_a)$	a_1	$T_m - T_a$	1
$a_2 \cdot (T_m - T_a)^2$	a_2	$(T_m - T_a)^2$	2
$a_5 \cdot \frac{dT_m}{dt}$	a_5	$\frac{dT_m}{dt}$	5
$a_8 \cdot (T_m - T_a)^4$	a_8	$(T_m - T_a)^4$	8

Table 4.4: Terms, coefficients, variables and respective abbreviation used in Quasi Dynamic

For the incidence angle modifier, the coefficients b_1 and c_1 are isolated by dividing the resulting number by the peak optical efficiency η_0 .

4.2.2 For Steady State

In this case the analysis logic is different, as we have to identify each period where the condition are met³, and so the exclusion of one or more rows of data means the end of the considered period, which should be at least 10 minutes long, excluding the first 15 minutes of the day (or the whole test set, if doing multiple per day) to reach a stability of the system. The most strict condition, for outdoor testing, is the inlet temperature, as on fairly clear sky days the variance of the solar radiation is not that impactfull.

To maximize the number and length of suitable periods found and also to be able to double check them for any deviance or behavior not included in the data read by the program, an intermediate step is needed. First, the program finds and prints all ranges of data that satisfy all the conditions, which can be consecutive of each other, overlapping, or independent. Then a human input is needed, in the form of selecting the most of them which are independent (not overlapping each other) and feeding them to the program again, which will then compute the variables needed (Table 4.5) for the linear regression for each test period:

Term	Coef	var
η_{hem}	-	$\frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A_G \cdot G}$
$a_1 \cdot \frac{T_m - T_a}{G}$	a_1	$\frac{T_m - T_a}{G}$
$a_2 \cdot \frac{(T_m - T_a)^2}{G}$	a_2	$\frac{(T_m - T_a)^2}{G}$
$a_8 \cdot \frac{(T_m - T_a)^4}{G}$	a_8	$\frac{(T_m - T_a)^4}{G}$

Table 4.5: Terms, coefficients and variables for Steady State

In this case, the equation used is:

$$\eta = \eta_0 + a_1 \frac{T_m - T_{amb}}{G} + a_2 \cdot \frac{(T_m - T_{amb})^2}{G} + a_8 \cdot \frac{(T_m - T_{amb})^4}{G} \quad 4.3$$

which differs from the formula in Chapter 3 again for having positive coefficients, as opposed to the model in the norm, so the value is expected to be negative for all of them. Also, similar to before, is either the coefficient a_2 or a_8 , having both of them is redundant and should be avoided.

It is worth noting that, requiring an operator input in the intermediate step, in the form of a choice of selected intervals to be considered, this method is always affected by the choice made, and so it is not free of biases.

4.2.3 Timeshift Logic

One considerable limitation of the ISO 9806 methodology is that all variables are measured, calculated, and taken into account simultaneously, at the same time stamp, while the fluid takes some time to evolve in the collectors: the bigger the system, the longer it takes. This is negligible in the Steady State, as the stable condition should be reached across all variables, therefore being time independent, while in the Quasi Dynamic all the variables are taken into account as single data points, in an evolving system, but treated as independent from each other.

In order to better capture the working condition of the studied systems (which have a considerable length), especially with Quasi Dynamic methodology, a time shift of some variables is proposed. To do so, the first thing to do is to evaluate the hydraulic time constant

³see Table 3.1

of the system, which depends on the fluid, the intern diameter of the receiver tube, the mass (or volume) flow, the length of the receiving tube:

$$\begin{aligned} time\ shift_C &= \frac{length}{velocity} = length \cdot \frac{cross\ area}{vol\ flow} = \\ &= length \cdot \frac{\pi \cdot (int\ diam/2)^2}{vol\ flow(= mass\ flow/density)} \end{aligned} \quad 4.4$$

The only thing that varies during the tests is the volume flow rate, which should anyway remain within 2% of its mean value, so it is considered stable during data analysis too (only suitable periods are analyzed).

The time shift contrast is therefore evaluated as the mean value of the above formula, averaged over the period of the test, as well confronted with the sampling ration, generating k , the number of data rows to include, therefore should be the closest integer to the following ratio:

$$k = \frac{timeshift}{sampling\ rate} \quad 4.5$$

If this parameter is more than one, for each sample time, the outlet temperature considered (to be compared with the n^{th} inlet temperature) should be the one at the reading closest to the sample time plus the timeshift constant (the $(n + k)^{th}$ reading).

Similarly, the ambient temperature and the radiation should be averaged over the t_n and the t_{n+k} rows of data.

$$T_{inlet} = T_{inlet, t=t_n} \quad 4.6$$

$$T_{outlet} = T_{outlet, t=t_{n+k}} \quad 4.7$$

$$T_{amb} = \sum_{t_n}^{t_{n+k}} T_{amb} \cdot \frac{1}{k} \quad 4.8$$

$$G = \sum_{t_n}^{t_{n+k}} G \cdot \frac{1}{k} \quad 4.9$$

In this subroutine is important to track each data row with a proper time evaluation, in this the *datetime* package of python has been very helpful.

4.2.4 Cleanness Factor F_c

The cleanliness of the reflector and the glass tube of the receiver would also have an important impact on its optical properties. Therefore, the cleanliness factor F_c , as calculated in Equation 4.10, was implemented and calculated from the available daily measurement, as suggest by (Janotte et al., 2014)[99].

$$F_c = \left(\frac{\rho}{\rho_{max, ref}} \right)^{3/2} \quad 4.10$$

where with $\rho_{max, ref}$ is the highest value, from a measurement of the reflector reflectance under perfectly clean conditions. The 3/2 exponent is a correction factor that takes into account the fact that both the reflectors and glass tubes are affected by the cleanliness, but this effect is measured only on the reflectors.

4.2.5 Python program

The Multiple Linear Regression is also performed inside the python program, using Ordinary Least Squared (OLS). Thanks to the *statemodel* python package the results are quite detailed, with lots of useful parameters to evaluate the quality of the fit, as well as the standard deviation on the values of the coefficients. In Figure 4.3 is reported a simplified flowchart of the python program's logic and procedure.

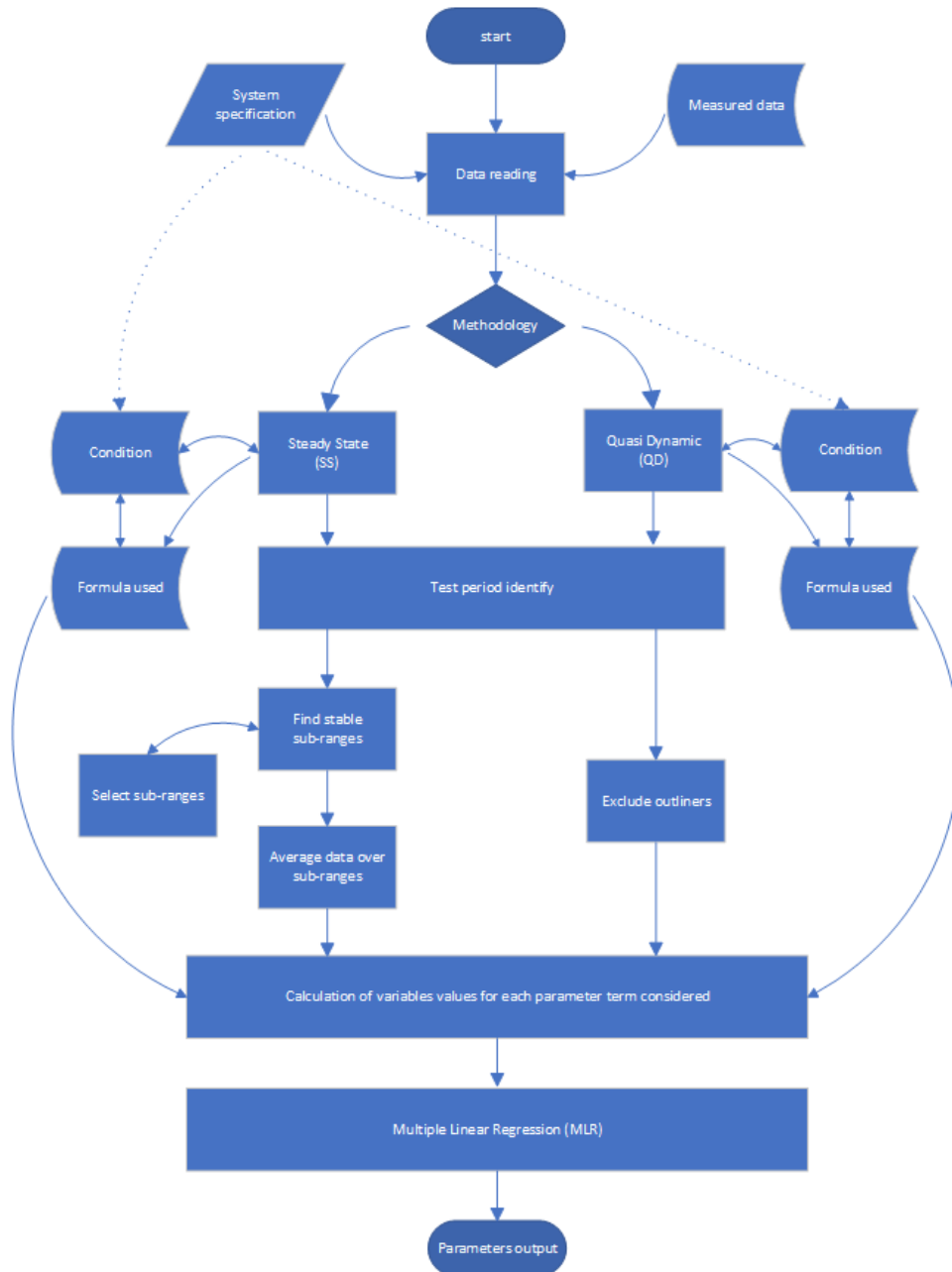


Figure 4.3: Flowchart of the Python analysis program

4.3 Data analysis

Here the data from previous test is analyzed again with new methodologies, and the results are compared with the published ones.

4.3.1 EUROTrough

The raw data comprise of more than 200 000 rows, registered during 16 days period, including temperatures from 170 to 340 °C. This is intentional and meant to avoid changes in the geometry of the system (namely the distance of the absorber tube from the mirrors, due to the thermal expansion), using only data in the temperature of full operation.

4.3.1.1 Previous best fit

The data considered was about 62 hours of total test time, for about 43 000 rows of data, from the total 200 000 rows collected during the test period.

In the original analysis, both a_2 and a_8 were considered and evaluated, and the dummy variables method was used, following the Quasi Dynamic methodology. It is also to be highlighted that the peak efficiency $\eta_{0,b}$ and the coefficients b_1 and b_2 were extrapolated independently, and so these tests were focused on the extrapolation of thermal performance of the module, in particular the coefficients a_1 , a_8 and a_5 .

The following formula was used:

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} \cdot K_b(\theta) \cdot G_d \cdot F_C - a_1 \cdot (T_m - T_a) - a_8 \cdot (T_m - T_a)^4 - a_5 \cdot \left(\frac{dT_m}{dt} \right) \quad 4.11$$

with

$$K_b(\theta) = 1 - \frac{b_1|\theta| + b_2\theta^2}{\cos\theta} \quad 4.12$$

The coefficients extrapolated, as well as their standard deviation, are reported in Table 4.6 and represented in Figure 4.4 below:

Parameter	Value	Std dev	τ value
$\eta_{0,b}$	0.699	0.003	203.4
b_1	$8.40 \cdot 10^{-4}$	$8.7 \cdot 10^{-5}$	9.7
b_2	$2.27 \cdot 10^{-5}$	$2.1 \cdot 10^{-6}$	11.0
a_1	0.085	0.0016	5.4
a_8	$1.96 \cdot 10^{-9}$	$2 \cdot 10^{-10}$	9.9
a_5	1781	106	16.9
R^2	0.999846		

Table 4.6: EUROTrough results as published

4.3.1.2 Fit with new analysis program

The Python program was utilized to perform the evaluation of data. In order to have better quality control over the data, only data used in the original article was utilized.

On top of the use of the same data, a screening to remove outlier points was still applied. This screening verifies the direct radiation, temperature difference between the inlet and outlet, and the temperature difference between the average temperature in the collector and the ambient temperature.

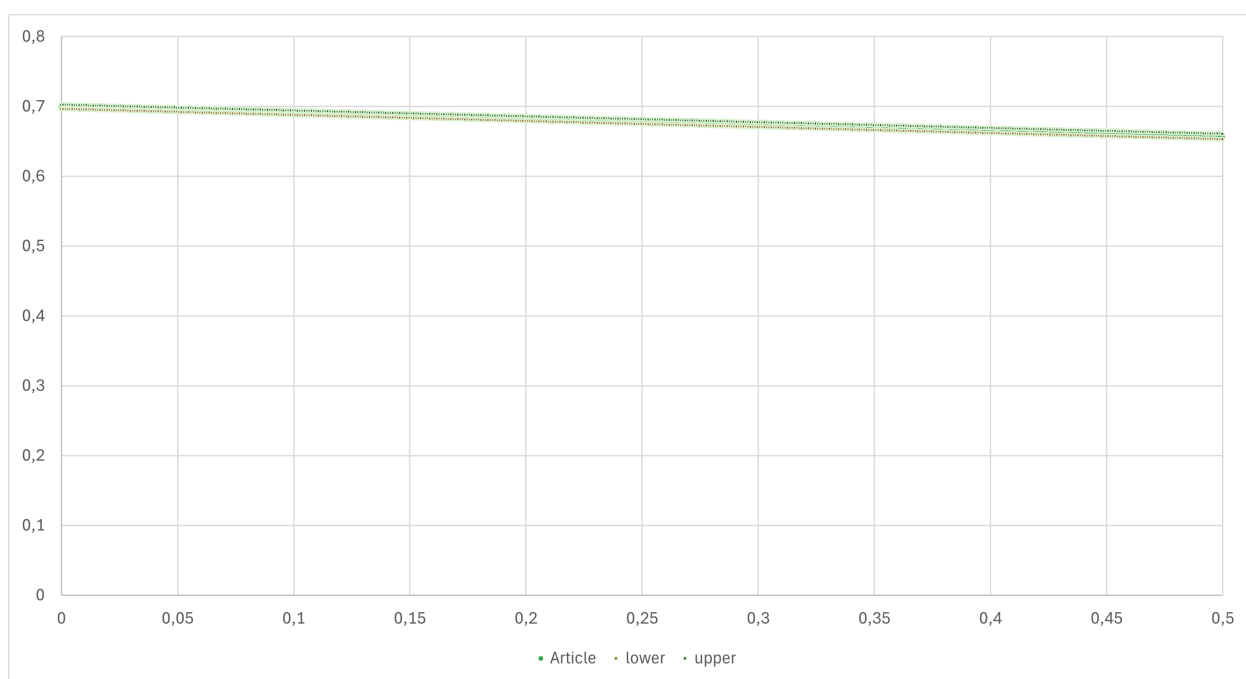


Figure 4.4: Performance graph with the published coefficient

A minimum of $0.1 \frac{W}{m^2}$ was implemented to remove data collected during night times, as well to avoid division by 0 during the program operation, which would result in errors and the crashing of the program itself.

A minimum threshold of $6^\circ C$ was included for the temperature difference. During testing times, this difference is around $30^\circ C$ or more, so this control will exclude points with the collector out of focus, as in this case the expected temperature difference should be much lower (even negative).

To take into account the same temperature ranges as the article, to not affect the geometry between the mirrors and the receiver, a further threshold on the inlet temperature was implemented, with a minimum of $170^\circ C$.

Since the Python program evaluates every coefficient at once, it's not possible to have a direct confrontation with the numbers published. To compensate, the same data was evaluated with the same formula as in the published paper, resulting in the values reported in Table 4.7 below.

Because in the program all the contributions are positive, the negative values of the coef-

Parameter	Value	Std dev	τ value
$\eta_{0,b}$	0.6505	0.0008	831
b_1	-0.00033	$8.7 \cdot 10^{-6}$	38
b_2	$-2 \cdot 10^{-5}$	$2.6 \cdot 10^{-7}$	77
a_1	-0.053	0.004	13.6
a_8	$-2.12 \cdot 10^{-9}$	$4.5 \cdot 10^{-11}$	47
a_5	-789.5	22	35
R^2	0.96122		

Table 4.7: EUROTrough from the Python program, same data as published

ficients here are expected. The τ values of this MLR are also very high, which is a good indication of a good fit, as well as the R^2 value, so this is considered a good base, and further variation of the methodology of analysis will be confronted with these.

We then analyzed the full extent of the test data, encompassing all 200,000 rows of test points. The goal was to automate the first screening process to remove all possible human biases from the analysis. Using only the screening thresholds previously described ($G_{d\text{minimum}} = 0.1 \frac{W}{m^2}$, $6^\circ C \Delta T$, $170^\circ C T_{in,min}$), the dataset was reduced to 91 000 rows of data. Looking at the distribution of the power produced per square meter ($\frac{\dot{Q}}{A_G}$), reported in the figure 4.5, there are a few of data points with very low power production, which can be reconducted to non operational times that have escaped our screening procedure (the distribution for the published data is in figure B.1 at page 131).

A further threshold was implemented, this time on the minimum η expected during the tests since test periods are designed to be only during clear sky or partially cloudy conditions, at least some radiation is expected, so a threshold of 0,15 minimum was implemented on the efficiency ($\frac{\dot{Q}}{A_G} = \eta \cdot G_d$).

This brought the data to 68 500 rows, effectively removing quite some undesired data from the set. This distribution is more similar to the published one, with more data points in the lower zone.

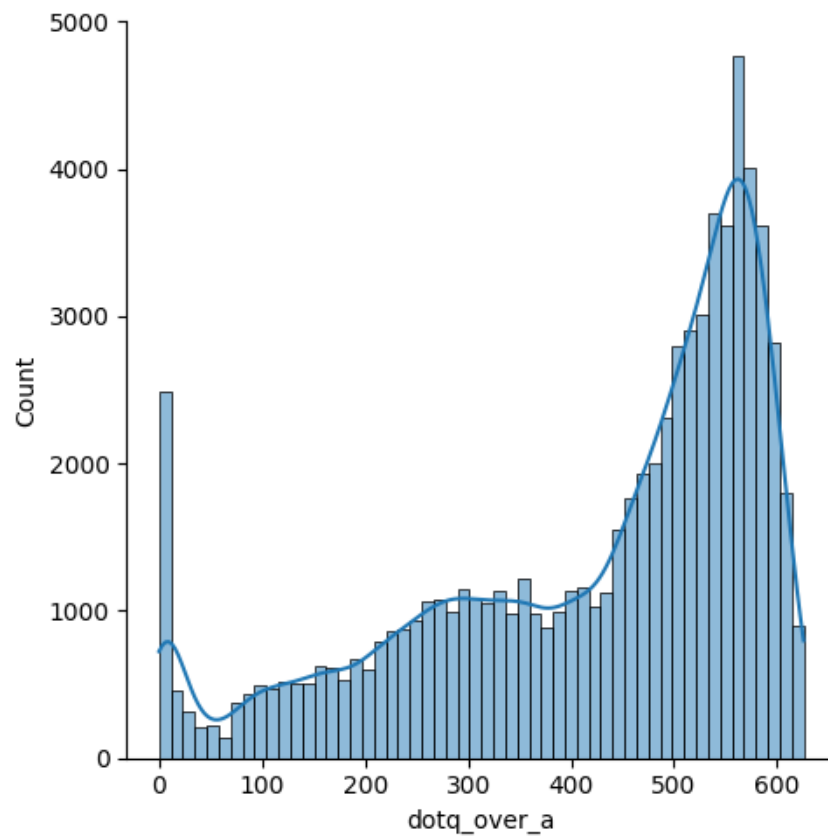


Figure 4.5: Distribution of the power produced per square meter, after the first screening on all data

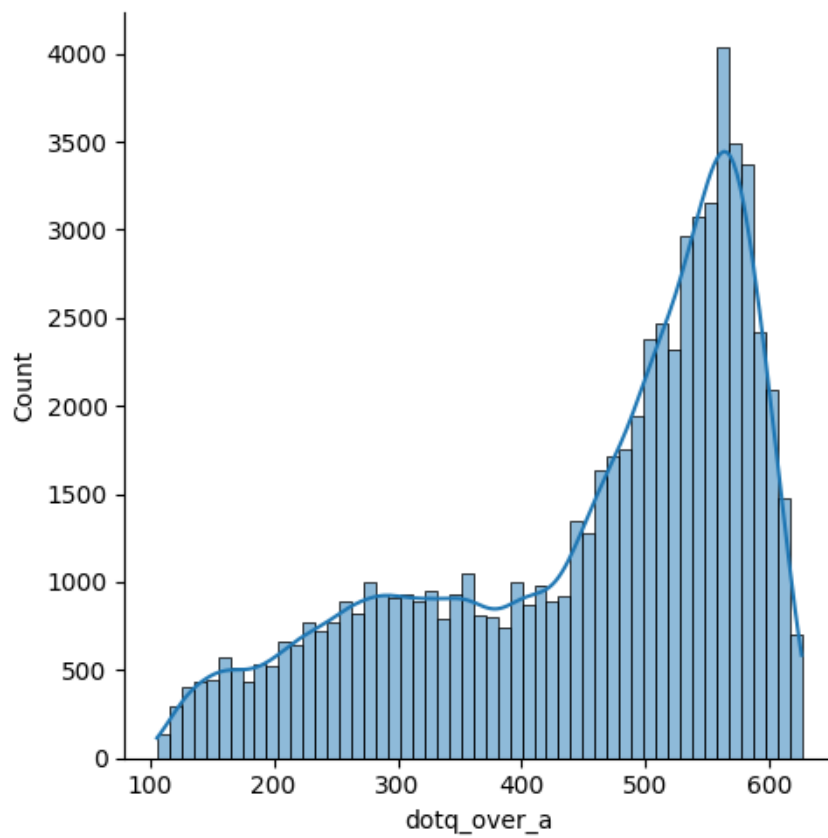


Figure 4.6: Distribution of the power produced per square meter, after the η screening on all data

Looking at the distribution of other variables, the data points selected for the article had the x_5 term very symmetrical, and with a very close distribution (see figure B.2 at page 134), while this dataset has a very wide distribution with a strange secondary peak (Figure 4.7 below).

Since the x_5 term is the derivate of the temperature, bigger values represent instability of

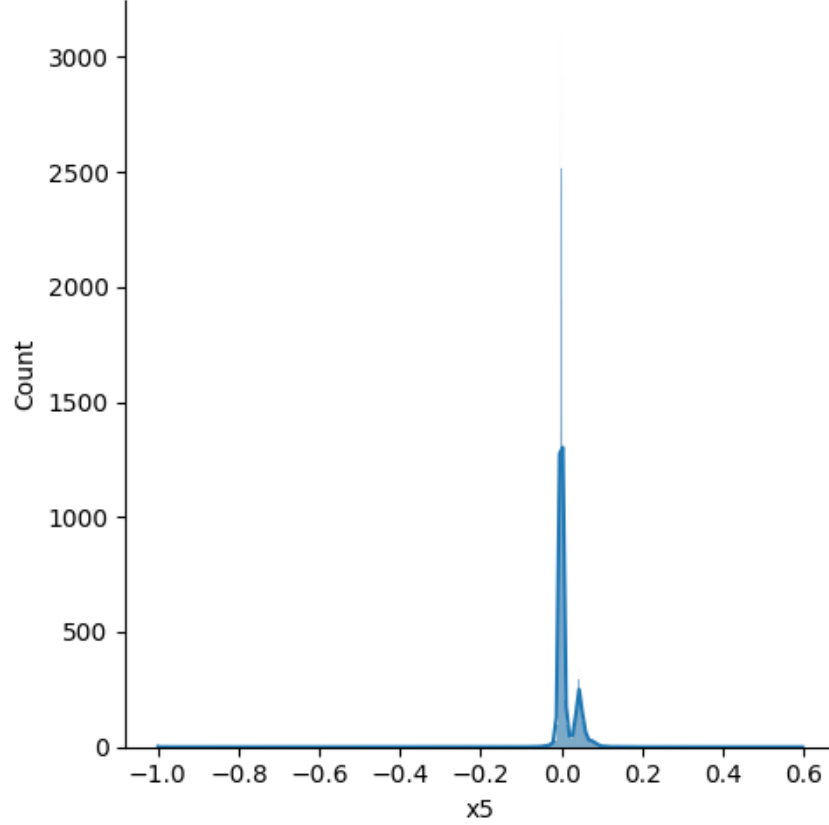


Figure 4.7: Distribution of the derivative term of the mean temperature, before screening

the system or transient periods. A threshold of $|x_{5,p}| < th_{x_5} = 0.025$ was implemented to have a more balanced distribution, as there is no secondary peak on the negative side.

With this last screening, we notice a flattening in the distribution in the lower region of the power per square meter (Figure 4.8), more similar to the published data set. This brought the dataset to 54 000 data points, which is very close to the published set, but still including more rows of data previously excluded.

So to fully automate the screening process, without biases, this set of thresholds was applied to any further analysis (Table 4.8).

The MLR using this new dataset is reported in Table 4.9 below. It has similar results to the published dataset, with a slightly smaller R^2 ; the τ values are also similar.

In Figure 4.10, the graph from the article publication and the results from the Python program are compared. Due to the difference in the method of extrapolating the coefficients (first the $\eta_{0,b}$, b_1 and b_2 the the thermal ones - a_1 , a_8 , and a_5 - in the publication, versus all coefficients together in the Python program) some difference are expected

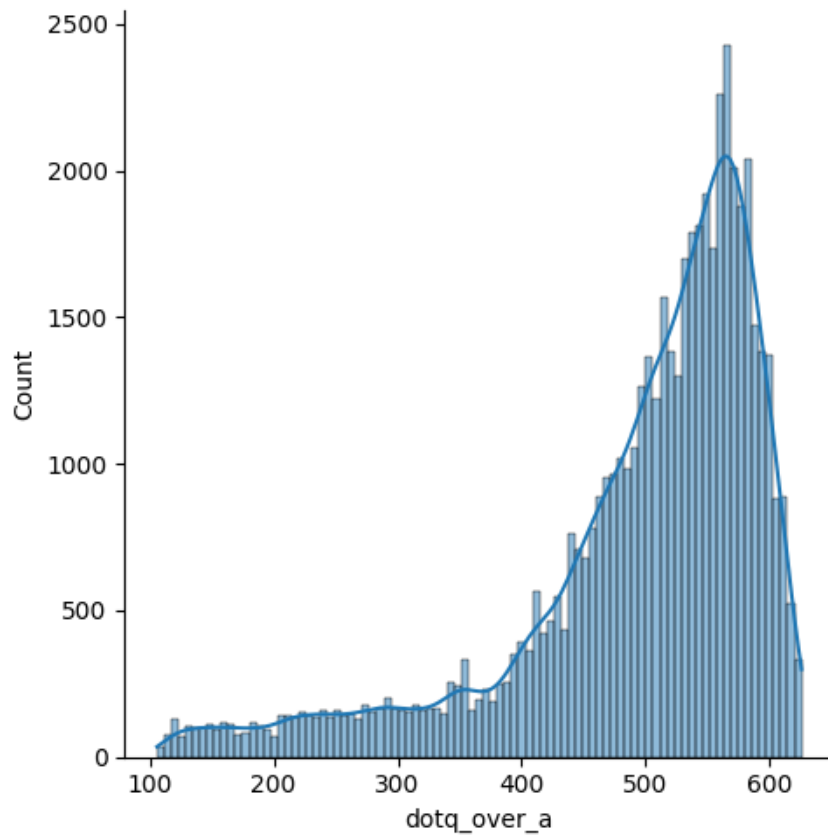


Figure 4.8: Distribution of the power produced per square meter, after the x_5 screening on all data

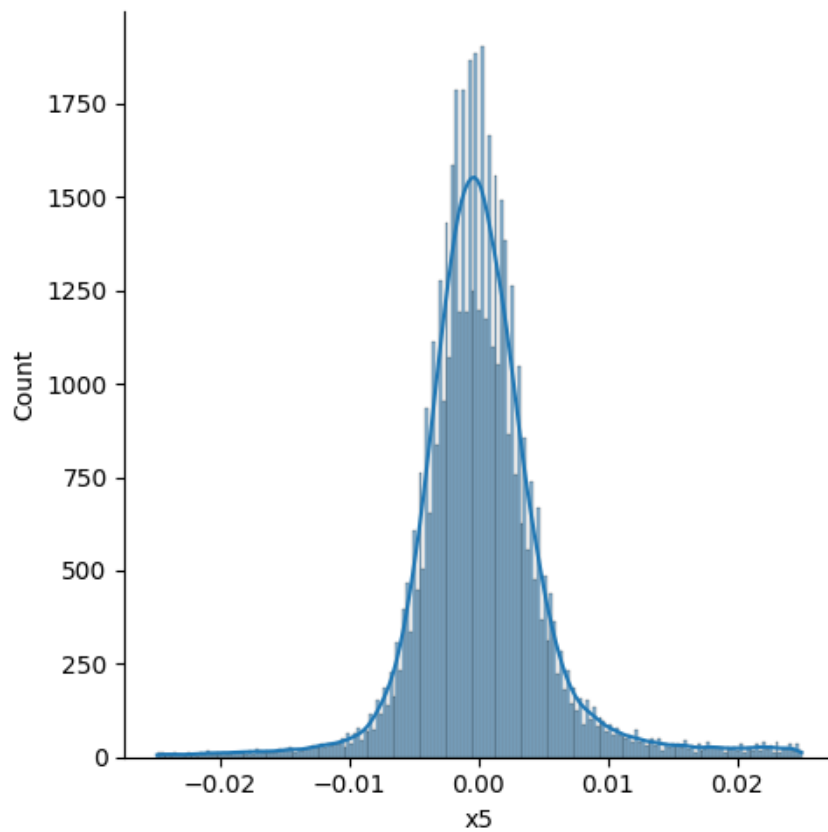
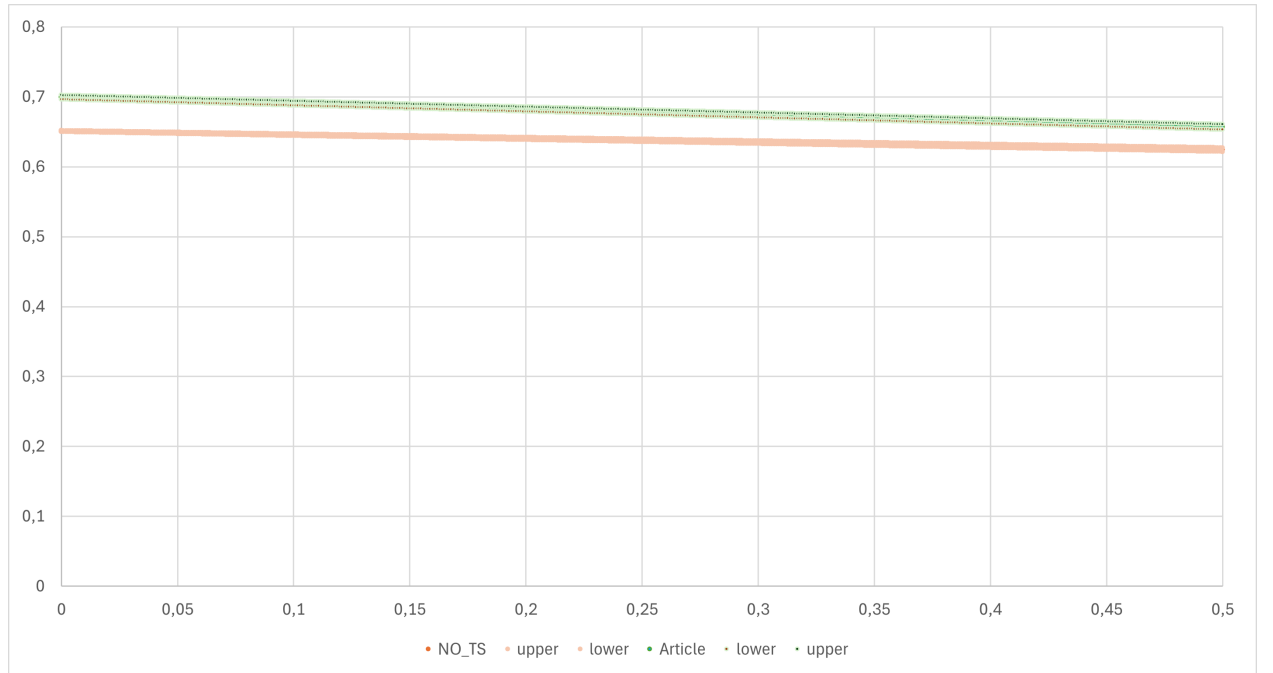


Figure 4.9: Distribution of the derivative term of the mean temperature, after screening

Variable Name	Variable	acceptance range	range used
Solar Radiation	G		$G > 0.1 \frac{W}{m^2}$
Inlet Temperature	T_{in}	T_{in} stable $\pm 1K$	T_{in} stable $\pm 1K$ and $T_{in} > 170^\circ C$
Mean Temperature derivate	$\frac{dT_m}{dt}$		$-0.02 < \frac{dT_m}{dt} < 0.02$
Minimum Temperature Difference Between Outlet and Inlet	ΔT		$\Delta T > 6$
Power produced	$\dot{Q}$	$\dot{Q} > 0$	$\dot{Q} > 0$
Expected η	η_p		$\eta_p > 0.15$

Table 4.8: Acceptance conditions and thresholds used for EUROTrough

Parameter	Value	Std dev	τ value
$\eta_{0,b}$	0.6507	0.0009	759
b_1	-0.00044	$8.6 \cdot 10^{-6}$	51
b_2	$-1.84 \cdot 10^{-5}$	$2.7 \cdot 10^{-7}$	68
a_1	-0.054	0.004	13
a_8	$-2.08 \cdot 10^{-9}$	$4.8 \cdot 10^{-11}$	43
a_5	-929	14	64
R^2	0.94418		

Table 4.9: EUROTrough from the Python program, full data with screening**Figure 4.10:** Performance graph with the published coefficient and the coefficients extracted with the Python program

4.3.1.3 Fit with Timeshift

The Timeshift logic was first applied to the published dataset. The timeshift constant (Equation 4.4) was found to be around 59 seconds across all the days of the test (Figure 4.11), which is expected to be fairly constant, since there is a constraint on the massflow across all the tests. This timeshift constant corresponds to 12 rows of data, since the sampling rate is 5 seconds (equation 4.5). The difference in the datasets can be seen in Figure 4.12, where it is represented in the plane $T^* - \eta$. With the timeshift logic applied, the data looks more compacted, with some of the previous dispersion linked probably to the data coupled only in the same timestamp.

```
for file D:/FC/Alm/test/data/20150527.csv time constant is 0:00:59.986514 and is 6173 rows long
for file D:/FC/Alm/test/data/20150528.csv time constant is 0:00:59.525501 and is 3965 rows long
for file D:/FC/Alm/test/data/20150602.csv time constant is 0:00:59.558075 and is 4097 rows long
for file D:/FC/Alm/test/data/20150603.csv time constant is 0:00:59.452436 and is 4393 rows long
for file D:/FC/Alm/test/data/20150918.csv time constant is 0:00:59.164468 and is 5127 rows long
for file D:/FC/Alm/test/data/20150923.csv time constant is 0:00:45.659418 and is 3628 rows long
for file D:/FC/Alm/test/data/20150925.csv time constant is 0:00:59.363392 and is 3806 rows long
for file D:/FC/Alm/test/data/20151001.csv time constant is 0:00:59.478156 and is 2588 rows long
for file D:/FC/Alm/test/data/20151002.csv time constant is 0:00:59.263714 and is 4944 rows long
for file D:/FC/Alm/test/data/20151023.csv time constant is 0:00:59.510565 and is 9532 rows long
for file D:/FC/Alm/test/data/20151029.csv time constant is 0:00:59.434202 and is 5077 rows long
for file D:/FC/Alm/test/data/20151110.csv time constant is 0:00:59.657157 and is 9573 rows long
for file D:/FC/Alm/test/data/20160225.csv time constant is 0:00:59.347636 and is 6955 rows long
for file D:/FC/Alm/test/data/20160225.csv time constant is 0:00:59.347636 and is 6955 rows long
for file D:/FC/Alm/test/data/20160301.csv time constant is 0:00:59.234360 and is 6897 rows long
for file D:/FC/Alm/test/data/20160302.csv time constant is 0:00:59.188332 and is 7092 rows long
for file D:/FC/Alm/test/data/20160303.csv time constant is 0:01:00.340241 and is 7250 rows long
```

Figure 4.11: Time constants of the EuroTrough data files

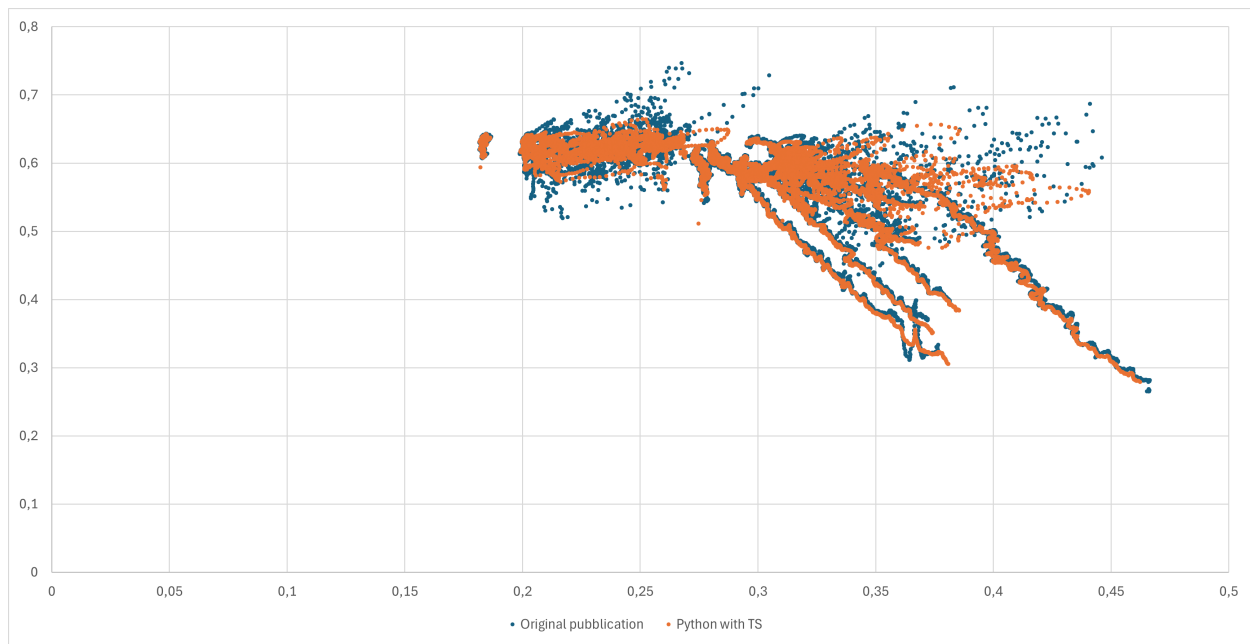


Figure 4.12: Visual representation of the difference between the Timeshift dataset and the no Timeshift dataset (publication data only)

The MLR results are reported in Table 4.10 below. Comparing the values in Table 4.10 (with timeshift) with the ones in Table 4.9 (without the

Parameter	Value	Std dev	τ value
$\eta_{0,b}$	0.65635	0.00052	1267
b_1	-0.00041	$6.5 \cdot 10^{-6}$	63
b_2	$-1.79 \cdot 10^{-5}$	$1.6 \cdot 10^{-7}$	109
a_1	-0.081	0.0025	32
a_8	$-1.81 \cdot 10^{-9}$	$3 \cdot 10^{-11}$	60
a_5	-366	7	51
R^2	0.971		

Table 4.10: EUROTrough from the Python program, published data with timeshift

timeshift), we can see an improvement in every statistical parameter, such as τ values and R^2 , signaling a more precise fit of the performance curve to the analyzed data. There is a slightly increase in the peak optical efficiency $\eta_{0,b}$, compensated with a little increase in the thermal coefficients a_1 and a_8 , but a very noticeable difference resides in the a_5 coefficient, which is strongly reduced by the timeshift, hinting at the possibility that this parameter was carrying more than just the evolution of the average temperature in the system, but, especially for system with bigger time constants, it was including the latency of the system too.

