A Techno-Economic Framework for the Analysis of Concentrating Solar Power Plants with Storage

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To my family

Abstract

Concentrating solar power plants can integrate cost-effective thermal energy storage systems and thereby supply controllable power on demand, an advantage against other renewable technologies. Storage integration allows a solar thermal power plant to increase its load factor and to shift production to periods of peak demand. It also enables output firmness, providing stability to the power block and to the grid. Thus, despite the additional investment, storage can enhance the performance and economic viability of the plants.

However, the levelized cost of electricity of these plants yet remains higher than for other technologies, so projects today are only viable through the provision of incentives or technology-specific competitive bid tenders. It is the variability of the solar resource, the myriad roles that storage can assume, and the complexity of enhancing the synergies between the solar field, the storage and the power block, what makes the development of adequate policy instruments, design and operation of these plants a challenging process.

In this thesis a comprehensive methodology for the pre-design and analysis of concentrating solar power plants is presented. The methodology is based on a techno-economic modeling approach that allows identifying optimum trade-off curves between technical, environmental, and financial performance indicators. A number of contemporary plant layouts and novel storage and hybridization concepts are assessed to identify optimum plant configurations, in terms of component size and storage dispatch strategies.

Conclusions highlight the relevance between the sizing of key plant components, the operation strategy and the boundaries set by the location. The interrelation between critical performance indicators, and their use as decisive parameters, is also discussed. Results are used as a basis to provide recommendations aimed to support the decision making process of key actors along the project development value chain of the plants. This research work and conclusions are primarily meant to set a stepping stone in the research of concentrating solar power plant design and optimization, but also to support the research towards understanding the value of storage in concentrating solar power plants and in the grid.

Keywords:

Concentrating solar power, thermal energy storage,
techno-economic analysis

Sammanfattning

Koncentrerad solkraft erbjuder möjligheten att integrera kostnadseffektiv termisk energilagring och därmed behovsstyrd kraftkontroll. Detta är en viktig fördel jämfört med andra förnybara energiteknologier. Lagringsintegration tillåter solkraftsanläggningar att öka sin lastfaktor och skifta produktion till tider med största efterfrågan. Vidare möjliggör lagring fast elproduktion vilket leder till förbättrad nät- och kraftturbinstabilitet. Därför kan termisk lagring öka anläggningsprestanda och ekonomiskt värde trots ökande initiala kapitalkostnader.

I termer av specifik elproduktionskostnad (LCOE) ligger koncentrerade solkraftsanläggningar med lagring fortfarande högre än andra kraftteknologier och anläggningsprojekt blir endast lönsamma genom subventionsmodeller eller teknologispecifika konkurrensutsatta anbudsförfaranden. Att hitta adekvata policylösningar och optimala design och operationsstrategier är en utmanande process eftersom det gäller att hitta rätt balans mellan variabel solinstrålning, lagring av energi och tid för produktion genom optimal design och operation av solmottagarfält, kraftblock och lagringskapacitet.

I denna avhandling presenteras en omfattande metodik för pre-design och analys av koncentrerande solkraftverk. Metodiken baseras på en tekno-ekonomisk modelleringsansats som möjliggör identifiering av optimala avvägningssamband för tekniska, ekonomiska och miljöprestanda indikatorer. Metodiken tillämpas på ett antal moderna anläggningslayouter och lagrings- och hybridiseringskoncept för att identifiera optimal kraftanläggningsdesign i termer av komponentprestanda och lagringsanvändningsstrategier. I slutsatsen poängteras relevansen av att hitta rätt storlek på nyckelkomponenter i relation till lagringsstrategi och randvillkoren som ges av konstruktionsläget för optimal ekonomisk och miljömässig prestanda. Resultaten används för att formulera rekommendationer till nyckelaktörer i beslutsprocessen genom hela kraftanläggningens värdekedja från politisk beslutsfattare till anläggningsingenjör. Forskningen och slutsatserna i detta arbete skall i första hand ta ett steg framåt för optimering och design av solkraftsanläggningar men även tillhandahålla en metodik för utvärdering av lagringslösningar och dess specifika värde för solkraftsanläggningar och elnätet.

Nyckelord

Termisk solkraft, termisk energilagring, techno-eknomiska analys.

Preface

This doctoral thesis was completed at the Heat and Power Technology (HPT) Division at KTH Royal Institute of Technology in Stockholm, Sweden, under main supervision of Associate Professor Björn Laumert. Research at HPT is focused in the fields of poly-generation, aeroelasticity, turbomachinery, biofuels in gas turbine cycles and concentrating solar power. The work was also co-supervised by Zhor Hassar, Solar Power Plant Architect at the New Energies Division of Total S.A. Total is a French multinational energy company active in the solar energy industry through ownership and operation of solar power plants and technology.

This thesis addresses the techno-economic modeling of concentrating solar power plants with thermal energy storage. The main motivation of the work is to be able to support the decision making process of key actors along the project development value chain of a concentrating solar power plant. The outcomes of this applied research add to the knowledge of pre-design engineering analysis tools for the decision making and optimization of energy storage integration in power plants, especially in solar power plants. The work is aimed at supporting the research towards understanding the value that storage integration delivers, both to the concentrating solar power industry and to the grid as a whole.

The present work is a compilation thesis. The thesis summarizes the background, motivation and key-findings from a number of research papers published in scientific journals or presented at different international conferences. These papers can be found in the Appendix section in the same order as they are referred to in the thesis.

The research has been funded by the European Institute of Innovation and Technology through the KIC-Innoenergy TESCONSOL project, and also by the Swedish Energy Agency through the TURBOPOWER research program, the support of which is gratefully appreciated.

Stockholm, September 2016
Rafael Guédez

List of appended publications

This thesis is based upon the following appended scientific articles. Main contributions of each to the state-of-the-art are summarized in Table 1 of Chapter 2, and they are further described in Chapter 9.

Paper I

R. Guédez, M. Topel, J. Spelling, and B. Laumert (2015) "*Enhancing the Profitability of Solar Tower Power Plants through Thermoeconomic Analysis Based on Multi-objective Optimization*", Elsevier Energy Procedia, Volume 69, Pages 1277-1286.

Paper II

R. Guédez, M. Topel, I. Conde, F. Ferragut, I. Callaba, J. Spelling, Z. Hassar, C.D. Pérez-Segarra, and B. Laumert (2016) "*A Methodology for Determining Optimum Solar Tower Plant Configurations and Operating Strategies to Maximize Profits Based on Hourly Electricity Market Prices and Tariffs*", ASME Journal of Solar Energy Eng., Vol. 138 (2).

Paper III

R. Guédez, D. Ferruza, M. Arnaudo, I. Rodríguez, C.D. Pérez-Segarra, Z. Hassar and B. Laumert (2016), "*Techno-economic Performance Evaluation of Solar Tower Plants with Integrated Multi-layered PCM Thermocline Thermal Energy Storage – A Comparative Study to Conventional Two-tank Storage Systems*", Proceedings of International SolarPACES 2015, AIP Conference Proceedings Volume 1734

Paper IV

R. Guédez, J. Spelling, and B. Laumert (2015) "*Enhancing the Economic Competitiveness of Concentrating Solar Power Plants through an Innovative Integrated Solar-Combined Cycle with Thermal Energy Storage*", ASME Journal of Engineering for Gas Turbines and Power, Volume 138 (2).

Paper V

R. Guédez, K. Larchet, J. Dent, A. Green, Z. Hassar and B. Laumert (2016) "*A Techno-Economic Analysis of Hybrid Concentrating Solar Power and Solar Photovoltaic Power Plants for Firm Power in Morocco*", Submitted to the ASME Journal of Solar Energy Engineering, (Paper under review).

Paper VI

R. Guédez, J. Spelling and B. Laumert (2014), "*Thermoeconomic Optimization of Solar Thermal Power Plants with Storage in High-penetration Renewable Electricity Markets*", Elsevier Energy Procedia, Volume 57, Pages 541-550.

Paper VII

R. Guédez, J. Spelling and B. Laumert (2014), "*Reducing the Number of Turbine Starts in Concentrating Solar Power Plants through the Integration of Thermal Energy Storage*", ASME Journal of Solar Energy Engineering, Vol. 137 (1).

Other research articles not included

The author of this thesis actively contributed to the following research articles also in connection to the present research work, but not appended to this book (neither discussed in detail).

Paper A

R. Guédez, J. Spelling, B. Laumert and T. Fransson (2014) "*Optimization of Thermal Energy Storage Integration Strategies for Peak Power Production by Concentrating Solar Power Plants*", Elsevier Energy Procedia, Volume 49, Pages 1642-1651.

<u>Contribution</u>*: All simulations and analyses performed by the author.*

Paper B

J. Spelling, **R. Guédez**, and B. Laumert (2014) "*A Thermo-Economic Study of Storage Integration in Hybrid Solar Gas-Turbine Power Plants*", ASME Journal of Solar Energy Engineering, Vol. 137 (1).

<u>Contribution</u>*: The author contributed to the implementation of the thermal storage components in the power plant model.*

Paper C

R. Guédez, M. Arnaudo, M. Topel, R. Zanino, Z. Hassar and B. Laumert (2016), "*Techno-economic Performance Evaluation of Direct Steam Generation Solar Tower Plants with Thermal Energy Storage Systems Based on High-temperature Concrete and Encapsulated Phase Change Materials*", Proceedings of International SolarPACES 2015, AIP Conference Proceedings Volume 1734

<u>Contribution:</u> *The author defined the research question, the method of attack and contributed to the model implementation and analysis.*

Paper D

M. Topel, **R. Guédez**, and B. Laumert (2015) "*Impact of Increasing Steam Turbine Flexibility on the Annual Performance of a Direct Steam Generation Tower Power Plant*", Elsevier Energy Procedia, Volume 69, Pages 1171-1180.

Contribution: The author contributed to the development of the power plant model, implementation of the techno-economic process, and to the analysis of the final results.

Paper E

M. Topel, F. Ellakany, **R. Guédez**, M. Genrup, and B. Laumert (2016) "*Thermo-Economic Study on the Implementation of Steam Turbine Concepts for Flexible Operation on a Direct Steam Generation Solar Tower Power Plant*", Proceedings of International SolarPACES 2015, AIP Conference Proceedings Volume 1734.

Contribution: The author contributed to the development and implementation of the control strategies in the power plant model.

Paper F

L. Hansson, K. Larchet, **R. Guédez**, and B. Laumert (2016) "*Development and Implementation of a Dynamic TES Dispatch Control Component in a PV-CSP Techno-Economic Performance Modelling Tool*", Proceedings of International SolarPACES 2016 (under review).

Contribution: The author contributed with all power plant techno-economic models used in the analysis; as well as with the definition of the research question, method of attack and to the analysis of results.

Paper G

R. Musi, B. Grange, S. Sgouridis, **R. Guédez**, P. Amstrong, A. Slocum, and N. Calvet (2016) "*Techno-Economic Analysis of Concentrated Solar Power Plants in terms of Levelized Cost of Electricity*", Proceedings of International SolarPACES 2016 (under review).

Contribution: The author contributed to the definition of the scope of research, to the methodology definition and to the analysis of the results.

Paper H

K. Larchet, **R. Guédez**, M. Topel, L. Gustavsson, A. Machirant, M.L. Hedlund, and B. Laumert (2016) "*Enhancing Economic Competiveness of Dish Stirling Technology through Production Volume and Localization: Case Study for Morocco*", Proceedings of International SolarPACES 2016 (under review).

Contribution: The author contributed to the definition of the scope of research, to the methodology and to the analysis of the results.

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Thanks to my friend, former colleague and first mentor James Spelling from whom I first learned and acquired all the needed scientific abilities and knowledge to embrace the challenges of the PhD, and from whom I inherited the first version of the modeling tool used and further developed in the thesis.

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Nomenclature

Abbreviations

BESS	Battery Electric Storage Systems
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CF	Capacity Factor
CR	Central Receiver
CSP	Concentrating Solar Power
DSG	Direct Steam Generation
DSG-STPP	Direct Steam Generation Solar Thermal Power Plant
DYESOPT	Dynamic Energy Systems Optimizer
EOH	Equivalent Operating Hours
EoI	Expression of Interest
EPC	Engineering, Procurement and Construction
FI	Financial Institution
GB	Gas Boiler
GT	Gas Turbine
HTF	Heat Transfer Fluid
HPT	High Pressure Turbine
IC	Installed Capacity
IEA	International Energy Agency
INV	Inverter
IPP	Independent Power Producer
IRR	Internal Rate of Return
L-TES	Latent Heat Thermal Energy Storage
LEC	Levelized Electricity Costs
LCOE	Levelized Cost of Electricity
LF	Linear Fresnel
LGC	Levelized Generation Costs
LTP	Low Pressure Turbine
MLSPCM	Multi-layered Solid PCM
MS	Molten Salts
MS-STPP	Molten Salt Solar Thermal Power Plant
NG	Natural Gas
NPV	Net Present Value
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
PB	Power Block
PCM	Phase Change Material

PD	Parabolic Dish
PPA	Power Purchase Agreement
PT	Parabolic Trough
PV	Solar Photovoltaic
RfP	Request for Proposals
SAM	System Advisor Model
SF	Solar Field
SM	Solar Multiple
S-TES	Sensible Heat Thermal Energy Storage
SSTCC	Solar Salt Tower Combined Cycle
STPP	Solar Tower Power Plant
TES	Thermal Energy Storage
TESCONSOL	Thermal Energy Storage for Concentrating Solar Plants
TSO	Transmission System Operator
WACC	Weighted Average Capital Costs

Latin Symbols

C	Cost	[USD]
c_c	Carbon content of the fuel	[$kgCO_2/MWh_{th}$]
E	Electricity Generated	[MWh/year]
$Debt_{\%}$	Debt Finance Percentage	[%]
$Eq_{\%}$	Equity Finance Percentage	[%]
F_{cap}	Capacity Factor	[%]
F_{cap}	Specific CO_2 Emissions	[$kgCO_2/MWh_e$]
i	Real debt interest rate	[%]
i_{debt}	Debt Interest Rate	[%]
IRR_{eq}	Equity Internal Rate of Return	[%]
N	Plant Lifetime	[-]
Q_f	Quantity of fuel burnt annually	[MWh_{th}/year]

Greek Symbols

α	Capital Return Factor	[-]
λ	Electricity price per hour	[USD/MWh]

Subscripts

BOP	*Balance of Plant*
cap	*Capacity*
con	*Construction*
cont	*Contingencies*
debt	*Debt*
eq	*Equity*
f	*fuel*
rec	*receiver*
ref	*reference*

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1. Introduction

Unlike most of renewable energy technologies, concentrating solar power (CSP) plants with integrated thermal energy storage (TES) units have the possibility of storing heat from the Sun cost-effectively, and thereby supply controllable power on-demand. It is such a dispatchable attribute of CSP which makes it a perfectly suited technology for supporting renewable integration towards a future low-carbon electricity system, especially in countries with high direct normal irradiance (DNI).