Looking at the graph in Figure 4.13, the two curves (no timeshift and timeshift) are very

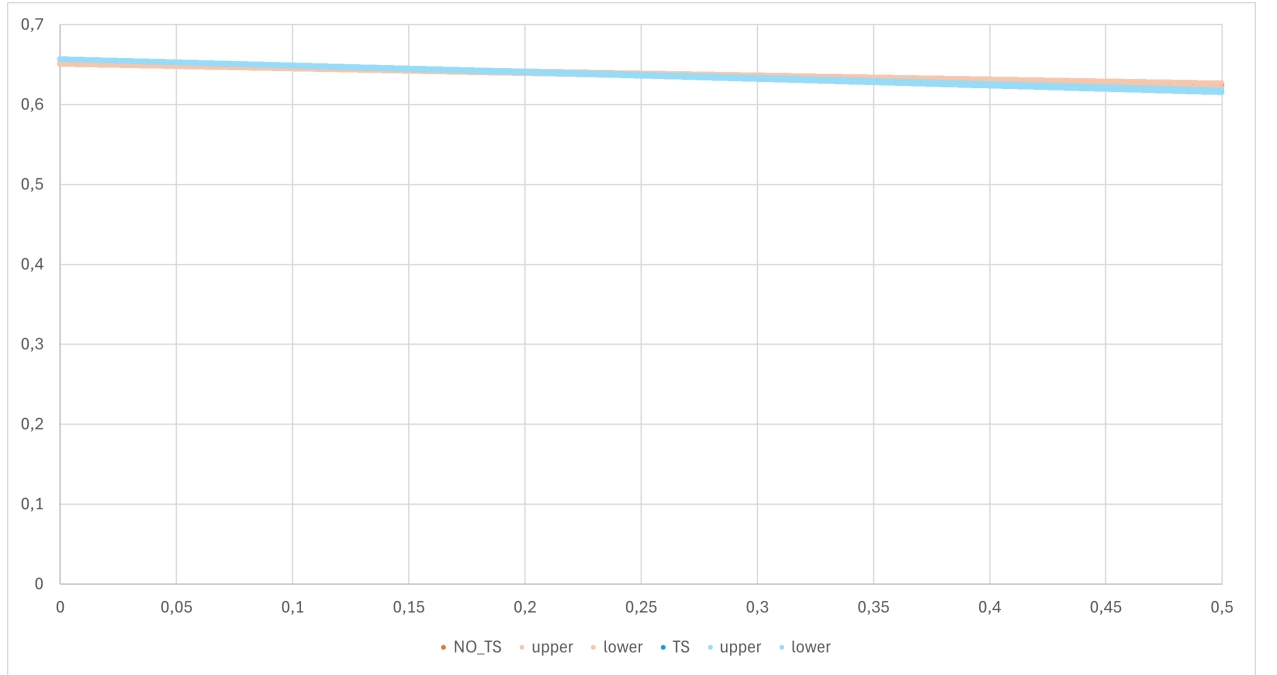


Figure 4.13: Visual representation of the difference between the Timeshift dataset (*abc185*) and the no Timeshift dataset (*abc185*)(published data, screened)

close to each other, with the timeshifted one hinting at a slightly higher $\eta_{0,b}$.

To better appreciate the difference, in Figure 4.14 there is the same graph, but with a reduced η (y axis) scale.

Near the $T^* = 0.2$, the two curves cross each other, and they are within each other's boundaries up until $T^* = 0.4$, the range where most of the data points of the dataset are located. Since the curves in the graph are calculated only from $\eta_{0,b}$, a_1 , and a_8 , as the other terms are

assumed to be 0 for the drawing of the curve and thus the comparison, we cannot appreciate the difference in other coefficients, such as b_1 and b_2 , or the effect of the change in a_5 .

The strong reduction in a_5 after the timeshift raises the question of whether this term truly

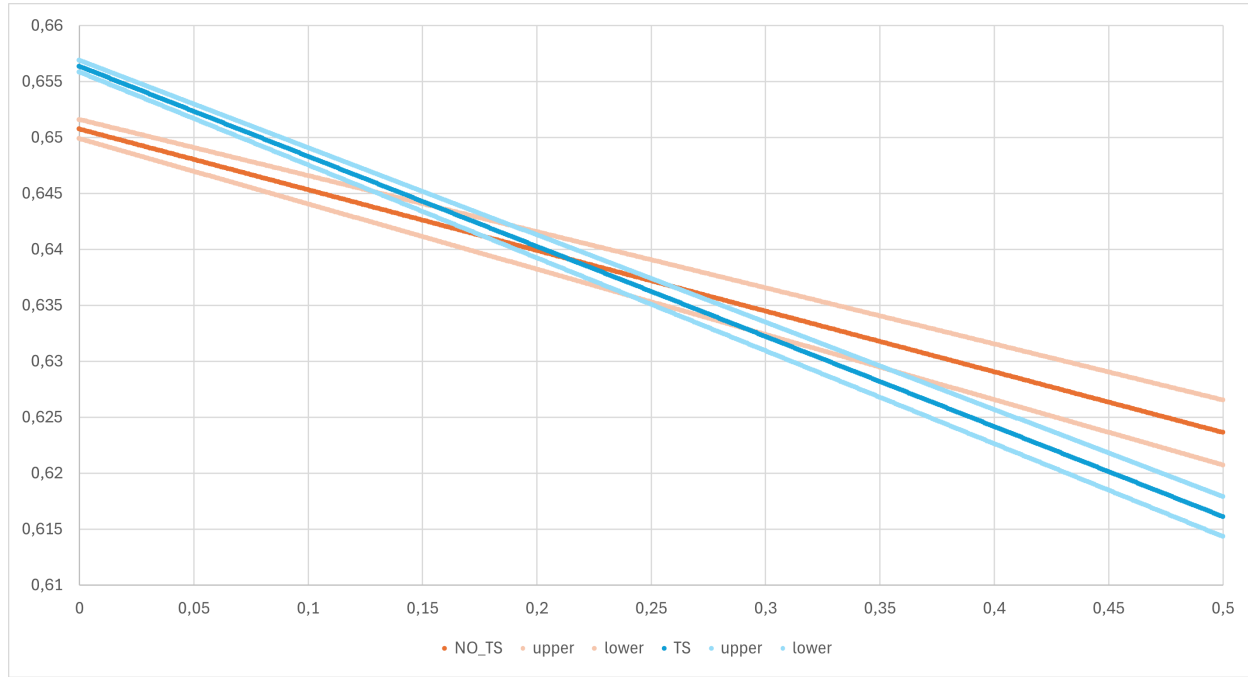


Figure 4.14: Visual representation of the difference between the Timeshift dataset (*abc18*) and the no Timeshift dataset (*abc185*)(published data, screened) - zoom

captures the system's evolution over time, or merely the delay in response due to the time it takes for the fluid to travel from the inlet to the outlet.

In order to verify this hypothesis, the comparison was extended to various combinations of variables to include in the fit. The results are summarized in Table 4.11 below. The *abc125*, *ac125*, and *a125* combinations of coefficients should not be considered a valid fit, as they have the a_1 or a_2 coefficient resulting in a positive value.

The R^2 values between the Timeshift dataset and the no Timeshift dataset are very close to each other (although the timeshifted ones are always better), as well as the other coefficient values. The real discrepancy is the results of the derivative term, a_5 , which comes out strongly reduced for every Timeshift dataset, consistently. This can also be seen visually in Figure 4.15 below.

This further indicates that the a_5 coefficient is not capturing just the increase (or decrease) in temperature of the system, as it is not in a stable condition, but it is including the latency of the system as the fluid evolves through it, and it takes a full minute (12 rows of data) to go from the inlet to the outlet.

case	noTS/TS	R^2	η	b_1	b_2	a_1	a_2	a_8	a_5
abe125	no TS	0,9466	0,6311	-3,97E-04	-2,28E-05	0,166	-7,26E-04	0	-919
	TS	0,9731	0,6383	-3,70E-04	-2,20E-05	0,119	-6,47E-04	0	-359
abe185	no TS	0,9442	0,6507	-4,38E-04	-1,84E-05	-0,054	0	-2,08E-09	-929
	TS	0,9710	0,6563	-4,08E-04	-1,80E-05	-0,080	0	-1,81E-09	-366
abe15	no TS	0,9400	0,6808	-5,07E-04	-1,13E-05	-0,205	0	0	-984
	TS	0,9678	0,6826	-4,67E-04	-1,17E-05	-0,212	0	0	-403
ab125	no TS	0,9363	0,6845	-1,14E-03	0	-0,155	-1,52E-04	0	-906
	TS	0,9634	0,6896	-1,09E-03	0	-0,189	-9,75E-05	0	-350
ab185	no TS	0,9362	0,6865	-1,12E-03	0	-0,192	0	-5,43E-10	-908
	TS	0,9634	0,6910	-1,07E-03	0	-0,214	0	-3,31E-10	-351
ab15	no TS	0,9358	0,6924	-1,05E-03	0	-0,227	0	0	-931
	TS	0,9632	0,6947	-1,03E-03	0	-0,235	0	0	-362
ae125	no TS	0,9447	0,6225	0	-3,05E-05	0,197	-7,82E-04	0	-954
	TS	0,9714	0,6303	0	-2,92E-05	0,147	-6,99E-04	0	-385
ae185	no TS	0,9419	0,6429	0	-2,66E-05	-0,039	0	-2,25E-09	-969
	TS	0,9690	0,6491	0	-2,56E-05	-0,067	0	-1,97E-09	-395
ae15	no TS	0,9369	0,6746	0	-2,01E-05	-0,202	0	0	-1036
	TS	0,9651	0,6769	0	-1,99E-05	-0,209	0	0	-441
a125	no TS	0,8951	0,7577	0	0	-0,756	9,17E-04	0	-1149
	TS	0,9254	0,7595	0	0	-0,763	9,23E-04	0	-532
a185	no TS	0,8886	0,7525	0	0	-0,569	0	3,61E-09	-1164
	TS	0,9191	0,7542	0	0	-0,575	0	3,64E-09	-546
a15	no TS	0,8541	0,7303	0	0	-0,421	0	0	-1077
	TS	0,8836	0,7317	0	0	-0,425	0	0	-485

Table 4.11: Results of MRL fit of various combination of coefficients considering a_5 between no Timeshift and Timeshift, with the published dataset, screened

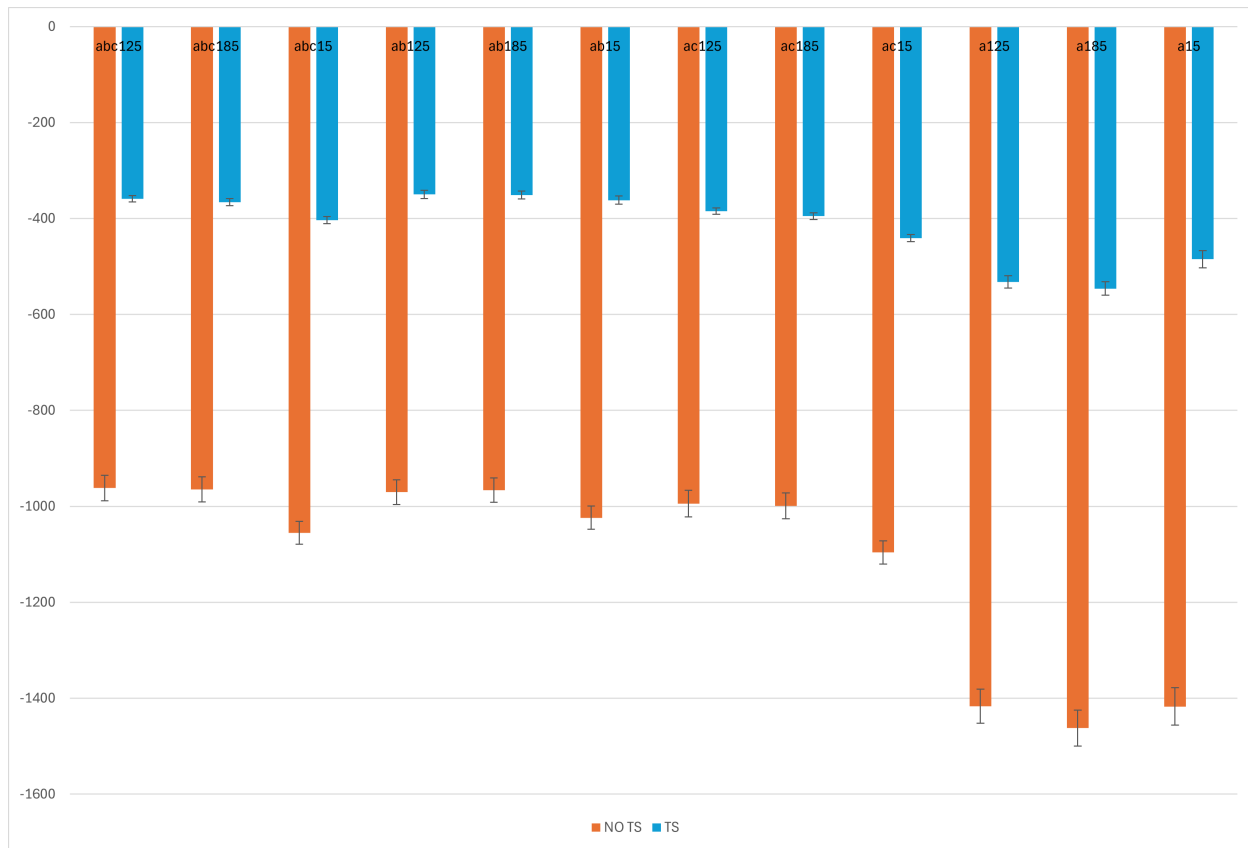


Figure 4.15: Visual representation of the a_5 coefficient between the Timeshift dataset and the no Timeshift dataset

Next, the Timeshift logic was applied to the dataset of 52 700 rows previously identified. Again, we can see the effect of the timeshift visually, in Figure 4.16, represented in the $T^* - \eta$ plane.

Similarly to the published dataset, the timeshift is cleaning some noise, with the data

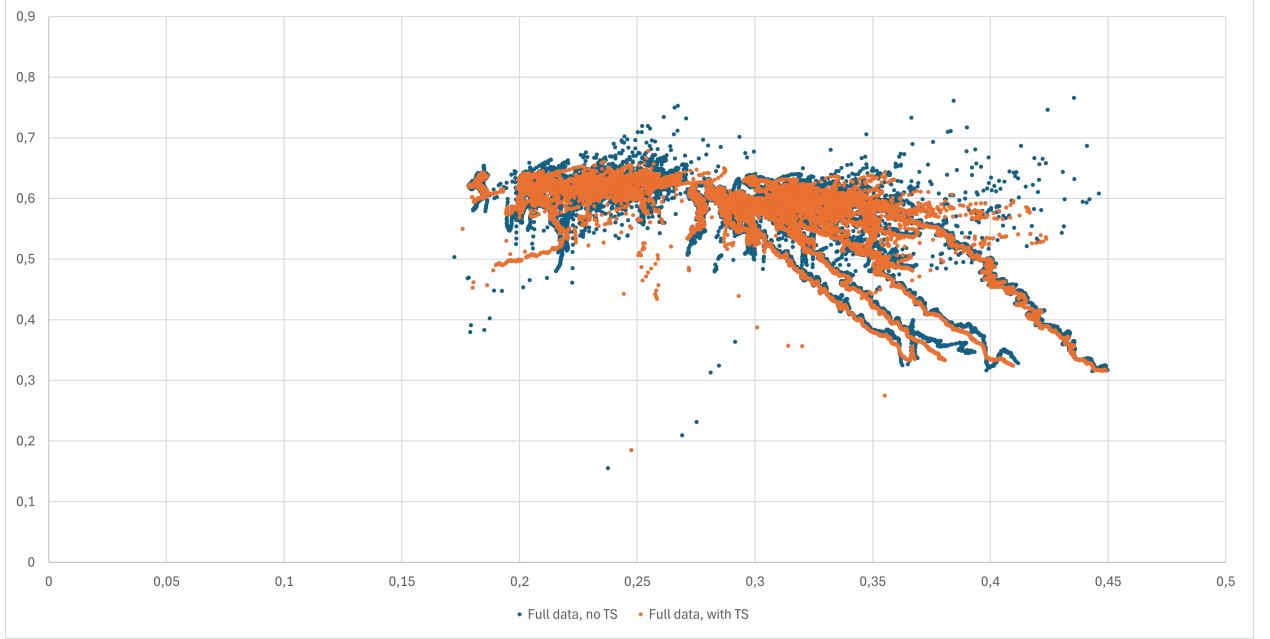


Figure 4.16: Visual representation of the difference between the Timeshift dataset and the no Timeshift dataset (all data, screened)

points closer together than the no timeshift dataset. The timeshift is also straightening some continuous rows of data, such as the lower trailing between $0.35 > T^* > 0.4$ and $0.3 > \eta > 0.4$. This suggests that those variations were due to the latency of the system, more than an actual sudden drop in efficiency during the tests.

The results of the MLR on the full dataset, after screening, with the timeshift logic applied, are reported in Table 4.12 below, while the results from the same dataset, but without the timeshift logic, are in Table 4.9 above.

With the full dataset, the a_5 term is negative, although highly reduced from the non

Parameter	Value	Std dev	τ value
$\eta_{0,b}$	0.65953	0.0006	1180
b_1	-0.00041	$6.8 \cdot 10^{-6}$	60
b_2	$-1.72 \cdot 10^{-5}$	$1.8 \cdot 10^{-7}$	93
a_1	-0.097	0.003	35
a_8	$-1.61 \cdot 10^{-9}$	$3.5 \cdot 10^{-11}$	45
a_5	-378	10	39
R^2	0.96475		

Table 4.12: EUROTrough from the Python program, all data with screening and timeshift

timeshifted MLR. The timeshifted MLR has higher R^2 values, closely matching the one from the dataset as published. Also, the τ values are higher, meaning that the standard deviations of the coefficient values are smaller.

These two sets of coefficients are compared graphically in Figure 4.17. Again, to better appreciate the difference, Figure 4.18 shows the same graph with a reduced η (y-axis) scale.

Once again, the timeshifted curve (in blue) hints at a higher peak optical efficiency and

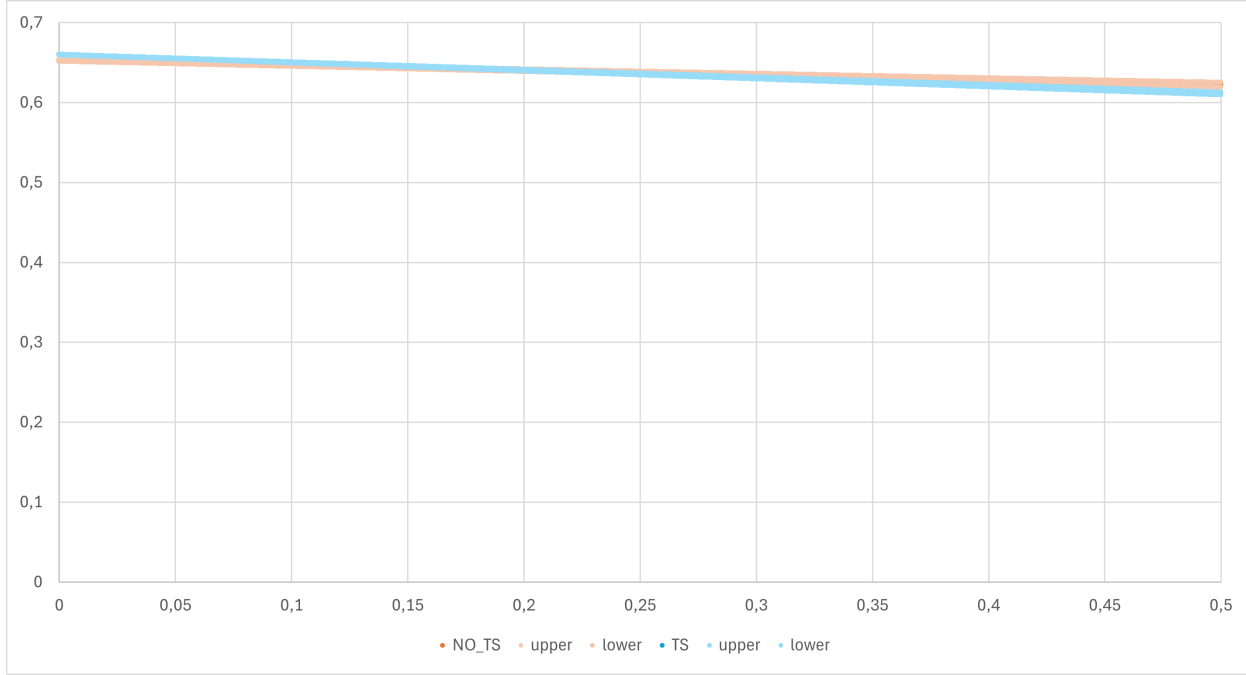


Figure 4.17: Visual representation of the difference between the Timeshift dataset and the no Timeshift dataset (full data, screened)

higher thermal losses.

Similarly to the published dataset, the effect of the timeshift on various combinations of coefficients considered is studied and reported in Table 4.13. The a_5 coefficient is also presented graphically in Figure 4.19.

The timeshift logic generally improves the R^2 values of the fit, drastically reduces the a_5 value, hinting at the possibility that this coefficient is always carrying on its value, as well as other effects, on top of the ones that are supposed to represent. Another systematic effect is the increase of the peak optical efficiency $\eta_{0,b}$ with an increase in the thermal coefficients, such as a_1 , a_2 , and a_8 .

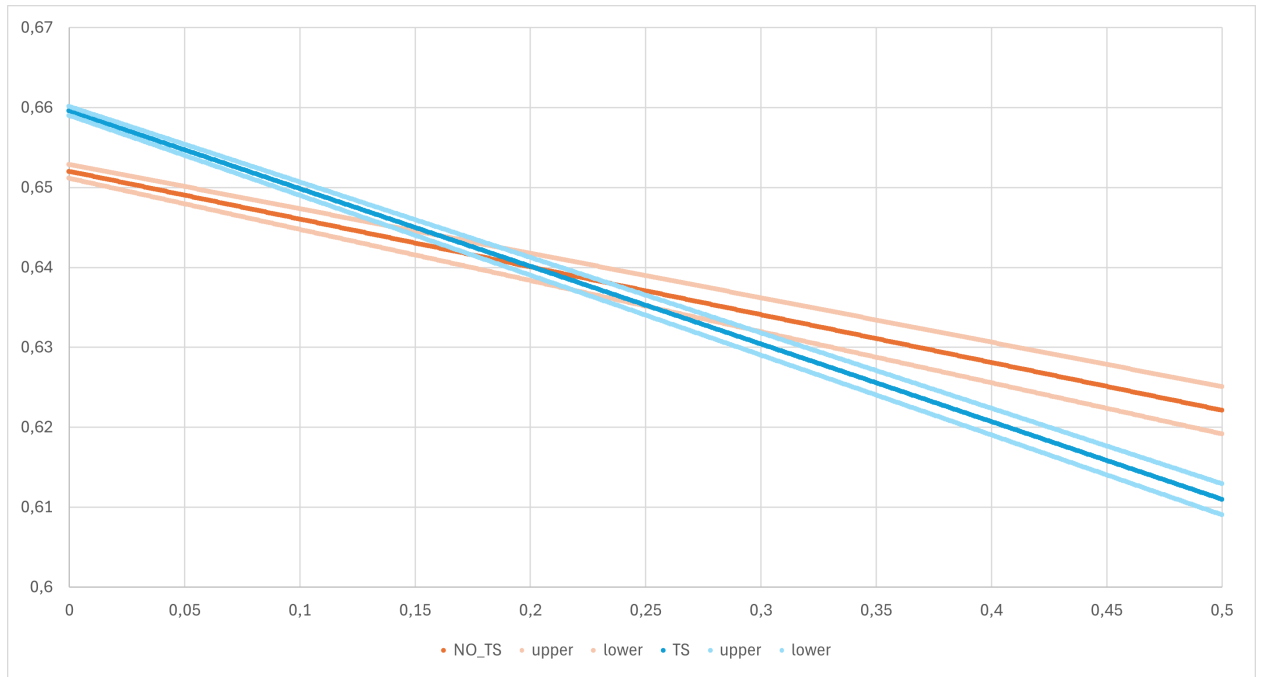


Figure 4.18: Visual representation of the difference between the Timeshift dataset and the no Timeshift dataset (full data, screened) - zoom

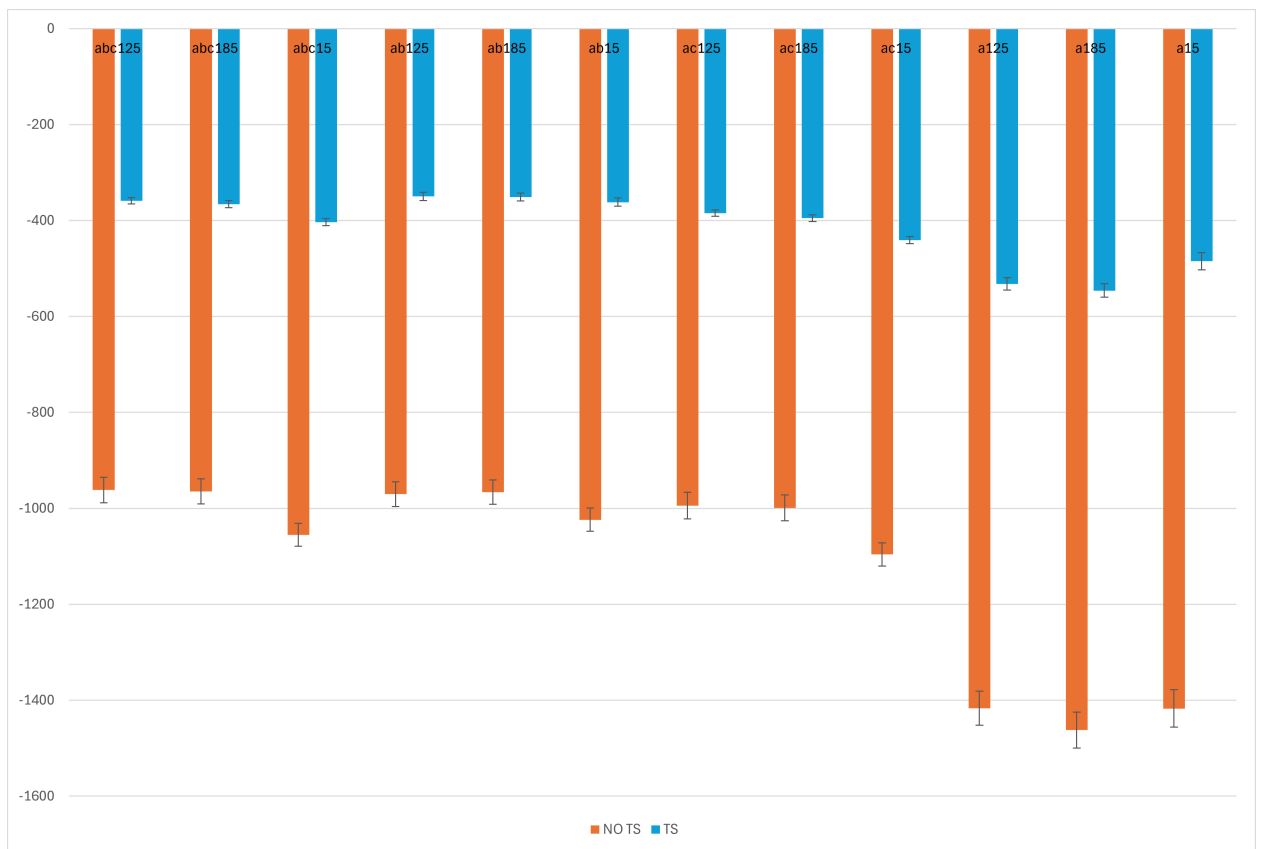


Figure 4.19: Visual representation of the a_5 coefficient between the Timeshift dataset and the no Timeshift dataset, full dataset

case	noTS/TS	R^2	η	b_1	b_2	a_1	a_2	a_8	a_5
abc125	no TS	0,9483	0,6324	-4,03E-04	-2,23E-05	0,159	-7,17E-04	0	-855
	TS	0,9663	0,6437	-3,78E-04	-2,07E-05	0,078	-5,70E-04	0	-373
abc185	no TS	0,9459	0,6520	-4,42E-04	-1,79E-05	-0,060	0	-0,00000000202887	-870
	TS	0,9648	0,6595	-4,11E-04	-1,72E-05	-0,097	0	-0,00000000160567	-378
abc15	no TS	0,9420	0,6816	-5,11E-04	-1,09E-05	-0,208	0	0	-919
	TS	0,9622	0,6828	-4,64E-04	-1,16E-05	-0,214	0	0	-409
ab125	no TS	0,9386	0,6849	-1,12E-03	0	-0,156	-1,54E-04	0	-806
	TS	0,9579	0,6922	-1,05E-03	0	-0,214	-4,86E-05	0	-362
ab185	no TS	0,9385	0,6871	-1,10E-03	0	-0,196	0	-5,2678E-10	-812
	TS	0,9579	0,6927	-1,05E-03	0	-0,225	0	-1,8207E-10	-362
ab15	no TS	0,9381	0,6929	-1,03E-03	0	-0,230	0	0	-838
	TS	0,9578	0,6947	-1,02E-03	0	-0,237	0	0	-367
ac125	no TS	0,9464	0,6235	0	-3,01E-05	0,191	-7,74E-04	0	-903
	TS	0,9646	0,6355	0	-2,80E-05	0,107	-6,24E-04	0	-400
ac185	no TS	0,9436	0,6439	0	-2,62E-05	-0,044	0	-0,00000000221198	-924
	TS	0,9628	0,6522	0	-2,48E-05	-0,083	0	-0,0000000017705	-408
ac15	no TS	0,9388	0,6753	0	-1,98E-05	-0,205	0	0	-987
	TS	0,9597	0,6771	0	-1,98E-05	-0,211	0	0	-447
a125	no TS	0,8989	0,7564	0	0	-0,744	8,86E-04	0	-1034
	TS	0,9228	0,7598	0	0	-0,769	9,39E-04	0	-533
a185	no TS	0,8932	0,7513	0	0	-0,563	0	0,00000000347893	-1026
	TS	0,9161	0,7544	0	0	-0,578	0	0,00000000369526	-548
a15	no TS	0,8611	0,7298	0	0	-0,419	0	0	-863
	TS	0,8797	0,7314	0	0	-0,425	0	0	-489

Table 4.13: Results of MRL fit of various combinations of coefficients considering a_5 between no Timeshift and Timeshift, with the full, screened, dataset

4.3.2 URSSATrough

Tests on the URSSATrough module were conducted before the ISO 9806:2013 norm, and the paper itself was an inspiration for it. In the published results, the analysis was conducted in what would become the Steady State methodology.

4.3.2.1 Previous best fit

The peak optical efficiency $\eta_{0,b}$ was calculated independently, as well as the Incidence angle modifier $K(\theta)$, then the thermal losses were later extrapolated. The formulas used in the paper were:

$$\eta = \eta_{opt,0} \cdot K(\theta) \cdot F_c - \frac{a_1 \cdot (T_m - T_a) + a_8 \cdot (T_m - T_a)^4}{A_C \cdot E_d \cdot \cos\theta} \quad 4.13$$

where E_d is the direct solar irradiance, and

$$K_b(\theta) = 1 - \frac{b_1\theta + b_2\theta^2}{\cos\theta} \quad 4.14$$

In equations 4.15 and 4.16 are reported as they were written, while in Table 4.14⁴ are reported in a form more similar to ISO 9806 standard.

$$\eta = (0.768 \pm 0.013) - \frac{(26 \pm 5) \cdot (\Delta T) + (8.5 \pm 1.6) \cdot 10^{-7} \cdot (\Delta T)^4}{409.908 \cdot E_d} \quad 4.15$$

$$K_b(\theta) = 1 - \frac{(7 \pm 4) \cdot 10^{-4} \cdot \theta + (36 \pm 6) \cdot 10^{-6} \cdot \theta^2}{\cos\theta} \quad 4.16$$

Parameter	Value	Std dev	τ value
η_0	0.768	0.013	59
b_1	$7 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	2
b_2	$36 \cdot 10^{-6}$	$6 \cdot 10^{-6}$	6
a_1	26	5	5
a_8	$8.5 \cdot 10^{-7}$	$1.6 \cdot 10^{-7}$	5

Table 4.14: URSSATrough results as published

⁴the values of b_1 and b_2 are taken as published, while for a_1 and a_8 a direct solar irradiance of 850 was supposed, as per ISO 9806. τ values are calculated from the original data. R^2 value was not reported in the original paper.

4.3.2.2 Fit with new analysis program - Steady State

An analysis, using the Steady State method of the ISO 9806:2017, was attempted, and the Python program found 7250 suitable stable points for the Steady State analysis. As previously explained, these are all suitable points, many of which overlap with each other. These were screened to select the ones with the least standard variation in the inlet temperature, as well as to cover the whole range of operating and testing temperatures, reducing them to 116 points.

From this point, any point that was removed changed the calculated coefficients, and there was no right way to exclude one over the other. Moreover, the timeshift logic was changing the starting and ending times of these stable points, making a direct comparison even more difficult. In order to have a proper comparison, it was decided to take the starting times and time length of the points used in the original paper, and compare them with and without the timeshift.

In Figure 4.20 (and in Figure 4.21, with some zoom) are reported the original paper points, in the $T^* - \eta$ plane. The analysis of these points with the ISO 9806 methodology was challenging, as every combination of coefficients resulted in at least one positive coefficient. In this case, the Steady State methodology is proving its limits, as it's very dependent on the point included in the analysis, and the original paper logic was too different from the ISO norm to allow to replicate the results.

The timeshift was still applied on the same points, and the results are shown in Figure 4.22 (and Figure 4.23, zoomed) for comparison.

The timeshift highlights how these points, after factoring in the latency of the systems, were not that steady, and resulted in a distribution of points that are not that aligned with a standard efficiency performance curve, with some points seeming to have at least 5% less efficiency at the same temperature.

The Steady State methodology was discarded, and the analysis continued with the Quasi Dynamic methodology to avoid further human biases and allow for a better comparison with the timeshift logic.