Previous research work has shown that TES integration can benefit the operation of CSP plants by multiple means: it allows excess solar energy to be harnessed during the daytime and be stored for use during times of insufficient solar supply; it allows power production to be shifted from periods of low to higher demand and electricity prices; and it increases the stability of operating conditions in the power block, plus potentially helping to mitigate the impact from cycling by lowering start-up frequency. Thus, despite representing an additional upfront investment, TES integration in a CSP plant can enhance its technical performance and economic viability.

However, levelized cost of electricity (LCOE) of CSP plants yet remains higher than for other technologies, so the successful development of a project today (as of 2016) is subject to the provision of premiums or technology-specific competitive bid tenders. It is then both the variable nature of the solar resource and the myriad potential roles that TES can assume in each location, coupled to the complexity of enhancing the synergies between the solar field, the TES block and power block of a CSP plant, what makes the development of adequate policy instruments, design and operation of these plants a challenging process.

The present thesis deals with the development of techno-economic performance evaluation models for identifying optimum power plant configurations for CSP plants with TES. The main conclusions of the work are based on the results and analyses performed throughout seven peer-reviewed research papers, all of which (and their interrelation) are hereafter described in the next chapters and ultimately appended. The specific research questions and author's main contributions to each of the papers appended are explained in this thesis. At the end, the results from these articles are compiled and analyzed together for providing general conclusions and future research work recommendations.

1.1. Thesis structure and reading disposition

The present work is a thesis by publication. A collection of papers published throughout the course of the research work are hereto appended at the end. Chapter 2 states the objectives of the thesis, provides an overview of the methodology, and summarizes the main contributions. Then Chapters 3 to 7 provide an extended background to the research work. Specifically:

- Chapter 3 introduces the main concepts and sub-systems in CSP plants with TES, including the contemporary CSP plant layouts.
- Chapter 4 describes the market perspectives and challenges for CSP, including a characteristic CSP project structure and actors.
- Chapter 5 presents previous work concerning the pre-design and analysis of CSP plants with TES. The chapter introduces techno-economic analysis and also briefs on the state-of-the-art of tools used for the pre-design of CSP plants.
- Chapter 6 briefly describes the research project framing the thesis.
- Chapter 7 introduces the techno-economic modeling tool used.

Then Chapter 8 summarizes the research questions addressed along the PhD thesis, in connection to the objectives and background. Chapter 9 summarizes the results and discussions found in each of the papers. Chapter 9 is split in four sections: §9.1 introduces the solar tower plant optimization model developed, including key findings and remarks from two case-studies (2 papers); §9.2 relates to the feasibility evaluation of a new TES concept (1 paper); §9.3 relates to the techno-economic feasibility evaluation of new hybrid layouts (2 papers); and §9.4 briefs on additional benefits that TES can deliver to a CSP plant (2 papers). Chapter 10 compiles all key findings into a general conclusion section and also suggests future work. The future work section recommends research paths for the field of pre-design and evaluation of CSP plants with TES, as well as for improving the modeling work performed in this PhD thesis.

At the end, all publications are appended in the same order as they are referred to in §9 of the thesis. The author recommends that the thesis is read in order from Chapters 1 to 10 to follow a background-research questions-results flow. It is suggested, though, that while reading Chapter 9 the corresponding paper being described in each sub-section is read a-priori before its discussion, as available in the Appendix.

2. Thesis Objectives and Methodology

The central objective of the present work is to support the search for applicable CSP plant design criteria through the development of techno-economic performance evaluation models. This, in particular for identifying optimum TES integration strategies in CSP plants, in terms of sizing and dispatch strategy, when considering boundaries set by the location. Similarly, for evaluating new TES concepts and advanced CSP plant hybridization schemes. The underlying motivation is twofold:

- To support the decision making process of key actors along the project development value chain of a CSP plant (i.e. policy designers, project developers and plant operators).
- To suggest research paths to the scientific community (i.e. technical concepts, hybridization schemes and methods) that can lead to increasing the competitiveness of CSP plants.

In general, this PhD thesis is meant to represent a stepping stone for further research in the field of CSP plant design optimization with particular focus on supporting the research towards understanding the value that TES integration can deliver to the CSP plant.

2.1. Specific objectives

This thesis targets the following specific objectives:

- To develop and establish a flexible pre-design techno-economic tool, and related engineering services, for decision making and optimization of CSP plants with TES.
- To implement such a tool in techno-economic studies concerning:
    - The interrelation between the designs of the key component-blocks (sub-systems) available in a CSP plant with TES, namely the power block, the solar field and the TES block.
    - The interrelation between the contractual electricity pricing schemes, the optimum size of CSP plant components, and the optimum TES dispatch operation strategies.
    - The impact of TES integration on the levelized electricity costs and profitability of CSP plants.

  - The interrelation and comparison between key performance indicators typically used for evaluation of CSP plants, including but not limited to: the capacity factor, the investment, the levelized costs and the profitability.
- To demonstrate the use of such a tool for the techno-economic pre-feasibility evaluation analysis of:
  - New TES concepts when integrated in contemporary CSP plants with TES.
  - Innovative CSP plant hybridization schemes combining state-of-the-art CSP technologies with other proven and less capital intensive technologies for electricity generation, both fossil-fuel based and renewable.

2.2. Methodology

The method of attack of the research work can be split in two:

- The general investigation strategy followed with regards to the choice and order of power plant case studies analyzed in the thesis. This specifically concerning the choice of CSP plant technology, TES concepts, locations and hybridization schemes.
- The techno-economic process followed for the analysis of each power plant case considered in the study. This specifically concerning the model development, implementation work and criteria for analysis of the results.

2.2.1. General Investigation Strategy

This thesis comprises applied incremental research work rather than fundamental. The research work is problem oriented as it aims at understanding how to enhance the competitiveness of CSP plants, leveraging from its TES integration capabilities, through the usage and development of power plant performance models built upon existing techno-economic modeling approaches already known to the scientific community. Furthermore, the research is deemed quantitative as it is based on the analysis of performance indicators obtained from detailed calculation work and optimization models.

First, already commercial and most promising contemporary CSP and TES technologies were chosen for evaluation (i.e. molten salt tower CSP plants). For this technology, a techno-economic performance model was developed combining existing thermodynamic and theoretical sub-component models representing their physical behavior (§9.1). Moreover, for the evaluation of the plants and, most importantly, of the impact of component sizing and operating strategies, standard performance indicators were deployed as used in the industry (e.g. levelized cost of electricity and capacity factor), and in some cases with modifications.

The evaluation of non-yet commercial TES concepts and hybridization schemes was based following the same techno-economic modeling process as for the analysis of the molten salt tower plants.

The choice of the new TES technology to evaluate when coupled to contemporary CSP plant layouts, corresponded to concepts at a technology readiness level (TRL) below or equal to 4 (basic technology research to feasibility status). The two new TES concepts evaluated throughout the PhD research corresponded to promising technologies and theoretical models being developed by research partners in parallel to this thesis (§6). The aim was to adapt such theoretical models and implement them into the existing techno-economic power plant models developed in this thesis, to at last evaluate the feasibility of the systems when varying critical sizing parameters. In this thesis, the modeling and evaluation of one of the concepts is explained in detail in §9.2.

Oppositely to the choice of TES concepts, the choice of the new hybrid power plant schemes studied was based solely on the combination of one of the most economically competitive CSP plant layouts (i.e. molten salt tower plants) with another less expensive and mature technology for electricity generation (TRL 9), for both fossil-fuel and renewable cases.

This thesis comprises the techno-economic feasibility analysis of a hybrid solar combined cycle composed of a topping gas-turbine plant and a bottoming molten salt tower CSP plant. The performance of this system was evaluated on the basis of its levelized cost and the specific emissions for different key component sizes and operating schemes. Results for most promising configurations were compared with the performance of conventional combined cycle power plants, in order to identify main competitive advantages (§9.3.1).

Moreover, the feasibility of a promising hybrid CSP-PV power plant concept for firm power generation at a high capacity factor objective was analyzed. The techno-economic evaluation of such a system was performed on the basis of levelized cost of electricity and capacity factor.

Optimum CSP-PV hybrid configurations identified from the analysis were compared against the performance of optimum standalone CSP plant and PV plant configurations, respectively, in order to pinpoint main competitive advantages and most sensitive assumptions (§9.3.2).

The locations chosen for all the case-studies corresponded to active markets for CSP technology (i.e. Spain, South Africa and Morocco). The source of the required model input data and information was a mixed between open literature, industry reports and also direct input from industrial co-authors at later stages of the thesis.

Conclusively, all key findings from the performance modelling of the systems analyzed were compiled and discussed to provide general recommendations for its future continuation in support of the field. The latter is done at the end of this thesis.

2.2.2. Techno-economic Modeling Process

For all case studies considered in this research, a techno-economic analysis methodology was applied. This methodology comprised the following main modeling steps: the power plant steady state design and component sizing, the dynamic simulation, and the output data post-processing phase. The post-processing phase involved the calculation of the performance indicators of different nature: financial, environmental and technical. The choice of the indicator varied for each case depending on the research question being addressed.

Further detailed explanation about the techno-economic modeling process can be found in sections §5.1 and §7.1, which deal with techno-economic modeling for CSP and with the software tool that was used and further developed in this thesis, respectively. Moreover, all relevant input and model details for each of the power plant cases evaluated can be found in each of the articles appended to this thesis, all of them briefly explained in Chapter 9.

2.3. Summary of Main Contributions to State-of-the-Art

The present work is a thesis by publication. Table 1 summarizes the main contributions of each research article to the state-of-the-art and provides an overview of the publication timeline. The contributions and the link between the papers are discussed in more detail in §9. An overall contribution of the thesis to the state-of-the-art is provided in §10.

Table 1: Summary of main contributions of the papers appended in this PhD thesis

<table>
<tr><td colspan="2">Paper I: “Enhancing the Profitability of Solar Tower Power Plants through Thermo-economic Analysis Based on Multi-objective Optimization”</td></tr>
<tr><td>Research Topic</td><td>Techno-economic Optimization of Solar Tower Plants</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at SolarPACES 2014 / Energy Procedia Vol. 69</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• A multi-variable techno-economic optimization method for the pre-design of solar tower plants is introduced.
• A pre-defined dispatch strategy routine is presented and proven to have an impact in the financial performance</td></tr>
<tr><td colspan="2">Paper II: “A Methodology for Determining Optimum Solar Tower Plant Configurations and Operating Strategies to Maximize Profits Based on Hourly Electricity Market Prices and Tariffs”</td></tr>
<tr><td>Research Topic</td><td>Techno-economic Optimization of Solar Tower Plants</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at ASME Power Energy 2015
Journal of Solar Energy Engineering Vol. 138</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• Applies sub-system optimization for the analysis of CSP plants under different price and operating regimes.
• Provides quantitative analysis to argue the use of profit base indicators combined with LCOE and others.</td></tr>
<tr><td colspan="2">Paper III: “Techno-economic Performance Evaluation of Solar Tower Plants with Integrated Multi-layered PCM Thermocline Thermal Energy Storage – A Comparative Study to Conventional Two-tank Storage Systems”</td></tr>
<tr><td>Research Topic</td><td>New Storage Concepts for Solar Tower Plants</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at SolarPACES 2015 / AIP Proc. Vol. 1734</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• A new TES concept for solar tower plants is introduced.
• A model of the new concept is developed and validated.
• New TES concept is compared against state-of-the-art
• Future research work for the new concept is outlined.</td></tr>
<tr><td colspan="2">Paper IV: “Enhancing the Economic Competitiveness of CSP Plants through an Innovative Integrated Solar-Combined Cycle with Thermal Energy Storage”</td></tr>
<tr><td>Research Topic</td><td>New Hybrid CSP Concepts</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at ASME Turbo Expo 2014
Journal of Gas Turbines and Power Vol. 138</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• A new hybrid concept based on the combination of gas turbines and molten salt solar tower plants is introduced.
• A model of the new hybrid concept is developed.
• New concept is compared against state-of-the-art.</td></tr>
</table>

<table>
<tr><td colspan="2">Paper V: “A Techno-Economic Analysis of Hybrid Concentrating Solar Power and Solar Photovoltaic Power Plants for Firm Power in Morocco”</td></tr>
<tr><td>Research Topic</td><td>New Hybrid CSP Concepts</td></tr>
<tr><td>Conference and/or Journal</td><td>Journal of Solar Energy Engineering
(submitted in June 2016)</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• A hybrid concept based on the combination of PV and molten salt solar tower plants is presented and assessed
• A model of the new CSP-PV concept is developed.
• A multi-variable techno-economic optimization model for PV-BESS utility-scale plants is presented.
• The new concept is compared against state-of-the-art.</td></tr>
<tr><td colspan="2">Paper VI: “Thermo-economic Optimization of Solar Thermal Power Plants with Storage in High-penetration Renewable Electricity Markets”</td></tr>
<tr><td>Research Topic</td><td>On the additional value of TES for CSP</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at ISES Solar World Congress 2013
Elsevier Energy Procedia Vol. 69</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• Shows impact of CSP sub-system design considerations (i.e. TES size) when performing scenario analysis</td></tr>
<tr><td colspan="2">Paper VII: “Reducing the Number of Turbine Starts in Concentrating Solar Power Plants through the Integration of Thermal Energy Storage”</td></tr>
<tr><td>Research Topic</td><td>On the additional value of TES for CSP</td></tr>
<tr><td>Conference and/or Journal</td><td>Presented at ASME Turbo Expo 2013
Journal of Solar Energy Engineering Vol. 137</td></tr>
<tr><td>Contributions to state-of-the-art</td><td>• Quantifies the impact of TES integration on the cycling operation of power blocks in CSP plants.
• Introduces the concepts of equivalent operating hours and maintenance requirements to CSP plant analysis</td></tr>
</table>

3. Concentrating Solar Power Plants

The share of renewable energy technologies in the global energy mix has been steadily increasing, particularly with regards to the electricity sector [1]. The causes of this trend are numerous and can be mainly attributed to several global challenges [2]. These challenges, which include the need of alternative sources of energy, climate change and sustainable development, have been stimulating technological advancements in the energy sector. However, if climate change goals are to be realized (i.e. keeping temperature increase to 2°C by 2050), these clean energy technological developments must be accelerated [2].