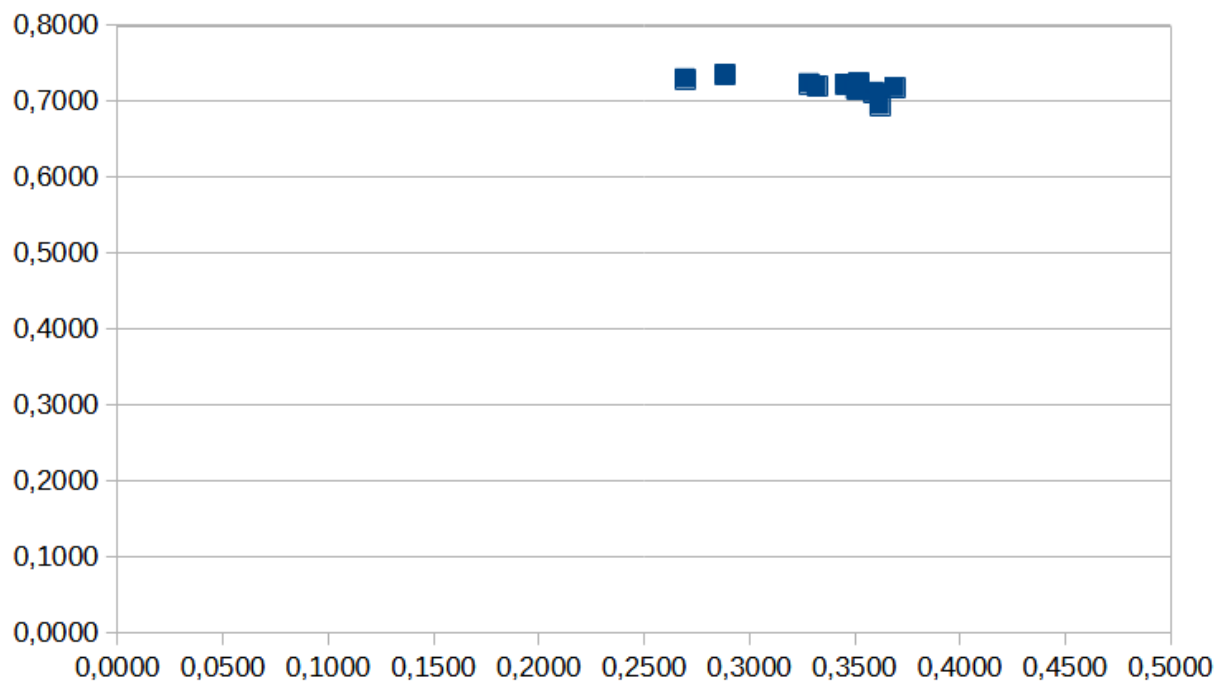


Figure 4.20: Data points for a Steady State like analysis of the URSSATrough, published dataset, no timeshift

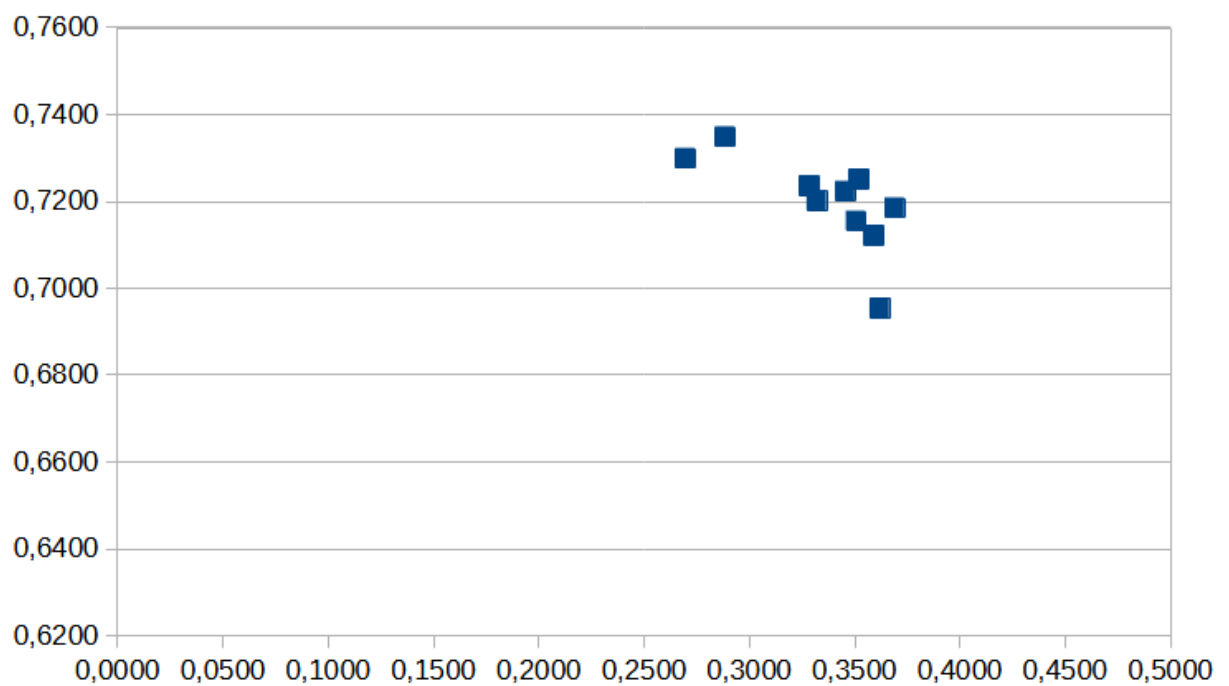


Figure 4.21: Data points for a Steady State like analysis of the URSSATrough, published dataset, no timeshift - zoom

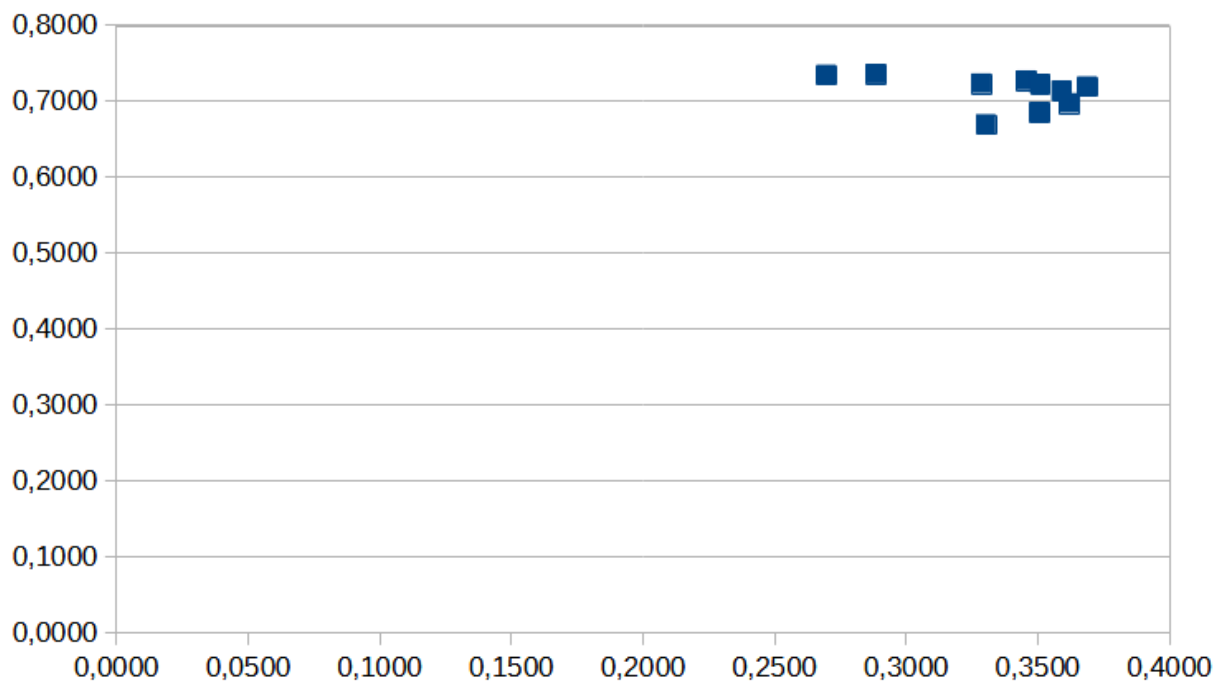


Figure 4.22: Data points for a Steady State like analysis of the URSSATrough, published dataset, timeshift

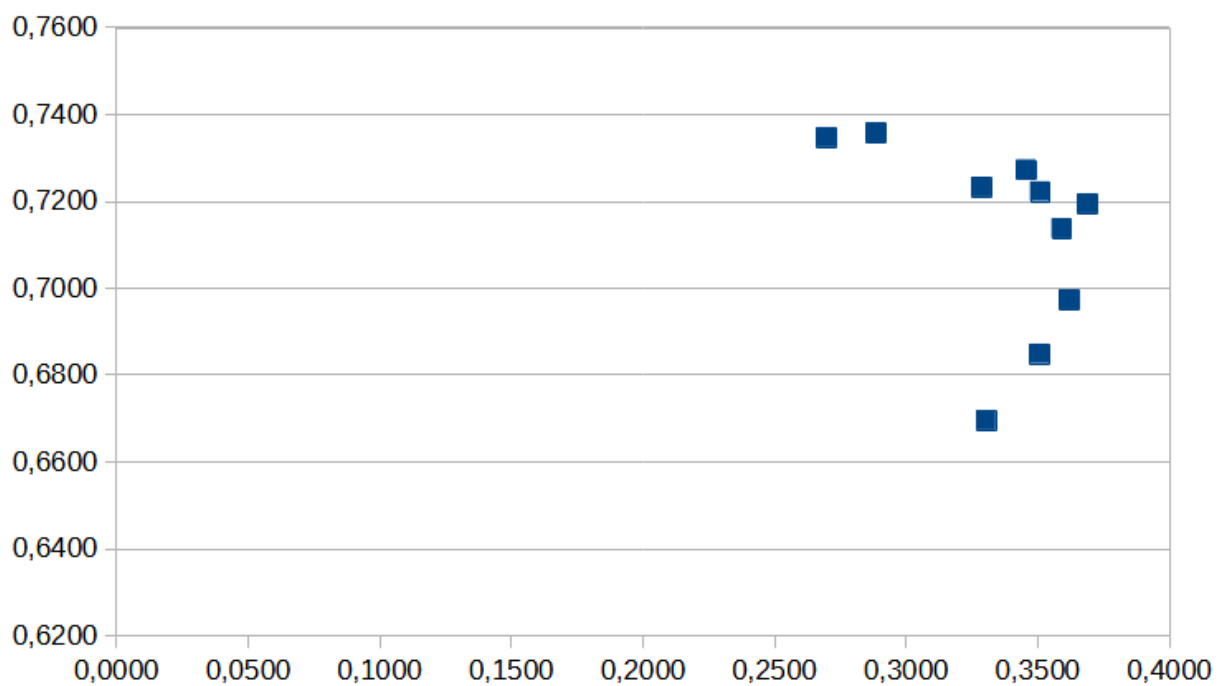


Figure 4.23: Data points for a Steady State like analysis of the URSSATrough, published dataset, timeshift - zoom

4.3.2.3 Fit with new analysis program - Quasi Dynamic

The analysis of the URSSATrough continued with the Quasi Dynamic methodology. The first step was to use, again, only the dataset used in the original publication.

Many coefficients combinations were tried, namely every combination using the b_1 , b_2 , a_1 , a_2 , a_8 , and a_5 coefficients, avoiding using the a_2 and a_8 coefficients together, as they express the same type of thermal losses, for a total of 32 different combinations.

Although the R^2 values were all quite high (0,999+), this was also related to the lesser dimension of the dataset, which is composed of just 1 300 rows of data from the original 121 000. Nevertheless, each one of these combinations resulted again (both with and without the timeshift) in at least one positive coefficient (except for the a_{15} , a_{25} , and a_{85} , although with the a_5 under the 3τ threshold for the timeshift dataset). Also, the a_1 , a_2 , and a_8 are negative, but those combinations are not significant.

The full sets of extrapolated coefficients for every combination are reported in Table B.1 below, a visual analysis of their value is shown in Figure 4.24, where the green dot means that coefficient is both negative and with a $\tau > 3$, yellow means the coefficient is negative but $\tau < 3$, red means is positive (with $\tau > 3$), black means the coefficient is positive and $\tau < 3$.

Notably, some combinations, without the timeshift, resulted in a peak optical efficiency higher than 1, which is thermodynamically impossible, but the timeshifted values are more similar to the original peak optical efficiency published.

It's worth noting how the timeshift logic consistently discards the a_5 term for at least the τ check, if not even the negativity one.

The analysis continued on the whole dataset, applying similar thresholds as for the EU-ROTrough collector to the screening process. The thresholds applied for the URSSATrough are reported in Table 4.15. Since the tests were calibrated for a Steady State model, a $650 \frac{W}{m^2}$ was applied, while the previous threshold for the minimum inlet temperature was discarded.

With the screening process, the dataset went from 121 000 rows to 35 000 rows. The results

Variable Name	Variable	acceptance range	range used
Solar Radiation	G		$G > 650 \frac{W}{m^2}$
Inlet Temperature	T_{in}	T_{in} stable $\pm 1K$	T_{in} stable $\pm 1K$
Mean Temperature derivate	$\frac{dT_m}{dt}$		$-0.02 < \frac{dT_m}{dt} < 0.02$
Minimum Temperature Difference Between Outlet and Inlet	ΔT		$\Delta T > 6$
Power produced	$\dot{Q}$	$\dot{Q} > 0$	$\dot{Q} > 0$
Expected η	η_p		$\eta_p > 0.15$

Table 4.15: Acceptance conditions and thresholds used for URSSATrough

of the MLR are presented in Table B.1 at page 132, and a graphical check of the quality of the coefficients is reported in Figure 4.25 (with the same color code as before).

Unfortunately, as with the published dataset, there are no acceptable combinations of coefficients. Every combination has at least one positive coefficient. It is worth noting again how the timeshift logic, consistently every time, renders the a_5 term not significant.

	b		c		1		2		8		5	
	NC	TS	NC	TS	NC	TS	NC	TS	NC	TS	NC	TS
abc1285	●	●	●	●	●	●	●	●	●	●	●	●
abc125	●	●	●	●	●	●	●	●	/	/	●	●
abc185	●	●	●	●	●	●	/	/	●	●	●	●
abc18	●	●	●	●	●	●	/	/	●	●	/	/
abc15	●	●	●	●	●	●	/	/	/	/	●	●
abc12	●	●	●	●	●	●	●	●	/	/	/	/
abc25	●	●	●	●	/	/	●	●	/	/	●	●
ab15	●	●	/	/	●	●	/	/	/	/	●	●
ab25	●	●	/	/	/	/	●	●	/	/	●	●
ab85	●	●	/	/	/	/	/	/	●	●	●	●
ab1	●	●	/	/	●	●	/	/	/	/	/	/
ab2	●	●	/	/	/	/	●	●	/	/	/	/
ab8	●	●	/	/	/	/	/	/	●	●	/	/
ac125	/	/	●	●	●	●	●	●	/	/	●	●
ac185	/	/	●	●	●	●	/	/	●	●	●	●
ac18	/	/	●	●	●	●	/	/	●	●	/	/
ac12	/	/	●	●	●	●	●	●	/	/	/	/
ac15	/	/	●	●	●	●	/	/	/	/	●	●
ac25	/	/	●	●	/	/	●	●	/	/	●	●
ac85	/	/	●	●	/	/	/	/	●	●	●	●
ac1	/	/	●	●	●	●	/	/	/	/	/	/
ac2	/	/	●	●	/	/	●	●	/	/	/	/
ac8	/	/	●	●	/	/	/	/	●	●	/	/
a125	/	/	/	/	●	●	●	●	/	/	●	●
a185	/	/	/	/	●	●	/	/	●	●	●	●
a18	/	/	/	/	●	●	/	/	●	●	/	/
a12	/	/	/	/	●	●	●	●	/	/	/	/
a15	/	/	/	/	●	●	/	/	/	/	●	●
a25	/	/	/	/	/	/	●	●	/	/	●	●
a85	/	/	/	/	/	/	/	/	●	●	●	●
a1	/	/	/	/	●	●	/	/	/	/	/	/
a2	/	/	/	/	/	/	●	●	/	/	/	/
a8	/	/	/	/	/	/	/	/	●	●	/	/

Figure 4.24: Visual representation of URSSATrough extrapolate coefficient, multiple combination, published data only, confront no timeshift with timeshift

case	noTS/TS	R^2	η	b_1	b_2	a_1	a_2	a_8	a_5
abe185	no TS	0,9999	1,1047	-4,21E-02	1,11E-03	0,229	0,00E+00	-0,00000000043271	0
	TS	1,0000	0,7886	-9,43E-03	2,49E-04	0,191	0,00E+00	-0,000000000397783	0
abe18	no TS	0,9999	1,1041	-4,20E-02	1,11E-03	0,229	0	-0,000000000432723	0
	TS	1,0000	0,7887	-9,44E-03	2,49E-04	0,191	0	-0,000000000397781	0
abe12	no TS	0,9999	1,0407	-3,68E-02	9,59E-04	0,522	-0,001232466	0	0
	TS	1,0000	0,7489	-6,47E-03	1,63E-04	0,455	-0,001123163	0	0
ab185	no TS	0,9999	0,7113	-1,55E-03	0	0,240	0,00E+00	-0,000000000447197	-2
	TS	1,0000	0,7034	-4,81E-04	0	0,194	0,00E+00	-0,000000000401098	-1
ab18	no TS	0,9999	0,7111	-1,54E-03	0	0,240	0	-0,000000000447261	0
	TS	1,0000	0,7033	-4,79E-04	0	0,194	0	-0,00000000040112	0
ab1	no TS	0,9999	0,7408	8,84E-04	0	-0,107	0	0	0
	TS	0,9999	0,7365	1,39E-03	0	-0,116	0	0	0
ac185	no TS	0,9999	0,6962	0	-4,12E-05	0,239	0,00E+00	-0,00000000044602	-2
	TS	1,0000	0,6988	0	-1,30E-05	0,193	0,00E+00	-0,000000000400756	-1
ac18	no TS	0,9999	0,6961	0	-4,09E-05	0,239	0	-0,00000000044606	0
	TS	1,0000	0,6988	0	-1,30E-05	0,193	0	-0,000000000400771	0
ac1	no TS	0,9999	0,7490	0	2,52E-05	-0,107	0	0	0
	TS	0,9999	0,7495	0	3,92E-05	-0,116	0	0	0
a185	no TS	0,9999	0,6942	0	0	0,179	0,00E+00	-0,000000000378641	0
	TS	1,0000	0,6984	0	0	0,174	0,00E+00	-0,000000000379318	0
a18	no TS	0,9999	0,6942	0	0	0,179	0	-0,000000000378722	0
	TS	1,0000	0,6984	0	0	0,174	0	-0,000000000379327	0
a1	no TS	0,9999	0,7571	0	0	-0,101	0	0	0
	TS	0,9999	0,7614	0	0	-0,107	0	0	0

Table 4.16: Results of MRL fit of various combinations of coefficients between no Timeshift and Timeshift, with only the published URSSATrough dataset

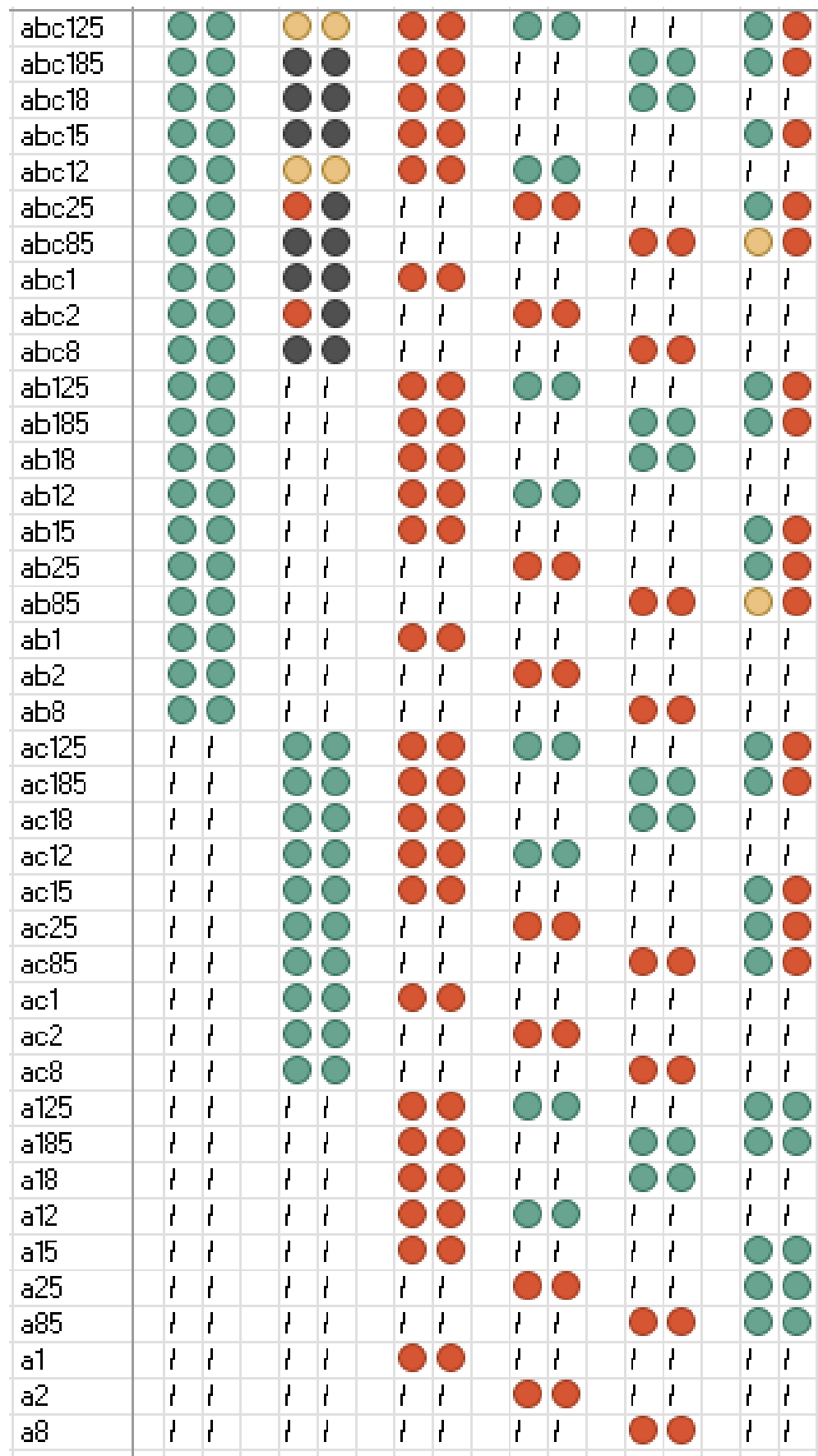


Figure 4.25: Visual representation of URSSATrough extrapolate coefficient, multiple combination, full screened data, confront no timeshift with timeshift

4.3.3 Point average logic

Taking inspiration from the SS methodology, which allows to congregate more rows of data into a single datapoint, the point logic was developed. It aggregates more rows of data into one, reducing the impact of random statistical variation in the measured data, and resulting in lesser number of datapoints in the datasets, which allows for lighter computing analysis, as well an easier operation of finding outlier values and removing them by hand, shouldn't them be already found and addressed.

For the evaluation of the impacts of the point logic, the EUROTrough full, screened dataset, was analyzed again, condensing the rows of data into points of variable length, ranging from 10 seconds (2 rows), 20 seconds (4 rows), 30 seconds (6 rows), 40 seconds (8 rows), 60 seconds (12 rows, and the time constant of the system), and 90 seconds (18 rows). The effect of this data manipulation was studied over the *abc185* combination of coefficients, comparing the timeshift and no timeshift datasets. The results of this analysis are reported in Table 4.18, and to ease the reading of the point logic effect, in Table 4.17 are reported the τ values of these results.

From these results, it can be noticed how the timeshifted R^2 remains higher than the

Case	τ_η	τ_{b_1}	τ_{b_2}	τ_{a_1}	τ_{a_8}	τ_{a_5}
no ts point 10sec	108	11	9	2	6	18
ts point 10sec	661	35	51	20	27	21
nots point 20sec	106	11	11	0	8	10
ts point 20sec	449	25	35	13	19	9
nots point 30sec	61	9	4	1	4	6
ts point 30sec	394	23	32	11	17	9
nots point 40sec	48	5	3	1	3	3
ts point 40sec	291	18	26	8	13	3
nots point 60sec	42	6	4	1	4	3
ts point 60sec	229	15	16	6	9	1
ts point 90sec	206	13	15	5	9	1

Table 4.17: Variation of τ values of MRL results on EUROTrough full screened dataset, no timeshift and timeshift, variable point duration

no timeshifted dataset for every point duration. This remains at comparable value as its value without the point logic up to 30 seconds point duration (which is the duration for the SS methodology, as well as half the time constant of the EUROTrough system). The τ values from these timeshifted results remain high up to the 30 seconds point duration (with values similar to no point logic applied), too, declining afterwards. In particular, with point durations higher than 40 seconds, the a_5 coefficient stops being relevant, and the difference between TS and noTS decreases. This is expected, as with higher point durations we are aggregating a bigger period of test data, and the timeshift logic stops to play its part as its effects are *diluted* in a broader set of data. With point durations higher than the time constant of the system, the timeshift logic gives roughly the same results as a single row, not timeshifted dataset (except for the a_5 coefficient, which, of course, is the most impacted from the timeshift logic).

The same procedure was applied to URSSATrough dataset too, and the results of the various MLR, with the same ranges described above, both for timeshift and no timeshift dataset, are reported in Section B.3 at page 135. Even with the point logic, all combinations have at least one positive coefficient, but the same pattern as previously described emerges again.

The point logic analysis further confirms the usefulness and rightness of the timeshift logic, both for row-to-row data analysis (such as the standard QD) and for rows-to-point analysis (such as the standard SS).

4.4 Summary

The timeshift logic finds its application in every system for which the time constant results higher than the sampling rate, but for those who are below or around the same value, a timeshift of just one row may be considered to adjust for some latency of the system (both thermically and from the sensors). Its use helps to alleviate the a_5 coefficient from taking into account more than it was supposed to, encouraging all the coefficients to results in more fitting values, with better statistical meaning.

The point making logic may help to simplify very big datasets, but should be implemented with caution, as longer point durations may lead to a decrease in the overall quality of the results, but it demonstrates similar quality results up to 30 seconds durations, which may help in reducing the impact of random statistical variation in the measured data.

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_8	std dev	a_5	std dev
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 10sec	0,9145	0,65367	0,0060	-5,05E-04	4,48E-05	-1,67E-05	1,96E-06	-0,066	0,027	-1,94E-09	3,11E-10	-1,02E+03	5,71E+01
full, ts, 700 6 150, etamin 0.15, dervmin 0.02, point 10sec	0,9650	0,65930	0,0010	-4,15E-04	1,18E-05	-1,72E-05	3,35E-07	-0,096	0,005	-1,62E-09	5,96E-11	-3,85E+02	1,84E+01
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 20sec	0,9004	0,63967	0,0060	-5,02E-04	4,37E-05	-1,97E-05	1,80E-06	-0,001	0,028	-2,62E-09	3,15E-10	-7,95E+02	7,84E+01
full, ts, 700 6 150, etamin 0.15, dervmin 0.02, point 20sec	0,9574	0,65856	0,0015	-4,38E-04	1,73E-05	-1,69E-05	4,88E-07	-0,093	0,007	-1,63E-09	8,68E-11	-2,91E+02	3,40E+01
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 30sec	0,8957	0,65414	0,0106	-6,28E-04	7,21E-05	-1,45E-05	3,30E-06	-0,064	0,048	-1,92E-09	5,40E-10	-8,82E+02	1,46E+02
full, ts, 700 6 150, etamin 0.15, dervmin 0.02, point 30sec	0,9601	0,65726	0,0017	-4,36E-04	1,87E-05	-1,72E-05	5,36E-07	-0,087	0,008	-1,69E-09	9,81E-11	-2,86E+02	3,16E+01
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 40sec	0,8704	0,64812	0,0134	-7,47E-04	1,47E-04	-1,38E-05	5,16E-06	-0,034	0,060	-2,20E-09	6,97E-10	-5,71E+02	1,70E+02
full, ts, 700 6 150, etamin 0.15, dervmin 0.02, point 40sec	0,9415	0,65621	0,0023	-4,70E-04	2,58E-05	-1,68E-05	6,50E-07	-0,084	0,011	-1,65E-09	1,31E-10	-1,61E+02	5,39E+01
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 60sec	0,8396	0,62669	0,0150	-6,54E-04	1,13E-04	-1,99E-05	4,79E-06	0,061	0,068	-3,23E-09	7,72E-10	-5,07E+02	1,81E+02
full, ts, 700 6 150, etamin 0.15, dervmin 0.02, point 60sec	0,9250	0,65734	0,0029	-5,03E-04	3,34E-05	-1,60E-05	9,84E-07	-0,089	0,014	-1,57E-09	1,78E-10	-8,03E+01	6,84E+01
full, notes, 700 6 150, etamin 0.15, dervmin 0.02, point 90sec	0,9288	0,65432	0,0032	-5,16E-04	3,95E-05	-1,64E-05	1,11E-06	-0,076	0,015	-1,68E-09	1,91E-10	1,07E+02	1,19E+02

Table 4.18: Variation of MRL results on EUROTrough full screened dataset, no timeshift and timeshift, variable point duration

5. BENCHMARK TESTS AND VALIDATION

During the PhD, the m-PTC collector was then tested, in open field condition, in order to evaluate its performance. The benchmark was designed and assembled during the period, and it is described in Section 5.1, while the method used to analyze the test data collected from the systems mounted on it, is derived from the ISO norm 9806:2017, previously summarized in Section 3.1, while in Section 3.2 the method used for this evaluation is described .

5.1 Benchmark

In order to evaluate the performance of the m-PTC system, a benchmark, comprising of full hydraulics, piping, mechanical system, sensors and acquisition assembly was designed and assembled. Its component are detailed below.

5.1.1 Support structure

The m-PTC collector, which has its build-in one axis tracking, is mounted over a rotating platform (schematics in figure 5.1). The platform can be rotated on the vertical axis thanks to a central electric motor, and has a fixed angle surface on which the collectors can be mounted, simulating the inclination of a roof, to be able to operate without any shading for the majority of the hours of light.

Thanks to the additional rotating axis of the platform, the collector was mounted in an East-West configuration, so that the two axis of rotation, with a tracking system each, results in a two axis tracking.

Thanks to this disposition, no incidence angle can be achieved during testing, as well as discrete or variable angles.

In Figure 5.2 we can see the m-PTC mounted over the platform, alongside a ETC system, used to validate the benchmark and to compare its performance to the m-PTC under the closest condition as possible. Its full characteristics will be described in Section 5.2.1.

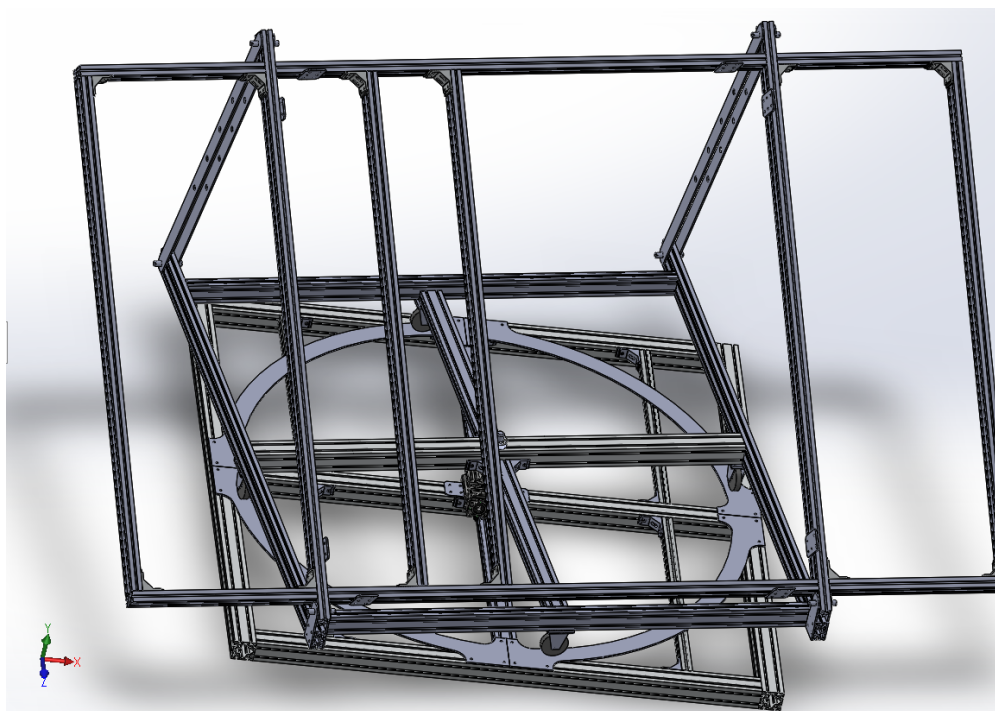


Figure 5.1: Schematics of the rotating support platform



Figure 5.2: m-PTC system on the rotating platform

5.1.2 Hydraulics

The hydraulic circuit was also constructed, consisting in two cold branch (one for each collector), one line of *hot* return, which feeds into the water reservoir (tank), which itself feeds the pump. The hydraulic circuit goes from the lower part of the tank to pump, then through an heat exchanger (connected on the other side with cold water from the aqueduct to be able di dissipate heat and better control the temperature), then through a splitter, then a mass flow measure system on each branch, which feed each collector. From them, the circuit links together the two outputs from the collectors, before entering the tank.

It also features a section of flexible tubing underneath the platform, for the two inlets and

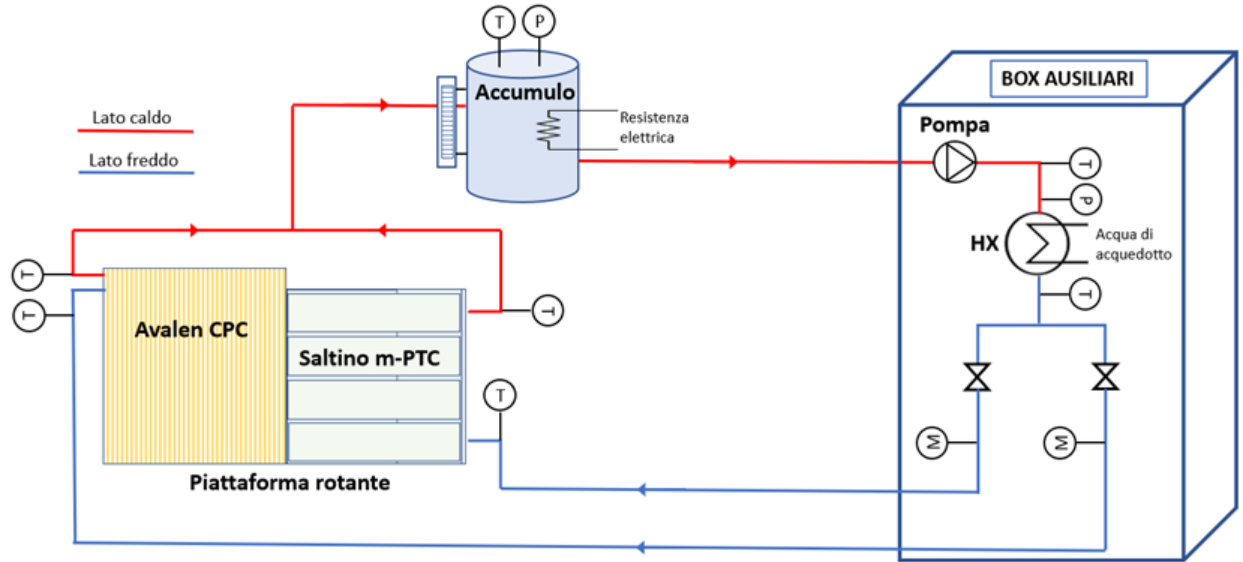


Figure 5.3: Hydraulic schematics of the benchmark

the common outlet, to allow rotation of the platform with the hydraulic and compensate the difference in length derived from the rotation. All the piping was also insulated, to mitigate its heat dispersion with ambient temperature.

All the tubing except the flexibles were provided by RACMET [103], which produces industrial systems, in our case providing a special high temperature seal to use and test, as our operational ranges were at the limit of their targets.

5.1.3 Power and electronics

In order to move the rotating platform, its motor needs a power supply from an inverter, which converts a single phase to three phase current, and can be modulated in frequency to set both the velocity and the direction of rotation. After some tests, it was chosen a frequency of 20 Hz, fast enough to move over the sun position, but slow enough to be able to control it and not going too much over it.

The inverter could also be controlled with a discrete input, that could be linked to the signal from a second solar flag sensor, to move the platform automatically, thus achieving a full two-axis testing system.

Inside the tank were inserted six electric resistances, with a combined power of 15 kW, divided in two set of three: the first with a capacity of 10 kW (3,3 kW each) and the second set of three with a capacity of 5 kW (1,7 kW each). This choice was made to be able to have many power levels without needing to regulate the power going through each one, having some stable power levels just by connecting or disconnecting some of them. Later a more precise

regulation for each element was introduced, reaching the capability to fine tune the power contribution of each and thus a better regulation of the final temperature. The pump is also moved by an electric motor, supplied by its own inverter, which too can be regulated to the desired speed.

5.1.4 Data acquisition and sensors

To measure and collect all the necessary variables, both for the performance evaluation and control of the system, a lot of different sensor were installed in the system, and are described below.

These sensor were connected to an AGILENT 34970a (figure 5.4) unit for the data acquisition process, mounting two 34901a (figure 5.5) modules to be able to read all the necessary channels, as there are 16 4-wire RDTs, which takes one and half 34901a by themselves.