A promising source for the generation of clean energy is solar energy. Solar energy is the most abundant energy resource on Earth, with approximately 885 million TWh of energy reaching the planet surface every year [2]. This amount of energy can well cover the annual energy consumption of the entire human population, estimated at 104,426 TWh by 2012 [3]. The fact, however, that the solar flux distribution over the surface of the planet is non-uniformly distributed, and is constantly changing, represents a large technical challenge. This is deemed as one of the reasons why solar power has not been harvested to its fullest in the past. Figure 1 shows the solar radiation map worldwide, measured in terms of typical annual global irradiance values. It is shown that some locations are more suitable than others for solar power deployment.

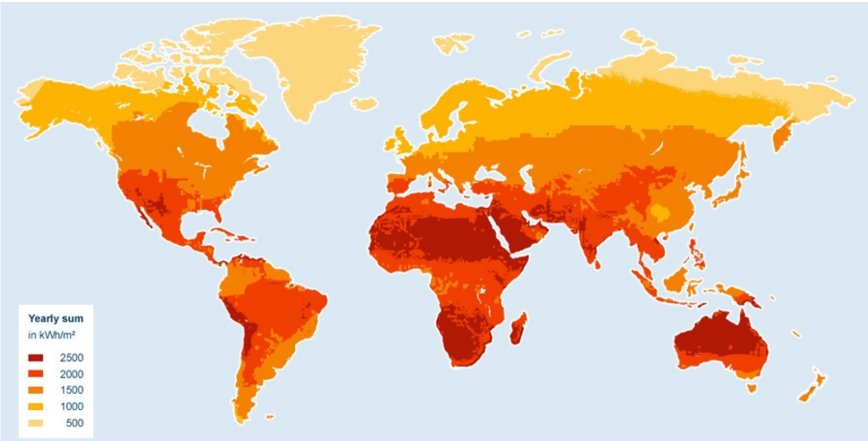

Figure 1 Global Irradiance Worldwide as extracted from the Meteonorm dataset [4]

Nevertheless, recent technology advances and cost reductions, pushed by policies reflecting the need for accelerating clean energy development, have led to the competitive penetration of solar power in suitable markets (e.g. South Africa), and in other well-developed nations (e.g. Germany). There are only two main types of solar energy technologies widely spread today that can harvest this abundant energy resource, these are solar photovoltaics (PV) and concentrating solar power (CSP). The latter, being the main subject of this thesis, is the focus of this chapter.

Concentrating Solar Power (CSP) is a technology where solar energy is collected and concentrated to form a high-temperature heat source, which can be used to provide heat (e.g. for industrial processes) or electricity as a final product. Specifically, in a CSP plant, the solar direct irradiation is collected by means of a field of mirrors called solar collectors, which concentrate the energy into a receiver. Here energy is absorbed to generate a source of high-temperature heat. This heat can be used to drive a conventional power cycle and ultimately generate electricity. The fact that high-temperature heat is generated as an intermediate step allows a CSP plant to incorporate cost-effective thermal energy storage (TES) systems that enable the plant to store the energy for a later use. Similarly, being coupled to conventional power generation cycles makes the technology flexible enough to allow for hybridization with other more-conventional fossil-fuel fired heat sources. This process is roughly summarized by the schematics shown in Figure 2.

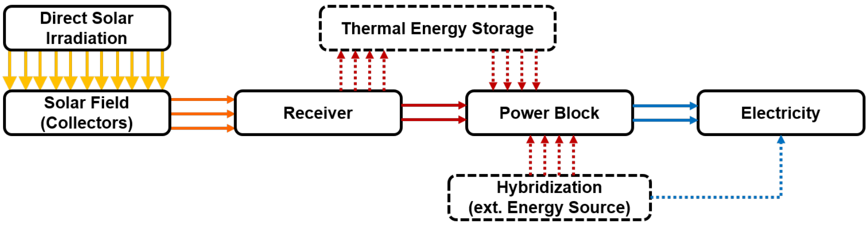

Figure 2 Schematic flow diagram of the processes in a CSP plant

The possibility to provide controllable power on demand, either through TES integration or through hybridization, is what makes CSP plants *"dispatchable"*, which is one of their main competitive advantages. Indeed, besides biomass, CSP is one of the few renewable dispatchable alternatives that have already penetrated the market of large power generation. As a consequence of its dispatchable attribute, a CSP plant can be designed to fulfill different roles in the electricity system. Figure 3 shows a characteristic hourly load demand curve for a sub-tropical location. In this figure, the power demands (in [MW]) are plotted for each hour of the day. Three demand loads can be identified: the base load, the intermediate load, and the peak load [5].

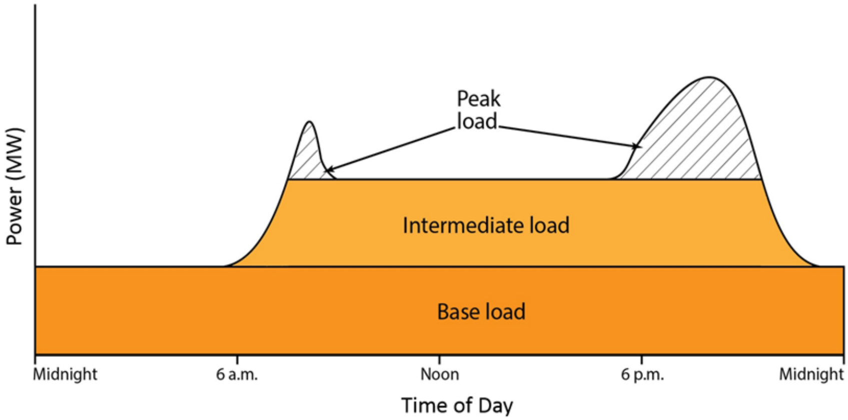

Figure 3 Example of a Characteristic Daily Power Demand Curve

The base load can be understood as the minimum level of demand on an electrical supply system over 24 hours. It is characterized by plants with lower generation costs and high capacity factors (e.g. coal, nuclear, and hydropower). The peak load refers to a period during the day where the demand is considerably higher than the average. Peak load variations can be seen on a day-to-day basis, monthly and even seasonally. Peak loads are covered by power plants often referred to as mid-merit plants and *"peakers"*. In most of the cases, peaker plants are required to have high flexibility in terms of start-up times and capabilities for load regulation. Lastly, the intermediate load is the load band in between the expected demand and the base load and is also covered by mid-merit power plants, but these are subject to less variations in their operation.

A CSP plant, including its sub-systems and operating schemes, can be designed to fulfil each of these market roles in the electricity system. The following sections are aimed at providing an understanding of the key component blocks in a CSP plant (i.e. the solar field -*including the receiver*-, the TES system and the power block), the main technologies available for each, and the contemporary CSP plant layouts.

3.1. The Solar Field

The solar field (SF) block is the responsible for concentrating the solar radiation, thus producing the heat at high temperatures. It is composed of three key elements: the collector field, the receiver and the heat transfer fluid (HTF). The HTF being understood as the heat carrier, a fluid passing through the receiver and that is able to transport the energy. The SF is often categorized according to two main criteria:

1. Fixed or Mobile receiver type SFs.
2. Line or Point focus collection systems.

In a fixed type receiver SF, the receiver is a stationary device that remains independent of the focusing collector, easing the transport of the heat to the power block (also often stationary). In contrary, in a "mobile receiver type" the receiver moves along with the collector, which in theory allows it to enhance its optical efficiency and thus to capture more energy.

Concerning the second criteria, line focus SFs are composed of collectors able to track the Sun's position only along a single axis, focusing the energy on a linear receiver (e.g. tubular). Oppositely, point focus SFs are composed of mirrors with a two-axis tracking mechanism, allowing each to focus the radiation at a single point. This increases the optical efficiencies and allows reaching higher temperatures at the receiver. The four key SF technologies are briefly described next.

Parabolic Trough CSP technology

Parabolic Trough (PT) collectors are linear-focus mobile collectors, formed by parabolic shaped mirrors that focus onto a tubular receiver [6]. It is the most mature among all CSP technologies and covers roughly 85% of the global CSP installations to date. The technology can be seen both in schematics (left) and under real operation (right) in Figure 4. In PT concentrators the HTF (usually oil [7]) is passed through the receiver, which usually consists of a metal pipe enclosed by a vacuumed tube (to minimize convection losses). The collector is able to track the path of the Sun on its longitudinal axis. To date, due to HTF property limitations, conventional system are capped to 390 °C. Research is placed on increasing the mirror area and improving the HTF properties. The heat carried by the HTF is commonly used to generate steam in a steam- cycle, for instance. A schematic of the typical PT CSP plant is shown in §3.5.2.

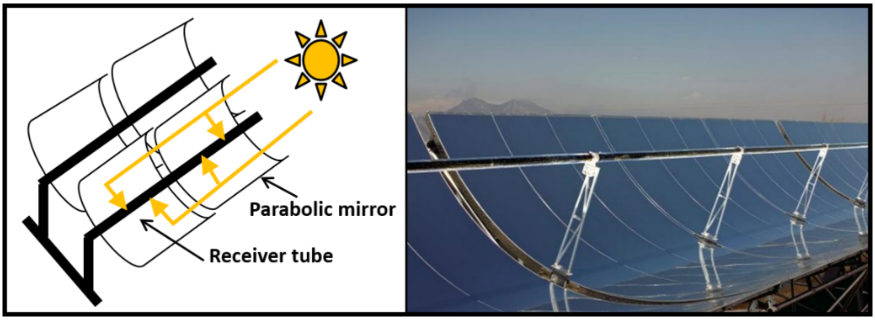

Figure 4 Parabolic Trough Collectors. Schematics (left) and real operation (right) [8]

Linear Fresnel CSP Technology

Linear Fresnel (LF) reflectors are analogues of PT collectors. LF collectors are composed of multiple long row flat mirror segments with focus on a fixed linear receiver, as can be seen on the left side of Figure 5. The flat mirrors rotate simultaneously to maintain the focus on the receiver, giving considerable freedom of design. Compared to PTs, these systems have the advantages of a low profile and less complex fixed structure, thus potentially leading to lower costs. However, the lower costs have not seem to compensate for the lower efficiencies, which is why these systems yet remain less deployed than PT collectors [9].

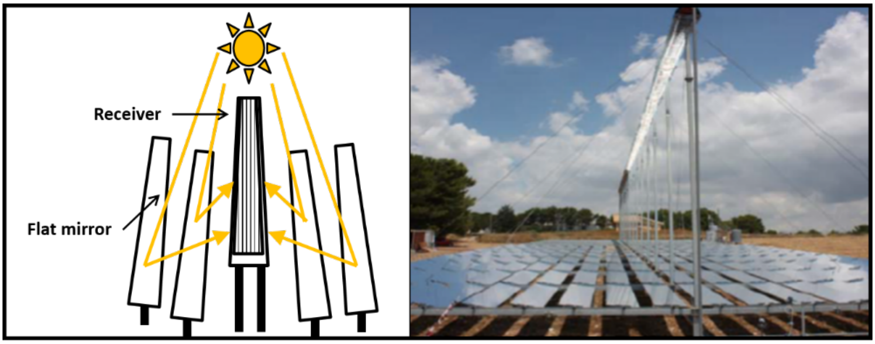

Figure 5 Linear Fresnel Collectors: Schematics (left) and real operation [10]

Central Receiver CSP technology

Central receiver (CR) systems consist of an array of tracking mirrors called heliostats, which concentrate the direct radiation onto a central receiver placed in an elevated support, usually referred to as the tower (Figure 6 left). These systems are also referred to as '*solar tower power plants*' (STPPs). This is the fastest increasing technology to date [9], accounting for approximately 14% of the CSP installed capacity [11]. An aerial photo from the Gemasolar molten salt solar tower power plant (MS-STPP) in southern Spain can be seen on the right side of Figure 6.