The 34970a was also connected to a PC, which was running a LabView program (example



Figure 5.4: AGILENT 34970a Data Aquisition System

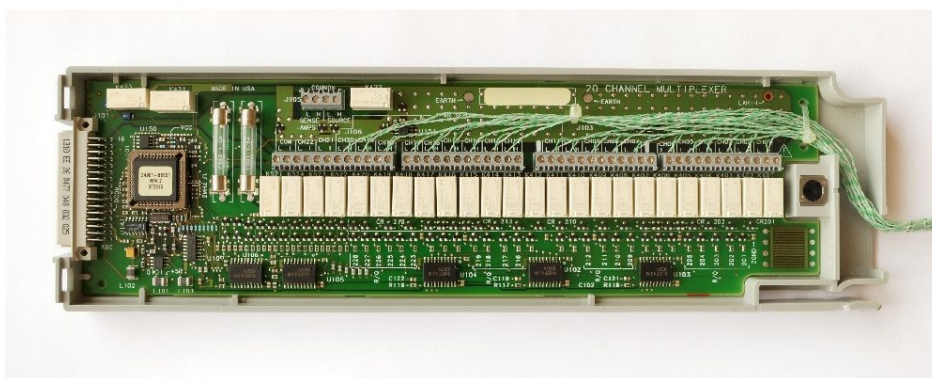


Figure 5.5: AGILENT 34901a Module

view in figure 5.6) to monitor all the variables and also save them on a file. The PC was also connected with a ModBUS 485 connection to the tracking control boards and a coriolis mass flow meter, to be able to issue commands to the boards and read the coriolis measurements directly.

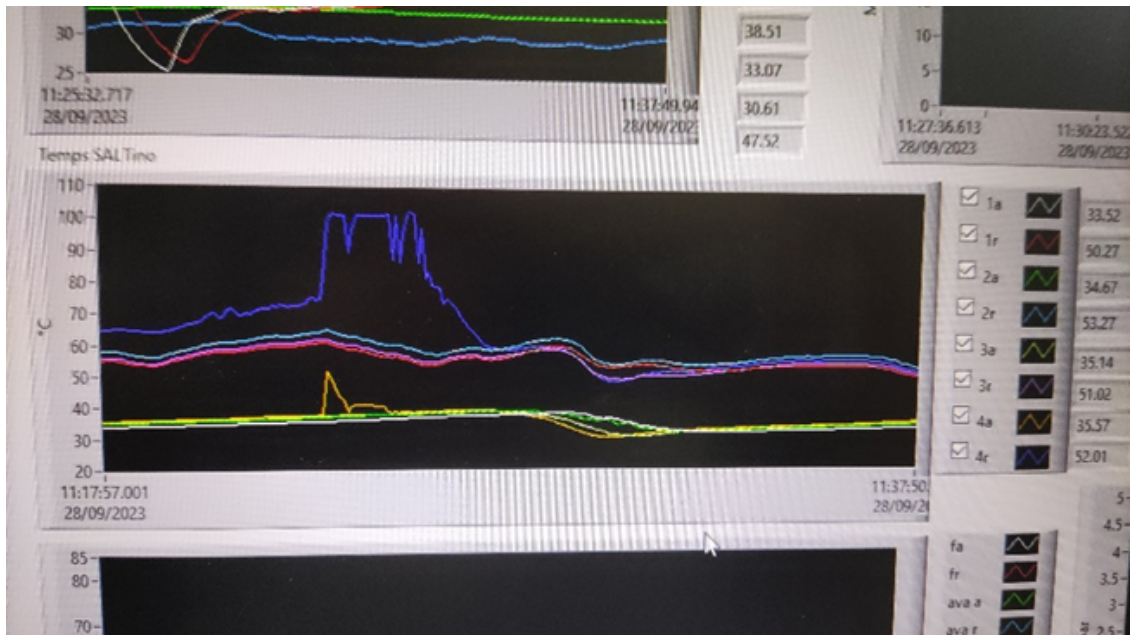


Figure 5.6: LabView program example screen during data collection

5.1.4.1 Massflow

Two coriolis mass flow sensor were used, installed each on the piping branch leading to each collector, to measure the respective mass flow directly, as shown in Figure 5.7. This is a better option than measuring the volume flow and then calculate the mass flow, as it requires less sensors, thus having a lower uncertainty overall. Declared accuracy for both coriolis is $0.0016 \cdot \dot{m} - 0.00001$.



Figure 5.7: Coriolis massflow sensors

5.1.4.2 Temperature

There are multiple Thermo Resistance Diode sensors (RTD), positioned as follows:

- one on the inlet and one on the outlet of each absorber tube of the m-PTC (for a total of 8)

- one on the inlet and one for the outlet of each collector system (for a total of 4)
- one ambient
- one in the tank
- one before and one after the "cold" heat exchanger (for a total of 2)

for a total of 16 RTDs.

In order to comply to the ISO 9806:2017 Steady State requirement, AA class, Pt100 $\frac{1}{10}$ DIN RTD temperature sensors were used for all sixteen temperature measures. These sensors are very precise, with an accuracy of 0.03 °C.

5.1.4.3 Radiation

The solar radiation was measured on the roof of the engineering faculty of the University of Florence (the weather station is shown in Figure 5.8), which features both a piroeliometer and two pirometer, thus being able to measure the direct (DNI or G_b), global radiation on the horizontal plane ($G_{global, horizontal}$) and the diffuse component (G_d). The latter is measured by obfuscating a pirometer from the direct sun and measuring its radiation. The direct component is measured with a classe I SOLYS2 [104] which has a declared 1% error.



Figure 5.8: Weather station over the roof of Santa Marta Engineering faculty in Florence

5.1.4.4 Errors summary

In table 5.1 are summarized the declared uncertainty. DAS refers to the Agilent Data Acquisition System.

Variable	declared uncertainty
T_{in}	0.03 [°C]
T_{out}	0.03 [°C]
T_{amb}	0.03 [°C]
$\dot{m}$	$0.0016 \cdot \dot{m} - 0.00001 \left[\frac{kg}{s} \right]$
G	$G/100 \left[\frac{W}{m^2} \right]$
DAS	0.006

Table 5.1: Sensor uncertainties

5.1.5 Data collection

All the data points were collected during numerous days of testing, logging all the sensors every 2-3 seconds. Different strategies were implemented to reach more stable results depending on the desired temperatures.

5.1.5.1 Open loop

In order to characterize the performance near the ambient temperature, and, in doing so, near the optical peak efficiency, an open loop configuration was used. The whole system needed an inlet water pipe for the fill (and refill as needed) of the system's piping, tank and collectors, so an access to the municipal water pipe was included in the piping system, which can be fed directly into the tank or just before the pump. The municipal water, coming mostly from underground piping, has its temperature quite stable, especially after the firsts minutes after its opening. This water was still lower than ambient temperature, but it is possible to control the temperature gain through the collectors by regulating their flow rate, thus having a mean temperature slightly above the ambient.

5.1.5.2 Closed loop

To reach higher temperatures, electric resistances were used. Each of the two is composed of three different elements, which can also be used singularly. One had three elements of 1,7 kW each, for a total of 5 kW, the other had three elements of 3,4 kW each, for a total of 10 kW. Each element could be powered independently, and also modulated thanks to a SCR. Varying the number and type of elements powered, and their power input, it was possible to achieve different inlet temperatures in the collectors. Also water recirculation was implemented, tanking advantage of the heat produced by the two collectors to increase the tank temperature.

5.2 Benchmark calibration

In order to check if our benchmark was up to standards, it was used to evaluate the performance of a commercially available collector, which was also officially certified. The collector of choice was an Evacuated Tube Collector (ETC) from Avalen, described in below in 5.2.1.

5.2.1 Avalen description



Figure 5.9: Avalen Zephyr, model 24

The Avalen model Zephyr 36 is an ETC system, with composed parabolic reflectors under its absorber tubes, that help redirect the sunlight that doesn't directly hit the tubes towards them. The absorber tubes are constituted of an U shaped tube, placed on a thin metal sheet that function as a fin, placed inside a circular aluminum tube, which sits inside a double glass tube with vacuum between the two glass layers, for better insulation, as we can see in Figure 5.10. The outside of the inner glass layer is also coated with a layer that maximize the absorbed radiation, while limiting the radiative emission (that are also reflected from the other layer of glass, contributing to its insulation effect).

On the top part of the collector are housed the distribution tubes, that redirect the main mass-flow between the collector's 15 singular absorber tubes. There is a main inlet and a main outlet distribution tube.

This commercial collector comes in various sizes, sharing the same height ($2,05\text{ m}$) and depth ($0,12\text{ m}$), but differing on the length, depending on the number of absorber tubes it features.

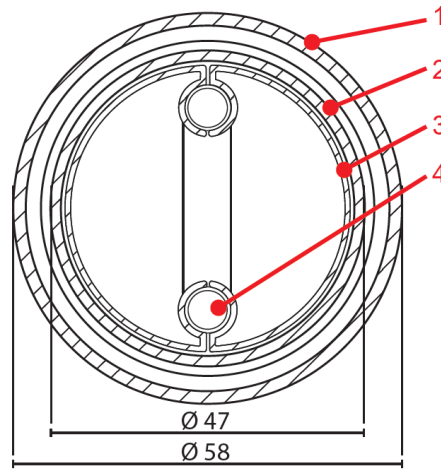


Figure 5.10: Section of the AVALEN absorber tube

Our model (Zephyr 36) has 15 absorber tubes, with a length of $1,74\text{ m}$, which brings our total surface to $3,55\text{ m}^2$. If we consider only the capturing surface area, we must subtract the housing of the distribution tubes and its counterpart at the bottom, bringing it to a height of $1,86\text{ m}$, for a net surface area of $3,23\text{ m}^2$. These values are taken from the information on its data-sheet (figure 5.11) and on field measurements.

As introduced above, this collector features on its datasheet the performance evaluation,

Modello	L2 Lorda (mm)	Area Lorda (m ²)	Volumi Fluidi (litri)	Peso a secco (Kg)	N° tubi	Conessioni Idrauliche
Zefyr 24	1166	2,38	2,23	52	10	DN 22
Zefyr 36	1741	3,55	3,33	76	15	DN 22
Zefyr 48	2316	4,72	4,43	100	20	DN 22
Zefyr 59	2891	5,90	5,54	123	25	DN 22
Zefyr 71	3466	7,07	6,64	149	30	DN 22
Zefyr 83	4041	8,24	7,75	173	35	DN 22

Figure 5.11: Dimensional specification of AVALEN Zephyr models

thank to the values reported in figure 5.12. This will be needed later in 5.2.3.1.

We can also notice that it has absorber tubes with a diameter of 50 mm . Comparing the width of the different models with the number of tubes (figure 5.11), it can be calculated they use 115 mm of aperture per each tube, plus 16 mm for the edges of the whole system. If we factor the geometrical concentrating ratio of this system, $\frac{115}{50} = 2,3$, but since is non concentrating, non tracking system, it uses most of the surface of the absorber tube, so its effective concentrating ration should be lower, even less than 1 ($\frac{115}{50 \cdot \pi} = 0,73$ if we account for its whole surface).

5.2.2 Avalen data pre processing

Since this is a non concentrating system, yet one with evacuated tubes, formula 3.8 was used for punctual efficiency evaluation, while equation 3.12 is used for the curve regression,

Caratteristiche tecniche	
Efficienza pan. 0* (A Ap): 72,5%	Assorbimento tubo: >93%
Coefficiente c1 *: 1,07 W/m²K	Attacchi idraulici: Ø 22mm
Coefficiente c2 *: 0,005 W/m²K	Pressione massima: 10 bar
IAM (50°)*: 1,1	Portata pannello: 0,02 kg/sm²
Capacità termica*: 32,58kJ/m²k	Perdita di carico: 71,0 mbar
Diametro tubo: 50mm	*Solar Keymark certification

Figure 5.12: Performance specification of AVALEN Zephyr

both using equation 3.5 for the incoming radiation. The incidence angle θ was calculated by the Python program, based on the timestamp and location provided, as well as the mounting angle on the platform. Since the platform was rotating during tests, only the incidence angle due to the declination was to account for. Tests were conducted for several days, in various conditions, varying in inlet temperature and benefiting from different radiation composition (different proportion of direct/diffuse radiation) in different days. A total of more than 39 hours of data were selected for the analysis, of which more than 10 hour passed the first screening. Subset candidates found are shown in Figure 5.13.

Lots of stable subsets were found at near ambient temperature, while very few were found

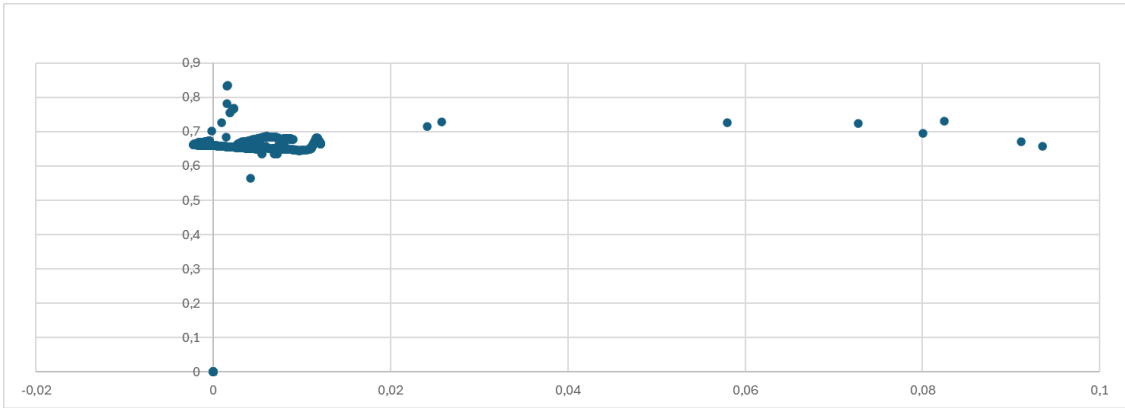


Figure 5.13: Subset candidates with a threshold of 0.1 K on inlet temperature

at higher ones (Figure 5.13). In order to have a more balanced distribution of points to extract the performance curve from, the threshold of the inlet temperatures for test days with higher temperatures goals was increased. The selected subsets from these tests are shown in Figure 5.14. Since the increased tolerance for the inlet temperature is the type A error associated with its measurement, its effect can be seen on the error bars, although the biggest contribution comes from the radiation variance, the points with the biggest bands are not the ones with an increased tolerance, but the ones with the most solar radiation variation during the subset, although still within the threshold of the ISO9806.

Fifteen points were selected, covering the whole operational range. Although fewer points were found at higher temperatures, the points are well spread. Their measured values can be found in Table C.1 at page 148.

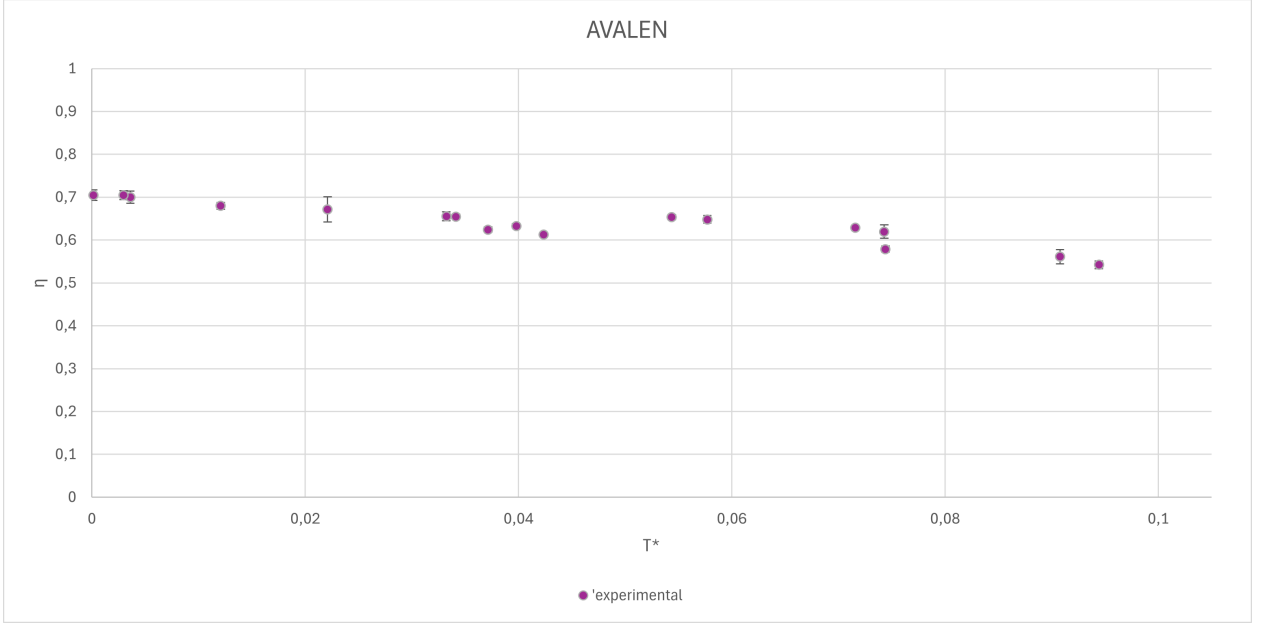


Figure 5.14: Selected subsets from AVALEN tests

5.2.3 Avalen results

From the data in figure 5.14 (the calculated values are reported in Table C.2 at page 149), a Multiple Linear Regression using formula 3.12 was performed, resulting in the values reported in Table 5.2, named *full*.

Since both a_1 and a_2 are negative, yet not significant ($\tau < 3$), the MLR was run again, excluding a_2 (*linear*) in one case and a_1 (*quadratic*) in the last. In figure 5.15 all three regression, each with its upper and lower bounds, are represented, compared to the experimental data.

As expected from the lower τ values of the *full* regression, its upper and lower bounds are

		η_0	a_1	a_2	R^2
full	value	0.6971	-0.6787	-0.0120	0.9993
	std dev	0.0089	0.5094	0.0079	
	τ	78.2	1.3	1.5	
linear	value	0.7060	-1.4285		0.9992
	std dev	0.0069	0.1329		
	τ	100.9	10.7		
quadratic	value	0.6878		-0.0222	0.9993
	std dev	0.0056		0.0020	
	τ	122.6		10.9	

Table 5.2: MLR on the AVALEN collector

quite far apart, and rapidly divergent. All data point are within the bounds, but the τ values of a_1 and a_2 suggests to exclude one of the two coefficient.

Moreover, comparing the *linear* and *quadratic* regressions, the latter has a R^2 very close to the *full* regression, on top of having higher τ values, so the *quadratic* was chosen, and it can be seen better in figure 5.16.

It may appear as the regression is very fitting with lower temperatures, but becomes more and more distant as the temperature reaches higher values, but it isn't the correct reading of the graph. As explained in Section 3.1.2, the regression has two variables, which are

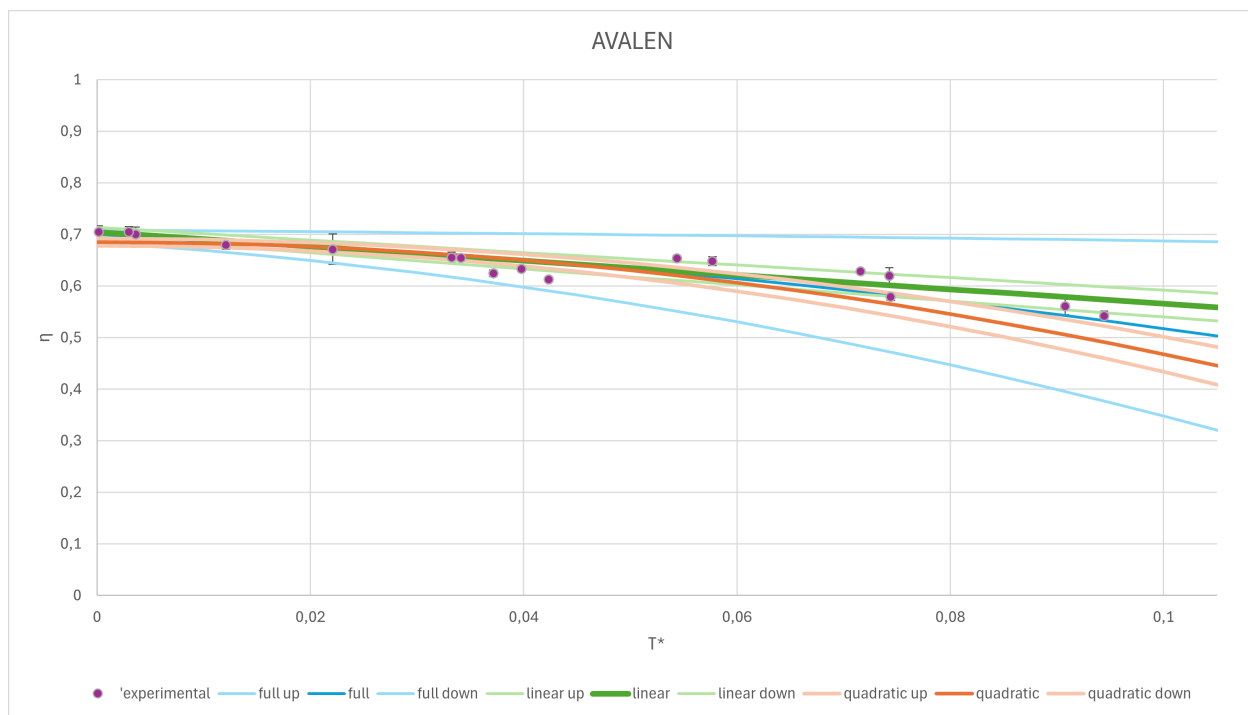


Figure 5.15: Comparison of MLR curves on experimental data

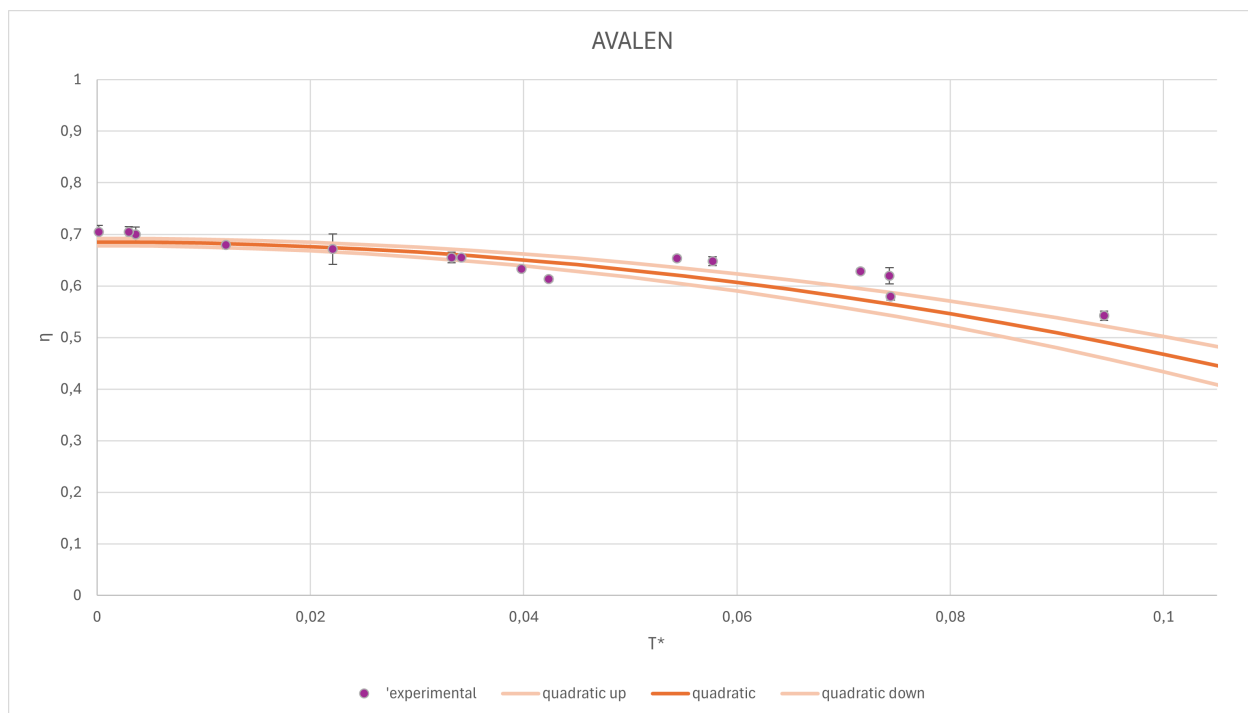


Figure 5.16: Extrapolated performance curve of the AVALEN collector

different from each other: T^*_1 is not T^*_1 squared, but T^*_1 squared then multiplied for the radiation. This means that although the term *linear* used in table 5.2 is correct, as it is a linear regression on the T^*_1 term, which is the variable used for the x values, the *quadratic* term is not. It is the missing radiation multiplication that causes the effect in the graph mentioned before. If a graph with point ordered on T^*_2 was to be made, the *quadratic* regression would be a linear, better visually, fit, but as suggested in the ISO9806 norm, data should be reported on $\eta - T^*_1$ plane.

5.2.3.1 Comparison with datasheet results

Since the Avalen system is commercially available, is possible to confront our experimental data with its datasheet [105] and certification [106] values. The datasheet's values are reported in Figure 5.12, while certification's values are reported in Figure 5.17.

In Table 5.3 are reported the coefficient to be compared, while in Figure 5.18 is shown

Data required for CDR (EU) No 812/2013 - Reference Area A_{sol}		
Zero-loss efficiency (η_0)	0.641	--
First-order coefficient (a_1)	0.94	W/(m ² K)
Second-order coefficient (a_2)	0.004	W/(m ² K ²)
Incidence angle modifier IAM (50°)	0.95	--
Remark: The data given in this section are related to collector reference area (A_{sol}) which is aperture area for values according to EN 12975-2 <u>or</u> gross area for ISO 9806. Consistent data sets for either aperture or gross area can be used in calculations like in the regulation 811 and 812 and simulation programs.		

Figure 5.17: Keymark certification of AVALEN

	η_0	a_1	a_2	IAM	R^2
regression	0.6878		-0.0222	(1)	0.9993
datasheet	0.725	-1.07	-0.005	1.1	
certification	0.641	-0.94	-0.004	0.95	

Table 5.3: Performance coefficients from tests and datasheet

a graphical comparison. For the regression, since the inclination was factored in in the calculation of the radiation and no further analysis was conducted, the IAM was implicitly set to 1. It is also worth mentioning that the certification explicitly refers to the gross area of the collector, the regression used the net area, and the datasheet values is unknown which area are referred to, although they may be using some sort of net area to boost the values for marketing, like using both net area and IAM modifier on η_0 .

In order to more accurately confront them, IAM was set to 1 for all curves, as well the certification was scaled to net area, as is shown in figure 5.19.

In this adjusted comparison we can see as the curves are more aligned with each other, with the regression being very close to the certification one, but diverging at higher temperatures, possibly due to lack of datapoints in that area.

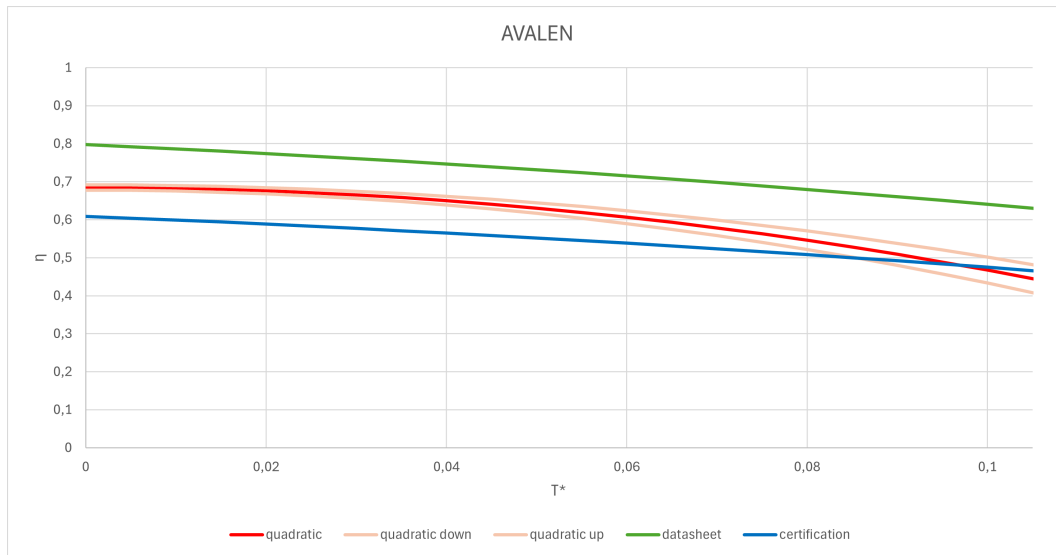


Figure 5.18: Avalen curves comparison

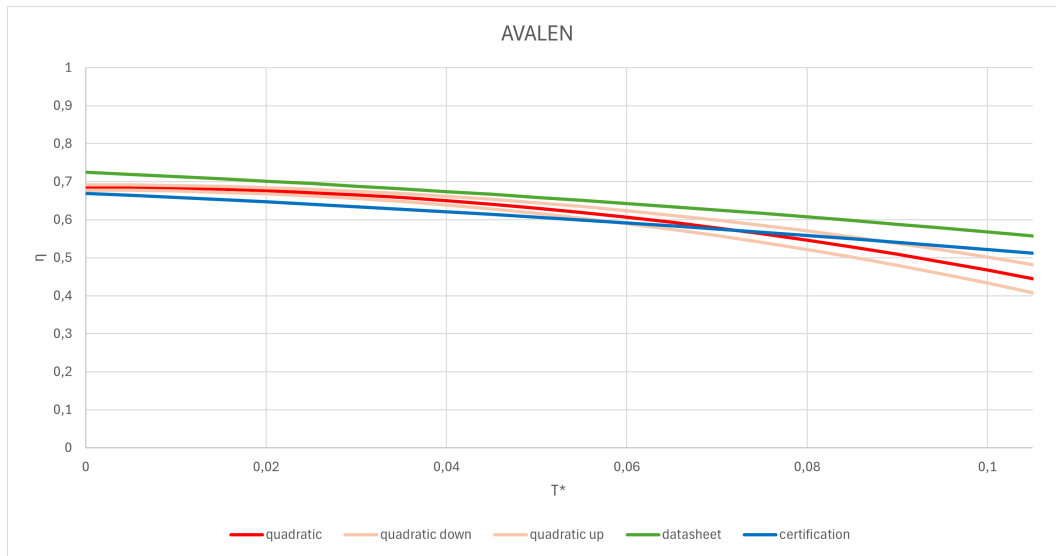


Figure 5.19: Avalen adjusted curves comparison

5.3 Summary

Overall the tests conducted on the Avalen collector resulted a dataset which was able to be used to extract the coefficients of its performance, especially at near ambient temperature for the η_0 targeting. The benchmark is validated as worthy for further testing.

6. M-PTC TESTS, PERFORMANCE EVALUATION AND DISCUSSION

Tests on the m-PTC systems were conducted during the PhD period, alongside the Avalen collector for the near-ambient, open loop configuration, as well as stand alone (closing valves both on the input and output branch of the Avalen's piping) on the benchmark in Florence. For mild temperatures (50-80 degrees Celsius) no additional heating was used, as the input from the collectors and the big insulated storage tank were enough to reach those temperature during a test day. For higher temperature additional heating was needed, and the electric resistances were turned on at various power levels to reach different temperatures. To avoid vapor production inside the piping, the system was also pressurized at 6 bar, with the help of an air compressor connected to the top of the tank. Both tests and analysis were made following the ISO 9806 Steady State format as guide.

Initially it was planned to conduct tests both on the full collector and with singular parabolas, in order to evaluate both the overall performance and the dispersion between the four tubes, but due to a couple of extraordinary winter weather phenomenon, one tube lost the vacuum halfway through the tests, so it was decided to select the second one, the one with the solar sensor attached, as reference. All data further below refers to one tube, so its net area was used, and not the gross area, as the norm suggests.

6.1 Water tests in Florence

Extensive tests were made, for a total of more than 50 hours of data, and more than 50 000 rows of data collected, over the course of many days. In Table 6.1 the distribution of inlet temperature is reported.

Tests were conducted during the summer season, which is very hot and sunny in Florence, with temperatures above 30 °C, and even the public aqueduct water was always above 20 °C. Tests need to be conducted with an average temperature (between inlet and outlet) close to the ambient, in order to improve the accuracy of the η_0 evaluation, and the inlet from the aqueduct was favorable, since the average temperature was close, but not below the ambient.

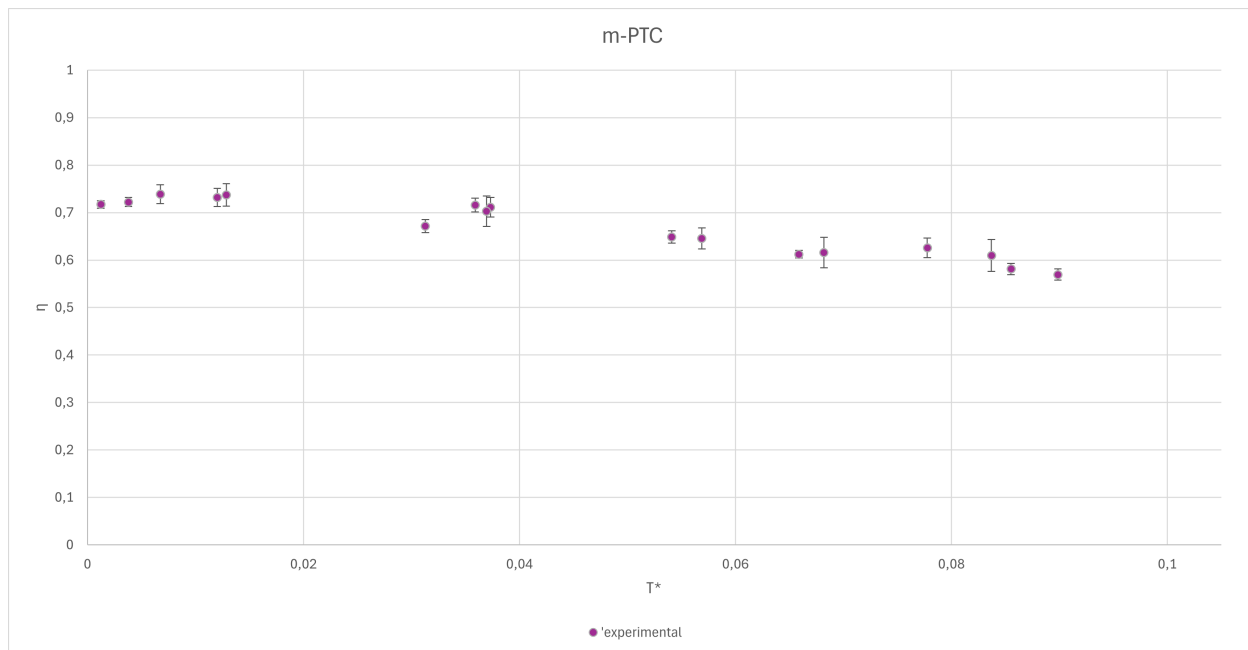
Temperature range [° C]	number of data rows
<20	0
20-30	7709
30-40	3925
40-50	5469
50-60	7567
60-70	7087
70-80	3073
80-90	3266
90-100	2013
100-110	1014
110-120	1274

Table 6.1: Distribution of inlet temperature

Effort was made to have a spread of data covering all temperatures, in order not to bias the later regression.

More than 800 possible subsets of data that respect the Steady State condition were found, but unfortunately they did not include the upper temperatures range, so the threshold of $0.1K$ for the inlet temperature was softened in steps, in order to have subset points evenly distributed in the tested temperature range, to achieve both a complete analysis while minimizing the inlet temperature deviation. This is reflected and taken into account with a wider error bar for those subset points. Subset points with up to $0.4K$ of inlet variation were considered, with an obvious preference towards lower threshold ones, sharing the same data. It is also worth noting that the variance of solar radiation has the biggest impact on the error value for each point, not the inlet temperature, so the decision to increase the threshold on the inlet will not disrupt the validity of tests with tremendously big errors.

In Figure 6.1 are shown the 17 subset points selected. Table C.3 (page 150) contains the full

**Figure 6.1:** Datapoints selected for m-PTC water tests

measured data for those points, while Table C.4 (page 151) contains the respective calculated

values. The points were selected to cover as much as possible the temperature range, trying to have a balanced number of point in each portion. For example, there were many valid points in the near ambient temperatures, with the open loop configuration, but only five were considered.

Multi Linear Regression was applied to extrapolate the η_0 , a_1 and a_2 coefficients. The results are shown in Figure 6.2 (and Figure 6.3 with zoomed y axis) and Table 6.2 summarize the results.