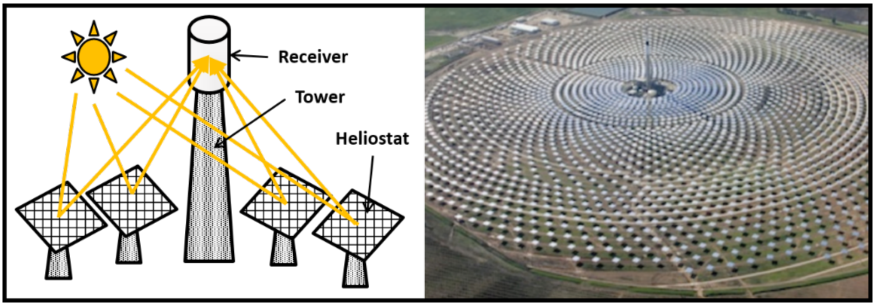

Figure 6 Solar Tower Plant: Schematics (left) and under real operation (right) [12]

In STPPs, the solar-to-heat and heat-to-electricity conversion processes occur in a confined area, which eases the operation [12][13]. Other advantages of such a technology are: it can reach higher temperatures than PTs; several commercially available TES systems can be integrated; and it has a great potential for efficiency improvements and cost reductions, given that it is still a young technology [9].

STPP configurations vary according to the type of HTF and TES system considered. To date, HTF options include air, molten salts or water/steam. When water is used as HTF in a CSP plant, it receives the name of a direct steam generation (DSG) system. Water is used as HTF in a number of STPPs, often called DSG-STPPs. One big advantage of DSG systems is that no intermediate heat carriers are needed, which decreases the conversion losses along the system. However, DSG-STPPs have a major disadvantage, which is that, to date, no cost-effective TES system exists for such a technology. This is later described in §3.2 and §3.5.3.

On the contrary, molten salts can be used both as HTF and TES media, therefore potentially reducing the number of components and the costs of integrating the TES system. Out of these reasons, MS-STPPs are rapidly becoming one of the preferred CSP technologies. The layout of a MS-STPP is described in detail in §3.5.1

Lastly, the high temperatures that can be reach by STPPs make it a suitable technology for using air as HTF in order to drive a gas turbine (GT). Although promising, this has not been proven at large scale, and yet needs to overcome several technical limitations. Two of these limitations are: the maximum allowable temperature of the materials used today for the receivers, and the development of a suitable TES system [14].

Parabolic Dish CSP Technology

Parabolic dish systems (PDs) consist of an array of mirrors forming a shape similar to a circular paraboloid section. They concentrate the energy into the focus point, where a receiver is mounted. PDs employ a two-axis tracking mechanism that allows the system to have the highest optical efficiency among all commercial concentrators, and thus enables it to reach higher temperatures. The heat collected in the receiver is either used locally by an engine, or transferred to a ground based plant. The most common use of this technology today is based on the adoption of Stirling engines. PDs using Stirling engines have proven the highest solar-to-electricity efficiency among all solar commercial applications (close to 30%) [15]. Another advantage of a PD system is its modularity. The key components in a PD-CSP technology (i.e. the dish concentrator, the receiver and the power block) can be seen on the left side of Figure 7, where a simple schematics of the technology is shown.

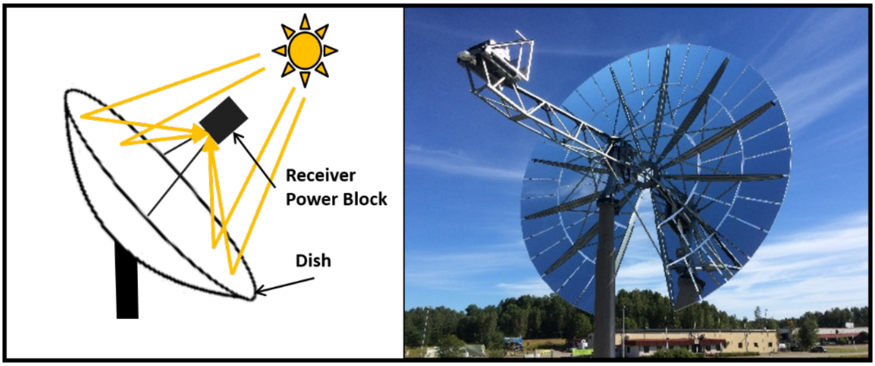

Figure 7 Parabolic Dish Systems: Schematics (left) and under real operation [17]

However, this technology is still today at demonstration scale. The costs and the lack of a commercial TES solution have stopped its broader penetration into market. There are, though, vast opportunities for cost reductions through high-volume production of the units. Besides, the potential integration of a TES system can also be deemed as disruptive. It is such a potential for cost-reduction and TES integration what makes the technology still worth of investigation.

3.2. The Thermal Energy Storage (TES) System

Energy storage is the storing of some form of energy that can be drawn upon at a later time to perform useful operation [18]. In the case of TES, heat is the useful energy that circulates in the storage system. CSP plants have the possibility to integrate cost-effective TES systems and thereby supply controllable power on demand [19]. This is a clear advantage against other renewable energy technologies. At pre-design stage, a number of TES concepts and materials can be considered depending on the CSP plant layout, the heat capacity and temperature requirements, and very importantly the desired operation strategy [19].

Indeed, depending upon their configuration (layout, component size and operation), CSP plants with TES can fulfil very different market roles. The IEA Solar Technology Roadmap identifies a number of key roles for CSP plants [2]. A first possible role is the provision of reliable and dispatchable baseload and mid-merit power in a future high-renewable penetration market, where CSP can form the back-bone of the electricity grid. Secondly, the provision of rapid-response peaking power to compensate for fluctuations in other, non-dispatchable, renewable energy technologies such as wind and solar PV. For a given CSP plant layout and TES concept, depending on the desired market niche, different sizes and operation strategies can be adopted for the TES system.

This section provides an overview of the state-of-the-art of high temperature TES applications for CSP plants. In this section TES systems are first classified and explained according to the storage media. Then the differentiation between active and passive TES concepts is introduced. Lastly, a summary of the TES concepts deployed today in large CSP plants and some other promising concepts is provided.

3.2.1. TES Classification according to the Storage Media

The storage media refers to the material used for storing the energy. According to the storage media, a TES system can be classified as sensible, latent and thermochemical. To date, sensible TES systems are the most commercially deployed [9][11][20].

Sensible Heat Storage

Sensible TES (S-TES) refers to the thermal energy that can be stored due to the change of temperature of a substance experiencing an internal energy change [18][21]. Density and specific heat of the material to be used are of main relevance for the technical design of a TES system. Other critical properties to consider are the desired operational temperatures for the system, the thermal conductivity of the media, the media vapor pressure, its compatibility with other materials and its stability [18][19][21]. S-TES systems mostly consist of a storage medium, a container and inlet/outlet devices. S-TES systems can make use of solid or liquid media.

Solid media is usually seen in forms of packed beds having a heat exchange fluid passing thru them [21]. When the fluid is a liquid then the system is called a dual TES system. An advantage of such systems is the use of easy-to-process and relatively inexpensive solids (e.g. rock or concrete). Concrete has shown high specific heat, good mechanical properties and high mechanical resistance to cyclic thermal loading. The main disadvantage for solid media systems is, though, that they manifest low heat storage density and higher thermal losses [22]. Most commonly used materials for CSP are castable ceramics and concrete [18][20][22].

Liquid media, mainly in the form of molten salts or oils, guarantee the desirable thermal gradient and have been widely preferred also for their higher heat capacity and conductivity [18]. Molten salts (MS) have come to dominate the landscape of TES systems for CSP applications. The main reasons for such are that these salts are liquid at atmospheric pressure, they can also be used as HTF, and their working temperatures are ideal for high temperature steam turbines [18]. In addition to this, experience with this kind of media existed already from the chemical and metal industries as HTF [18][19][21]. The most common MS in the CSP industry is the HitecXL, or so-called '*solar salt*' which consists of a mixture of $NaNO_3$ and KNO_3 (60/40 %) [18][20][23].

Latent Heat Storage

Latent TES (L-TES) involves the storing capability of some substances during the phase change [21]. The phenomena takes place at a constant temperature and can involve the latent heat of phase change during fusion (solid-liquid transition) or during vaporization (liquid-vapor transition) [23]. Nowadays, though, mainly the solid-liquid transition has been studied [20][24]. Substances which are used to store energy during the phase change are called Phase Change Materials (PCM). PCM-TES systems can be smaller in size compared to S-TES systems given that their storage density is higher, which is a key advantage. Among the options available, organic PCMs have revealed excellent thermo-physical properties, congruent freezing and melting processes, thermal stability and non-corrosiveness [18][24]. In the case of CSP, $NaNO_3$ and $LiBr$ based PCM salts are worth mentioning as they can have melting points around 307 °C and 550 °C, respectively, similar to the operating range of the more conventional solar salts used in S-TES systems [18].

The main drawback for PCMs is their low thermal conductivity, which is connected to lower charging and discharging rates [24]. In addition, PCMs can be complex to handle, they induce a thermodynamic penalty to the operation due to shift between sensible and latent heat, and there is uncertainty over its lifetime under high-cycling performance [24]. To overcome these issues, innovative heat exchanger designs with different geometrical configurations containing the PCM have been proposed, so that the contact area is extended and the heat exchange enhanced (e.g. through encapsulation or finned tubes)[20][26]-[31].

Thermochemical Heat Storage

Thermochemical heat storage is an advanced TES mechanism that consists on exploiting the enthalpy of reaction of reversible chemical reactions [18]. During the TES charging process the heat produced by the solar field is used to induce an endothermic reaction. Then during the discharging, the reverse exothermic reaction takes place, releasing the necessary heat to the HTF. To do so reactions must be fully reversible [18][32]. The technology is promising as it can offer much higher storage densities than S-TES and L-TES solutions [33]. Thermochemical TES concepts, though, are still in their early research and development phase for use in industrial applications, especially for CSP [18][33].

3.2.2. TES Classification according to the Storage Concept

TES systems can be classified as active or passive according to the heat transfer mechanism between the HTF and the storage media [18]. Figure 8 shows a simple representation such a classification. Furthermore, when designing a TES system, it can be composed of a combination of separate active and passive TES concepts (sub-parts). In the following, active and passive TES systems are described.

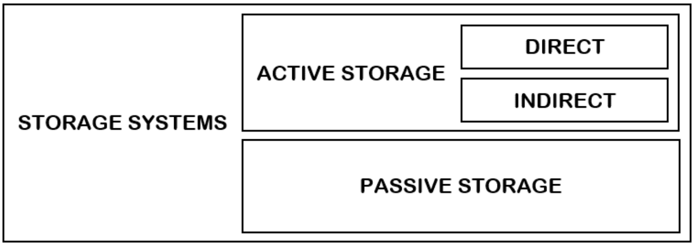

Figure 8 TES classification according to the concept and heat transfer mechanism [18]

Active TES Systems

In active TES systems the TES media circulates through a heat exchanger during both charging and discharging processes. In these systems often one or two insulated tanks are required as containers for the TES media. Active systems are classified as direct or indirect depending on if the HTF and the TES media are the same. A simple schematic of a two-tank direct TES system can be seen on the left side of Figure 9, when integrated in a typical MS-STPP layout, as is also described later in §3.5.1.

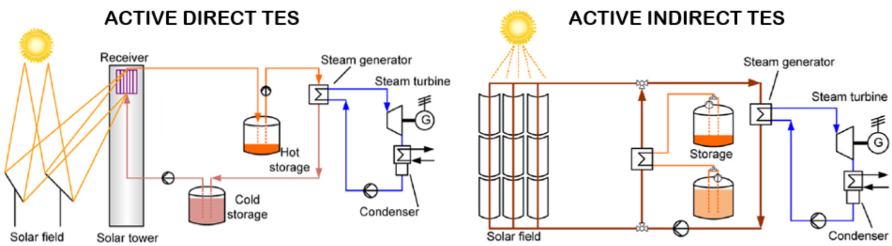

Figure 9 Schematics of active TES concepts in conventional CSP plant layouts [35]

Similarly, Figure 9 also shows to the right a two-tank indirect TES system when integrated in a typical parabolic trough CSP plant layout, also described later in §3.5.2. The two-tank active TES concept, either direct or indirect, using molten salts as TES media is the most deployed TES system in operating CSP plants to date [11].

Direct Active TES systems

In direct active TES systems the TES media used is the same as the HTF (or the power block working fluid). Typical TES media are molten salts, oil or even steam (e.g. in DSG plants). The use of a same material eliminates the cost of having extra heat exchangers which can potentially allow the power block to be operated at higher temperatures. This, in turn, can positively impact the efficiency of the system. To date, the most commonly deployed concept relates to the direct molten-salt two-tank system, similar to the one shown on the left side of Figure 9. Another concept under this classification is the single-tank molten salt system, where both hot and cold fluids are stored in the same tank (usually separated through a mechanical barrier). The latter, though, has not been fully deployed commercially as, despite potentially reducing costs, the tank and the barrier would be constantly exposed to severe thermal stresses under cycling operation, which could affect its lifetime [18][23].

Indirect Active TES systems

Contrary to direct active TES systems, in an indirect active TES system an intermediate medium is used as HTF, different to the TES media. This implies that an intermediate heat exchange process is required. Indirect active TES systems in the form of the two-tank indirect molten salt system are the most deployed concept in CSP plants today [11]. The latter is mainly because it has been considered in the layout of the typical oil-driven (HTF) parabolic trough CSP plant, which is explained in §3.5.2. A simple schematic representation of the two-tank indirect active TES system integrated in a CSP plant can be seen on the right side of Figure 9.

Passive TES Systems

Passive TES systems are usually dual medium TES systems in which the HTF passes though the TES material in order to charge it or to discharge it, correspondingly [18]. In passive systems the TES media itself does not circulate. Usually the TES media is solid (i.e. concrete or solid PCMs). The main disadvantage of these systems is that the HTF temperature decreases during the discharging process as the TES cools down [18][23]. Another potential disadvantage is in relation to the thermal cycling of the solid TES media, which can affect its lifetime.