The regression with all three of the terms (*full* in Table 6.2) results in both a_1 and a_2

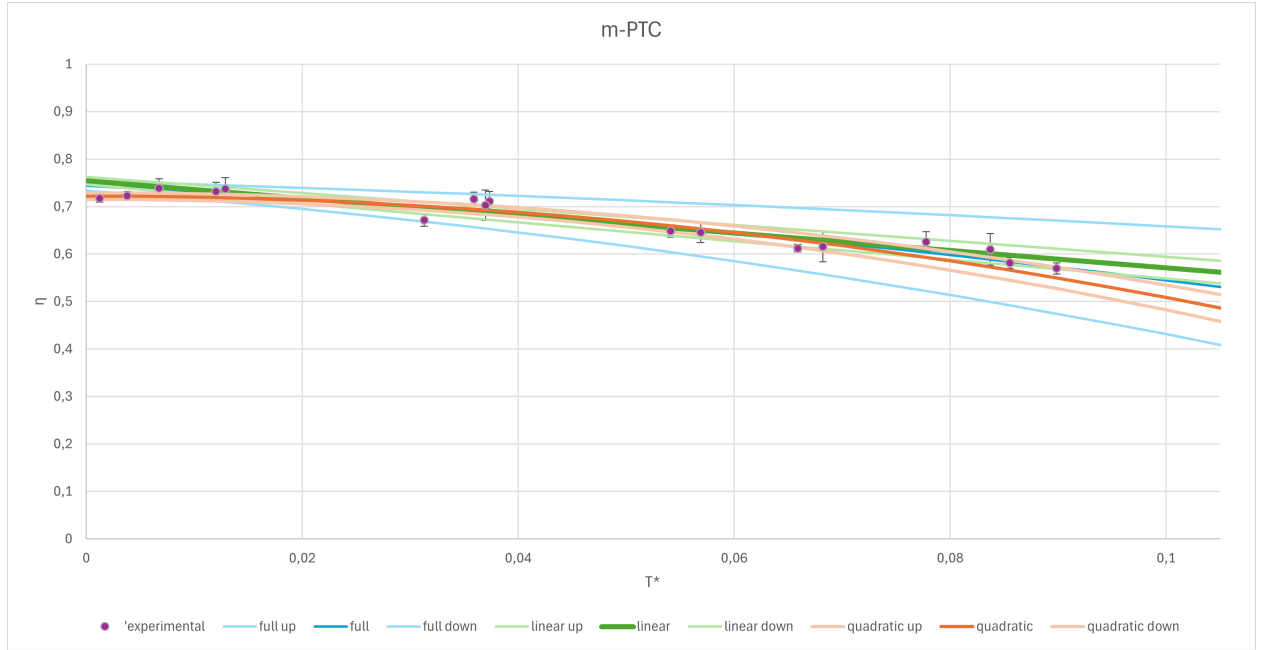


Figure 6.2: MLR on m-PTC datapoints with water testing

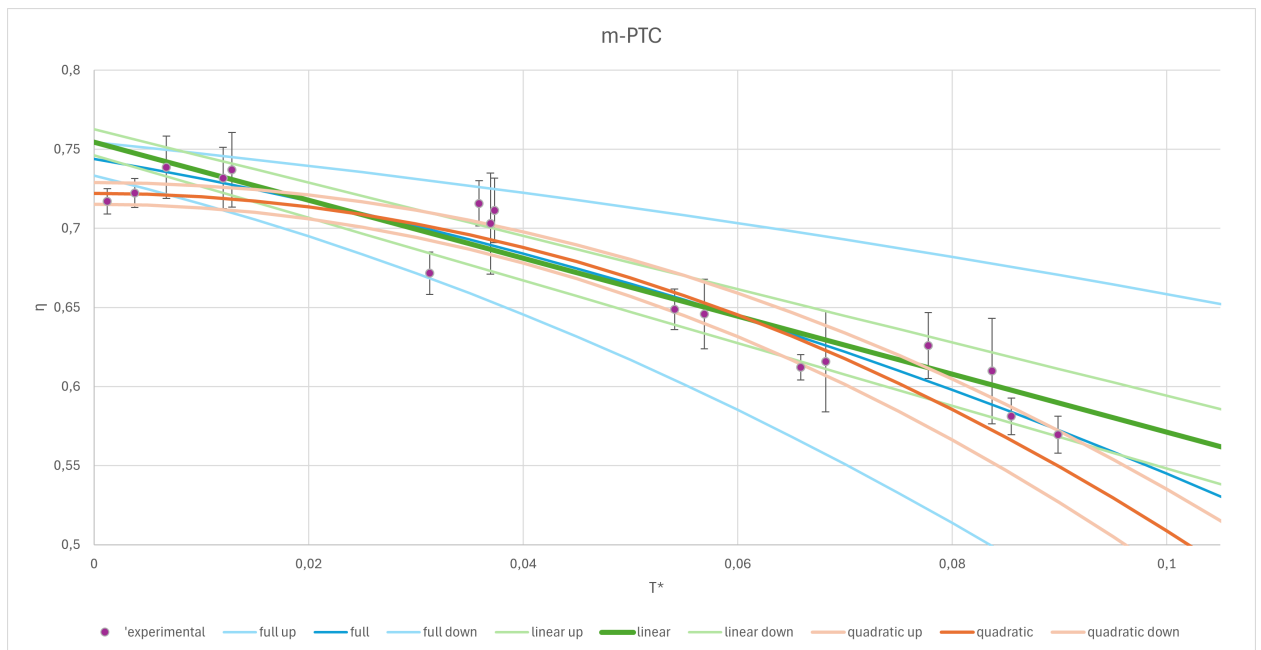


Figure 6.3: MLR on m-PTC datapoints with water testing - zoom

negative coefficients, as should be expected, but the statistical deviation of their value is

		η_0	a_1	a_2	R^2
full	value	0.7439	-1.1649	-0.0082	0.9995
	std dev	0.010606	0.47278	0.00557	
	τ	70.1	2.5	1.5	
linear	value	0.7544	-1.8323		0.9994
	std dev	0.008153	0.148385		
	τ	92.5	12.3		
quadratic	value	0.7221		-0.0213	0.9992
	std dev	0.00679		0.00194	
	τ	106.3		10.96	

Table 6.2: MLR on the m-PTC collector

quite relevant, with τ values of 2.5 and 1.5, respectively. Regressions with only a_1 or a_2 were also considered. The *quadratic* regression was chosen, for its higher τ values. The peak optical efficiency η_0 have a lower value than the other regressions with different coefficients, as well as the presence of some of the points in the near ambient temperature range suggest it can be even higher.

6.2 Oil tests at Casaccia

In later season, the benchmark alongside the m-PTC module was moved to ENEA research center in Casaccia, near Rome, to conduct further tests, especially at higher temperatures, taking advantage of their synthetic oil circuit for testing. This circuit uses oil as vector fluid, and can reach temperatures up to 300 °C, although is designed for bigger systems, and thus higher flows, than our. After the linking of the hydraulic systems and few days of set up, the system was ready for new tests. Similarly to before, the c_p curve for the oil was set up in the python program, the density was not needed, since a coriolis mass flow meter was used, so the massflow was directly measured. Since the whole benchmark was moved and used, it was possible to use the same sensors, the same DAS and analysis tools as before, the only difference being the c_p calculation and the weather data, which still needed to be paired, but came from a different, yet using same instruments, weather monitoring system.

The oil also changes its viscosity with temperature, and with the small cross section area of the m-PTC absorber tubes, the massflow is very low, so only tests at high temperatures were planned. The low massflow required meant also a low fluid velocity, which resulted in some heat losses in the piping from the heater to the system, despite the double layer of insulation installed. For this reason the highest inlet temperature reached was only 265 °C and not the 300 °C, which was the heater temperature set. Lower temperatures, overlapping with water tests points, were not achieved, due to the aforementioned viscosity of the oil fluid, that necessitate at least 120 °C to be able to flow properly in the hydraulic system.

Following a similar analysis than before, 16 subset datapoints were selected. Again, it was necessary to soften the inlet temperature thresholds, as it was not an easy task to maintain the 0.1K, as with the bypass, installed to allow the system to run at design point despite the heavy difference in massflow required, there were high instability in the inlet temperature, possibly due to the turbulence of the almost close bypass valve, as well as dispersions in the pipe highly dependent on the massflow, which was itself dependent on the temperature due to the high viscosity sensibility of the oil.

Sixteen points were selected, which are shown in Figure 6.4. The wider error bars are again due to high solar radiation variation, linked to the hot and high humidity weather connected

to the site, one day of test had particularly high radiation variations, despite still being clear sky, and still below the $\text{ISO } 9806 \pm 50 \frac{\text{W}}{\text{m}^2}$ threshold.

A Multiple Linear Regression was also applied to these points, to evaluate the performance

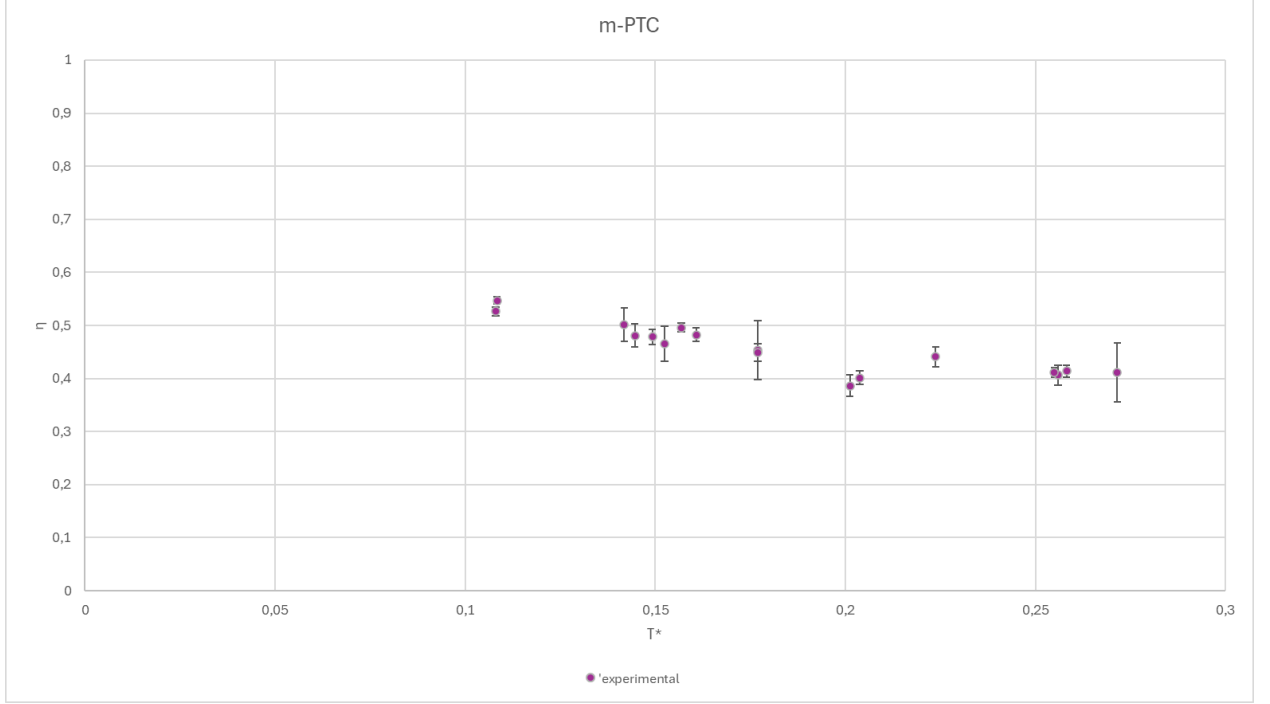


Figure 6.4: Datapoints for ENEA tests

of the collector at higher temperatures. In Table 6.3 are reported values and information about the regressions.

Once again, in the *full* regression not both a_1 and a_2 are negative, so *linear* and *quadratic*

		η_0	a_1	a_2	R^2
full	value	0.7738	-2.5907	0.0051	0.9986
	std dev	0.083543	0.803687	0.002093	
	τ	9.3	3.2	2.4	
linear	value	0.57667	-0.6608		0.9980
	std dev	0.02067	0.103951		
	τ	27.9	6.4		
quadratic	value	0.5062		-0.0016	0.9975
	std dev	0.01183		0.0003	
	τ	42.8		5.5	

Table 6.3: MLR on the ENEA data, m-PTC collector

options, considering only a_1 and a_2 respectively, were extrapolated, as the τ for the remaining coefficient is very close to the threshold (3.2). These results are more disperse than before, with lower τ values, and the extrapolated coefficients change very much in value depending on which of them are considered, with the optical peak efficiency going from 77% to 50%. Unfortunately, due to limited testing time, it wasn't possible to acquire more datapoints to analyze, and thus improving the quality of the regression (reflected in τ values) by using better quality ones (lower inlet variability, higher sunlight stability).

Both a_1 and a_2 coefficients in the *linear* and *quadratic* regressions, respectively, appear to

have lower values at higher temperatures than previous lower temperatures tests using water, hinting at lower thermal losses and better performance at higher temperature than previously expected, while the lower peak optical efficiency η_0 , which is not informed by any near ambient temperature points, suggests some incompatibility between the water and oil test, which cannot be analyzed together and their relationship should be studied with tests on similar temperatures using different fluids.

These tests confirmed the capacity of the m-PTC to maintain efficiency at the higher end of its operational range of temperatures, producing power above 200 °C with efficiencies between 40% and 50%. For the 265 °C inlet points, the module was able to produce an output of more than 1000 W (1056-1105 W).

6.3 Comparisons

Based on the water tests and their regression, we can confront the m-PTC system with the AVALEN results, as shown in Figure 6.5 (orange m-PTC, violet AVALEN). Both system were confronted on the net area, so the AVALEN curve was scaled accordingly. Although AVALEN starts with an higher peak optical efficiency, the m-PTC is able to sustain its efficiency higher at higher temperatures, due to its concentrating nature and reduced number of absorber tubes, which reduce the overall surface that might change heat with the ambient, thus contributing to the reduced heat losses, as well as benefiting from an higher concentrating ratio.

In Figure 6.6 is shown the same comparison, but on gross area.

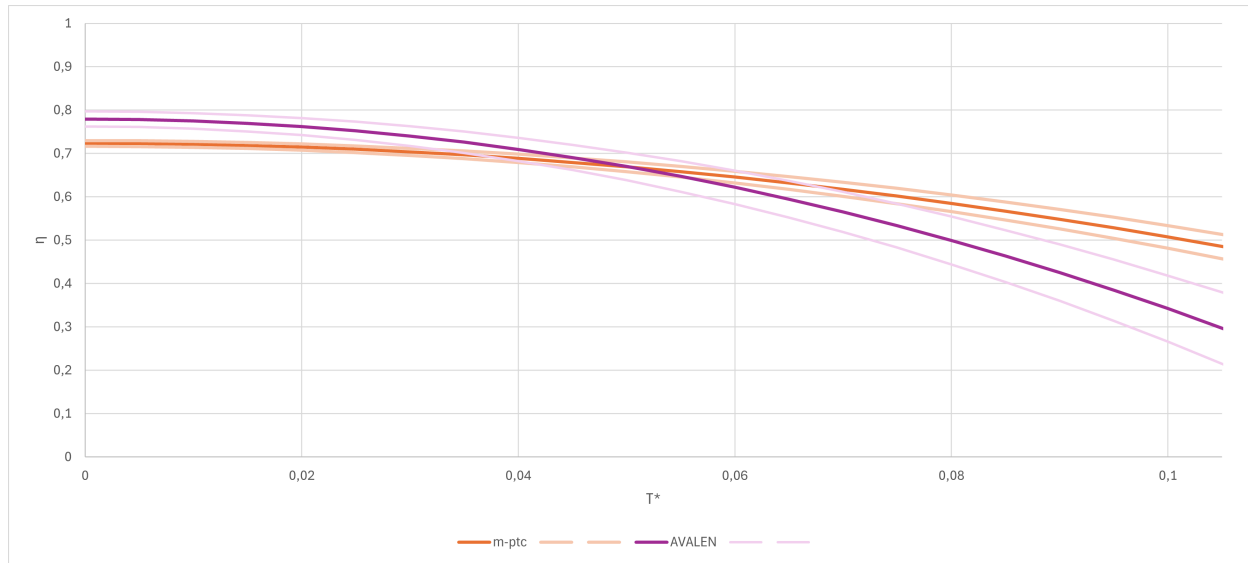


Figure 6.5: Comparison of AVALEN and m-PTC collectors, water tests, net area

Both trends are very close to the expected theoretical trend for their technology, shown in Figure 6.7, in which the PTC (violet, e) intercept and goes above the Evacuated Tube Collector (orange, b) near 100 °C working temperature, with $800 \frac{W}{m^2}$ of global radiation, which is 0,1 of reduced temperature with 20 °C ambient temperature. This may come even at lower temperatures, especially with higher direct radiation fraction than in figure 6.7 ($800 \frac{W}{m^2}$ global, $600 \frac{W}{m^2}$ direct), such as the one proposed in norm ISO 9806 and used in the analysis ($1000 \frac{W}{m^2}$ global, $850 \frac{W}{m^2}$ direct) for the graphical comparisons.

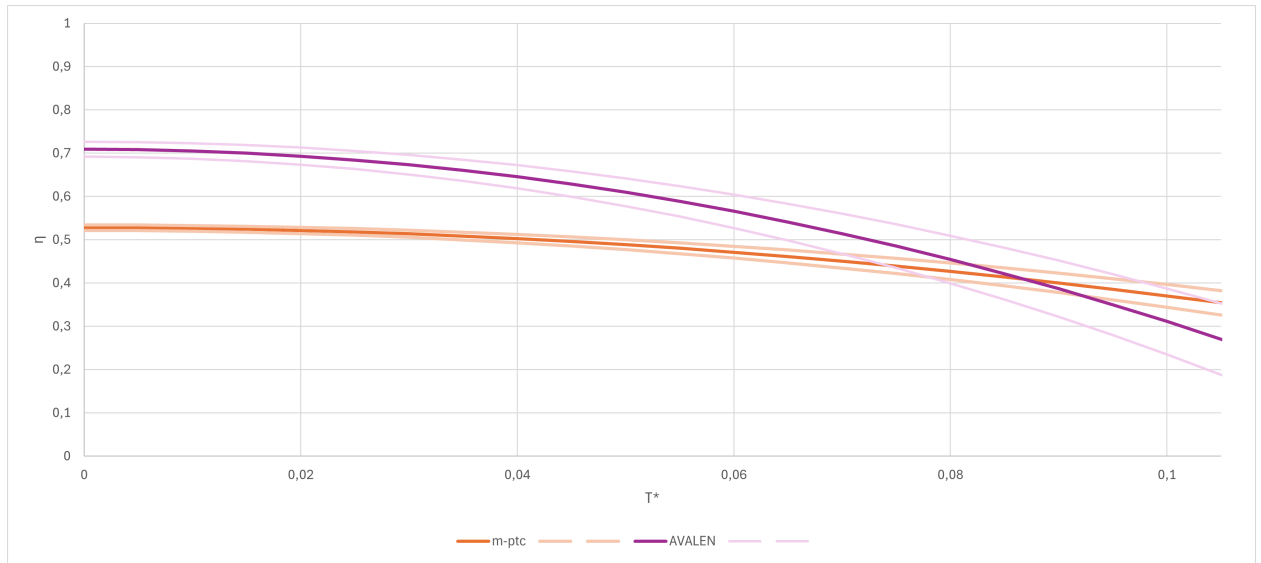


Figure 6.6: Comparison of AVALEN and m-PTC collectors, water tests, gross area

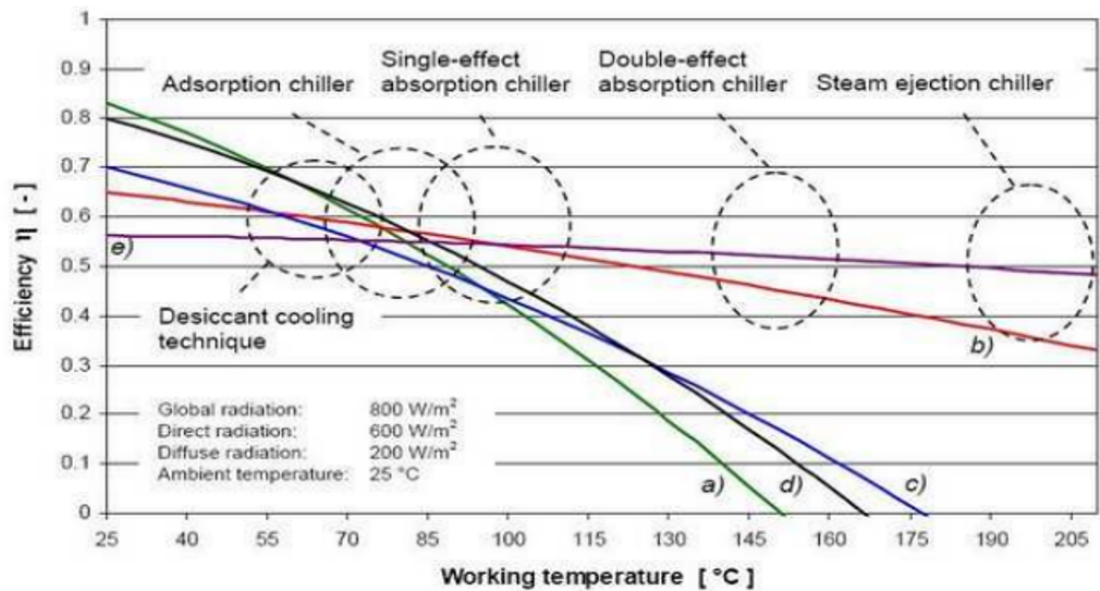


Fig. 6.7: Comparison of different collectors at 800 W/m^2 . a) Single glazed flat-plate with AR, b) Evacuated tube collector of the Sydney type, c) CPC flat-plate with Teflon foil, d) Flat-plate with double AR-glazing and inert gas filling, e) Small parabolic trough (under development; only the fraction of direct radiation = 600 W/m^2 can be used). The values are for normal irradiance and refer to the aperture area.

Figure 6.7: Theoretical performance curves of different technology systems

In Figure 6.8 are shown the data points of both Florence and ENEA Casaccia tests, with their respective error bands.

Direct comparison or aggregation of these points is not possible, but it can be observed that

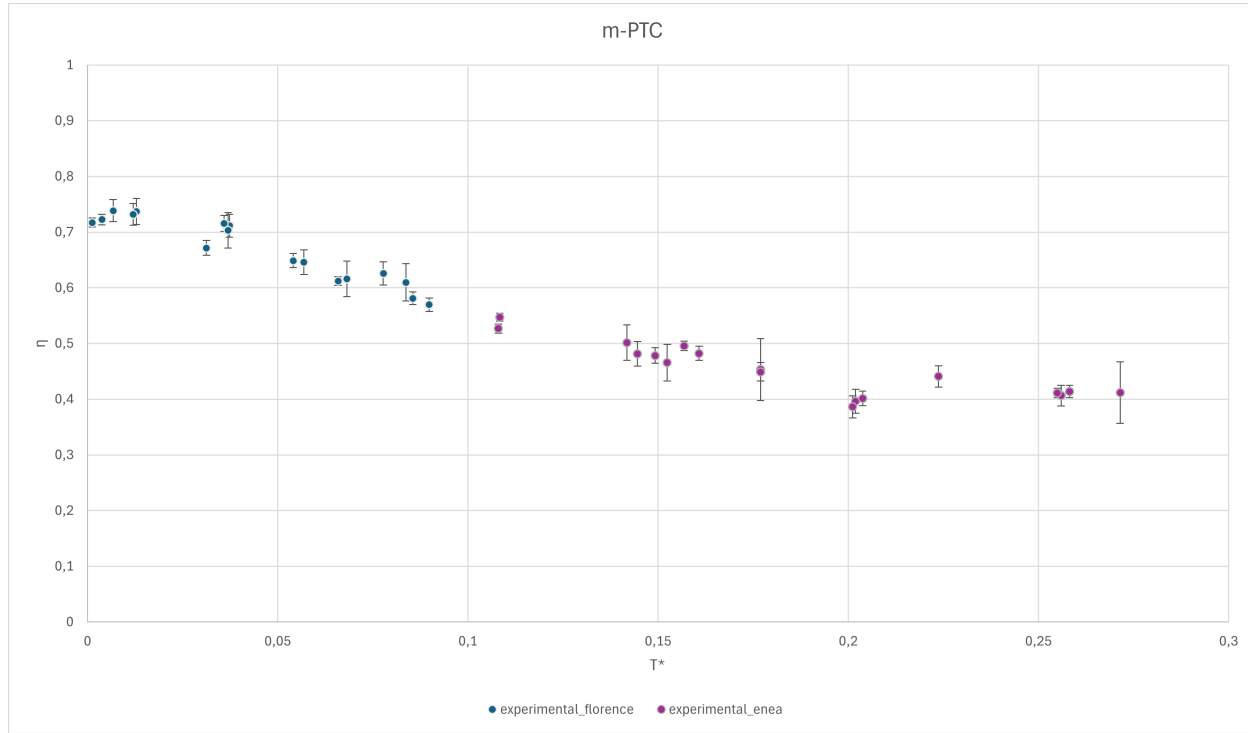


Figure 6.8: Data points for m-PTC, in blue water tests, purple oil tests

tests at higher temperatures resulted in a considerable power output at high temperatures, which suggests heat losses coefficients low enough not to intercept the x axis at these temperature, confirming the validness of the m-PTC in its whole operating range. From low temperature testing it was also assessed a peak optical efficiency above 70%, which is higher than both Figures 6.7 and 1.15 report as typical for this technology. This suggests a performance above average over the whole operational range.

7. CONCLUSIONS

Decarbonization of emissions has been a focus of global and EU policies, with both the residential and industrial sectors having trouble reaching their goals, both in demand reduction through efficiency gains and an increase in the share of renewables in their energy mix.

Heavily urbanized areas play a crucial role in achieving climate neutrality by 2050, a key goal of the European Green Deal. These areas represent only 4% of the EU land area, but 75% of EU citizens live in them. Furthermore, these areas absorb over 65% of the energy and account for over 70% of global CO_2 emissions.

Heating and cooling constitute 50% of the final energy demand in Europe and represent, by far, the largest energy sector to be decarbonized. In the European Union, all buildings are responsible for around 40% of total consumption, and the residential sector for 26%. Since 2000, consumption of the sector has grown significantly, and the vast majority (78%) is used for space heating and domestic hot water. In 2019, most energy for heating and cooling was produced from fossil fuels (75% of the total), while renewable sources provided only 22%.

Since 2010, the energy mix of the industry sector has remained relatively stable, with a heavy reliance on fossil fuels. The share of fossil fuel use in industry declined slightly from 87.2% in 2011 to 82.7% in 2021, mainly due to the ongoing electrification of industrial heat combined with the rise of renewable electricity use, which more than doubled during the decade, but renewable heat accounted only for 0.1% in 2021.

Experience shows that highly anthropized environments, such as urban contexts, are characterized by the presence of limited spaces that can be made available for renewable sources. In these contexts, the key to the diffusion of renewable energy systems is the creation of systems that can be easily integrated into the context and mainly onto buildings. In this context, if flat solar systems are an efficient response to the production of low temperature thermal energy, new solutions need to be developed for medium and high temperature up to 150-300 °C.

Commercially available solar technologies are either small-scale or large-scale. Small scale have often low operating temperature, with limiting performance, starting from ambient temperature up to maximum operating temperature, depending on the technology: non concentrating ones have high performance at low temperature, but their efficiency drops quickly and thus limits maximum operating temperature, but are often cheap and easy to implement, even on roof surfaces; large concentrating technologies can extend the operation range of temperature, but not substantially, with increased complexity and necessity of open field installation, with lower peak efficiency compared to non concentrating ones and heavy

impact of soil use. Large scale Concentrated Solar technologies have demonstrated their effectiveness, both in operating temperatures, reaching up to 600 °C with molten salts, but necessitate an increased initial investment and management difficulty, demand large open field installation near the site, and are scalable only on the up-size term. Systems using molten salts also necessitate heat power input to maintain the salts in liquid state, with a further increase in costs and complexity, especially for the start up of plants, while systems using oil have the maximum temperature capped by the operating temperature range of the fluid, to avoid its degradation.

Both the residential and industrial sectors would benefit from a scalable, cheap, and efficient solution to cover their heat demand from a renewable source. Since most of the buildings, especially in Europe, are in high density areas, this system should be able to be installed on available surfaces, such as rooftops.

The m-PTC system was developed to cover these needs, with an emphasis on self management, scalability, modularity, operating ranges, and efficiency.

The module is very compact in its dimensions, allowing for installation on rooftops and allowing freedom in the positioning of the modules. The one sided mounting on the piping facilitates its installation and linking of multiple modules together in different configurations, allowing the tuning of the full system to both massflow and temperature increase. Its dual motor movemementation ensures precision alignment of both sides of parabolic mirrors, avoiding skews.

The tracking system was developed to achieve the accuracy necessary to maintain the mirrors focusing the direct component of solar radiation on the absorber tube, which was designed to maximize the absorption and transmission of the heat from the concentrated solar radiation to the fluid vector. The flag sensor was developed and calibrated, and is simple yet effective in its role of keeping the system aligned to the sun, while providing information on the sun's position relative to it, which the control board can use to command the motors.

The absorber tube, mounted inside the parabola, thanks to the rim angle above 90°, stays fixed while the mirror rotates around it, avoiding complex flexible piping to move the tube too, reducing the total number of moving parts. The absorber tube is also optimized in its reduced diameter, which still allows for a good intercept factor, thanks to the reduced focal distance of the module. It also features a Cermet selective coating on the receiver tube and is vacuum insulated thanks to a glass envelopment. The vacuum insulation proved to be effective in limiting heat losses, especially at high temperatures.

The control board reads the solar tracking sensor and powers the two motors to ensure proper tracking of the sun. It can also be controlled from a master PC or master control system to turn on the whole system, turn off a single module for maintenance operation, lack of sun, or to shield it from bad weather, to monitor for possible problems and also modulate the power output by disabling some part of the system. It can be programmed to search for the sun from certain hours and/or to go into sleep position at a set time, to avoid wasting electric power in search of a sun which is not in a favorable position.

ISO 9806:2017 norm was chosen for the performance evaluation, with a focus on the Steady State method. This requires achieving stable input conditions (standard deviation less than 0.1K) for extended periods of time (more than 10 minutes, for 16 datapoints spanning the full operational temperature range of the tested collector). Minimum solar radiation is also required, which restricts the testing times to summer and clear sky conditions, usually less frequent in other seasons.

A methodology review for Quasi Dynamic tests on large scale PTC systems was conducted, due to their dimension and massflow, the fluid takes about a minute to flow from the inlet to the outlet, but this two temperatures are collected at the same time and used to evaluate the PTC performance, with only the a_5 , the derivative term, to account for the evolution

of temperatures in the collector. This was applied to previously published data from EU-RO-Trough and URSSAT-Trough. The timeshift logic reduces the impact of the a_5 coefficient, improving the quality of the fit for every statistical parameter, and is recommended for every system that has a sampling rate lower than its time constant. The point logic, also used in the evaluation of the stability of SS tests, can be used even in QD without losing much, if any, quality of the fit, only if the timeshift logic is first applied. For these reasons, the timeshift is suggested even in SS testing and analysis.

The benchmark for water tests was assembled, with a rotating platform to add an axis of tracking to reduce the incidence angle influence over the performance, and be able to extend the direct incidence period. Sensors and components were chosen to be able to respect the ISO 9806:2017 norm for the Steady State condition.

The benchmark was validated by comparing measured data with the performance coefficients from the certification of a commercial evacuated tube collector, AVALEN Zephyr 36. Data was collected for more than 39 hours and was analyzed with the Python program developed for the Steady State analysis. Thanks to the rotating platform of the benchmark, only the incidence angle due to elevation was factored into the calculation, still inside the Python program, which calculated it from the timestamp of the data and location provided. For the near ambient temperatures, more than enough subpoints were found, while for higher temperatures it was necessary to increase the inlet temperature threshold to find enough suitable datapoints. This would not excessively increase the error value for each datapoint, as the variation of the solar radiation has the most impact on the final error, obscuring other sources of error. The results are similar to the certification values, especially at lower temperatures where lots of datapoints were selected, highlighting the need for a dataset spanning the whole operation range and balanced over it to extrapolate the performance curve.

Tests on the m-PTC were conducted for more than 50 hours, 50 000 rows of data, from near ambient temperature up to 140 °C, with many datapoints in stable condition at lower temperatures, which needed to be screened and selected. The Python program was used to facilitate the screening and selection of the datapoints, with many found at near ambient temperatures. The high reactivity of the small system with little thermal inertia resulted in increased difficulties in maintaining stable conditions with higher temperatures, yet a sufficient balanced set of datapoints was found, spanning up to 100 °C, by increasing the threshold on the inlet temperature. Again, this would not impact the overall error on η on each point, as the main contribution comes from the variation of the solar radiation. Thanks to the rotating platform of the benchmark and the onboard tracking system, the m-PTC module was always working in direct sunlight, with no incidence angle to be factored in, simplifying its performance analysis. The regression of the performance curve points to a peak optical efficiency over 72%, well above PTC systems of similar dimensions.

Further tests were conducted at ENEA Casaccia research center near Rome, using the oil test circuit capable of reaching temperatures up to 300 °C. Inlet temperatures span from 125 °C to 265 °C. The m-PTC module was able to produce a sensible thermal power output even at the higher end of its temperature range, confirming its capabilities to produce heat over the whole range of operating temperatures, yet its temperature of zero power output was not reached.

The m-PTC module is confirmed to be a system capable of supply heat both at lower and high temperatures, with efficiencies rivaling ETC technologies at lower temperatures and big scale PTC systems at higher temperatures, with its dimensions and design features that allows for installation in high density areas, both in residential and industrial sector, making the most out of available surfaces like rooftops, without the need for a regular, open field space for its installation.

Future developments

- While low temperature collectors can be tested with water circuits, pressurized in case of above 100°C operating ranges, and big scale, high temperature collectors are usually tested only with oil, the m-PTC system sits between both worlds, with oil testing in the higher end of its temperature range, but needing water testing for near ambient temperatures to avoid viscosity and flow problems connected with the oil. The overlapping of water and oil test points remains to be determined to allow the extrapolation of the performance curve over the full range of operational temperatures, as well as CFD validation of tests, by matching results with both fluids at the same temperatures.
- With the Torre degli Agli pilot project plant going into test and operational phases, overall performance and operation management tasks are to be addressed, with focus on real application use, instead of just experimental environments. This will show its capabilities in the residential sector, with integration in Positive Energy Districts (PEDs). As heat generation for ambient heating and sanitary hot water constitutes almost three quarters of total energy consumption by the residential sector, a reduction of its consumption from the electric network, still reliant on fossil fuel sources, can be an impactful way to reduce emissions and costs.
- A pilot project plant with an industrial use of direct heat is also suggested, to evaluate its effectiveness in reducing the carbon footprint of industrial processes that are highly heat dependent. The new FER 2 policy from the Italian Ministry of the Environment and Energy Security (MASE: Ministero dell'Ambiente e della Sicurezza Energetica) could provide the framework for its development. With the capacity to produce heat up to 300°C, the m-PTC module can be an effective way to increase the renewable share of energy consumption, generating the heat required by many industrial processes from solar energy.

Five articles are going to be submitted:

- ISO 9806:2017 methodology review for large scale PTC systems
- Design of an Energy community in the North of Italy powered by different renewable energy sources
- Design of a residential system based on small parabolic trough collectors: first experimental test and modeling
- Design and Development of an innovative small parabolic trough collector for heat process
- Analyzing the cost efficient production of medium heat temperature through concentrating collectors in Italy

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LINEAR REGRESSION

The basic target of solar collector efficiency testing is the determination of the collector efficiency by measurements under specific conditions. More specifically, it is assumed that the behavior of the collector can be described by a M-parameter single node, steady-state or quasi-dynamic model:

$$\eta = c_1 p_1 + c_2 p_2 + \dots + c_m p_m \quad \text{A.1}$$

where

η is the collector instantaneous efficiency

$p_1, p_2, \dots, p_m$ are quantities, the values of which are determined experimentally through testing

$c_1, c_2, \dots, c_m$ are characteristic constants of the collector that are determined through testing

In the case of the steady-state model, for example, $M = 3$, $c_1 = \eta_0$, $c_2 = u_1$, $c_3 = u_2$, $p_1 = 1$, $p_2 = \frac{(T_m - T_a)}{G}$ and $p_3 = \frac{(T_m - T_a)^2}{G}$.

During the experimental phase, the output, solar energy and the basic climatic quantities are measured in J steady-state or quasi-dynamic state points, depending on the model used. From these primary measurements the values of parameters $\eta, p_1, p_2, \dots, p_m$ are derived for each point of observation $j, j = 1 \dots J$. Generally, the experimental procedure of the testing leads to a formation of a group of J observations which comprise, for each one of the J testing points, the values of $\eta_j, p_{1,j}, p_{2,j}, \dots, p_{m,j}$. For the determination of uncertainties, it is essential to calculate the respective combined standard uncertainties $u(\eta_j), u(p_{1,j}), \dots, u(p_{m,j})$ in each observations point. It should be noted that in practice the uncertainties $u(\eta_j), u(p_{1,j}), \dots, u(p_{m,j})$ are almost never constant and the same for all points, but that each testing point has its own standard deviation. This is explained in section (REF).

During analyzing the data a least square fitting of the model formula is performed, in order to determine the values of coefficients $c_1, c_2, \dots, c_m$ for which the model of equation A.1 represents the series of J observations with the greatest accuracy.

Since in reality the typical deviation is almost never constant and the same for all observations, but each data point $(\eta_j, p_{1,j}, p_{2,j}, \dots, p_{m,j})$ has its own standard deviation σ_j , an interesting solution is the use of the weighted least square (WLS) method, which calculates, on the base of the measured values and their uncertainties, not only the model parameters but also their uncertainty. In the case of WLS, the maximum likelihood estimate of the model parameters is obtained by minimizing the chi-squared function:

$$\chi^2 = \sum_{j=1}^J \frac{(\eta_j - (c_1 p_{1,j} + c_2 p_{2,j} + \dots + c_m p_{m,j}))^2}{u_j^2} \quad \text{A.2}$$

where u_j^2 is the variance of the difference given in

$$\eta_j - (c_1 p_{1,j} + c_2 p_{2,j} + \dots + c_m p_{m,j})$$

as

$$u_j^2 = [\eta_j - (c_1 p_{1,j} + c_2 p_{2,j} + \dots + c_m p_{m,j})]^2 = [u(\eta_j)]^2 + c_1^2 [u(p_{1,j})]^2 + \dots + c_m^2 [u(p_{m,j})]^2 \quad \text{A.3}$$

Finding the coefficients $c_1, c_2, \dots, c_m$ and their standard uncertainties by minimizing chi-squared function is complicated, because of the non linearity present in formula A.2. A strategy is therefore to find the uncertainties numerically. A method for the case of M-parameter model is presented below.