3.2.3. Commercially deployed TES systems for CSP plants

By combining different TES media and concepts, multiple TES systems can be designed and ultimately integrated into a CSP plant. Today a number of TES systems have reached commercial maturity for CSP applications, and others are undergoing large-scale demonstration. The aim of this section is to briefly introduce the state-of-the-art of TES systems already available, or soon in their way to, for CSP applications.

Two-Tank Molten Salt Systems

Nowadays the two-tank TES systems are the most acquainted technology in CSP plants [11][2]. Two-tanks TES systems are S-TES systems that in the majority of the cases use molten salts as TES media. As mentioned earlier, these systems belong to the category of active TES systems as the molten salt itself is circulating through a heat exchanger during charging and discharging. Two-tank molten salt systems are found today in both presentations: direct (e.g. MS-STPPs) and indirect (e.g. parabolic through CSP plants). Figure 10 shows two operational two-tank systems. On the left side, the two-tank system of an operational MS-STPP is highlighted [12]. On the right side, the TES system of the '*Andasol I*' parabolic trough CSP plant is shown [36].

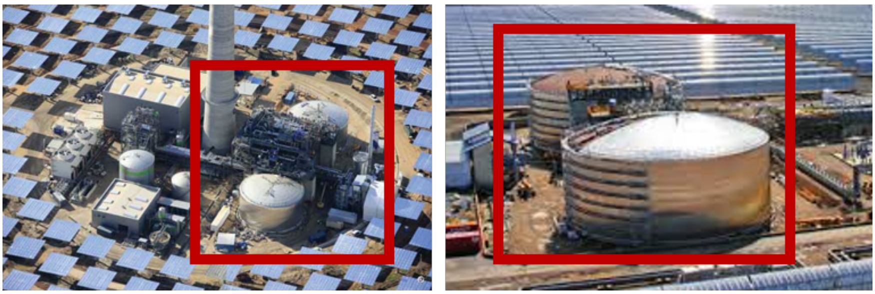

Figure 10 Two-tank TES systems in Gemasolar (left) and in Andasol I (right) [12][36]

The main advantage of the two-tank TES system is the ease for controlling the charging and discharging processes [23], and thereby the smooth integration with the rest of the power plant blocks (i.e. the solar field and the power block). Their main disadvantage, though, is that it requires two similar insulated tanks of large volume to act as buffers [18]. In these systems, each tank has the capacity to store the whole volume of TES media available in the plant. This requires large investments. Moreover, the use of molten salts as preferred TES media imposes the limitation of the working temperature range for the system. Commercial salts today are characterized for having a maximum operating temperature of approximately 580°C, which matches the operation of commercial steam-cycles, but they also characterize for having a high freezing point of 250°C. This last adds additional complexity to the system, such as the need for additional preheating stages in the power block, and also the need for installation of electric heat-tracing systems along the pipes in the TES system [18][23].

In the case of indirect two-tank TES systems integrated in parabolic trough plants the freezing point issue becomes more relevant. Because of the freezing point of the molten salts and the properties of the oils used, the power cycle in these systems is restricted to operate between 250°C and 390°C (approximately), which negatively impacts the efficiency of the system. Secondly, additional heat exchangers are needed, which can further increase the required investment for the TES system.

Two-tank TES systems can be found today in a number of parabolic trough plants and MS-STPPs under operation [11]. In addition, the majority of the projects under development or construction also include these systems [9][11]. This is mainly because the industry has learned best practices for design operation and installation of these systems [13]. Also because associated material costs have decreased with experience and with new actors getting involved [13]. To improve these systems, most of the research today is focused on the enhancement of the TES media properties (e.g. improved or new molten salts) [18][23].

Steam Accumulators

Steam accumulators use sensible heat storage in the form of pressurized saturated liquid [37]. These are active direct TES systems. In these systems the charging occurs when the surplus steam from the cycle is fed into a container with pressurized liquid water volume [18]. This results in a condensing steam that increases the temperature as well as the pressure of the liquid volume, which ultimately acts as a storage volume for the steam. The liquid is stored in a horizontal cylinder in which 90% is saturated liquid and the rest is saturated steam [37]. The main advantage of storing liquid, and not directly steam, is the higher volumetric capacity and therefore higher energy density. During the discharge phase, steam is subtracted from the vessel and the pressure of the liquid decreases. Since water can be both TES media and working fluid, high discharge rates are possible [37][38]. Figure 11 shows both a simple schematic of the steam accumulator on the left and also a real steam accumulator in operation in a CSP plant on the right.

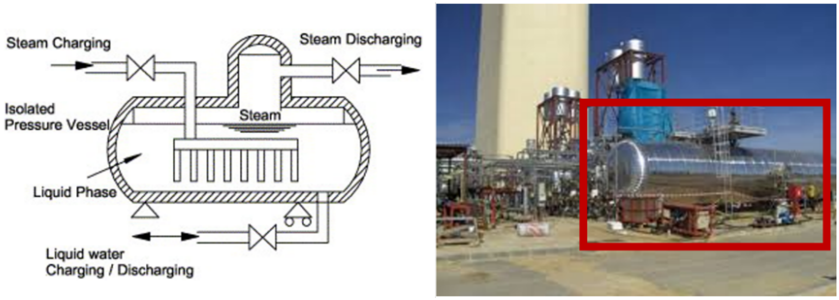

Figure 11 Steam accumulators: schematics (left) and in real plants (right) [37]

Another advantage of steam accumulators is that they have been previously used as buffers in other heat demanding industries [38]. However, the main disadvantage of these systems is that, due to the high pressures involved, the tanks are limited in volume, which means that often several accumulators are needed per plant. Moreover, the higher the operational pressures, the higher the involved costs. In turn, these systems are only viable today at lower operational temperatures (i.e. 300 °C) than what can be handled by high-pressure turbines, and are thus inefficient and not economically attractive at large scales [40]. Instead, these systems can be used for short peak power production or for regulating the steam load during cloudy passages [40].

Steam accumulators have been installed in a number of CSP plants [11], mainly as they seem a natural choice to integrate in DSG plants. However, with the reduction in cost and the large scale applicability of other TES systems, even DSG plants under development are considering different and more innovative concepts for TES [20].

High-Temperature Concrete Storage Systems

The use of relatively inexpensive concrete based materials for S-TES concepts has been considered as a promising cost-competitive TES system alternative [22]. Nevertheless, as mentioned in earlier sections, using concrete involves the complexity of accurately designing the heat exchanger (e.g. in form of embedded pipes) and puts a question mark on its durability [18]. These two main reasons have impeded the deployment of TES technologies using such a media in a large-scale CSP project.

A commercially available concrete-based solution is shown on the right side of Figure 12 while undergoing field tests [41]. This is based on a heat exchanger design similar to that shown in the left of the figure, as originally proposed by [22], and covered by a storage insulation box [42]. Designers of this concept claim that it can withstand cyclic operation for temperature ranges varying from 50°C to 565°C. They also ensure that the concept is scalable, durable and thus perfectly suited to meet medium to large scale storage requirements [42]. They also claim that such properties withhold for a number of different HTFs. To date, tests are being performed using oil as HTF [41], but the demonstration of such a concept for water-steam as HTF could eventually represent a disruptive technology for integration in direct steam generation plants.

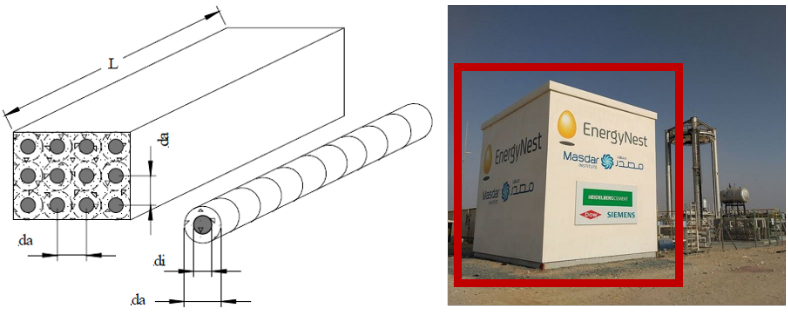

Figure 12 Concrete TES system: schematics (left) and real demonstration (right) [43][41]

3.3. The Power Block

A number of conventional thermodynamic power blocks can be used for electricity generation in CSP plants. The choice of the power block mainly depends on the temperature that can be reach in the receiver [14]. Therefore some power cycles are more suitable for specific CSP technologies than for others. To date, all CSP plants make use of commercial power block solutions. Table 2 provides an overview of the different power cycles available for CSP applications, along with the relevant temperature ranges and their typical cycle efficiencies [14].

Table 2: Typical Power Generation Cycles for CSP applications (adapted from [14])

Power Cycle	Working Fluid	Temperature Range	Cycle Conversion Efficiency
Rankine	Organic Fluid	< 250°C	10 – 20 %
	Water / Steam	250 - 600°C	30 – 40 %
Stirling Engine	Helium	600 – 850°C	30 – 50 %
Brayton	Air	> 850°C	30 – 40 % (Simple Cycle)
			45 – 60 % (Combined Cycle)

Table 2 implies that the use of high-efficiency Gas-Turbine (GT) cycles (Brayton) in their simple or combined cycle configuration [44] (with a bottoming Rankine steam-cycle [45]) can be seen as one of the most promising options for CSP to increase its competitiveness [14]. GT cycles, though, are able to reach high efficiencies only when operated at temperatures exceeding 1200°C. This imposes new challenges when considered for CSP applications. Two important ones are the material limitations (maximum allowed temperature) on the receiver side [14], and also the lack of commercial TES concepts for such high-temperatures [13] (being TES integration one of the main competitive advantages of CSP). In such regards, the use of GT for CSP applications yet remains an issue of research and development and no large-scale system has been built to date [11][13]. This topic has been the main subject of investigation of the techno-economic modeling work preceding this thesis, as is further explained in §7.2 [14].

Similarly, Table 2 shows that the use of Stirling engines for CSP applications is very efficient. Indeed, as mentioned earlier, Stirling engines can be coupled to PD CSP concentrators to reach the highest proven Solar-to-Electricity conversion efficiency amongst all commercial solar energy technologies for electricity generation [16]. However, the challenge to incorporate cost-effective TES solutions and the engine's maintenance requirements have led this technology to cover less than 1% of the installed capacity worldwide [11]. TES systems are complex to integrate in PD-Stirling applications mainly because of two reasons: first, the lack of commercially available TES media and concepts for the operating temperatures (from approximately 80°C to 850°C); and secondly, the complexity of integrating a TES unit in a system where all other components are movable (i.e. the dish concentrator, the receiver and the engine). However, the development of a suitable TES concept could well represent a disruptive solution for such a modular CSP system.

Summarizing, all large-scale cotemporary CSP applications for electricity generation to date are based on conventional Rankine water-steam thermodynamic cycle power blocks [45]. The reasons are:

- The technology is mature and thus have low associated risks.
- Operating temperature range matches that of commercially available TES concepts and media, thus effective integration with TES is deemed possible.
- Operating temperature range makes it suitable to a number of concentrating technologies (i.e. PT, STPP and LF).

This is likely to continue being so until new high-temperature TES concepts reach state of maturity [13]. Therefore, all case studies considered in this thesis (appended publications) were based on CSP plant layouts that involve a reheat Rankine steam-cycle.

3.4. CSP Hybridization

CSP hybridization is understood as the process of combining CSP technologies with other means of power generation. It is often related to the integration of fossil-fuel based components for backing up the operating conditions of the HTF (i.e. in the solar field) or also for boosting the operating conditions of the fluid driving the power cycle. However, due to its advantageous storage capabilities, hybridization of CSP with other more-established intermittent renewable technologies is also considered attractive as a means to provide firm, dispatchable and overall ‘cheaper’ output than a stand-alone CSP plant. For all cases, hybridization represents a design challenge in terms of identifying the optimal integration of the components from each system (i.e. in terms of size) and also the combined operation.

3.4.1. CSP Hybridization with Fossil-Fuel

One form of fossil fuel CSP hybridization is the integration of small solar field to a conventional fossil fuel thermal plant. For instance, the addition of a solar field to either a combined cycle or coal fired plant can lead to costs and CO_2 emission reductions [46] (less fuel consumption). Integrated solar combined cycles (ISCC) use solar fields to provide steam generation for use in a combined-cycle. The high temperatures achieved with solar towers could also be used to pre-heat pressurized air that is fed directly into a Gas Turbine. Excess heat can then be fed into a bottoming steam cycle to run a second generator. This type of setup could produce a solar to electricity efficiency of higher than 30% [2][13]. Similarly, solar boosters can be used in coal based thermal plants to boost the cycle efficiency, by preheating the feed-water into the boiler.

To date, a large number of operating CSP plants use fossil fuel backup systems, mainly for start-up purposes [47]. However these backup systems could also be utilized to complement the output from the TES system and thereby maximize the power output of the plant, depending on the desired operating regime (e.g. baseload). As such, it can be stated that hybridization can offer similar benefits than storage from the possibilities of offering controllable power, but certainly not from an environmental standpoint. In this way there is a cost vs. CO_2 emissions trade-off to evaluate when hybridizing a CSP plant with fossil fuels.

In any case, the most common form of fossil backup for CSP today is with a natural gas (NG) boiler. As mentioned in the introductory part of this section, most of these gas boilers (GB) are integrated within the HTF cycle [47]. However, energy is lost in the steam generation heat exchangers train and, therefore backup should ideally be integrated directly within the steam cycle when aimed at stabilizing production, unless it is used for preventing degradation of the HTF itself (e.g. to prevent oil or salts from reaching freezing points). In these regards, Peterseim et al. states that other enhancements to CSP backup boilers can be made to ensure that the boiler can efficiently operate through sharp DNI transients in order to guarantee stable turbine inlet conditions [47]. A similar hybrid concept is used in the Shams 1 CSP plant, where a GB is not used only as backup but instead also for boosting the inlet steam conditions in order to reach higher steam cycle efficiencies [47][49].