Let K be a matrix whose $J \times M$ components $k_{j,m}$ are constructed from M basic functions evaluated at the J experimental values of $p_1, p_2, \dots, p_m$ weighted by the uncertainty u_j :

$$k_{j,m} = \frac{p_{m,j}}{u_j} = \begin{bmatrix} \frac{p_{1,1}}{u_1} & \dots & \frac{p_{M,1}}{u_1} \\ \vdots & \ddots & \vdots \\ \frac{p_{1,J}}{u_J} & \dots & \frac{p_{M,J}}{u_J} \end{bmatrix} \quad \text{A.4}$$

Let also L be a vector of length J whose components l_j are constructed from values of η_j to be fitted, weighted by the uncertainty u_j as:

$$l_j = \frac{\eta_j}{u_j}, \quad L = \begin{bmatrix} \frac{\eta_1}{u_1} \\ \vdots \\ \frac{\eta_J}{u_J} \end{bmatrix} \quad \text{A.5}$$

The normal formula of the least square problem can be written as:

$$(K^T \cdot K) \cdot C = K^T \cdot L \quad \text{A.6}$$

where C is a vector whose elements are the fitted coefficients. given the fact that for the calculation of variances u_j^2 , the knowledge of coefficients $c_1, c_2, \dots, c_m$ is needed, a possible solution is to use the values of coefficients calculated by standard least square fitting as initial values. These initial values can be used in equation A.3 for the calculation of u_j^2 for $j = 1 \dots J$ and the formation of matrix K and vector L .

The solution of equation A.6 gives new values of coefficients $c_1, c_2, \dots, c_m$, which, however, are not expected to differ noticeably from those calculated by standard least squares fitting and used as initial values for the calculation of u_j .

Moreover, $Z = INV(K^T \cdot K)$ is a matrix whose diagonal elements $z_{k,k}$ are the squared uncertainties (variances) and the off-diagonal elements $z_{l,k} = z_{k,l}$, $k \neq l$ are the covariance between fitted coefficients:

$$u(c_m) = \sqrt{z_{m,m}}, \quad m = 1 \dots M \quad \text{A.7}$$

$$Cov_{(c_k, c_l)} = z_{l,k} = z_{k,l}, \quad k = 1 \dots M \text{ and } l = 1 \dots M \text{ and } k \neq l \quad \text{A.8}$$

EUROTROUGH AND URSSATROUGH DATA

B.1 EUROTrough Published dataset

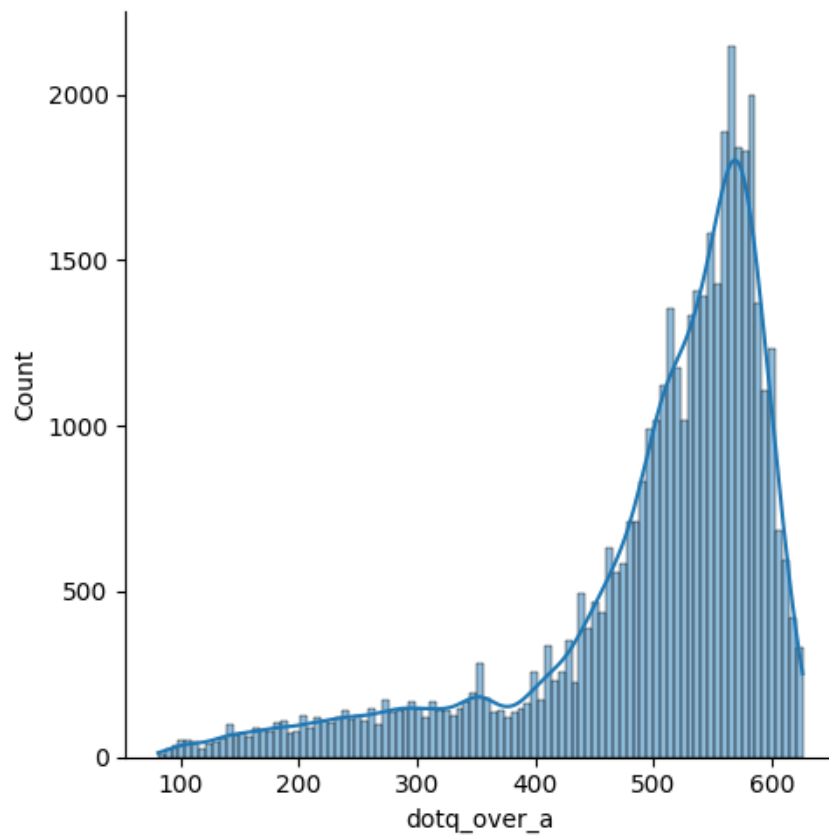


Figure B.1: Distribution of the power produced per square meter, published data

B.2 URSSATrough full data, screened

case	noTS/TS	R^2	η	b_1	b_2	a_1	a_2	a_8	a_5
abe1285	no TS	0,6792	0,6772	-1,60E-03	7,36E-06	0,053	1,59E-03	-1,26E-08	-3,27E+02
	TS	0,7082	0,6829	-1,52E-03	7,00E-06	-0,046	1,98E-03	-1,38E-08	1,05E+02
abe185	no TS	0,6751	0,6506	-1,59E-03	2,43E-06	0,455	0,00E+00	-7,08E-09	-2,85E+02
	TS	0,7016	0,6499	-1,51E-03	1,12E-06	0,454	0,00E+00	-7,01E-09	1,51E+02
abe125	no TS	0,6591	0,6240	-1,57E-03	-2,99E-06	0,882	-1,81E-03	0,00E+00	-2,35E+02
	TS	0,6827	0,6244	-1,49E-03	-3,92E-06	0,866	-1,77E-03	0,00E+00	1,92E+02
abe1285	no TS	0,6792	0,6772	-1,60E-03	7,36E-06	0,053	1,59E-03	-1,26E-08	-3,27E+02
	TS	0,7082	0,6829	-1,52E-03	7,00E-06	-0,046	1,98E-03	-1,38E-08	1,05E+02
abe185	no TS	0,6751	0,6506	-1,59E-03	2,43E-06	0,455	0	-7,08E-09	-2,85E+02
	TS	0,7016	0,6499	-1,51E-03	1,12E-06	0,454	0	-7,01E-09	1,51E+02
abe125	no TS	0,6591	0,6240	-1,57E-03	-2,99E-06	0,882	-1,81E-03	0	-2,35E+02
	TS	0,6827	0,6244	-1,49E-03	-3,92E-06	0,866	-1,77E-03	0	1,92E+02
abe18	no TS	0,6734	0,6512	-1,61E-03	2,42E-06	0,453	0	-7,08E-09	0
	TS	0,7010	0,6496	-1,50E-03	1,18E-06	0,455	0	-7,01E-09	0
abe185	no TS	0,6751	0,6506	-1,59E-03	2,43E-06	0,455	0	-7,08E-09	-2,85E+02
	TS	0,7016	0,6499	-1,51E-03	1,12E-06	0,454	0	-7,01E-09	1,51E+02
abe15	no TS	0,5782	0,6822	-1,53E-03	4,00E-06	0,183	0	0	-2,72E+02
	TS	0,6021	0,6811	-1,45E-03	2,78E-06	0,185	0	0	1,53E+02
abe18	no TS	0,6734	0,6512	-1,61E-03	2,42E-06	0,453	0	-7,08E-09	0
	TS	0,7010	0,6496	-1,50E-03	1,18E-06	0,455	0	-7,01E-09	0
abe12	no TS	0,6580	0,6243	-1,59E-03	-3,02E-06	0,882	-1,82E-03	0	0
	TS	0,6818	0,6241	-1,48E-03	-3,83E-06	0,866	-1,76E-03	0	0
abe15	no TS	0,5782	0,6822	-1,53E-03	4,00E-06	0,183	0	0	-2,72E+02
	TS	0,6021	0,6811	-1,45E-03	2,78E-06	0,185	0	0	1,53E+02
abe25	no TS	0,5326	0,7005	-1,53E-03	5,43E-06	0	4,35E-04	0	-2,42E+02
	TS	0,5546	0,6995	-1,45E-03	4,27E-06	0	4,41E-04	0	1,75E+02
abe12	no TS	0,6580	0,6243	-1,59E-03	-3,02E-06	0,882	-1,82E-03	0	0
	TS	0,6818	0,6241	-1,48E-03	-3,83E-06	0,866	-1,76E-03	0	0
abe85	no TS	0,4376	0,7128	-1,53E-03	3,83E-06	0	0	3,31E-09	-1,24E+02
	TS	0,4529	0,7118	-1,46E-03	2,91E-06	0	0	3,38E-09	2,70E+02
abe25	no TS	0,5326	0,7005	-1,53E-03	5,43E-06	0	4,35E-04	0	-2,42E+02
	TS	0,5546	0,6995	-1,45E-03	4,27E-06	0	4,41E-04	0	1,75E+02
abe1	no TS	0,5767	0,6828	-1,55E-03	3,99E-06	0,181	0	0	0
	TS	0,6015	0,6808	-1,44E-03	2,83E-06	0,186	0	0	0
abe85	no TS	0,4376	0,7128	-1,53E-03	3,83E-06	0	0	3,31E-09	-1,24E+02
	TS	0,4529	0,7118	-1,46E-03	2,91E-06	0	0	3,38E-09	2,70E+02
abe2	no TS	0,5314	0,7009	-1,54E-03	5,40E-06	0	4,31E-04	0	0
	TS	0,5539	0,6992	-1,44E-03	4,34E-06	0	4,44E-04	0	0
abe1	no TS	0,5767	0,6828	-1,55E-03	3,99E-06	0,181	0	0	0
	TS	0,6015	0,6808	-1,44E-03	2,83E-06	0,186	0	0	0
abe8	no TS	0,4373	0,7129	-1,54E-03	3,82E-06	0	0	3,29E-09	0
	TS	0,4511	0,7115	-1,44E-03	3,01E-06	0	0	3,41E-09	0
abe2	no TS	0,5314	0,7009	-1,54E-03	5,40E-06	0	4,31E-04	0	0
	TS	0,5539	0,6992	-1,44E-03	4,34E-06	0	4,44E-04	0	0
ab125	no TS	0,6591	0,6247	-1,67E-03	0	0,880	-1,81E-03	0	-2,35E+02
	TS	0,6826	0,6254	-1,63E-03	0	0,865	-1,76E-03	0	1,91E+02
abe8	no TS	0,4373	0,7129	-1,54E-03	3,82E-06	0	0	3,29E-09	0
	TS	0,4511	0,7115	-1,44E-03	3,01E-06	0	0	3,41E-09	0
ab185	no TS	0,6751	0,6501	-1,50E-03	0	0,455	0	-7,08E-09	-2,85E+02
	TS	0,7016	0,6496	-1,47E-03	0	0,454	0	-7,01E-09	1,51E+02
ab125	no TS	0,6591	0,6247	-1,67E-03	0	0,880	-1,81E-03	0	-2,35E+02
	TS	0,6826	0,6254	-1,63E-03	0	0,865	-1,76E-03	0	1,91E+02
ab18	no TS	0,6734	0,6507	-1,52E-03	0	0,454	0	-7,08E-09	0
	TS	0,7010	0,6493	-1,46E-03	0	0,455	0	-7,01E-09	0
ab185	no TS	0,6751	0,6501	-1,50E-03	0	0,455	0	-7,08E-09	-2,85E+02
	TS	0,7016	0,6496	-1,47E-03	0	0,454	0	-7,01E-09	1,51E+02
ab12	no TS	0,6579	0,6251	-1,69E-03	0	0,881	-1,81E-03	0	0
	TS	0,6816	0,6251	-1,62E-03	0	0,864	-1,76E-03	0	0
ab18	no TS	0,6734	0,6507	-1,52E-03	0	0,454	0	-7,08E-09	0
	TS	0,7010	0,6493	-1,46E-03	0	0,455	0	-7,01E-09	0
ab15	no TS	0,5781	0,6814	-1,39E-03	0	0,183	0	0	-2,72E+02
	TS	0,6020	0,6805	-1,35E-03	0	0,185	0	0	1,54E+02

Table B.1: Results of MRL fit of various combinations of coefficients between no Timeshift and Timeshift, full URSSATrough dataset, screened

case	noTS/TS	R^2	η	b_1	b_2	a_1	a_2	a_8	a_5
ab12	no TS	0,6579	0,6251	-1,69E-03	0	0,881	-1,81E-03	0	0
	TS	0,6816	0,6251	-1,62E-03	0	0,864	-1,76E-03	0	0
ab18	no TS	0,6734	0,6507	-1,52E-03	0	0,454	0	-7,08E-09	0
	TS	0,7010	0,6493	-1,46E-03	0	0,455	0	-7,01E-09	0
ab15	no TS	0,5781	0,6814	-1,39E-03	0	0,183	0	0	-2,72E+02
	TS	0,6020	0,6805	-1,35E-03	0	0,185	0	0	1,54E+02
ab12	no TS	0,6579	0,6251	-1,69E-03	0	0,881	-1,81E-03	0	0
	TS	0,6816	0,6251	-1,62E-03	0	0,864	-1,76E-03	0	0
ab25	no TS	0,5324	0,6994	-1,33E-03	0	0	4,34E-04	0	-2,42E+02
	TS	0,5545	0,6986	-1,30E-03	0	0	4,41E-04	0	1,76E+02
ab15	no TS	0,5781	0,6814	-1,39E-03	0	0,183	0	0	-2,72E+02
	TS	0,6020	0,6805	-1,35E-03	0	0,185	0	0	1,54E+02
ab25	no TS	0,5324	0,6994	-1,33E-03	0	0	4,34E-04	0	-2,42E+02
	TS	0,5545	0,6986	-1,30E-03	0	0	4,41E-04	0	1,76E+02
ab85	no TS	0,4375	0,7120	-1,40E-03	0	0	0	3,31E-09	-1,23E+02
	TS	0,4529	0,7112	-1,36E-03	0	0	0	3,38E-09	2,71E+02
ab1	no TS	0,5765	0,6820	-1,40E-03	0	0,181	0	0	0
	TS	0,6014	0,6802	-1,34E-03	0	0,186	0	0	0
ab2	no TS	0,5312	0,6998	-1,35E-03	0	0	4,31E-04	0	0
	TS	0,5537	0,6983	-1,28E-03	0	0	4,44E-04	0	0
ab8	no TS	0,4372	0,7121	-1,41E-03	0	0	0	3,29E-09	0
	TS	0,4510	0,7108	-1,34E-03	0	0	0	3,41E-09	0
ae125	no TS	0,6437	0,6136	0	-4,45E-05	0,879	-1,80E-03	0	-2,67E+02
	TS	0,6679	0,6145	0	-4,33E-05	0,863	-1,76E-03	0	1,68E+02
ae185	no TS	0,6593	0,6400	0	-3,96E-05	0,454	0	-7,04E-09	-3,17E+02
	TS	0,6865	0,6398	0	-3,87E-05	0,453	0	-6,97E-09	1,26E+02
ae18	no TS	0,6572	0,6406	0	-4,02E-05	0,452	0	-7,03E-09	0
	TS	0,6861	0,6396	0	-3,84E-05	0,454	0	-6,97E-09	0
ae12	no TS	0,6422	0,6139	0	-4,50E-05	0,879	-1,81E-03	0	0
	TS	0,6671	0,6144	0	-4,30E-05	0,863	-1,76E-03	0	0
ae15	no TS	0,5636	0,6719	0	-3,64E-05	0,183	0	0	-3,03E+02
	TS	0,5881	0,6712	0	-3,55E-05	0,186	0	0	1,30E+02
ae25	no TS	0,5180	0,6902	0	-3,50E-05	0	4,36E-04	0	-2,73E+02
	TS	0,5407	0,6896	0	-3,39E-05	0	4,43E-04	0	1,52E+02
ae85	no TS	0,4229	0,7024	0	-3,67E-05	0	0	3,33E-09	-1,55E+02
	TS	0,4388	0,7019	0	-3,56E-05	0	0	3,40E-09	2,47E+02
ae1	no TS	0,5617	0,6724	0	-3,70E-05	0,182	0	0	0
	TS	0,5877	0,6710	0	-3,52E-05	0,186	0	0	0
ae2	no TS	0,5164	0,6905	0	-3,55E-05	0	4,32E-04	0	0
	TS	0,5401	0,6895	0	-3,36E-05	0	4,45E-04	0	0
ae8	no TS	0,4224	0,7026	0	-3,70E-05	0	0	3,31E-09	0
	TS	0,4372	0,7017	0	-3,51E-05	0	0	3,43E-09	0
a125	no TS	0,4036	0,6254	0	0	0,520	-8,25E-04	0	-7,58E+02
	TS	0,4260	0,6265	0	0	0,508	-7,93E-04	0	-2,89E+02
a185	no TS	0,4512	0,6263	0	0	0,425	0	-5,81E-09	-7,73E+02
	TS	0,4756	0,6266	0	0	0,423	0	-5,73E-09	-2,99E+02
a18	no TS	0,4384	0,6271	0	0	0,419	0	-5,75E-09	0
	TS	0,4732	0,6269	0	0	0,421	0	-5,71E-09	0
a12	no TS	0,3913	0,6266	0	0	0,509	-8,06E-04	0	0
	TS	0,4238	0,6269	0	0	0,504	-7,85E-04	0	0
a15	no TS	0,3850	0,6538	0	0	0,200	0	0	-7,31E+02
	TS	0,4080	0,6538	0	0	0,201	0	0	-2,67E+02
a25	no TS	0,3554	0,6734	0	0	0	4,92E-04	0	-6,94E+02
	TS	0,3776	0,6734	0	0	0	4,95E-04	0	-2,36E+02
a85	no TS	0,2431	0,6859	0	0	0	0	3,85E-09	-5,90E+02
	TS	0,2590	0,6859	0	0	0	0	3,89E-09	-1,55E+02
a1	no TS	0,3736	0,6543	0	0	0,197	0	0	0
	TS	0,4061	0,6539	0	0	0,200	0	0	0
a2	no TS	0,3451	0,6735	0	0	0	4,84E-04	0	0
	TS	0,3761	0,6734	0	0	0	4,93E-04	0	0
a8	no TS	0,2356	0,6858	0	0	0	0	3,79E-09	0
	TS	0,2584	0,6859	0	0	0	0	3,88E-09	0

Table B.2: Results of MRL fit of various combinations of coefficients between no Timeshift and Timeshift, full URSSATrough dataset, screened - cont

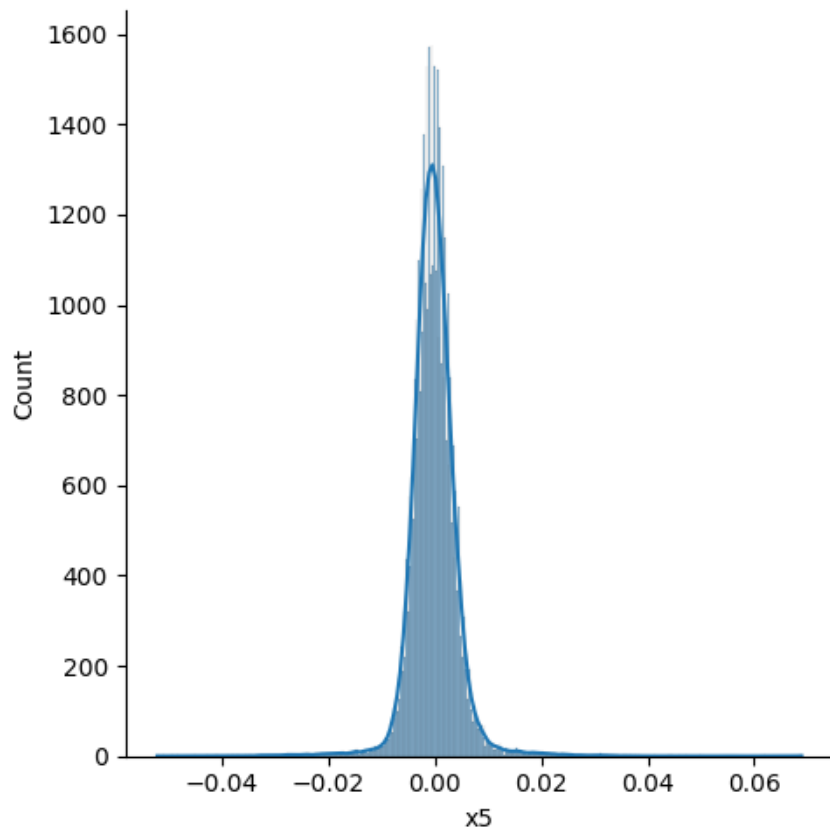


Figure B.2: Distribution of the derivative term of the mean temperature, published data

B.3 URSSATrough full dataset, points

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_3	std dev	a_4	std dev
abc125	0,6526	0,6235	1,09E-03	-0,0014	5,82E-05	-8,42E-06	1,72E-06	0,8824	0,0104	-1,82E-03	2,53E-05	/	/	-212,7933	50,9017
abc185	0,6697	0,6502	7,55E-04	-0,0014	5,85E-05	-2,90E-06	1,74E-06	0,4519	0,0040	/	/	-7,04E-09	8,03E-11	-260,3299	50,4792
abc18	0,6682	0,6508	7,48E-04	-0,0014	5,94E-05	-3,02E-06	1,77E-06	0,4503	0,0040	/	/	-7,04E-09	8,12E-11	/	/
abc15	0,5573	0,6830	6,28E-04	-0,0013	6,62E-05	-1,73E-06	1,97E-06	0,1770	0,0017	/	/	/	/	-252,4695	53,0920
abc12	0,6516	0,6239	1,09E-03	-0,0014	5,88E-05	-8,53E-06	1,74E-06	0,8826	0,0105	-1,83E-03	2,55E-05	/	/	/	/
abc25	0,5065	0,7015	5,39E-04	-0,0013	6,91E-05	-5,38E-07	2,06E-06	/	/	4,12E-04	4,42E-06	/	/	-218,9520	54,6451
abc85	0,4073	0,7148	5,20E-04	-0,0013	7,29E-05	-2,37E-06	2,17E-06	/	/	/	/	2,96E-09	4,14E-11	-100,0627	57,2515
abc1	0,5559	0,6835	6,23E-04	-0,0013	6,71E-05	-1,84E-06	2,00E-06	0,1756	0,0017	/	/	/	/	/	/
abc2	0,5054	0,7019	5,40E-04	-0,0013	6,99E-05	-6,49E-07	2,09E-06	/	/	4,09E-04	4,37E-06	/	/	/	/
abc8	0,4070	0,7149	5,24E-04	-0,0013	7,33E-05	-2,41E-06	2,18E-06	/	/	/	/	2,95E-09	4,14E-11	/	/
ab125	0,6519	0,6256	1,13E-03	-0,0017	1,44E-05	/	/	0,8788	0,0106	-1,81E-03	2,57E-05	/	/	-214,5126	50,7143
ab185	0,6697	0,6508	7,81E-04	-0,0015	1,41E-05	/	/	0,4518	0,0040	/	/	-7,04E-09	8,07E-11	-260,8499	50,3948
ab18	0,6681	0,6514	7,69E-04	-0,0015	1,33E-05	/	/	0,4502	0,0040	/	/	-7,04E-09	8,16E-11	/	/
ab12	0,6509	0,6259	1,13E-03	-0,0017	1,36E-05	/	/	0,8790	0,0107	-1,82E-03	2,59E-05	/	/	/	/
ab15	0,5573	0,6833	6,16E-04	-0,0014	1,61E-05	/	/	0,1771	0,0017	/	/	/	/	-252,7810	52,9933
ab25	0,5065	0,7016	5,01E-04	-0,0013	1,69E-05	/	/	/	/	4,12E-04	4,39E-06	/	/	-219,0608	54,5762
ab85	0,4072	0,7152	4,64E-04	-0,0014	1,80E-05	/	/	/	/	/	/	2,96E-09	4,12E-11	-100,4943	57,0874
ab1	0,5559	0,6838	6,05E-04	-0,0014	1,52E-05	/	/	0,1756	0,0017	/	/	/	/	/	/
ab2	0,5054	0,7020	4,93E-04	-0,0014	1,59E-05	/	/	/	/	4,09E-04	4,34E-06	/	/	/	/
ab8	0,4070	0,7154	4,60E-04	-0,0014	1,69E-05	/	/	/	/	/	/	2,95E-09	4,12E-11	/	/
ac125	0,6397	0,6147	1,15E-03	/	/	-4,51E-05	4,72E-07	0,8789	0,0105	-1,81E-03	2,54E-05	/	/	-237,6016	52,0026
ac185	0,6565	0,6411	7,96E-04	/	/	-4,02E-05	4,71E-07	0,4504	0,0041	/	/	-6,99E-09	7,97E-11	-285,2878	51,6030
ac18	0,6546	0,6416	7,88E-04	/	/	-4,08E-05	4,49E-07	0,4486	0,0041	/	/	-6,99E-09	8,07E-11	/	/
ac12	0,6384	0,6150	1,15E-03	/	/	-4,56E-05	4,47E-07	0,8791	0,0106	-1,82E-03	2,57E-05	/	/	/	/
ac15	0,5455	0,6741	6,18E-04	/	/	-3,70E-05	5,24E-07	0,1773	0,0018	/	/	/	/	-276,1037	54,5418
ac25	0,4948	0,6928	4,86E-04	/	/	-3,56E-05	5,46E-07	/	/	4,13E-04	4,57E-06	/	/	-242,6423	56,2067
ac85	0,3956	0,7060	4,42E-04	/	/	-3,73E-05	5,77E-07	/	/	/	/	2,97E-09	4,25E-11	-123,8979	58,9689
ac1	0,5438	0,6746	6,09E-04	/	/	-3,75E-05	5,00E-07	0,1757	0,0018	/	/	/	/	/	/
ac2	0,4934	0,6931	4,81E-04	/	/	-3,61E-05	5,18E-07	/	/	4,10E-04	4,51E-06	/	/	/	/
ac8	0,3953	0,7061	4,41E-04	/	/	-3,75E-05	5,42E-07	/	/	/	/	2,96E-09	4,24E-11	/	/
a125	0,3809	0,6249	1,36E-03	/	/	/	/	0,5492	0,0130	-9,19E-04	3,21E-05	/	/	-775,5603	56,8124
a185	0,4335	0,6279	9,28E-04	/	/	/	/	0,4222	0,0051	/	/	-5,87E-09	1,04E-10	-785,0414	56,6671
a18	0,4194	0,6288	9,24E-04	/	/	/	/	0,4160	0,0051	/	/	-5,82E-09	1,06E-10	/	/
a12	0,3671	0,6261	1,36E-03	/	/	/	/	0,5376	0,0131	-8,99E-04	3,22E-05	/	/	/	/
a15	0,3543	0,6569	6,77E-04	/	/	/	/	0,1919	0,0021	/	/	/	/	-743,2640	55,8037
a25	0,3194	0,6764	4,99E-04	/	/	/	/	/	/	4,64E-04	5,33E-06	/	/	-702,3178	55,8077
a85	0,2033	0,6900	4,52E-04	/	/	/	/	/	/	/	/	3,44E-09	5,03E-11	-598,5940	56,6806
a1	0,3416	0,6575	6,75E-04	/	/	/	/	0,1881	0,0021	/	/	/	/	/	/
a2	0,3081	0,6765	4,97E-04	/	/	/	/	/	/	4,55E-04	5,37E-06	/	/	/	/
a8	0,1950	0,6899	4,50E-04	/	/	/	/	/	/	/	/	3,38E-09	5,09E-11	/	/

Table B.3: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, No timeshift, point duration 10 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6768	0,6236	9,24E-04	-0,0013	4,98E-05	-8,74E-06	1,40E-06	0,8710	0,0083	-1,79E-03	1,96E-05	/	/	181,4939	33,9683
abc185	0,6971	0,6494	6,87E-04	-0,0013	4,92E-05	-3,50E-06	1,39E-06	0,4519	0,0034	/	/	-6,99E-09	6,45E-11	140,7963	33,3620
abc18	0,6965	0,6491	6,87E-04	-0,0013	4,92E-05	-3,39E-06	1,38E-06	0,4528	0,0034	/	/	-6,99E-09	6,42E-11	/	/
abc15	0,5800	0,6819	5,98E-04	-0,0013	5,58E-05	-2,26E-06	1,57E-06	0,1791	0,0017	/	/	/	/	153,9009	36,8722
abc12	0,6759	0,6233	9,21E-04	-0,0013	4,98E-05	-8,58E-06	1,39E-06	0,8710	0,0083	-1,79E-03	1,96E-05	/	/	/	/
abc25	0,5265	0,7006	5,06E-04	-0,0013	5,83E-05	-1,00E-06	1,65E-06	/	/	4,19E-04	4,30E-06	/	/	181,3489	38,8968
abc85	0,4193	0,7139	4,84E-04	-0,0012	6,22E-05	-2,66E-06	1,76E-06	/	/	/	/	3,02E-09	4,07E-11	280,3376	42,3501
abc1	0,5794	0,6816	6,00E-04	-0,0013	5,57E-05	-2,13E-06	1,57E-06	0,1800	0,0017	/	/	/	/	/	/
abc2	0,5255	0,7003	5,09E-04	-0,0012	5,82E-05	-8,46E-07	1,64E-06	/	/	4,21E-04	4,31E-06	/	/	/	/
abc8	0,4171	0,7135	4,88E-04	-0,0012	6,21E-05	-2,42E-06	1,75E-06	/	/	/	/	3,06E-09	4,10E-11	/	/
ab125	0,6761	0,6257	9,55E-04	-0,0016	1,27E-05	/	/	0,8673	0,0084	-1,78E-03	2,00E-05	/	/	178,8751	33,8833
ab185	0,6970	0,6501	7,08E-04	-0,0015	1,19E-05	/	/	0,4518	0,0034	/	/	-6,99E-09	6,50E-11	139,8094	33,3109
ab18	0,6964	0,6498	7,06E-04	-0,0014	1,16E-05	/	/	0,4527	0,0034	/	/	-6,99E-09	6,47E-11	/	/
ab12	0,6752	0,6254	9,53E-04	-0,0016	1,23E-05	/	/	0,8673	0,0084	-1,78E-03	2,00E-05	/	/	/	/
ab15	0,5800	0,6823	5,90E-04	-0,0013	1,35E-05	/	/	0,1792	0,0017	/	/	/	/	153,2618	36,8011
ab25	0,5264	0,7008	4,80E-04	-0,0013	1,43E-05	/	/	/	/	4,19E-04	4,28E-06	/	/	181,0470	38,8464
ab85	0,4192	0,7144	4,47E-04	-0,0013	1,57E-05	/	/	/	/	/	/	3,02E-09	4,04E-11	279,5781	42,2327
ab1	0,5793	0,6820	5,91E-04	-0,0013	1,31E-05	/	/	0,1800	0,0017	/	/	/	/	/	/
ab2	0,5255	0,7004	4,81E-04	-0,0013	1,38E-05	/	/	/	/	4,21E-04	4,29E-06	/	/	/	/
ab8	0,4170	0,7140	4,49E-04	-0,0013	1,52E-05	/	/	/	/	/	/	3,06E-09	4,08E-11	/	/
ac125	0,6642	0,6151	9,80E-04	/	/	-4,36E-05	3,97E-07	0,8676	0,0083	-1,78E-03	1,95E-05	/	/	163,3074	34,6438
ac185	0,6842	0,6407	7,31E-04	/	/	-3,89E-05	3,79E-07	0,4505	0,0035	/	/	-6,95E-09	6,32E-11	122,5802	34,0420
ac18	0,6838	0,6404	7,30E-04	/	/	-3,86E-05	3,66E-07	0,4513	0,0034	/	/	-6,95E-09	6,29E-11	/	/
ac12	0,6635	0,6149	9,78E-04	/	/	-4,32E-05	3,83E-07	0,8676	0,0083	-1,78E-03	1,95E-05	/	/	/	/
ac15	0,5685	0,6734	5,98E-04	/	/	-3,57E-05	4,18E-07	0,1795	0,0017	/	/	/	/	136,6155	37,8059
ac25	0,5151	0,6922	4,70E-04	/	/	-3,43E-05	4,39E-07	/	/	4,20E-04	4,46E-06	/	/	164,0137	39,9071
ac85	0,4080	0,7055	4,29E-04	/	/	-3,58E-05	4,75E-07	/	/	/	/	3,04E-09	4,18E-11	262,8835	43,4594
ac1	0,5680	0,6732	5,98E-04	/	/	-3,54E-05	4,04E-07	0,1802	0,0017	/	/	/	/	/	/
ac2	0,5143	0,6920	4,72E-04	/	/	-3,39E-05	4,23E-07	/	/	4,22E-04	4,46E-06	/	/	/	/
ac8	0,4060	0,7053	4,32E-04	/	/	-3,52E-05	4,57E-07	/	/	/	/	3,07E-09	4,21E-11	/	/
a125	0,4039	0,6255	1,22E-03	/	/	/	/	0,5435	0,0111	-9,03E-04	2,72E-05	/	/	-325,0774	40,8258
a185	0,4597	0,6281	8,84E-04	/	/	/	/	0,4217	0,0045	/	/	-5,84E-09	8,92E-11	-334,5885	40,1815
a18	0,4565	0,6285	8,82E-04	/	/	/	/	0,4189	0,0045	/	/	-5,81E-09	8,95E-11	/	/
a12	0,4009	0,6261	1,21E-03	/	/	/	/	0,5378	0,0111	-8,92E-04	2,71E-05	/	/	/	/
a15	0,3768	0,6569	6,69E-04	/	/	/	/	0,1928	0,0021	/	/	/	/	-290,6589	40,4405
a25	0,3403	0,6764	4,93E-04	/	/	/	/	/	/	4,66E-04	5,21E-06	/	/	-253,4076	40,9696
a85	0,2165	0,6901	4,44E-04	/	/	/	/	/	/	/	/	3,47E-09	4,93E-11	-168,6916	42,8668
a1	0,3744	0,6571	6,70E-04	/	/	/	/	0,1914	0,0021	/	/	/	/	/	/
a2	0,3384	0,6765	4,92E-04	/	/	/	/	/	/	4,64E-04	5,24E-06	/	/	/	/
a8	0,2157	0,6901	4,43E-04	/	/	/	/	/	/	/	/	3,45E-09	4,97E-11	/	/

Table B.4: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, timeshift, point duration 10 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_3	std dev	a_5	std dev
abc125	0.6536	0.6239	1.36E-03	-0.0014	7.53E-05	-6.77E-06	2.22E-06	0.8798	0.0132	-1.82E-03	3.20E-05	/	/	-90.8747	68.1609
abc185	0.6707	0.6505	9.49E-04	-0.0015	7.52E-05	-1.23E-06	2.25E-06	0.4513	0.0052	/	/	-7.02E-09	1.04E-10	-145.6864	67.5774
abc18	0.6702	0.6508	9.43E-04	-0.0015	7.59E-05	-1.24E-06	2.27E-06	0.4503	0.0052	/	/	-7.02E-09	1.05E-10	/	/
abc15	0.5606	0.6830	7.88E-04	-0.0014	8.50E-05	-1.09E-08	2.55E-06	0.1776	0.0022	/	/	/	/	-125.3799	71.2533
abc12	0.6535	0.6241	1.36E-03	-0.0014	7.56E-05	-6.78E-06	2.23E-06	0.8797	0.0133	-1.82E-03	3.21E-05	/	/	/	/
abc25	0.5104	0.7015	6.78E-04	-0.0014	8.88E-05	1.19E-06	2.67E-06	/	/	4.15E-04	5.62E-06	/	/	-88.0026	73.4967
abc85	0.4116	0.7146	6.59E-04	-0.0014	9.40E-05	-7.10E-07	2.82E-06	/	/	/	/	3.00E-09	5.26E-11	42.8843	77.3720
abc1	0.5602	0.6833	7.88E-04	-0.0014	8.58E-05	-2.06E-08	2.57E-06	0.1769	0.0022	/	/	/	/	/	/
abc2	0.5102	0.7017	6.83E-04	-0.0014	8.95E-05	1.17E-06	2.69E-06	/	/	4.13E-04	5.59E-06	/	/	/	/
abc8	0.4116	0.7146	6.66E-04	-0.0014	9.42E-05	-7.07E-07	2.82E-06	/	/	/	/	3.01E-09	5.28E-11	/	/
ab125	0.6532	0.6256	1.44E-03	-0.0017	1.84E-05	/	/	0.8769	0.0135	-1.81E-03	3.27E-05	/	/	-91.2483	67.9333
ab185	0.6706	0.6508	1.00E-03	-0.0015	1.82E-05	/	/	0.4513	0.0052	/	/	-7.02E-09	1.04E-10	-145.7251	67.5301
ab18	0.6702	0.6511	9.96E-04	-0.0015	1.74E-05	/	/	0.4503	0.0052	/	/	-7.02E-09	1.05E-10	/	/
ab12	0.6530	0.6257	1.44E-03	-0.0017	1.76E-05	/	/	0.8768	0.0135	-1.81E-03	3.28E-05	/	/	/	/
ab15	0.5606	0.6830	7.92E-04	-0.0014	2.09E-05	/	/	0.1776	0.0022	/	/	/	/	-125.3802	71.2419
ab25	0.5104	0.7013	6.43E-04	-0.0013	2.20E-05	/	/	/	/	4.15E-04	5.58E-06	/	/	-87.9352	73.5493
ab85	0.4116	0.7148	5.96E-04	-0.0014	2.36E-05	/	/	/	/	/	/	3.00E-09	5.22E-11	42.8596	77.3080
ab1	0.5602	0.6833	7.84E-04	-0.0014	1.99E-05	/	/	0.1769	0.0022	/	/	/	/	/	/
ab2	0.5102	0.7014	6.38E-04	-0.0013	2.09E-05	/	/	/	/	4.13E-04	5.55E-06	/	/	/	/
ab8	0.4116	0.7147	5.93E-04	-0.0014	2.22E-05	/	/	/	/	/	/	3.01E-09	5.25E-11	/	/
ac125	0.6398	0.6147	1.47E-03	/	/	-4.51E-05	6.07E-07	0.8765	0.0134	-1.81E-03	3.21E-05	/	/	-123.7724	69.8206
ac185	0.6564	0.6410	1.03E-03	/	/	-4.02E-05	6.07E-07	0.4498	0.0052	/	/	-6.98E-09	1.03E-10	-178.7965	69.2901
ac18	0.6557	0.6413	1.02E-03	/	/	-4.05E-05	5.84E-07	0.4486	0.0052	/	/	-6.97E-09	1.04E-10	/	/
ac12	0.6395	0.6148	1.47E-03	/	/	-4.53E-05	5.79E-07	0.8764	0.0134	-1.81E-03	3.23E-05	/	/	/	/
ac15	0.5477	0.6738	7.93E-04	/	/	-3.70E-05	6.85E-07	0.1779	0.0023	/	/	/	/	-156.9651	73.4212
ac25	0.4976	0.6924	6.23E-04	/	/	-3.57E-05	7.16E-07	/	/	4.16E-04	5.82E-06	/	/	-119.6290	75.8034
ac85	0.3989	0.7055	5.66E-04	/	/	-3.74E-05	7.59E-07	/	/	/	/	3.01E-09	5.41E-11	11.1399	79.8542
ac1	0.5472	0.6740	7.85E-04	/	/	-3.73E-05	6.55E-07	0.1770	0.0023	/	/	/	/	/	/
ac2	0.4973	0.6925	6.19E-04	/	/	-3.59E-05	6.81E-07	/	/	4.14E-04	5.77E-06	/	/	/	/
ac8	0.3989	0.7055	5.65E-04	/	/	-3.74E-05	7.14E-07	/	/	/	/	3.01E-09	5.41E-11	/	/
a125	0.3839	0.6247	1.73E-03	/	/	/	/	0.5469	0.0166	-9.10E-04	4.09E-05	/	/	-676.1349	75.1109
a185	0.4361	0.6275	1.18E-03	/	/	/	/	0.4229	0.0065	/	/	-5.87E-09	1.33E-10	-692.9223	75.0163
a18	0.4260	0.6283	1.17E-03	/	/	/	/	0.4172	0.0065	/	/	-5.81E-09	1.35E-10	/	/
a12	0.3743	0.6258	1.73E-03	/	/	/	/	0.5364	0.0166	-8.92E-04	4.09E-05	/	/	/	/
a15	0.3583	0.6564	8.55E-04	/	/	/	/	0.1932	0.0027	/	/	/	/	-639.9396	74.1104
a25	0.3239	0.6759	6.29E-04	/	/	/	/	/	/	4.68E-04	6.75E-06	/	/	-595.1773	74.3611
a85	0.2075	0.6893	5.70E-04	/	/	/	/	/	/	/	/	3.49E-09	6.39E-11	-479.6837	75.8748
a1	0.3496	0.6568	8.54E-04	/	/	/	/	0.1900	0.0027	/	/	/	/	/	/
a2	0.3164	0.6760	6.26E-04	/	/	/	/	/	/	4.60E-04	6.81E-06	/	/	/	/
a8	0.2027	0.6893	5.67E-04	/	/	/	/	/	/	/	/	3.45E-09	6.47E-11	/	/