Lastly, fossil fuel hybridization is also possible by integrating diesel fuelled generators systems as backup instead of GBs. However, numerous advantages from using GBs instead, prevail from the commercial integration of such diesel generators. Some of these are the dirtier burning process in diesel fired generators (higher specific CO_2 emissions), and also the overall larger volatility and higher values for diesel costs compared to NG costs today, especially in some countries with high DNI.

3.4.2. CSP Hybridization with other renewables

It is possible to combine CSP with other thermal-based renewable technologies such as biomass-firing and geothermal energy power plants, by integrating a solar field in the process. This has been demonstrated by the 22 MW Termosolar Borges plant in Spain, where two biomass burners heat the HTF when the solar irradiance is insufficient [2]. The hybridization of CSP and geothermal power has also been demonstrated in the US, where a solar field is coupled to a 33 MWe geothermal plant [2], with the goal of increasing the efficiency of the system.

However, other potential means of CSP hybridization can occur when combining CSP with other 'cheaper' intermittent renewable technologies (i.e. wind and solar PV). This is done, for instance, with the objective of achieving a higher-capacity factor compared with PV, wind or even CSP alone; and potentially at a lower cost than an equivalent CSP plant [50][51](based on today's cost estimations [13][52]). This is deemed possible through the capabilities of CSP plant for integrating TES and hybridization. The main challenge, remains on the design of suitable smart-operating strategies and related controllers in order for the CSP plant to adjust its load in response of the output of the other technologies [50]. In general, the hybridization of CSP and PV can be deemed interesting given that both technologies require good solar resource conditions and can, in principle, complement each other in terms of one being 'cheap' (PV) and another one being fully controllable (CSP) [51]. This concept has gained momentum recently by several solar power plant developers [50][53], but yet remains new and challenging.

In this thesis, the feasibility of hybrid CSP-PV power plants is one of the study cases considered, mainly in response to the market demands for a high-capacity solar solution [54]. Moreover, in this thesis the feasibility analysis of a hybrid CSP (integrated with a backup GB) is performed when aimed at complementing the variable output of wind and PV farms in an isolated grid to meet a specific demand curve. This is done in an attempt to demonstrate the large flexibility potential of CSP plants.

3.5. Layout of contemporary CSP plants with TES

As mentioned in the previous section, all large-scale operational CSP plants are based on steam-turbine technology. The difference then lies on the different CSP technologies involved for raising the temperature in the water-steam cycle. Such CSP technology will determine the cycle operating conditions and, ultimately, the type of suitable TES or hybridization scheme, if any. Table 3 summarizes the typical operating conditions for contemporary plants according to the CSP technology type.

Table 3: Typical operating conditions of contemporary CSP plants (adapted from [14])

Power Plant Type	High Steam Temperature [°C]	High Steam Pressure [bar]	Power Block Size [MW_e]	TES size [h]
Parabolic Trough (oil)	370 to 385	80 to 150	50 to 250	0 to 8
Molten Salt Tower	540 to 550	80 to 150	20 to 150	3 to 15
Direct-Steam Tower	550 to 560	Up to 165	20 to 150	0 to 3

As is later discussed in the following section, the power plant types shown in in Table 3 add up to more than 95% of the total CSP installed capacity worldwide [11]. Therefore, these power plants were considered as the basis for the techno-economic performance models developed throughout the research. The performance models were built using their typical CSP plant layouts, which are described next. Although the three power plant types were modeled, in this thesis most of the work is focused on the MS-STPP configuration (6 out of the 7 papers appended). These plants are deemed by the author, and multiple other sources [2][13], as the most promising technology in the near term.

3.5.1. Molten Salt Solar Tower Power Plants (MS-STPPs)

Figure 13 illustrates the typical layout of a molten salt solar tower power plant (MS-STPP). In these plants, the solar field is composed of heliostats that concentrate the solar radiation onto a receiver mounted on the top of a tower. Molten salts are pumped from a “cold” TES tank (salts at approximately 265°C) up to the receiver where they are heated up to 565°C, and then sent to a “hot” TES tank for storage. The salts are then dispatched (drawn from the hot tank) to operate a Rankine cycle. As mentioned in section §3.3, the temperature limitations in these plants is due to the properties of the so-called ‘solar salts’, which are the characteristic molten salts used as HTF in these plants.

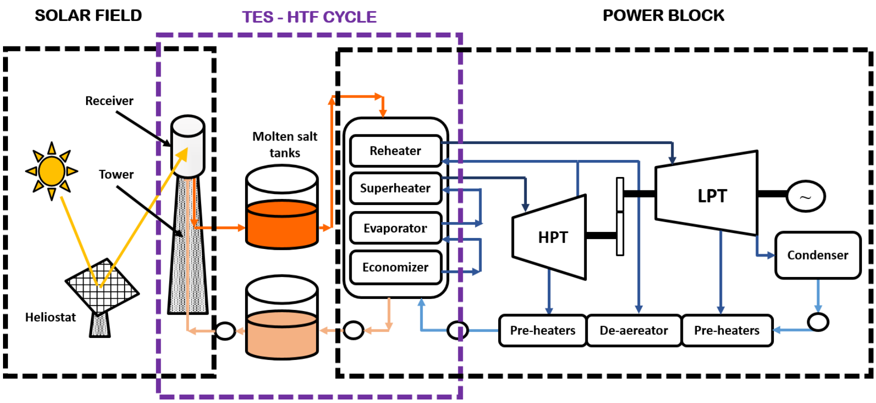

Figure 13 Layout and main component blocks of contemporary MS-STPPs

The three main design blocks in these systems can be seen in Figure 13, these are the Solar Field (SF) block, the TES-HTF Block and the Power Block (PB). The SF block includes the heliostats, the tower and the receiver. In these systems the TES block is the same as the HTF cycle as molten salts are used both as TES media and HTF (orange lines). Main parameters involved in the design of the TES-HTF block are the tanks, the pumping requirements in the tower, the interrelation with the solar field (i.e. receiver design), and the interrelation with the PB (i.e. the design of the heat exchangers in the steam generation train). The PB in these plants is composed by a ‘conventional’ reheat Rankine cycle, where water is converted into steam by passing through a so-called steam generation train, composed by multiple heat exchangers. The live steam at the inlet of the high pressure turbine (HPT) in these plants is usually at operating conditions of around 550°C with pressures varying from 80 to 150 bar [45]. As such, the main design parameters in connection to the PB relate to the desired operating conditions, the number of extractions, and the cooling mechanism. As for any conventional Rankine cycle, these plants can make use of wet-cooled, evaporative, or dry-cooled condensers [45]. Dry-cooling is often preferred in CSP plants. The latter is mainly because despite having a negative impact on the cycle efficiency, Dry-cooling leads to significant less water consumption [14].

The first 'large-scale' project with such a configuration was the Gemasolar power plant at Fuentes de Andalucía in Spain [12], put into operation in 2011. This is why the layout is often referred to as "the Gemasolar type". Gemasolar is a 20 MWe MS-STPP that employs a wet-cooling condensing system and is characterized by its large TES capabilities. When fully charged, the TES system in Gemasolar allows it to operate at nameplate capacity for approximately 15 hours, in this way proving to operate as a 'baseload' plant during the summer [2][12][13].

MS-STPPs have gained momentum ever since Gemasolar's successful demonstration. By end of 2015 US developer Solar Reserve commissioned the first 110 MWe project with similar configuration, the Crescent Dunes Power Plant in Tonopah, USA [50]. Also a number of projects of same magnitude are in the pipeline and are expected to be commissioned by end of 2017 (i.e. Atacama I in Chile [53], Redstone Solar [55], and Noor III [56]). The recent interest in such a technology comes with no surprise as it offers a number of advantages when compared to the more mature parabolic-trough CSP plants using oil as HTF (explained next) [2][9][13]:

- Higher temperatures and efficiencies can be reached.
- The HTF is non-flammable and is restricted to a confined area.
- No need for additional heat exchangers. The HTF and TES media are the same (molten salts).
- Higher storage density. The TES temperature range is doubled as molten salts are operated from approximately 265°C to 565°C, compared to approximately 265°C to 385°. This translates into more cost-effective TES systems, which is key for CSP plants.
- There is enormous potential for cost-reduction in the SF components as technology matures.
- The technology has been proven and is now more 'bankable'.

3.5.2. Parabolic Trough CSP Plants

Parabolic trough (PT) technology is the most mature among all CSP technologies. In specific, the oil-driven PT CSP plants account for the vast majority of projects installed and currently in operation [11]. A simple representation of the layout of such a plant can be seen in Figure 14, including their key blocks: the solar field (SF) and HTF block, the TES block and the Power Block (the PB). In the SF-HTF block, high-temperature thermal oils (often Therminol VP-1 [7]) are commonly used as HTF (depicted in green in Figure 14). The HTF flows through a field composed of PT concentrators to reach temperatures of approximately 390°C (commercial oils degrade above 400°C). Such heat is used to generate steam and drive the PB (usually a reheat Rankine cycle [45]) or to be stored, depending on the operation desired. Energy is stored through an indirect two-tank molten salt system as explained in §3.2.3.

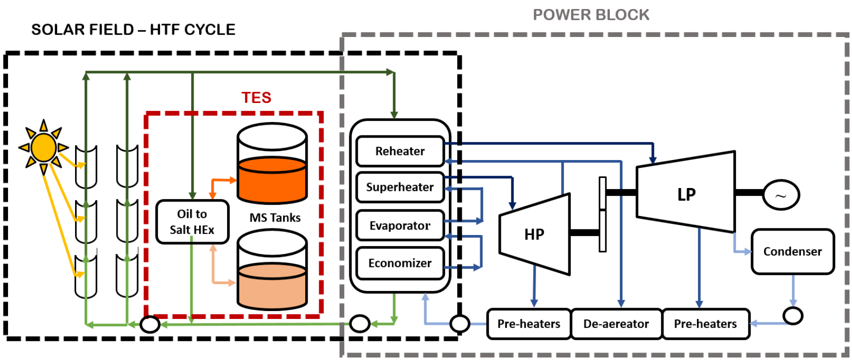

Figure 14 Layout and main component blocks of contemporary PT CSP plants

One of the first power plants after the re-birth of CSP in 2006 was the Andasol CSP plant complex (3 x 50 MW_e) located in the south of Spain. Andasol set the standard for the following plants to come in the industry until 2011 [12]. This is the reason why this layout is also often referred to as the '*Andasol*' type CSP plant layout. As discussed earlier, the key limitation of the *Andasol* layout is the low operating temperature imposed by the use of thermal oil as HTF. This has mainly two consequences: a lower power cycle efficiency, and a less efficient TES system (low storage density) [14]. A number of advanced propositions have been put forward to overcome this issue including the use of molten salts instead as direct HTF and TES media. However, the risk for molten salts to freeze in the SF is large considering the amount of piping involved. The main scope of research for these systems today concerns the development of new PT concentrators with larger aperture areas (more efficient), and also new HTF to overcome the temperature restriction problem [2][9]. Nevertheless, these type of power plants will continue to penetrate the market out of a number of reasons:

- Maturity:
  - Components are becoming 'standard'.
  - Large number of experienced actors involved.
  - Achieved already significant cost reductions.
  - O&M practices have improved over time. For instance, despite no new capacity has been added, operators in Spain have been successful in increasing annual production steadily over last 5 years [9].
  - More bankable (as explained in §4.2).
- Theoretically, the SF is not limited in size. This means that large PBs can be used, with the main limitation being the HTF pumping requirements. This is not the case for STPPs, where the efficiency of a heliostat decreases the further away it is placed from the tower (e.g. due to attenuation, spillage, shadowing and blocking).

3.5.3. Direct Steam Generation Solar Tower Power Plants

A schematics of a direct steam generation solar tower power plant (DSG-STPP) is shown in Figure 15. The main advantage of DSG-STPPs is that no intermediate HTFs are used. In DSG-STPPs water is directly pumped at high-pressures up to a receiver mounted on top of a tower, where is heated to reach high-temperature steam conditions. This steam is used to drive the power block (the PB). The use of a single fluid allows reaching higher temperatures and thus higher efficiencies in the PB [13]. The two main blocks in the system are the SF and the PB (Figure 15).

The main drawback of DSG-STPPs is that storage of superheated steam is complex and no effective TES technology is commercially available [2][13]. As mentioned in section §3.2.3, steam accumulators can be integrated, but they do not supply the required live-steam conditions, so these are often used to provide steam directly into the low-pressure turbine (LPT) [37][40]. To date, DSG-STPPs with steam accumulators operate at lower temperatures, or instead use the steam accumulator to provide partial load for a limited time lapse [39][40].

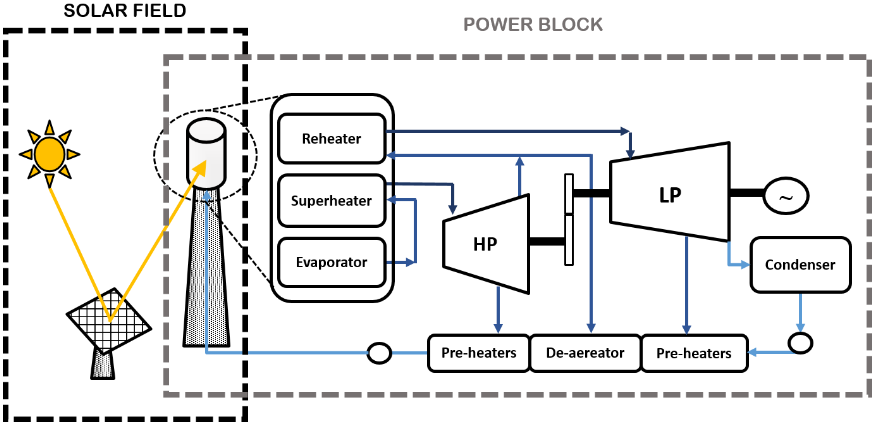

Figure 15 Layout and main component blocks of contemporary DSG-STPPs

On-going research on the use of concrete TES for steam generation or other media, such as PCM, can increase the viability of these systems. The lack of TES has led to an increased utilization of the GB backup system for start-up [57]. This is not only undesirable, but there is also the case that often the use of NG for back-up in a CSP plant is limited in order for it to sell electricity at the contracted subsidized price [2][57].

The largest project, in terms of installed capacity, is the Ivanpah Solar Power Complex in California (approx. 360 MW_e in total) [58]. Ivanpah is composed of 3 independent DSG-STPPs, each one with a layout similar to the one shown in Figure 15. Ivanpah has proven that DSG-STPP technology is viable at large scale. The experiences from Ivanpah have significantly contributed to the research of turbine flexibility [59].

Despite its successful demonstration, to date the Ivanpah Solar Power Complex has yet failed to meet its design annual output after almost 3 years in operation [11]. This has been used as an argument by many CSP detractors to claim that CSP is not a competitive technology, without considering that Ivanpah has a particular CSP plant layout: first in its kind at large-scale and without a TES system. On the contrary, for the CSP industry, in general, it has served as a good example case to highlight the value that TES can deliver, not only by allowing the plant to provide controllable power on demand, but also in improving the stabilizing and thereby improving the operating conditions and lifetime of the PB [2].

4. Market Perspectives for CSP Plants

The present section provides the context of the CSP market today and the perspectives for the future. The description of the current market situation includes the global installed capacity and reflects on the competitiveness of CSP in the global electricity generation landscape. An example of a successful structure for developing CSP projects followed in emerging markets is also described along with the main actors involved (i.e. Morocco and South Africa). Lastly, the perspectives for CSP are given by briefing the findings from a number of third-party scenarios that deal with the expected installed capacity for CSP in the future. This section ends outlining the key challenges for CSP.

4.1. Global CSP Installed Capacity (as of Q1 2016)

As of the first quarter of the year 2016 (Q1 2016) the global installed capacity of CSP plants (plants in operation) accounted for approximately 4.9 $GW_{e.}$ [11]. Table 4 provides an overview of the global share of CSP installed capacity in operation per country as of Q1 2016. It shows that almost half of the CSP capacity installed worldwide is in Spain, which is the reason why most of the know-how and companies involved in the industry today are of Spanish origin [11][13]. This was fostered by a Feed-in-Tariffs (FiTs) program put forward by the Spanish government in 2006, and removed in 2010 [9]. Since then, the CSP capacity in Spain has remained almost the same, but the industry has internationalized [9].

Table 4: Share of CSP Installed Capacity per country (adapted from [11])

Country	Share
Spain	46 %
USA	38 %
India	5 %
Morocco	4 %
South Africa	4 %
United Arab Emirates (UAE)	2 %
Others	1 %

Table 4 also shows that the USA accounts for approximately 38% of the global installed CSP capacity. The CSP technology in the USA dates back to 1980 when the Solar Energy Generation System, in California, launched the development of the CSP technology. Interestingly so, this large complex (approx. 350MW_e) is to date still in operation, demonstrating the long durability of CSP plants [11]. Recently, the development of CSP projects in the USA was pushed by the Investment Tax Credit (ITC) federal program. The original ITC program initiated in 2006, it allowed a 30% tax credit mechanism for investors in solar energy projects, provided that the projects were in operation by end of 2015 [60]. In order for the developers to have plants fully operational by end of 2015, the last CSP projects in the USA initiated construction in late 2012 [11]. Nevertheless, the unexpected extension of the ITC program in December 2015 for additional 5 years, the learning experiences from the Crescent Dunes project [61] and the storage mandate put recently in place in California, make the USA an attractive market for CSP again [9].

Since 2012, most of CSP project development has taken place in emerging markets [11]. Today India accounts for 5% of the installed CSP capacity, more than half of it based on Linear Fresnel technology [11]. Worth mentioning are the Moroccan and South African experiences [56][62]. To date both African nations account for approximately 4% each of the installed CSP capacity in operation [11]. This was deemed possible through technology-specific competitive-bid tenders put forward by the governments in each country. The deterministic choice of CSP for such tenders was mainly due to its advantageous TES capabilities [9]. As will be mentioned later, the share of CSP in each of these two countries is expected to keep increasing, with a number of projects under construction and new tenders being planned [54][56][62]. This is also the case for the UAE, where the 110 MWe Shams 1 CSP plant was inaugurated in 2013, and who has recently announced that a 200 MW_e tender is under preparation as part of a 1 GW_e CSP plan [11].

Table 5 shows the distribution of the global CSP installed capacity according to the type of CSP technology. It shows that there is a clear dominance of Parabolic Trough (PT) technology, which adds to around 84% of the global installed capacity [11]. Almost all CSP projects built between 2006 and 2011 (mostly in the USA and Spain), where based in such a technology. The first large scale MS-STPP, Gemasolar, began operation in 2011 and demonstrated that the technology was not only viable at multi MW scale, but also that it had numerous advantages over PTs as mentioned in §3.5.1 [12]. This marked the beginning of a number of STPP projects, including the Ivanpah Solar Complex [58] and the Crescent Dunes Project [61]. Lastly, Table 5 shows the low penetration of Linear Fresnel (LF) and Parabolic Dish (PD) CSP technologies, reasons for are mentioned in §3.1, the lack a cost-competitive TES is a key one.

Table 5: Share of CSP Installed Capacity per technology (adapted from [11])

CSP Technology	Share
Parabolic Trough Plants	84 %
Tower Plants (Central Receiver)	12 %
Linear Fresnel Plants	4 %
Parabolic Dish	< 1%

4.2. CSP Plant Project Structure and Key Actors

Today, CSP technology is growing in emerging markets (e.g. Morocco and South Africa). In most of these markets, the projects are built on the basis of competitive bid tenders leading to a Power Purchase Agreement (PPA) between the 'off-taker' (electricity buyer) and a privately owned power producer (or independent power producer – IPP) [9][11][54][62]. In most cases the off-taker is a state-owned electric utility (e.g. ESKOM in South Africa) or a state-own entity (e.g. MASEN in Morocco). Figure 16 illustrates the main processes and actors involved in the development of a CSP plant in these markets (i.e. the Value Chain of a CSP plant project).

This section gives a brief explanation for each of the main steps shown in Figure 16. The aim is to provide the reader with relevant information about the key decision-making processes that typically take place along the development of a CSP plant. At the end, a sub-section exemplifies how the techno-economic modeling used in this thesis, as presented in §5.1, §7.1 and §9, can be applied to support the key actor's decisions along the mentioned processes. Moreover, although the description below applies to an IPP-type PPA agreement, most of the processes described also occur under other project developing schemes (e.g. in deregulated markets). Regardless the electricity selling-contract type, developing a project will involve a Proposal Preparation phase, securing finance, a construction phase and an operational phase.

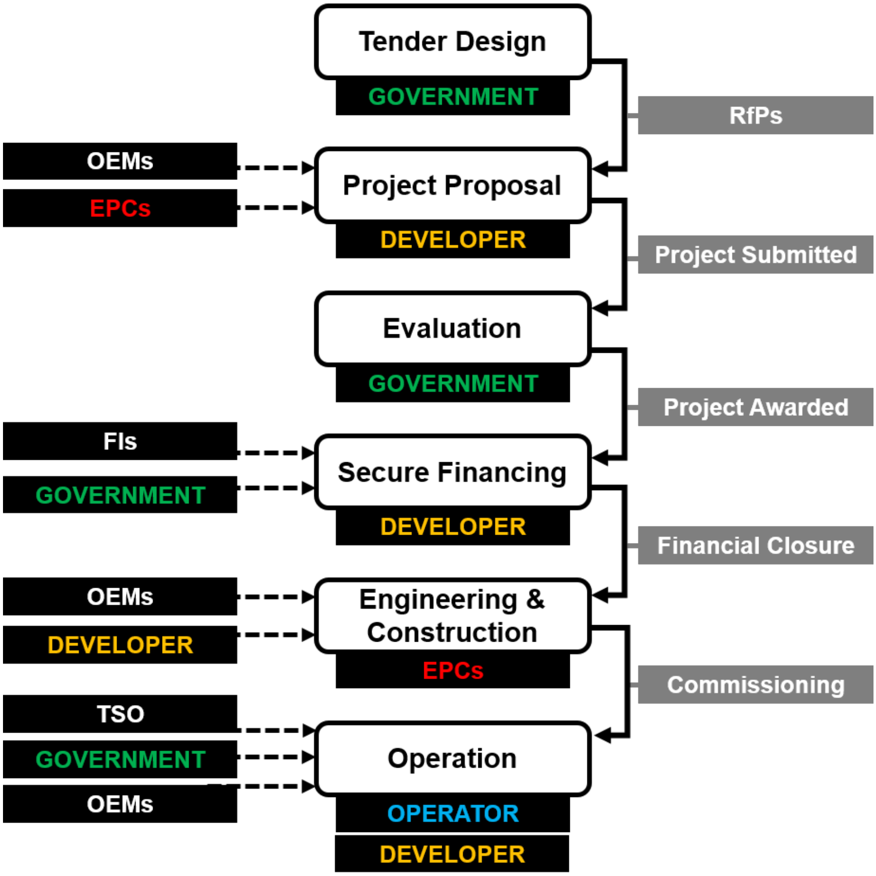

Figure 16 Simple representation of an IPP-PPA Project Structure for CSP plants

Public Tender Design

The overall process starts with the design of a public tender for a new CSP plant. This process is usually led by the off-taker (i.e. the government). The design of the tender often requires a number of actors and sub-processes not included in Figure 16. For instance, the design of a public tender for a CSP plant is usually preceded by an Expression of Interest (EoI), where developers are pre-assessed and pre-qualified based on their experience before the public tender. Similarly, the tender design might involve a preceding public tender for consultants to perform feasibility analyses and assist with the environmental, socio-economical, technological and political aspects of the project. Public tenders are often deemed open once a Request for Proposals (RfP) is made public. This request might already restrict the design of the plants to a specific technology type, land area, pricing scheme, capacity and operational requirements (e.g. firm output or specific hours of production).

Project Proposal Preparation (Bid)

Once an RfP is made public, pre-qualified developers lead the power plant proposal preparation. This is typically done in a consortium in which the developer usually partners with an Engineering-Procurement-Construction (EPC) company and a CSP technology owner or original equipment manufacturer (OEM). The preparation of the proposal involves, among others, the site pre-assessment (e.g. solar resource) and the preliminary plant configuration in terms of layout. This last relates to the size and key design specifications of the main blocks in the proposed CSP plant (the SF, the TES, and the PB). Lastly, and more importantly, the project proposal should include key performance indicators that are used for the bidding, being usually the most relevant one the bidding price for the PPA. Other pertinent indicators, often mandatory (to prove that the project complies with the tender requirements), are the expected annual production (also called yield), the annual load factor, and the degree of localization of the project or so-called 'local content' (e.g. how much of the required investment will be re-invested in local products).

Evaluation of Proposals

After all consortia have submitted their proposals, is then time for the public entity in charge of the tender to evaluate all of them, and thereafter select a winner consortium to be awarded the project. The evaluation involves a number of criteria including the verification of the technical configuration, an environmental analysis, and a thorough risk analysis of the whole project and actors involved. Often a number of projects are pre-selected and consortia are requested to complement their proposals. The evaluation of the proposals ends when a project is announced the pre-selected winner. At this point the negotiations for the PPA agreement can start (e.g. contract start/length and ownership after conclusions) and the winner consortium (led by the developer) is requested to secure the financing for the rest of the development of project.

Financial Securement

The investment required for a CSP project is large (sometimes up to USD billions), and this means that often the winning consortium needs to raise large amounts of funding to ultimately secure the construction and development of the project. In the process of securing the needed funding for a CSP project, financial negotiations take place with financial institutions (FIs) and typical power plant financial structures are set up (e.g. equity-to-debt ratio and loan conditions). It can happen that, through international agreements with global organizations (e.g. the World Bank), the governments help the developer in securing the investment needed. Furthermore, in some cases the public entity itself (i.e. the government) also takes ownership in the project (e.g. MASEN for Noor projects in Morocco [56]). Once the investment is agreed upon all parties, it is deemed that the project has reached 'financial closure'. It is important to state that in the process of securing finance, all prospective investors are required to make a thorough evaluation and risk assessment of the project including, but not limiting to, the technical aspects. A CSP technology is considered 'bankable' once a project using such technology has been able to raise funding, usually after years of demonstration.

Engineering, Procurement and Construction Phase

The construction of the power plant begins in most cases soon after finance closure has been reached. For the construction phase, usually an agreement between the developer and one (or several) EPC company takes place (the "EPC agreement"). The leading EPC in charge of the construction phase is usually the EPC Company involved as consortium member since the beginning of the project. During construction, the EPC is responsible for the procurement of all required equipment and for the construction of the plant, following though the basic specifications and design criteria laid down in the project proposal. In doing so, the EPC typically disposes of a planned budget (part of the proposal), and is committed to construct and ultimately commission the plant under a specified time (usually 2 years from starting construction date). Although the general layout and main design specifications of the plant have been already decided in the proposal, still a number of more specific technicalities are required. This involves both design engineering work, and also the evaluation of multiple technology suppliers (OEMs) to which request for quotations (RfQs) are sent out. In evaluating all potential technologies, the EPC needs to assess if a technology meets the required design specifications, including how it will impact the performance. The construction phase is deemed concluded once the power plant has been commissioned. This occurs once the plant is proven to operate as required for a period of time, as specified in the EPC agreement. After commissioning, the operation of the plant is handed out to the 'operator'.