Table B.5: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, No timeshift, point duration 20 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6637	0,6243	1,24E-03	-0,0014	6,66E-05	-7,27E-06	1,89E-06	0,8677	0,0114	-1,78E-03	2,71E-05	/	/	329,6784	52,5469
abc185	0,6836	0,6500	8,98E-04	-0,0014	6,58E-05	-1,98E-06	1,88E-06	0,4501	0,0046	/	/	-6,99E-09	8,87E-11	284,7886	51,7690
abc18	0,6816	0,6494	8,98E-04	-0,0014	6,60E-05	-1,78E-06	1,86E-06	0,4517	0,0046	/	/	-6,99E-09	8,86E-11	/	/
abc15	0,5705	0,6823	7,69E-04	-0,0013	7,46E-05	-2,21E-07	2,13E-06	0,1782	0,0022	/	/	/	/	288,3195	55,5431
abc12	0,6609	0,6238	1,24E-03	-0,0014	6,68E-05	-7,01E-06	1,87E-06	0,8669	0,0114	-1,78E-03	2,73E-05	/	/	/	/
abc25	0,5190	0,7008	6,52E-04	-0,0013	7,81E-05	1,18E-06	2,24E-06	/	/	4,17E-04	5,57E-06	/	/	314,6034	57,7862
abc85	0,4151	0,7139	6,27E-04	-0,0013	8,34E-05	-3,46E-07	2,39E-06	/	/	/	/	3,03E-09	5,25E-11	418,4574	61,7788
abc1	0,5684	0,6817	7,77E-04	-0,0013	7,45E-05	-1,55E-08	2,11E-06	0,1797	0,0022	/	/	/	/	/	/
abc2	0,5164	0,7003	6,63E-04	-0,0013	7,80E-05	1,42E-06	2,21E-06	/	/	4,22E-04	5,55E-06	/	/	/	/
abc8	0,4107	0,7134	6,38E-04	-0,0013	8,33E-05	-3,90E-08	2,37E-06	/	/	/	/	3,08E-09	5,29E-11	/	/
ab125	0,6632	0,6261	1,28E-03	-0,0016	1,64E-05	/	/	0,8642	0,0116	-1,77E-03	2,77E-05	/	/	327,5326	52,4129
ab185	0,6836	0,6504	9,25E-04	-0,0015	1,55E-05	/	/	0,4500	0,0046	/	/	-6,99E-09	8,93E-11	284,2604	51,6912
ab18	0,6815	0,6498	9,20E-04	-0,0014	1,52E-05	/	/	0,4517	0,0046	/	/	-6,99E-09	8,92E-11	/	/
ab12	0,6605	0,6256	1,28E-03	-0,0016	1,62E-05	/	/	0,8636	0,0117	-1,77E-03	2,79E-05	/	/	/	/
ab15	0,5705	0,6823	7,59E-04	-0,0013	1,78E-05	/	/	0,1782	0,0022	/	/	/	/	288,2605	55,4832
ab25	0,5189	0,7006	6,16E-04	-0,0013	1,89E-05	/	/	/	/	4,17E-04	5,54E-06	/	/	314,9434	57,7834
ab85	0,4151	0,7140	5,75E-04	-0,0013	2,08E-05	/	/	/	/	/	/	3,03E-09	5,22E-11	418,3626	61,6851
ab1	0,5684	0,6817	7,60E-04	-0,0013	1,73E-05	/	/	0,1797	0,0021	/	/	/	/	/	/
ab2	0,5164	0,7000	6,19E-04	-0,0013	1,82E-05	/	/	/	/	4,22E-04	5,53E-06	/	/	/	/
ab8	0,4107	0,7134	5,79E-04	-0,0013	1,99E-05	/	/	/	/	/	/	3,08E-09	5,26E-11	/	/
ac125	0,6503	0,6153	1,31E-03	/	/	-4,35E-05	5,22E-07	0,8654	0,0114	-1,78E-03	2,70E-05	/	/	308,0565	53,5468
ac185	0,6698	0,6408	9,53E-04	/	/	-3,88E-05	5,02E-07	0,4491	0,0047	/	/	-6,95E-09	8,70E-11	263,0267	52,8131
ac18	0,6681	0,6404	9,50E-04	/	/	-3,82E-05	4,84E-07	0,4506	0,0046	/	/	-6,95E-09	8,68E-11	/	/
ac12	0,6479	0,6150	1,31E-03	/	/	-4,28E-05	5,06E-07	0,8647	0,0114	-1,77E-03	2,71E-05	/	/	/	/
ac15	0,5578	0,6733	7,69E-04	/	/	-3,55E-05	5,65E-07	0,1786	0,0022	/	/	/	/	267,4493	57,1847
ac25	0,5063	0,6919	6,04E-04	/	/	-3,41E-05	5,96E-07	/	/	4,19E-04	5,78E-06	/	/	293,6385	59,6202
ac85	0,4024	0,7050	5,52E-04	/	/	-3,56E-05	6,46E-07	/	/	/	/	3,05E-09	5,40E-11	397,3241	63,8301
ac1	0,5560	0,6729	7,69E-04	/	/	-3,49E-05	5,40E-07	0,1800	0,0022	/	/	/	/	/	/
ac2	0,5041	0,6915	6,06E-04	/	/	-3,34E-05	5,67E-07	/	/	4,23E-04	5,75E-06	/	/	/	/
ac8	0,3984	0,7046	5,56E-04	/	/	-3,48E-05	6,12E-07	/	/	/	/	3,09E-09	5,43E-11	/	/
a125	0,3966	0,6261	1,60E-03	/	/	/	/	0,5339	0,0149	-8,79E-04	3,67E-05	/	/	-215,5845	60,3765
a185	0,4506	0,6283	1,14E-03	/	/	/	/	0,4192	0,0060	/	/	-5,80E-09	1,20E-10	-223,8066	60,0484
a18	0,4493	0,6286	1,13E-03	/	/	/	/	0,4174	0,0060	/	/	-5,78E-09	1,20E-10	/	/
a12	0,3954	0,6265	1,59E-03	/	/	/	/	0,5305	0,0148	-8,73E-04	3,64E-05	/	/	/	/
a15	0,3716	0,6567	8,49E-04	/	/	/	/	0,1924	0,0027	/	/	/	/	-185,1371	59,0906
a25	0,3368	0,6761	6,23E-04	/	/	/	/	/	/	4,67E-04	6,68E-06	/	/	-148,6828	59,2649
a85	0,2165	0,6895	5,63E-04	/	/	/	/	/	/	/	/	3,49E-09	6,32E-11	-60,5964	61,0072
a1	0,3707	0,6568	8,50E-04	/	/	/	/	0,1916	0,0027	/	/	/	/	/	/
a2	0,3362	0,6761	6,23E-04	/	/	/	/	/	/	4,65E-04	6,71E-06	/	/	/	/
a8	0,2164	0,6895	5,62E-04	/	/	/	/	/	/	/	/	3,49E-09	6,37E-11	/	/

Table B.6: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, timeshift, point duration 20 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6338	0,6243	1,75E-03	-0,0015	8,94E-05	-5,36E-06	2,63E-06	0,8815	0,0171	-1,82E-03	4,16E-05	/	/	98,1564	104,2796
abc185	0,6501	0,6510	1,17E-03	-0,0015	8,86E-05	6,67E-08	2,62E-06	0,4507	0,0064	/	/	-7,05E-09	1,32E-10	38,1508	103,8125
abc18	0,6501	0,6510	1,18E-03	-0,0015	8,78E-05	8,80E-08	2,62E-06	0,4510	0,0065	/	/	-7,05E-09	1,32E-10	/	/
abc15	0,5435	0,6835	9,35E-04	-0,0014	9,86E-05	7,12E-07	2,92E-06	0,1761	0,0026	/	/	/	/	60,7277	109,5284
abc12	0,6336	0,6242	1,76E-03	-0,0015	8,85E-05	-5,30E-06	2,63E-06	0,8815	0,0171	-1,82E-03	4,14E-05	/	/	/	/
abc25	0,4955	0,7019	7,92E-04	-0,0014	1,02E-04	1,65E-06	3,04E-06	/	/	4,11E-04	6,74E-06	/	/	100,7315	112,3262
abc85	0,4013	0,7148	7,60E-04	-0,0014	1,08E-04	-5,23E-07	3,20E-06	/	/	/	/	2,98E-09	6,28E-11	240,7710	116,5073
abc1	0,5435	0,6834	9,33E-04	-0,0014	9,77E-05	7,46E-07	2,92E-06	0,1765	0,0027	/	/	/	/	/	/
abc2	0,4953	0,7017	7,90E-04	-0,0014	1,01E-04	1,71E-06	3,03E-06	/	/	4,13E-04	6,78E-06	/	/	/	/
abc8	0,4002	0,7145	7,60E-04	-0,0014	1,07E-04	-3,91E-07	3,18E-06	/	/	/	/	3,01E-09	6,34E-11	/	/
ab125	0,6336	0,6256	1,81E-03	-0,0017	2,20E-05	/	/	0,8795	0,0173	-1,82E-03	4,21E-05	/	/	96,7168	104,1775
ab185	0,6501	0,6510	1,22E-03	-0,0015	2,17E-05	/	/	0,4507	0,0064	/	/	-7,05E-09	1,32E-10	38,1673	103,8813
ab18	0,6501	0,6509	1,25E-03	-0,0015	2,13E-05	/	/	0,4510	0,0065	/	/	-7,05E-09	1,32E-10	/	/
ab12	0,6334	0,6254	1,84E-03	-0,0017	2,13E-05	/	/	0,8795	0,0173	-1,82E-03	4,19E-05	/	/	/	/
ab15	0,5435	0,6834	9,41E-04	-0,0014	2,49E-05	/	/	0,1761	0,0026	/	/	/	/	60,9042	109,6251
ab25	0,4955	0,7015	7,60E-04	-0,0014	2,62E-05	/	/	/	/	4,11E-04	6,68E-06	/	/	101,1784	112,4708
ab85	0,4013	0,7149	7,01E-04	-0,0014	2,80E-05	/	/	/	/	/	/	2,98E-09	6,23E-11	240,6439	116,5124
ab1	0,5434	0,6833	9,55E-04	-0,0014	2,44E-05	/	/	0,1765	0,0026	/	/	/	/	/	/
ab2	0,4953	0,7013	7,71E-04	-0,0013	2,55E-05	/	/	/	/	4,13E-04	6,73E-06	/	/	/	/
ab8	0,4001	0,7145	7,09E-04	-0,0014	2,69E-05	/	/	/	/	/	/	3,01E-09	6,29E-11	/	/
ac125	0,6194	0,6148	1,83E-03	/	/	-4,54E-05	7,12E-07	0,8762	0,0171	-1,81E-03	4,15E-05	/	/	68,7939	105,6339
ac185	0,6353	0,6413	1,24E-03	/	/	-4,05E-05	7,05E-07	0,4486	0,0065	/	/	-6,99E-09	1,31E-10	8,9121	105,0816
ac18	0,6353	0,6412	1,26E-03	/	/	-4,05E-05	6,95E-07	0,4487	0,0066	/	/	-6,99E-09	1,31E-10	/	/
ac12	0,6193	0,6148	1,85E-03	/	/	-4,53E-05	6,94E-07	0,8763	0,0171	-1,81E-03	4,13E-05	/	/	/	/
ac15	0,5304	0,6741	9,37E-04	/	/	-3,74E-05	7,89E-07	0,1763	0,0027	/	/	/	/	33,0521	110,9739
ac25	0,4827	0,6925	7,32E-04	/	/	-3,62E-05	8,23E-07	/	/	4,12E-04	6,98E-06	/	/	73,0209	113,8566
ac85	0,3886	0,7055	6,63E-04	/	/	-3,80E-05	8,72E-07	/	/	/	/	2,99E-09	6,45E-11	212,9264	118,2208
ac1	0,5304	0,6740	9,47E-04	/	/	-3,74E-05	7,73E-07	0,1765	0,0027	/	/	/	/	/	/
ac2	0,4826	0,6924	7,41E-04	/	/	-3,60E-05	8,01E-07	/	/	4,13E-04	7,00E-06	/	/	/	/
ac8	0,3878	0,7053	6,71E-04	/	/	-3,75E-05	8,39E-07	/	/	/	/	3,02E-09	6,50E-11	/	/
a125	0,3708	0,6241	2,13E-03	/	/	/	/	0,5515	0,0208	-9,24E-04	5,15E-05	/	/	-551,8424	111,7357
a185	0,4214	0,6273	1,41E-03	/	/	/	/	0,4242	0,0079	/	/	-5,92E-09	1,64E-10	-569,0826	111,2700
a18	0,4151	0,6279	1,41E-03	/	/	/	/	0,4193	0,0080	/	/	-5,87E-09	1,66E-10	/	/
a12	0,3648	0,6251	2,14E-03	/	/	/	/	0,5425	0,0209	-9,08E-04	5,16E-05	/	/	/	/
a15	0,3454	0,6563	1,01E-03	/	/	/	/	0,1927	0,0032	/	/	/	/	-511,1016	112,2420
a25	0,3122	0,6757	7,39E-04	/	/	/	/	/	/	4,66E-04	8,02E-06	/	/	-462,8753	113,2014
a85	0,2001	0,6890	6,72E-04	/	/	/	/	/	/	/	/	3,49E-09	7,58E-11	-341,0814	114,9954
a1	0,3403	0,6566	1,01E-03	/	/	/	/	0,1900	0,0032	/	/	/	/	/	/
a2	0,3080	0,6758	7,39E-04	/	/	/	/	/	/	4,61E-04	8,12E-06	/	/	/	/
a8	0,1978	0,6890	6,69E-04	/	/	/	/	/	/	/	/	3,46E-09	7,69E-11	/	/

Table B.7: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, No treshift, point duration 30 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6564	0,6250	1,55E-03	-0,0014	8,05E-05	-7,19E-06	2,28E-06	0,8613	0,0145	-1,77E-03	3,48E-05	/	/	448,6976	72,1124
abc185	0,6755	0,6506	1,10E-03	-0,0014	7,99E-05	-1,88E-06	2,27E-06	0,4469	0,0057	/	/	-6,93E-09	1,14E-10	398,6442	71,2860
abc18	0,6718	0,6497	1,09E-03	-0,0014	7,94E-05	-1,54E-06	2,24E-06	0,4495	0,0057	/	/	-6,94E-09	1,13E-10	/	/
abc15	0,5667	0,6826	9,18E-04	-0,0013	8,87E-05	-2,01E-07	2,52E-06	0,1773	0,0026	/	/	/	/	417,3750	73,1607
abc12	0,6517	0,6243	1,54E-03	-0,0014	8,00E-05	-6,78E-06	2,25E-06	0,8614	0,0145	-1,76E-03	3,50E-05	/	/	/	/
abc25	0,5168	0,7009	7,76E-04	-0,0013	9,23E-05	1,13E-06	2,63E-06	/	/	4,16E-04	6,58E-06	/	/	449,1925	74,9057
abc85	0,4162	0,7139	7,40E-04	-0,0013	9,78E-05	-5,88E-07	2,78E-06	/	/	/	/	3,03E-09	6,20E-11	565,8047	78,4536
abc1	0,5626	0,6817	9,22E-04	-0,0013	8,82E-05	1,61E-07	2,49E-06	0,1797	0,0025	/	/	/	/	/	/
abc2	0,5121	0,7002	7,84E-04	-0,0013	9,19E-05	1,54E-06	2,60E-06	/	/	4,22E-04	6,56E-06	/	/	/	/
abc8	0,4087	0,7132	7,51E-04	-0,0013	9,75E-05	-8,99E-08	2,75E-06	/	/	/	/	3,10E-09	6,25E-11	/	/
ab125	0,6560	0,6268	1,59E-03	-0,0016	1,97E-05	/	/	0,8579	0,0147	-1,76E-03	3,54E-05	/	/	446,0812	72,1036
ab185	0,6755	0,6510	1,12E-03	-0,0015	1,89E-05	/	/	0,4468	0,0058	/	/	-6,93E-09	1,14E-10	398,0041	71,2701
ab18	0,6718	0,6500	1,11E-03	-0,0014	1,82E-05	/	/	0,4495	0,0057	/	/	-6,94E-09	1,14E-10	/	/
ab12	0,6513	0,6260	1,57E-03	-0,0016	1,93E-05	/	/	0,8581	0,0147	-1,75E-03	3,56E-05	/	/	/	/
ab15	0,5667	0,6826	8,96E-04	-0,0014	2,14E-05	/	/	0,1773	0,0026	/	/	/	/	417,3061	73,1224
ab25	0,5168	0,7007	7,25E-04	-0,0013	2,26E-05	/	/	/	/	4,16E-04	6,54E-06	/	/	449,6052	74,8948
ab85	0,4162	0,7140	6,75E-04	-0,0014	2,45E-05	/	/	/	/	/	/	3,03E-09	6,16E-11	565,6000	78,3697
ab1	0,5626	0,6817	8,96E-04	-0,0013	2,05E-05	/	/	0,1797	0,0025	/	/	/	/	/	/
ab2	0,5121	0,6999	7,28E-04	-0,0013	2,16E-05	/	/	/	/	4,22E-04	6,53E-06	/	/	/	/
ab8	0,4087	0,7132	6,82E-04	-0,0013	2,34E-05	/	/	/	/	/	/	3,10E-09	6,22E-11	/	/
ac125	0,6431	0,6160	1,61E-03	/	/	-4,39E-05	6,23E-07	0,8590	0,0144	-1,76E-03	3,44E-05	/	/	427,9087	72,6282
ac185	0,6617	0,6413	1,14E-03	/	/	-3,92E-05	6,05E-07	0,4458	0,0058	/	/	-6,90E-09	1,11E-10	377,7523	71,8139
ac18	0,6584	0,6406	1,14E-03	/	/	-3,84E-05	5,77E-07	0,4484	0,0057	/	/	-6,91E-09	1,11E-10	/	/
ac12	0,6388	0,6154	1,60E-03	/	/	-4,30E-05	6,00E-07	0,8591	0,0144	-1,76E-03	3,47E-05	/	/	/	/
ac15	0,5540	0,6735	9,01E-04	/	/	-3,60E-05	6,70E-07	0,1777	0,0027	/	/	/	/	397,2397	74,3081
ac25	0,5042	0,6919	7,06E-04	/	/	-3,46E-05	7,02E-07	/	/	4,17E-04	6,81E-06	/	/	428,9802	76,2363
ac85	0,4036	0,7049	6,45E-04	/	/	-3,63E-05	7,52E-07	/	/	/	/	3,04E-09	6,37E-11	545,4599	80,0056
ac1	0,5503	0,6728	9,03E-04	/	/	-3,52E-05	6,33E-07	0,1799	0,0026	/	/	/	/	/	/
ac2	0,4999	0,6914	7,12E-04	/	/	-3,36E-05	6,63E-07	/	/	4,23E-04	6,78E-06	/	/	/	/
ac8	0,3966	0,7044	6,53E-04	/	/	-3,51E-05	7,12E-07	/	/	/	/	3,11E-09	6,42E-11	/	/
a125	0,3911	0,6264	1,96E-03	/	/	/	/	0,5283	0,0185	-8,65E-04	4,55E-05	/	/	-125,9862	80,2245
a185	0,4437	0,6283	1,36E-03	/	/	/	/	0,4176	0,0074	/	/	-5,76E-09	1,49E-10	-140,8948	80,1821
a18	0,4432	0,6285	1,36E-03	/	/	/	/	0,4163	0,0073	/	/	-5,75E-09	1,48E-10	/	/
a12	0,3907	0,6267	1,94E-03	/	/	/	/	0,5261	0,0183	-8,61E-04	4,51E-05	/	/	/	/
a15	0,3675	0,6565	9,99E-04	/	/	/	/	0,1925	0,0031	/	/	/	/	-88,6632	78,3023
a25	0,3339	0,6758	7,32E-04	/	/	/	/	/	/	4,67E-04	7,90E-06	/	/	-46,5607	78,1004
a85	0,2162	0,6891	6,62E-04	/	/	/	/	/	/	/	/	3,51E-09	7,47E-11	53,5502	79,6018
a1	0,3673	0,6566	1,00E-03	/	/	/	/	0,1920	0,0031	/	/	/	/	/	/
a2	0,3338	0,6758	7,33E-04	/	/	/	/	/	/	4,67E-04	7,92E-06	/	/	/	/
a8	0,2161	0,6891	6,62E-04	/	/	/	/	/	/	/	/	3,52E-09	7,53E-11	/	/

Table B.8: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, timeshift, point duration 30 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6197	0,6270	2,35E-03	-0,0016	1,21E-04	-3,77E-06	3,77E-06	0,8582	0,0225	-1,77E-03	5,50E-05	/	/	198,4436	122,0578
abc185	0,6366	0,6526	1,50E-03	-0,0016	1,19E-04	1,53E-06	3,68E-06	0,4424	0,0082	/	/	-6,89E-09	1,68E-10	140,2174	119,9260
abc18	0,6362	0,6523	1,46E-03	-0,0016	1,19E-04	1,50E-06	3,64E-06	0,4431	0,0081	/	/	-6,88E-09	1,69E-10	/	/
abc15	0,5319	0,6845	1,14E-03	-0,0015	1,29E-04	2,64E-06	3,98E-06	0,1739	0,0031	/	/	/	/	126,8714	121,0386
abc12	0,6190	0,6267	2,33E-03	-0,0015	1,21E-04	-3,79E-06	3,70E-06	0,8571	0,0225	-1,76E-03	5,52E-05	/	/	/	/
abc25	0,4844	0,7027	9,68E-04	-0,0015	1,34E-04	3,69E-06	4,11E-06	/	/	4,05E-04	7,96E-06	/	/	152,7353	122,5584
abc85	0,3915	0,7157	9,31E-04	-0,0015	1,40E-04	1,64E-06	4,29E-06	/	/	/	/	2,90E-09	7,34E-11	269,6635	126,4229
abc1	0,5316	0,6842	1,13E-03	-0,0015	1,30E-04	2,61E-06	3,94E-06	0,1745	0,0030	/	/	/	/	/	/
abc2	0,4840	0,7025	9,72E-04	-0,0015	1,34E-04	3,66E-06	4,06E-06	/	/	4,07E-04	7,71E-06	/	/	/	/
abc8	0,3901	0,7154	9,45E-04	-0,0014	1,39E-04	1,58E-06	4,21E-06	/	/	/	/	2,93E-09	7,26E-11	/	/
ab125	0,6196	0,6279	2,30E-03	-0,0017	3,01E-05	/	/	0,8567	0,0225	-1,77E-03	5,47E-05	/	/	198,6671	121,7349
ab185	0,6365	0,6523	1,52E-03	-0,0015	2,90E-05	/	/	0,4424	0,0082	/	/	-6,89E-09	1,69E-10	140,0583	120,1395
ab18	0,6362	0,6520	1,46E-03	-0,0015	2,58E-05	/	/	0,4431	0,0081	/	/	-6,88E-09	1,69E-10	/	/
ab12	0,6188	0,6276	2,27E-03	-0,0017	2,68E-05	/	/	0,8556	0,0225	-1,76E-03	5,51E-05	/	/	/	/
ab15	0,5319	0,6840	1,14E-03	-0,0014	3,23E-05	/	/	0,1738	0,0031	/	/	/	/	126,5939	121,4046
ab25	0,4843	0,7020	9,19E-04	-0,0014	3,37E-05	/	/	/	/	4,05E-04	7,89E-06	/	/	152,4347	123,0366
ab85	0,3915	0,7154	8,41E-04	-0,0014	3,55E-05	/	/	/	/	/	/	2,90E-09	7,28E-11	269,4942	126,7217
ab1	0,5316	0,6837	1,09E-03	-0,0014	2,89E-05	/	/	0,1745	0,0030	/	/	/	/	/	/
ab2	0,4839	0,7017	8,82E-04	-0,0013	3,00E-05	/	/	/	/	4,07E-04	7,65E-06	/	/	/	/
ab8	0,3901	0,7151	8,17E-04	-0,0014	3,16E-05	/	/	/	/	/	/	2,93E-09	7,21E-11	/	/
ac125	0,6038	0,6170	2,39E-03	/	/	-4,51E-05	1,07E-06	0,8536	0,0233	-1,76E-03	5,69E-05	/	/	156,3182	126,9313
ac185	0,6202	0,6424	1,54E-03	/	/	-4,03E-05	1,02E-06	0,4405	0,0084	/	/	-6,83E-09	1,70E-10	97,9501	124,4202
ac18	0,6200	0,6422	1,49E-03	/	/	-4,01E-05	9,15E-07	0,4409	0,0082	/	/	-6,83E-09	1,70E-10	/	/
ac12	0,6033	0,6170	2,37E-03	/	/	-4,48E-05	9,53E-07	0,8528	0,0233	-1,75E-03	5,70E-05	/	/	/	/
ac15	0,5172	0,6746	1,12E-03	/	/	-3,71E-05	1,10E-06	0,1740	0,0033	/	/	/	/	86,8260	125,6557
ac25	0,4699	0,6929	8,82E-04	/	/	-3,58E-05	1,13E-06	/	/	4,06E-04	8,24E-06	/	/	112,7486	127,1954
ac85	0,3773	0,7059	7,94E-04	/	/	-3,75E-05	1,18E-06	/	/	/	/	2,91E-09	7,55E-11	229,6562	131,2698
ac1	0,5170	0,6744	1,09E-03	/	/	-3,70E-05	9,89E-07	0,1745	0,0031	/	/	/	/	/	/
ac2	0,4697	0,6927	8,58E-04	/	/	-3,56E-05	1,02E-06	/	/	4,07E-04	7,96E-06	/	/	/	/
ac8	0,3763	0,7058	7,82E-04	/	/	-3,70E-05	1,05E-06	/	/	/	/	2,94E-09	7,44E-11	/	/
a125	0,3544	0,6269	2,58E-03	/	/	/	/	0,5260	0,0255	-8,66E-04	6,27E-05	/	/	-409,5301	123,9937
a185	0,4038	0,6290	1,69E-03	/	/	/	/	0,4125	0,0098	/	/	-5,69E-09	2,04E-10	-418,4450	125,2628
a18	0,4003	0,6294	1,66E-03	/	/	/	/	0,4100	0,0096	/	/	-5,68E-09	2,03E-10	/	/
a12	0,3511	0,6273	2,55E-03	/	/	/	/	0,5222	0,0251	-8,61E-04	6,21E-05	/	/	/	/
a15	0,3313	0,6571	1,17E-03	/	/	/	/	0,1894	0,0037	/	/	/	/	-393,2205	120,3930
a25	0,2992	0,6763	8,62E-04	/	/	/	/	/	/	4,58E-04	9,34E-06	/	/	-360,6788	119,0851
a85	0,1898	0,6897	7,85E-04	/	/	/	/	/	/	/	/	3,40E-09	8,78E-11	-259,9090	118,8228
a1	0,3283	0,6574	1,17E-03	/	/	/	/	0,1876	0,0037	/	/	/	/	/	/
a2	0,2966	0,6764	8,60E-04	/	/	/	/	/	/	4,54E-04	9,32E-06	/	/	/	/
a8	0,1884	0,6897	7,81E-04	/	/	/	/	/	/	/	/	3,37E-09	8,83E-11	/	/

Table B.9: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, No timeshift, point duration 40 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6604	0,6260	1,73E-03	-0,0014	9,43E-05	-7,74E-06	2,75E-06	0,8513	0,0158	-1,75E-03	3,77E-05	/	/	433,6563	69,8097
abc185	0,6799	0,6511	1,24E-03	-0,0014	9,35E-05	-2,45E-06	2,74E-06	0,4430	0,0063	/	/	-6,86E-09	1,22E-10	386,5998	68,8573
abc18	0,6762	0,6502	1,25E-03	-0,0014	9,20E-05	-2,10E-06	2,65E-06	0,4457	0,0063	/	/	-6,87E-09	1,22E-10	/	/
abc15	0,5690	0,6830	1,05E-03	-0,0013	1,03E-04	-6,89E-07	2,98E-06	0,1758	0,0029	/	/	/	/	409,7920	71,6238
abc12	0,6558	0,6253	1,74E-03	-0,0013	9,25E-05	-7,33E-06	2,65E-06	0,8519	0,0159	-1,74E-03	3,78E-05	/	/	/	/
abc25	0,5181	0,7014	8,85E-04	-0,0013	1,07E-04	6,39E-07	3,09E-06	/	/	4,11E-04	7,52E-06	/	/	442,9301	74,3477
abc85	0,4166	0,7145	8,43E-04	-0,0013	1,12E-04	-1,10E-06	3,25E-06	/	/	/	/	2,96E-09	7,09E-11	557,5145	79,6727
abc1	0,5648	0,6821	1,06E-03	-0,0013	1,01E-04	-3,21E-07	2,89E-06	0,1781	0,0029	/	/	/	/	/	/
abc2	0,5133	0,7007	8,91E-04	-0,0013	1,05E-04	1,06E-06	3,00E-06	/	/	4,17E-04	7,58E-06	/	/	/	/
abc8	0,4090	0,7138	8,48E-04	-0,0013	1,11E-04	-5,91E-07	3,15E-06	/	/	/	/	3,03E-09	7,19E-11	/	/
ab125	0,6598	0,6279	1,77E-03	-0,0016	2,36E-05	/	/	0,8476	0,0161	-1,74E-03	3,84E-05	/	/	430,8063	69,1992
ab185	0,6798	0,6516	1,27E-03	-0,0015	2,26E-05	/	/	0,4430	0,0063	/	/	-6,85E-09	1,23E-10	385,7462	68,5860
ab18	0,6762	0,6506	1,27E-03	-0,0014	2,10E-05	/	/	0,4457	0,0063	/	/	-6,87E-09	1,23E-10	/	/
ab12	0,6553	0,6271	1,78E-03	-0,0016	2,21E-05	/	/	0,8484	0,0161	-1,73E-03	3,86E-05	/	/	/	/
ab15	0,5690	0,6831	1,03E-03	-0,0014	2,49E-05	/	/	0,1758	0,0029	/	/	/	/	409,5492	71,4379
ab25	0,5181	0,7013	8,34E-04	-0,0013	2,62E-05	/	/	/	/	4,10E-04	7,47E-06	/	/	443,1698	74,2716
ab85	0,4166	0,7148	7,77E-04	-0,0014	2,84E-05	/	/	/	/	/	/	2,96E-09	7,03E-11	557,1216	79,3942
ab1	0,5648	0,6822	1,03E-03	-0,0013	2,34E-05	/	/	0,1781	0,0029	/	/	/	/	/	/
ab2	0,5133	0,7005	8,33E-04	-0,0013	2,45E-05	/	/	/	/	4,17E-04	7,54E-06	/	/	/	/
ab8	0,4090	0,7140	7,76E-04	-0,0013	2,66E-05	/	/	/	/	/	/	3,03E-09	7,15E-11	/	/
ac125	0,6469	0,6170	1,80E-03	/	/	-4,39E-05	7,82E-07	0,8495	0,0158	-1,74E-03	3,74E-05	/	/	414,0615	72,8142
ac185	0,6660	0,6419	1,30E-03	/	/	-3,92E-05	7,54E-07	0,4420	0,0063	/	/	-6,82E-09	1,19E-10	366,8502	71,9447
ac18	0,6626	0,6412	1,30E-03	/	/	-3,84E-05	6,91E-07	0,4446	0,0063	/	/	-6,84E-09	1,19E-10	/	/
ac12	0,6427	0,6165	1,80E-03	/	/	-4,29E-05	7,15E-07	0,8500	0,0158	-1,74E-03	3,74E-05	/	/	/	/
ac15	0,5561	0,6740	1,04E-03	/	/	-3,61E-05	8,10E-07	0,1760	0,0030	/	/	/	/	390,6881	75,1902
ac25	0,5052	0,6925	8,18E-04	/	/	-3,47E-05	8,43E-07	/	/	4,11E-04	7,79E-06	/	/	423,7612	78,0312
ac85	0,4038	0,7056	7,46E-04	/	/	-3,63E-05	8,98E-07	/	/	/	/	2,97E-09	7,28E-11	538,2310	83,4288
ac1	0,5523	0,6734	1,04E-03	/	/	-3,52E-05	7,44E-07	0,1783	0,0030	/	/	/	/	/	/
ac2	0,5008	0,6919	8,21E-04	/	/	-3,37E-05	7,74E-07	/	/	4,18E-04	7,84E-06	/	/	/	/
ac8	0,3967	0,7051	7,50E-04	/	/	-3,51E-05	8,24E-07	/	/	/	/	3,03E-09	7,38E-11	/	/
a125	0,3880	0,6271	2,25E-03	/	/	/	/	0,5245	0,0210	-8,59E-04	5,15E-05	/	/	-122,9174	78,5031
a185	0,4414	0,6290	1,58E-03	/	/	/	/	0,4141	0,0084	/	/	-5,70E-09	1,68E-10	-138,4143	78,9313
a18	0,4410	0,6292	1,58E-03	/	/	/	/	0,4128	0,0083	/	/	-5,69E-09	1,68E-10	/	/
a12	0,3876	0,6274	2,24E-03	/	/	/	/	0,5223	0,0209	-8,55E-04	5,12E-05	/	/	/	/
a15	0,3636	0,6571	1,16E-03	/	/	/	/	0,1907	0,0036	/	/	/	/	-83,8259	76,0506
a25	0,3292	0,6763	8,54E-04	/	/	/	/	/	/	4,62E-04	9,09E-06	/	/	-40,9583	75,8477
a85	0,2104	0,6898	7,69E-04	/	/	/	/	/	/	/	/	3,43E-09	8,57E-11	57,9824	77,5115
a1	0,3635	0,6571	1,17E-03	/	/	/	/	0,1903	0,0036	/	/	/	/	/	/
a2	0,3292	0,6764	8,56E-04	/	/	/	/	/	/	4,61E-04	9,17E-06	/	/	/	/
a8	0,2103	0,6898	7,69E-04	/	/	/	/	/	/	/	/	3,44E-09	8,68E-11	/	/

Table B.10: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, timeshift, point duration 40 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6129	0,6257	2,51E-03	-0,0016	1,36E-04	-3,85E-06	4,22E-06	0,8739	0,0248	-1,81E-03	5,97E-05	/	/	402,9105	127,9387
abc185	0,6288	0,6522	1,68E-03	-0,0016	1,36E-04	1,58E-06	4,24E-06	0,4461	0,0097	/	/	-7,00E-09	1,97E-10	334,8254	128,1939
abc18	0,6269	0,6516	1,69E-03	-0,0016	1,34E-04	1,67E-06	4,22E-06	0,4477	0,0098	/	/	-6,99E-09	1,97E-10	/	/
abc15	0,5243	0,6847	1,30E-03	-0,0015	1,49E-04	3,44E-06	4,64E-06	0,1737	0,0038	/	/	/	/	328,1610	127,6545
abc12	0,6102	0,6253	2,54E-03	-0,0015	1,35E-04	-3,70E-06	4,19E-06	0,8720	0,0249	-1,80E-03	5,98E-05	/	/	/	/
abc25	0,4776	0,7029	1,10E-03	-0,0015	1,54E-04	4,69E-06	4,80E-06	/	/	4,05E-04	9,52E-06	/	/	359,2056	130,1148
abc85	0,3865	0,7159	1,06E-03	-0,0015	1,61E-04	2,88E-06	5,00E-06	/	/	/	/	2,90E-09	8,77E-11	492,7651	134,9726
abc1	0,5225	0,6840	1,31E-03	-0,0015	1,47E-04	3,53E-06	4,61E-06	0,1754	0,0038	/	/	/	/	/	/
abc2	0,4754	0,7024	1,10E-03	-0,0015	1,52E-04	4,81E-06	4,76E-06	/	/	4,10E-04	9,63E-06	/	/	/	/
abc8	0,3825	0,7153	1,07E-03	-0,0015	1,59E-04	3,03E-06	4,96E-06	/	/	/	/	2,96E-09	8,90E-11	/	/
ab125	0,6128	0,6266	2,72E-03	-0,0017	3,33E-05	/	/	0,8722	0,0253	-1,81E-03	6,10E-05	/	/	402,1729	128,1079
ab185	0,6288	0,6519	1,86E-03	-0,0015	3,37E-05	/	/	0,4461	0,0097	/	/	-7,00E-09	1,98E-10	335,0498	128,1618
ab18	0,6269	0,6513	1,88E-03	-0,0015	3,33E-05	/	/	0,4477	0,0098	/	/	-7,00E-09	1,99E-10	/	/
ab12	0,6101	0,6262	2,75E-03	-0,0017	3,26E-05	/	/	0,8704	0,0254	-1,80E-03	6,12E-05	/	/	/	/
ab15	0,5242	0,6840	1,36E-03	-0,0014	3,81E-05	/	/	0,1737	0,0038	/	/	/	/	328,6472	127,6551
ab25	0,4774	0,7019	1,09E-03	-0,0014	3,97E-05	/	/	/	/	4,04E-04	9,45E-06	/	/	359,9997	130,1656
ab85	0,3865	0,7153	9,91E-04	-0,0014	4,17E-05	/	/	/	/	/	/	2,90E-09	8,70E-11	493,1954	135,0619
ab1	0,5224	0,6833	1,38E-03	-0,0014	3,76E-05	/	/	0,1754	0,0038	/	/	/	/	/	/
ab2	0,4752	0,7014	1,10E-03	-0,0013	3,91E-05	/	/	/	/	4,09E-04	9,56E-06	/	/	/	/
ab8	0,3824	0,7147	1,00E-03	-0,0014	4,08E-05	/	/	/	/	/	/	2,96E-09	8,84E-11	/	/
ac125	0,5974	0,6155	2,72E-03	/	/	-4,58E-05	1,13E-06	0,8714	0,0249	-1,80E-03	5,98E-05	/	/	366,1564	127,6924
ac185	0,6128	0,6419	1,86E-03	/	/	-4,09E-05	1,14E-06	0,4449	0,0098	/	/	-6,96E-09	1,96E-10	297,8846	127,7154
ac18	0,6113	0,6414	1,88E-03	/	/	-4,03E-05	1,12E-06	0,4463	0,0099	/	/	-6,96E-09	1,96E-10	/	/
ac12	0,5951	0,6153	2,74E-03	/	/	-4,50E-05	1,10E-06	0,8697	0,0250	-1,79E-03	5,99E-05	/	/	/	/
ac15	0,5094	0,6745	1,34E-03	/	/	-3,75E-05	1,26E-06	0,1740	0,0039	/	/	/	/	292,5513	127,7591
ac25	0,4628	0,6928	1,04E-03	/	/	-3,62E-05	1,30E-06	/	/	4,06E-04	9,87E-06	/	/	323,5074	130,4480
ac85	0,3718	0,7058	9,33E-04	/	/	-3,79E-05	1,36E-06	/	/	/	/	2,92E-09	9,02E-11	456,8945	135,7630
ac1	0,5080	0,6741	1,36E-03	/	/	-3,70E-05	1,24E-06	0,1755	0,0039	/	/	/	/	/	/
ac2	0,4610	0,6924	1,05E-03	/	/	-3,56E-05	1,28E-06	/	/	4,10E-04	9,95E-06	/	/	/	/
ac8	0,3683	0,7054	9,43E-04	/	/	-3,70E-05	1,32E-06	/	/	/	/	2,97E-09	9,13E-11	/	/
a125	0,3508	0,6257	3,16E-03	/	/	/	/	0,5373	0,0310	-8,95E-04	7,61E-05	/	/	-292,5089	152,7502
a185	0,3994	0,6285	2,04E-03	/	/	/	/	0,4161	0,0119	/	/	-5,78E-09	2,47E-10	-305,1289	155,0319
a18	0,3978	0,6287	2,03E-03	/	/	/	/	0,4141	0,0118	/	/	-5,77E-09	2,46E-10	/	/
a12	0,3493	0,6261	3,14E-03	/	/	/	/	0,5342	0,0308	-8,90E-04	7,56E-05	/	/	/	/
a15	0,3270	0,6569	1,40E-03	/	/	/	/	0,1898	0,0045	/	/	/	/	-268,0753	147,6252
a25	0,2951	0,6761	1,02E-03	/	/	/	/	/	/	4,59E-04	1,12E-05	/	/	-228,7039	145,8769
a85	0,1876	0,6894	9,25E-04	/	/	/	/	/	/	/	/	3,41E-09	1,05E-10	-114,2971	145,7493
a1	0,3257	0,6570	1,40E-03	/	/	/	/	0,1886	0,0046	/	/	/	/	/	/
a2	0,2942	0,6761	1,02E-03	/	/	/	/	/	/	4,57E-04	1,13E-05	/	/	/	/
a8	0,1874	0,6894	9,21E-04	/	/	/	/	/	/	/	/	3,40E-09	1,07E-10	/	/

Table B.11: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, centered, No timeshift, point duration 60 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6535	0,6264	2,17E-03	-0,0014	1,10E-04	-6,43E-06	3,19E-06	0,8555	0,0194	-1,76E-03	4,63E-05	/	/	579,5093	92,0409
abc185	0,6724	0,6517	1,53E-03	-0,0015	1,09E-04	-9,52E-07	3,19E-06	0,4432	0,0077	/	/	-6,91E-09	1,51E-10	522,0668	91,1652
abc18	0,6665	0,6507	1,53E-03	-0,0014	1,07E-04	-1,05E-06	3,10E-06	0,4457	0,0077	/	/	-6,90E-09	1,51E-10	/	/
abc15	0,5623	0,6838	1,26E-03	-0,0014	1,24E-04	1,57E-06	3,60E-06	0,1746	0,0036	/	/	/	/	513,2568	97,2938
abc12	0,6461	0,6257	2,18E-03	-0,0014	1,08E-04	-6,47E-06	3,11E-06	0,8523	0,0195	-1,75E-03	4,66E-05	/	/	/	/
abc25	0,5124	0,7021	1,05E-03	-0,0014	1,29E-04	3,13E-06	3,77E-06	/	/	4,08E-04	9,18E-06	/	/	537,5378	100,8268
abc85	0,4134	0,7151	9,93E-04	-0,0014	1,37E-04	1,59E-06	4,00E-06	/	/	/	/	2,94E-09	8,61E-11	649,9428	106,7449
abc1	0,5566	0,6827	1,26E-03	-0,0014	1,21E-04	1,47E-06	3,46E-06	0,1773	0,0036	/	/	/	/	/	/
abc2	0,5061	0,7012	1,05E-03	-0,0014	1,26E-04	3,05E-06	3,62E-06	/	/	4,15E-04	9,18E-06	/	/	/	/
abc8	0,4041	0,7142	9,99E-04	-0,0014	1,33E-04	1,48E-06	3,81E-06	/	/	/	/	3,02E-09	8,71E-11	/	/
ab125	0,6531	0,6280	2,17E-03	-0,0017	2,64E-05	/	/	0,8520	0,0196	-1,75E-03	4,67E-05	/	/	579,7132	91,9068
ab185	0,6724	0,6519	1,55E-03	-0,0015	2,58E-05	/	/	0,4432	0,0078	/	/	-6,91E-09	1,52E-10	522,1477	91,1260
ab18	0,6665	0,6509	1,54E-03	-0,0015	2,47E-05	/	/	0,4457	0,0078	/	/	-6,90E-09	1,51E-10	/	/
ab12	0,6457	0,6273	2,17E-03	-0,0016	2,57E-05	/	/	0,8488	0,0197	-1,74E-03	4,70E-05	/	/	/	/
ab15	0,5623	0,6835	1,24E-03	-0,0014	2,99E-05	/	/	0,1745	0,0036	/	/	/	/	513,1202	97,4166
ab25	0,5124	0,7014	9,97E-04	-0,0013	3,18E-05	/	/	/	/	4,08E-04	9,14E-06	/	/	537,3541	101,1338
ab85	0,4134	0,7147	9,22E-04	-0,0014	3,46E-05	/	/	/	/	/	/	2,94E-09	8,56E-11	649,8268	106,9503
ab1	0,5565	0,6824	1,23E-03	-0,0013	2,80E-05	/	/	0,1772	0,0036	/	/	/	/	/	/
ab2	0,5060	0,7005	9,91E-04	-0,0013	2,94E-05	/	/	/	/	4,15E-04	9,14E-06	/	/	/	/
ab8	0,4041	0,7139	9,20E-04	-0,0013	3,19E-05	/	/	/	/	/	/	3,02E-09	8,66E-11	/	/
ac125	0,6390	0,6168	2,22E-03	/	/	-4,43E-05	8,80E-07	0,8554	0,0195	-1,76E-03	4,64E-05	/	/	542,6501	94,0869
ac185	0,6574	0,6420	1,58E-03	/	/	-3,95E-05	8,69E-07	0,4428	0,0078	/	/	-6,89E-09	1,49E-10	484,5535	93,2874
ac18	0,6522	0,6413	1,57E-03	/	/	-3,86E-05	8,16E-07	0,4451	0,0078	/	/	-6,88E-09	1,49E-10	/	/
ac12	0,6325	0,6164	2,21E-03	/	/	-4,32E-05	8,37E-07	0,8524	0,0196	-1,75E-03	4,66E-05	/	/	/	/
ac15	0,5479	0,6742	1,25E-03	/	/	-3,62E-05	9,83E-07	0,1749	0,0037	/	/	/	/	476,6034	100,8630
ac25	0,4979	0,6925	9,80E-04	/	/	-3,47E-05	1,04E-06	/	/	4,09E-04	9,52E-06	/	/	500,7225	104,8630
ac85	0,3988	0,7055	8,90E-04	/	/	-3,64E-05	1,11E-06	/	/	/	/	2,95E-09	8,87E-11	612,9380	111,3739
ac1	0,5429	0,6735	1,25E-03	/	/	-3,53E-05	8,99E-07	0,1774	0,0037	/	/	/	/	/	/
ac2	0,4924	0,6919	9,78E-04	/	/	-3,38E-05	9,39E-07	/	/	4,16E-04	9,48E-06	/	/	/	/
ac8	0,3906	0,7050	8,92E-04	/	/	-3,52E-05	9,99E-07	/	/	/	/	3,03E-09	8,94E-11	/	/
a125	0,3802	0,6279	2,71E-03	/	/	/	/	0,5158	0,0255	-8,40E-04	6,24E-05	/	/	1,6074	111,5882
a185	0,4330	0,6293	1,89E-03	/	/	/	/	0,4118	0,0102	/	/	-5,68E-09	2,05E-10	-9,3180	111,9702
a18	0,4330	0,6293	1,89E-03	/	/	/	/	0,4118	0,0101	/	/	-5,68E-09	2,04E-10	/	/
a12	0,3802	0,6279	2,70E-03	/	/	/	/	0,5158	0,0253	-8,40E-04	6,21E-05	/	/	/	/
a15	0,3573	0,6572	1,39E-03	/	/	/	/	0,1897	0,0044	/	/	/	/	19,3165	107,7056
a25	0,3242	0,6763	1,01E-03	/	/	/	/	/	/	4,60E-04	1,10E-05	/	/	51,1917	106,6440
a85	0,2081	0,6896	9,11E-04	/	/	/	/	/	/	/	/	3,43E-09	1,04E-10	147,9767	107,6106
a1	0,3573	0,6571	1,39E-03	/	/	/	/	0,1898	0,0044	/	/	/	/	/	/
a2	0,3241	0,6763	1,01E-03	/	/	/	/	/	/	4,61E-04	1,10E-05	/	/	/	/
a8	0,2076	0,6896	9,12E-04	/	/	/	/	/	/	/	/	3,45E-09	1,04E-10	/	/

Table B.12: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, timeshift, point duration 60 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6252	0,6279	2,76E-03	-0,0016	1,60E-04	-2,77E-06	4,89E-06	0,8433	0,0274	-1,73E-03	6,61E-05	/	/	271,0667	156,3756
abc185	0,6412	0,6529	1,91E-03	-0,0016	1,61E-04	2,57E-06	4,95E-06	0,4376	0,0111	/	/	-6,72E-09	2,23E-10	206,2272	156,7238
abc18	0,6405	0,6524	1,88E-03	-0,0016	1,64E-04	2,25E-06	4,94E-06	0,4389	0,0108	/	/	-6,72E-09	2,22E-10	/	/
abc15	0,5430	0,6843	1,56E-03	-0,0016	1,82E-04	4,65E-06	5,65E-06	0,1757	0,0045	/	/	/	/	214,8213	155,7079
abc12	0,6239	0,6274	2,72E-03	-0,0016	1,63E-04	-3,16E-06	4,86E-06	0,8427	0,0275	-1,72E-03	6,69E-05	/	/	/	/
abc25	0,4968	0,7027	1,35E-03	-0,0016	1,91E-04	6,04E-06	5,94E-06	/	/	4,11E-04	1,14E-05	/	/	253,2089	158,1296
abc85	0,4048	0,7158	1,33E-03	-0,0016	2,03E-04	4,26E-06	6,30E-06	/	/	/	/	2,97E-09	1,05E-10	402,2005	163,2306
abc1	0,5423	0,6838	1,59E-03	-0,0016	1,85E-04	4,31E-06	5,63E-06	0,1769	0,0044	/	/	/	/	/	/
abc2	0,4957	0,7022	1,40E-03	-0,0016	1,93E-04	5,67E-06	5,90E-06	/	/	4,14E-04	1,12E-05	/	/	/	/
abc8	0,4022	0,7152	1,39E-03	-0,0015	2,04E-04	3,64E-06	6,21E-06	/	/	/	/	3,02E-09	1,06E-10	/	/
ab125	0,6251	0,6285	3,00E-03	-0,0017	4,03E-05	/	/	0,8419	0,0281	-1,72E-03	6,77E-05	/	/	273,1800	157,0869
ab185	0,6411	0,6524	2,11E-03	-0,0015	4,03E-05	/	/	0,4377	0,0111	/	/	-6,72E-09	2,25E-10	204,1336	157,8920
ab18	0,6404	0,6520	2,04E-03	-0,0015	3,79E-05	/	/	0,4389	0,0108	/	/	-6,73E-09	2,24E-10	/	/
ab12	0,6239	0,6282	2,94E-03	-0,0017	3,85E-05	/	/	0,8412	0,0282	-1,72E-03	6,86E-05	/	/	/	/
ab15	0,5428	0,6834	1,64E-03	-0,0014	4,60E-05	/	/	0,1756	0,0045	/	/	/	/	211,0490	157,3858
ab25	0,4964	0,7015	1,33E-03	-0,0014	4,84E-05	/	/	/	/	4,10E-04	1,13E-05	/	/	248,5053	160,0699
ab85	0,4047	0,7149	1,22E-03	-0,0014	5,15E-05	/	/	/	/	/	/	2,97E-09	1,04E-10	398,7852	165,2135
ab1	0,5421	0,6829	1,59E-03	-0,0014	4,26E-05	/	/	0,1768	0,0044	/	/	/	/	/	/
ab2	0,4954	0,7011	1,30E-03	-0,0014	4,45E-05	/	/	/	/	4,14E-04	1,11E-05	/	/	/	/
ab8	0,4020	0,7144	1,21E-03	-0,0014	4,71E-05	/	/	/	/	/	/	3,01E-09	1,05E-10	/	/
ac125	0,6085	0,6173	3,07E-03	/	/	-4,53E-05	1,39E-06	0,8424	0,0280	-1,72E-03	6,72E-05	/	/	194,9661	161,7612
ac185	0,6240	0,6422	2,17E-03	/	/	-4,06E-05	1,41E-06	0,4369	0,0113	/	/	-6,69E-09	2,23E-10	129,1142	162,2071
ac18	0,6237	0,6420	2,10E-03	/	/	-4,04E-05	1,31E-06	0,4377	0,0110	/	/	-6,69E-09	2,23E-10	/	/
ac12	0,6079	0,6172	3,03E-03	/	/	-4,49E-05	1,30E-06	0,8420	0,0281	-1,72E-03	6,80E-05	/	/	/	/
ac15	0,5267	0,6738	1,64E-03	/	/	-3,75E-05	1,59E-06	0,1761	0,0047	/	/	/	/	139,5505	162,4745
ac25	0,4804	0,6922	1,29E-03	/	/	-3,61E-05	1,66E-06	/	/	4,12E-04	1,19E-05	/	/	177,7435	165,3518
ac85	0,3884	0,7052	1,16E-03	/	/	-3,79E-05	1,75E-06	/	/	/	/	2,98E-09	1,09E-10	326,5046	171,0276
ac1	0,5264	0,6736	1,60E-03	/	/	-3,73E-05	1,47E-06	0,1768	0,0046	/	/	/	/	/	/
ac2	0,4799	0,6920	1,27E-03	/	/	-3,58E-05	1,53E-06	/	/	4,14E-04	1,16E-05	/	/	/	/
ac8	0,3867	0,7050	1,15E-03	/	/	-3,74E-05	1,59E-06	/	/	/	/	3,02E-09	1,08E-10	/	/
a125	0,3616	0,6270	3,50E-03	/	/	/	/	0,5146	0,0341	-8,27E-04	8,38E-05	/	/	-378,4595	170,2514
a185	0,4088	0,6284	2,36E-03	/	/	/	/	0,4108	0,0135	/	/	-5,56E-09	2,79E-10	-398,4222	172,8682
a18	0,4062	0,6288	2,34E-03	/	/	/	/	0,4080	0,0132	/	/	-5,53E-09	2,78E-10	/	/
a12	0,3591	0,6274	3,46E-03	/	/	/	/	0,5104	0,0336	-8,21E-04	8,30E-05	/	/	/	/
a15	0,3409	0,6558	1,69E-03	/	/	/	/	0,1930	0,0054	/	/	/	/	-355,5977	165,7967
a25	0,3097	0,6753	1,24E-03	/	/	/	/	/	/	4,68E-04	1,34E-05	/	/	-313,1255	164,4817
a85	0,1997	0,6887	1,13E-03	/	/	/	/	/	/	/	/	3,50E-09	1,26E-10	-179,5437	165,1284
a1	0,3387	0,6561	1,69E-03	/	/	/	/	0,1913	0,0054	/	/	/	/	/	/
a2	0,3080	0,6753	1,24E-03	/	/	/	/	/	/	4,64E-04	1,35E-05	/	/	/	/
a8	0,1992	0,6887	1,12E-03	/	/	/	/	/	/	/	/	3,49E-09	1,28E-10	/	/

Table B.13: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, centered, No timeshift, point duration 90 seconds

Case	R^2	η	std dev	b_1	std dev	b_2	std dev	a_1	std dev	a_2	std dev	a_8	std dev	a_5	std dev
abc125	0,6219	0,6281	2,69E-03	-0,0014	1,39E-04	-5,83E-06	4,05E-06	0,8345	0,0251	-1,71E-03	6,06E-05	/	/	554,4365	128,3422
abc185	0,6407	0,6527	1,88E-03	-0,0015	1,39E-04	-3,08E-08	4,07E-06	0,4349	0,0100	/	/	-6,76E-09	2,02E-10	495,7459	127,1759
abc18	0,6358	0,6516	1,90E-03	-0,0014	1,39E-04	2,09E-07	4,00E-06	0,4378	0,0100	/	/	-6,76E-09	2,04E-10	/	/
abc15	0,5362	0,6844	1,55E-03	-0,0015	1,57E-04	4,39E-06	4,59E-06	0,1722	0,0043	/	/	/	/	497,5834	129,1576
abc12	0,6158	0,6274	2,71E-03	-0,0014	1,38E-04	-5,48E-06	3,96E-06	0,8328	0,0254	-1,70E-03	6,18E-05	/	/	/	/
abc25	0,4886	0,7025	1,32E-03	-0,0015	1,65E-04	6,53E-06	4,82E-06	/	/	4,02E-04	1,11E-05	/	/	529,9909	132,1312
abc85	0,3937	0,7154	1,27E-03	-0,0015	1,74E-04	5,38E-06	5,07E-06	/	/	/	/	2,90E-09	1,05E-10	660,9947	139,1431
abc1	0,5313	0,6833	1,59E-03	-0,0015	1,56E-04	4,63E-06	4,49E-06	0,1750	0,0044	/	/	/	/	/	/
abc2	0,4830	0,7016	1,36E-03	-0,0015	1,64E-04	6,84E-06	4,72E-06	/	/	4,10E-04	1,12E-05	/	/	/	/
abc8	0,3850	0,7146	1,30E-03	-0,0015	1,72E-04	5,75E-06	4,95E-06	/	/	/	/	2,98E-09	1,07E-10	/	/
ab125	0,6216	0,6297	2,68E-03	-0,0016	3,42E-05	/	/	0,8301	0,0253	-1,70E-03	6,11E-05	/	/	552,6898	128,5524
ab185	0,6407	0,6527	1,89E-03	-0,0015	3,29E-05	/	/	0,4349	0,0100	/	/	-6,76E-09	2,04E-10	495,7387	127,0662
ab18	0,6358	0,6516	1,89E-03	-0,0014	3,21E-05	/	/	0,4378	0,0100	/	/	-6,76E-09	2,05E-10	/	/
ab12	0,6155	0,6289	2,69E-03	-0,0016	3,38E-05	/	/	0,8287	0,0257	-1,69E-03	6,22E-05	/	/	/	/
ab15	0,5360	0,6834	1,50E-03	-0,0013	3,77E-05	/	/	0,1721	0,0043	/	/	/	/	498,6253	129,0286
ab25	0,4882	0,7011	1,22E-03	-0,0013	3,99E-05	/	/	/	/	4,02E-04	1,11E-05	/	/	531,8275	132,1395
ab85	0,3934	0,7143	1,14E-03	-0,0014	4,31E-05	/	/	/	/	/	/	2,89E-09	1,04E-10	662,4568	139,2755
ab1	0,5311	0,6823	1,51E-03	-0,0013	3,60E-05	/	/	0,1749	0,0044	/	/	/	/	/	/
ab2	0,4826	0,7002	1,23E-03	-0,0012	3,79E-05	/	/	/	/	4,10E-04	1,12E-05	/	/	/	/
ab8	0,3846	0,7134	1,15E-03	-0,0013	4,06E-05	/	/	/	/	/	/	2,98E-09	1,07E-10	/	/
ac125	0,6071	0,6179	2,76E-03	/	/	-4,35E-05	1,15E-06	0,8406	0,0253	-1,73E-03	6,09E-05	/	/	521,0604	127,8628
ac185	0,6250	0,6426	1,94E-03	/	/	-3,87E-05	1,14E-06	0,4363	0,0101	/	/	-6,78E-09	2,01E-10	460,9168	126,6359
ac18	0,6208	0,6418	1,94E-03	/	/	-3,77E-05	1,08E-06	0,4389	0,0100	/	/	-6,78E-09	2,03E-10	/	/
ac12	0,6017	0,6175	2,77E-03	/	/	-4,23E-05	1,10E-06	0,8389	0,0256	-1,72E-03	6,20E-05	/	/	/	/
ac15	0,5199	0,6741	1,52E-03	/	/	-3,51E-05	1,29E-06	0,1727	0,0045	/	/	/	/	462,0463	130,2027
ac25	0,4718	0,6922	1,20E-03	/	/	-3,36E-05	1,36E-06	/	/	4,03E-04	1,15E-05	/	/	494,1893	133,7829
ac85	0,3765	0,7050	1,10E-03	/	/	-3,52E-05	1,44E-06	/	/	/	/	2,91E-09	1,08E-10	624,9924	141,6048
ac1	0,5157	0,6734	1,53E-03	/	/	-3,41E-05	1,20E-06	0,1754	0,0045	/	/	/	/	/	/
ac2	0,4669	0,6916	1,21E-03	/	/	-3,25E-05	1,26E-06	/	/	4,11E-04	1,16E-05	/	/	/	/
ac8	0,3686	0,7045	1,11E-03	/	/	-3,38E-05	1,33E-06	/	/	/	/	2,99E-09	1,10E-10	/	/
a125	0,3621	0,6302	3,34E-03	/	/	/	/	0,4933	0,0317	-7,87E-04	7,77E-05	/	/	-132,4130	151,8883
a185	0,4120	0,6307	2,32E-03	/	/	/	/	0,4022	0,0128	/	/	-5,49E-09	2,63E-10	-145,9368	154,2891
a18	0,4116	0,6308	2,30E-03	/	/	/	/	0,4010	0,0126	/	/	-5,48E-09	2,60E-10	/	/
a12	0,3617	0,6304	3,30E-03	/	/	/	/	0,4912	0,0312	-7,83E-04	7,69E-05	/	/	/	/
a15	0,3419	0,6576	1,68E-03	/	/	/	/	0,1876	0,0053	/	/	/	/	-97,9664	144,4565
a25	0,3106	0,6765	1,23E-03	/	/	/	/	/	/	4,55E-04	1,33E-05	/	/	-53,1860	141,2248
a85	0,1992	0,6897	1,11E-03	/	/	/	/	/	/	/	/	3,40E-09	1,26E-10	57,7531	140,2660
a1	0,3417	0,6576	1,68E-03	/	/	/	/	0,1872	0,0053	/	/	/	/	/	/
a2	0,3106	0,6765	1,23E-03	/	/	/	/	/	/	4,55E-04	1,34E-05	/	/	/	/
a8	0,1992	0,6897	1,11E-03	/	/	/	/	/	/	/	/	3,40E-09	1,27E-10	/	/

Table B.14: Results of MRL fit of various combinations of coefficients, full URSSATrough dataset, screened, point duration 90 seconds

DATA TABLES

C.1 Avalen

C.1.0.1 measured values

C.1.0.2 calculated values

C.2 m-PTC

C.2.1 water tests

C.2.1.1 measured values

C.2.1.2 calculated values

	timestamp	length	T_{in}	std dev T_{in}	T_{out}	std dev T_{out}	ΔT	std dev ΔT	T_{amb}	std dev T_{amb}	$\dot{m}$	std dev $\dot{m}$	c_p	G_b	std dev G_b	inclination
1	11/9/23 10.40	00:40:14	25,799	0,100	36,580	0,353	10,781	0,254	31,067	3,065	45,841	0,279	4,179	801,664	8,692	5,199
2	12/9/23 10.36	00:12:44	25,271	0,102	44,539	0,098	19,268	0,115	25,333	0,513	25,063	0,028	4,179	789,185	7,647	2,591
3	12/9/23 11.00	00:12:08	25,898	0,096	45,561	0,100	19,663	0,110	32,952	0,662	24,945	0,033	4,178	762,888	14,526	5,655
4	12/9/23 11.12	00:13:24	26,242	0,091	46,072	0,093	19,830	0,050	33,879	0,901	24,867	0,044	4,178	758,349	9,839	7,228
5	15/9/23 14.15	00:10:02	56,657	0,099	72,883	0,261	16,226	0,193	34,169	0,909	29,390	0,020	4,183	758,771	2,999	10,317
6	15/9/23 14.25	00:22:43	57,038	0,100	73,433	0,177	16,395	0,090	33,314	0,394	29,451	0,033	4,183	744,654	2,769	8,883
7	29/9/23 14.27	00:31:13	62,523	0,098	80,966	0,179	18,444	0,187	30,605	0,438	23,650	0,044	4,184	753,821	3,647	2,788
8	29/9/23 15.21	00:20:08	62,144	0,100	79,595	0,328	17,451	0,298	29,811	0,245	23,602	0,036	4,184	714,184	7,965	-2,669
9	12/10/23 14.11	00:12:55	71,758	0,095	83,636	0,257	11,878	0,264	27,585	0,255	35,676	0,015	4,184	700,158	2,872	-0,130
10	12/10/23 14.57	00:09:45	71,832	0,109	82,278	0,082	10,446	0,138	27,445	0,259	35,697	0,012	4,184	670,774	6,685	-4,074
11	13/10/23 14.29	00:16:37	84,833	0,190	95,815	0,415	10,982	0,458	26,598	0,609	34,570	0,017	4,181	676,760	10,278	-1,916
12	12/10/23 14.23	00:11:08	72,092	0,194	83,523	0,109	11,431	0,159	27,119	0,316	35,669	0,028	4,184	683,205	16,906	-0,929
13	15/9/23 13.37	00:13:11	53,817	0,189	69,634	0,961	15,818	0,804	35,528	1,066	29,383	0,036	4,182	775,527	2,523	12,473
14	15/9/23 13.51	00:10:05	54,689	0,200	70,752	0,237	16,063	0,074	36,003	0,499	29,396	0,022	4,182	770,622	2,009	11,917
15	12/9/23 14.38	00:10:13	37,740	0,281	58,270	1,041	20,530	0,761	31,174	0,409	21,766	0,125	4,179	752,004	29,050	9,407

Table C.1: Measured values of datapoints for AVALEN

	η	T^*_1	T^*_2	relative error				G_b	η	η absolute error
				T_{in}	T_{out}	T_{amb}	$\dot{m}$			
1	0,7049	0,0002	1,86E-05	0,0039	0,0097	0,0987	0,0061	0,0123	0,0121	0,0086
2	0,6796	0,0121	0,1157	0,0041	0,0022	0,0203	0,0015	0,0113	0,0083	0,0057
3	0,7000	0,0036	0,0100	0,0037	0,0022	0,0201	0,0016	0,0199	0,0143	0,0100
4	0,7046	0,0030	0,0068	0,0035	0,0020	0,0266	0,0020	0,0142	0,0105	0,0074
5	0,6331	0,0398	1,2177	0,0018	0,0036	0,0266	0,0011	0,0070	0,0051	0,0033
6	0,6131	0,0424	1,3523	0,0018	0,0024	0,0118	0,0015	0,0069	0,0047	0,0029
7	0,6534	0,0544	2,2370	0,0016	0,0022	0,0143	0,0021	0,0075	0,0054	0,0035
8	0,6482	0,0577	2,3695	0,0016	0,0041	0,0082	0,0018	0,0126	0,0087	0,0056
9	0,6285	0,0716	3,5875	0,0013	0,0031	0,0093	0,0010	0,0071	0,0050	0,0031
10	0,5790	0,0744	3,6918	0,0015	0,0010	0,0094	0,0010	0,0115	0,0068	0,0039
11	0,5422	0,0944	6,0181	0,0022	0,0043	0,0229	0,0011	0,0162	0,0092	0,0050
12	0,6197	0,0743	3,7661	0,0027	0,0013	0,0117	0,0012	0,0254	0,0159	0,0098
13	0,6552	0,0332	0,8710	0,0035	0,0138	0,0300	0,0015	0,0066	0,0103	0,0068
14	0,6549	0,0341	0,9122	0,0037	0,0034	0,0139	0,0012	0,0063	0,0053	0,0035
15	0,6712	0,0221	0,3721	0,0075	0,0179	0,0131	0,0058	0,0391	0,0295	0,0198

Table C.2: Calculated values of datapoints for AVALEN

	timestamp	length	T_{in}	std dev T_{in}	T_{out}	std dev T_{out}	ΔT	std dev ΔT	T_{amb}	std dev T_{amb}	$\dot{m}$	std dev $\dot{m}$	c_p	G_b	std dev G_b
1	10/5/24 10.40	00:09:42	42,92	0,38	60,06	0,45	17,14	0,08	23,33	0,12	6,08	0,01	4,18	900,08	2,08
2	4/6/24 12.38	00:14:10	100,85	0,59	109,55	0,55	8,70	0,12	25,39	0,42	10,05	0,02	4,16	888,14	5,67
3	12/10/23 14.07	00:13:23	60,16	0,19	70,99	0,55	10,83	0,44	27,76	0,28	7,21	0,01	4,18	698,77	5,35
4	10/5/24 14.55	00:09:48	74,94	0,26	95,22	0,18	20,28	0,14	26,27	0,65	4,51	0,03	4,18	862,33	26,16
5	6/9/23 12.22	00:17:25	28,61	0,10	41,41	0,16	12,80	0,07	31,77	0,67	8,31	0,04	4,18	854,18	1,62
6	11/9/23 11.47	00:10:40	27,64	0,10	38,64	0,13	11,00	0,03	32,12	0,58	9,32	0,01	4,18	830,17	2,00
7	12/9/23 11.01	00:11:26	27,40	0,13	48,86	0,39	21,46	0,38	33,02	0,69	4,49	0,01	4,18	757,98	12,32
8	27/9/23 14.51	00:11:32	47,64	0,10	64,43	0,12	16,79	0,06	29,42	0,42	5,20	0,01	4,18	713,06	13,70
9	12/9/23 12.41	00:10:50	30,42	0,05	51,09	0,44	20,67	0,44	31,09	0,45	4,62	0,01	4,18	751,73	15,64
10	12/9/23 12.54	00:10:30	30,75	0,14	51,09	0,54	20,35	0,42	31,86	0,31	4,65	0,01	4,18	753,84	10,73
11	12/10/23 14.26	00:19:47	60,21	0,20	70,62	0,42	10,41	0,25	27,14	0,36	7,19	0,01	4,18	672,76	13,51
12	10/5/24 14.43	00:10:02	74,90	0,14	95,41	0,19	20,51	0,15	26,61	0,12	4,57	0,01	4,18	888,67	3,63
13	27/9/23 15.07	00:10:20	46,16	0,18	64,43	0,44	18,27	0,27	29,53	0,27	4,63	0,08	4,18	696,99	17,50
14	27/9/23 14.33	00:10:07	47,86	0,40	65,29	0,50	17,43	0,12	30,31	0,10	5,18	0,02	4,18	731,66	3,44
15	4/6/24 12.25	00:13:16	98,66	0,60	107,58	0,56	8,92	0,08	26,40	0,35	10,10	0,02	4,17	897,08	5,06
16	4/6/24 11.59	00:11:04	93,47	0,99	102,64	0,91	9,17	0,19	24,05	0,28	10,13	0,18	4,17	884,16	21,00
17	4/6/24 11.27	00:09:21	85,38	0,37	95,82	0,75	10,44	0,41	24,19	0,15	8,81	0,01	4,18	853,94	15,20

Table C.3: Measured values of datapoints for m-PTC water tests

	η	T^*_{-1}	T^*_{-2}	relative error				η		η absolute error
				T_{in}	T_{out}	T_{amb}	$\dot{m}$	G_b		
1	0,6716	0,0313	0,8814	0,0089	0,0076	0,0052	0,0023	0,0062	0,0134	0,0090
2	0,5696	0,0899	7,1723	0,0059	0,0050	0,0166	0,0021	0,0086	0,0117	0,0067
3	0,6488	0,0541	2,0463	0,0032	0,0077	0,0102	0,0022	0,0096	0,0129	0,0084
4	0,6158	0,0682	4,0117	0,0035	0,0018	0,0246	0,0067	0,0309	0,0318	0,0196
5	0,7224	0,0038	0,0123	0,0035	0,0038	0,0210	0,0047	0,0061	0,0092	0,0067
6	0,7172	0,0012	0,0013	0,0036	0,0033	0,0180	0,0012	0,0063	0,0080	0,0057
7	0,7386	0,0067	0,0345	0,0049	0,0080	0,0209	0,0022	0,0172	0,0198	0,0146
8	0,7113	0,0373	0,9938	0,0021	0,0018	0,0143	0,0016	0,0201	0,0203	0,0145
9	0,7370	0,0129	0,1244	0,0016	0,0086	0,0145	0,0032	0,0216	0,0235	0,0173
10	0,7318	0,0120	0,1090	0,0046	0,0105	0,0099	0,0024	0,0154	0,0193	0,0141
11	0,6458	0,0569	2,1778	0,0033	0,0059	0,0134	0,0013	0,0209	0,0220	0,0142
12	0,6121	0,0659	3,8575	0,0019	0,0020	0,0045	0,0026	0,0071	0,0080	0,0049
13	0,7030	0,0370	0,9521	0,0040	0,0068	0,0092	0,0172	0,0258	0,0320	0,0225
14	0,7158	0,0359	0,9431	0,0084	0,0077	0,0032	0,0046	0,0074	0,0143	0,0102
15	0,5812	0,0855	6,5614	0,0061	0,0052	0,0132	0,0020	0,0081	0,0116	0,0067
16	0,6098	0,0837	6,1960	0,0106	0,0089	0,0116	0,0180	0,0244	0,0333	0,0203
17	0,6259	0,0778	5,1654	0,0044	0,0079	0,0063	0,0016	0,0187	0,0208	0,0130

Table C.4: Calculated values of datapoints for m-PTC water tests