Operation Phase

The operation of the CSP plant involves the normal day-to-day tasks to guarantee production successfully. This involves operational decisions and also proper planning of maintenance requirements. The operation of a CSP plant is in some cases led by one of the power plant owners (e.g. the developer). However, it can be so that an operating lease is put in place, in which the operation is handed out to a third party (this can be even the same EPC during construction). The operation phase extends to the full lifetime of the plant, until it is 'decommissioned'. Nonetheless, in some cases the operation phase refers to the operation during the length of the PPA contract. This is done so because, in some plants, the ownership changes after culmination of the PPA, so potentially a new selling scheme will be deemed needed and also a new operator will take over. During normal operation, aside the operator, usually other actors get involved such as the OEM of the technologies in the plant, the grid operator (or TSO from transmission system operator), or even the government (regulator) itself. The OEM gets involved through maintenance and service contracts. The TSO or the government, on the contrary, can provide input to the actual operational decisions of the plant.

4.2.1. Techno-economic analysis for decision-making in CSP

Techno-economic analysis can be used to support the decision making required in the different steps along the development of a CSP project. With regards to the project structure described in Figure 16, a key parameter under which projects are measured in competitive bids is the bidding PPA price. As is discussed in §9, both developers and tender-designers can well make use of techno-economic models to estimate this price. For instance, for a specific IRR objective a developer can calculate the bidding price by building power plant techno-economic models and adapting them to the conditions and requirements set by the tender (e.g.

hourly operating regimes). Indeed, prior to the bidding process, tender-designers can make use of the same approach to estimate the price at which electricity will be bought from the developers. This, for example, with the purpose to understand the implications of the requirements set, as well as to plan ahead in preparation of the evaluation phase.

Furthermore, although decisive, the bidding price is not the only factor to consider. Both developers and tender-designers need often to evaluate if the project complies with environmental or technical requirements (e.g. specific CO_2 emissions and load factor, respectively). The assessment of all objectives for particular plant configurations can be done through techno-economic performance modeling.

Likewise, FI's require of performance models that allow them to assess if a project is worth investing in or not. FI's are thus mainly interested in the required investment and in the profitability of such projects. At the same time, though, they need to verify that the technical proposal is able to comply with the performance promised. Again, in order for FI's to simultaneously address that a power plant configuration is able to meet the promised technical performance and also to quantify its profitability, they can make use of techno-economic models comprising the desired financial performance indicators. In fact, financial advisors are required to couple detailed financial models to detailed technical models upfront suggesting decision makers at FI's to invest or not in a technology.

Moreover, even once financing closure is reached, EPCs and OEMs can also make use of techno-economic analysis with a different approach. At this point, OEMs begin the race to demonstrate EPCs that their products are the best in terms of cost-efficiency for the project, and that they should be therefore selected. One way of demonstrating such is by setting power plant performance models and showing the EPC how their product will compare against others (e.g. CAPEX required, impact in OPEX, etc.). EPCs, on the other side, once the construction begins are required to build a power plant that meets the specifications laid down in the technical proposal for a given contract amount, agreed between the EPC and the developer once financing is secured (this is one of the reasons why EPCs and developers form a joint-bidding consortium since the beginning). As such, the profits for the EPC increase if they are able to comply with the technical specifications at the lowest cost possible. It is clear then that EPCs can also make use of techno-economic models to assess all technologies involved.

Lastly, operators are in constant need of improving the efficiency of their power plants. In doing so, for instance, they often consider how new technologies or operational strategies can help them increase the annual yield, or also decrease the operational expenditures (OPEX). These are the main indicators upon which operators measure the performance of the plant. Techno-economic analysis can be of use to help operators assess if an 'improvement' is worth the investment, or what is the impact (in yield) of adopting a different operating strategy.

In consequence, the relevance of fast and accurate tools and related engineering services for the industry is clear, and as it is discussed in §5.2.1, there is margin for improvement with regards to state-of-the-art. This is especially true when considering that CSP is a 'young' technology and that it is expected to grow in a much faster pace in the near term, as is discussed in the following sections of this Chapter.

4.3. Competitiveness of CSP

Although CSP plants are today, in most cases, built under technology-specific tender processes as the one described in the previous section [9], they are also often compared against other electricity generation technologies. The competitiveness of a technology can be measured by multiple means. One of the most common performance indicators used in the power industry to compare different technologies is the levelized cost of electricity (also called LCOE or LEC) [63]. The LCOE is a simplified parameter that relates all lifetime costs of a power plant to its added lifetime generation [63]. It is typically measured in the units of USD/MWh_e (or USD¢/KWh_e). The use of the LCOE as a fair indicator for comparing technologies, CSP included, has been the topic of discussion of multiple recent studies [64][65][66]. Figure 17 shows a comparison among main power generation technologies on the basis of the LCOE. The calculation process followed for estimating the LCOE was based on the simplified LCOE calculation model described [67], from a number of updated references consulted [68]. In this figure, an overall mean LCOE value for each technology is shown (in black), as resulting from averaging the minimum and maximum LCOE values found for a number of 'suitable' sites for deployment of each of the technologies.

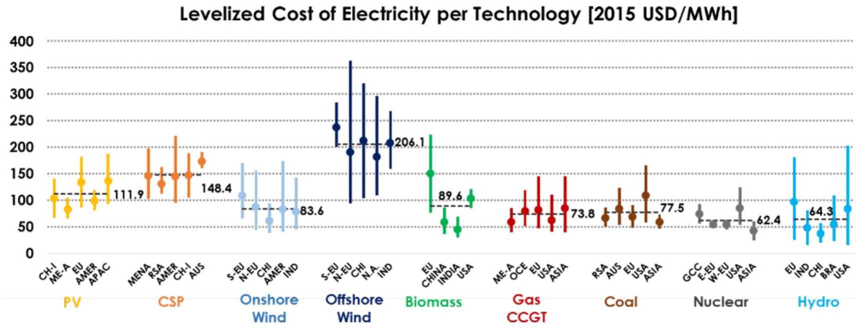

Figure 17 Levelized Cost of Electricity per Technology [68]

For instance, for CSP, maximum and minimum LCOE values were calculated for 5 different locations (i.e. MENA region, South Africa, Americas, China and Australia). Then, the mean LCOE value for each location was estimated, and finally all 5 means were averaged to estimate an overall CSP LCOE value of approximately 148.4 USD/MWh.

It can be seen that the average LCOE of CSP is higher than for most of other renewables, solar PV inclusive. Important to recall, though, that the LCOE of CSP has been reached only after approx. 4.9 GW_e of installed capacity, unlike the case of solar PV with 150 GW_e [1]. Another aspect to consider is that, although LCOE is yet the standard in the industry for comparing technologies, it does not value the time of generation and thus does not fully capture the value of TES in CSP. On-going research proposes that technologies should be compared instead on the basis of the Net System Costs (NEC) [66]. In any case, it is clear that the potential for reducing the LCOE of CSP is large [2][9], but in order to do so several challenges need to be addressed (as highlighted section §4.5).

Nowadays, several opportunities have been identified for increasing the competitiveness of CSP by leveraging from its ability to integrate TES [2][9][13]. Among these opportunities, three can be highlighted: the optimization of the sub-systems in the plant with regards to TES integration; the introduction of more cost-effective TES systems; and the hybridization of CSP with other more cost-competitive technologies. All of these the subject of this thesis.

4.4. Future Installed Capacity (Market Perspectives)

Near term Market Perspectives (Projects under construction)

As of Q2 2016, approximately 1.1 GW_e of CSP have been awarded PPA contracts through IPP tenders and are under construction. Table 6 and Table 7 show the share of CSP plant capacity under construction (for projects awarded a PPA) by country and by technology, respectively [11].

Table 6: Share of CSP capacity under construction per country

Country	Share
South Africa	35 %
Morocco	31 %
Israel	20 %
Chile	10 %
Others	< 5 %

Table 7: Share of CSP capacity under construction per technology

CSP Technology	Share
Parabolic Trough	53 %
Central Receiver	47 %
Linear Fresnel	≈ 0 %
Parabolic Dish	≈ 0 %

It can be seen that no projects are expected to come online soon in neither Spain nor USA, the traditional dominant markets, instead all new CSP plants are under construction in emerging markets. Particular focus is placed on Morocco and South Africa, both with a public tender process similar to the one described in section §4.2. Furthermore, it is also noticeable that the share of STPPs under construction almost equals that of the PT CSP plants, potentially indicating a shift in technology preference or, at minimum, market penetration and acceptance of STPPs. Moreover, over 80% of such CSP capacity under construction will incorporate TES [11]. In fact, the integration of TES is one of the main reasons why Morocco and South Africa have deterministically favored the development of CSP, as part of their renewable targets [56][62]. Worth highlighting is the 110 MWe Atacama 1 tower CSP plant in Northern Chile, which will integrate a two-tank direct TES system with a capacity large enough to operate the PB for 17 hours at nominal capacity [53].

These trends confirm that CSP is nowadays mostly active in emerging markets with great solar resource (e.g. Morocco, South Africa, and Chile), where TES systems are highly valued. Moreover trends also confirm that in these markets there is now a preference for tower CSP plants. In addition, most of the CSP projects under development phase in Chile, Morocco and South Africa are also expected to be STPPs with TES [11]. Besides, while all projects considered in Table 6 and Table 7 relate to projects awarded a PPA contract, there are also other CSP plants under construction [11]. Also, a number of CSP projects are under development in China, where results from an RfP for qualification for a 1GW CSP demonstration program based on Feed-In-Tariffs are expected [69].

Lastly, concerning new project development, it can be expected that most of new CSP projects in these emerging markets continue to develop following a competitive-bid public tender process similar the one briefly explained in the previous section. One important reason for such, is that in both Morocco and South Africa it has been demonstrated as an effective structure to lower the bid prices over time [9][56][62].

Long term Market Perspectives (Energy System Scenarios)

By end of 2014, the International Renewable Energy Agency (IRENA) published the REmap 2030, a study that suggested a roadmap to double the share of renewables up to 36% by 2030 [70]. One of the key findings from such a study can be seen in Figure 18, which compares the total cumulative installed renewable capacity by end of 2013 (left) to the projections of the REmap 2030 scenario (right). The circles inside each of the rings relate to a specific renewable technology, which is differentiated by the color. The size of these circles is proportional (approximately) to the installed capacity of each technology under each scenario.

Concerning CSP, one of the key findings from the study is that, together with offshore wind, it is projected to show the fastest growth rate among all technologies in terms of cumulative capacity [70]. Specifically, IRENA's estimates suggest that CSP capacity will increase up to 83 GW_e by 2030. The study highlights that a key reason for such is the ability of integrating low-cost TES in order to provide dispatchable electricity to the grid and to capture peak market prices [70]. The study also highlights that with the technology being at its infancy by end of 2014, in terms of deployment, the potential for cost reduction is vast and that STPPs with TES seem to become the most competitive CSP technology [70].

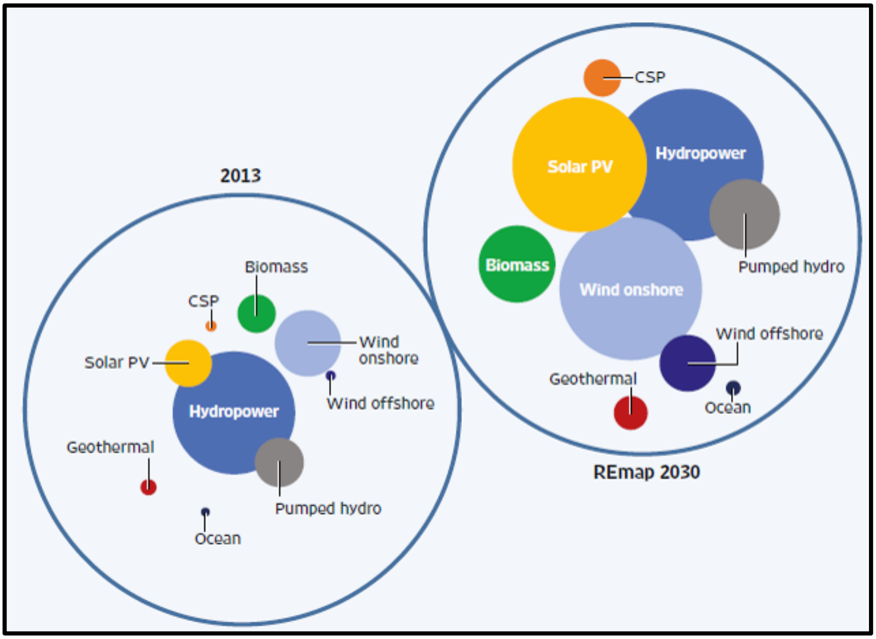

Figure 18 Total cumulative installed renewable capacity by 2013 and in REmap 2030 [70]

The Solar Thermal Electricity Technology Roadmap developed by the International Energy Agency (IEA) also shows a promising future for CSP despite its current higher LCOE [2]. The IEA highlights that this is deemed possible because of the advantage of being able to integrate TES systems and the large potential for cost reduction, potentially leading to the only cost-competitive dispatchable renewable technology for countries in the Sunbelt [2].

In their Energy Technology Perspectives 2014 study [71], the IEA shows three scenarios concerning their projections for the global electricity mix outlook by 2050. The first scenario, the '6DS' scenario, was a projection made assuming 'business-as-usual' and current trend development, in which case the global mean temperature is expected to increase by 6°C. The second scenario, the '2DS' scenario, sees energy systems transformed to achieve the goal of limiting the global mean temperature increase to 2°C. The third and last scenario was an optimistic scenario called the 'hi-Ren' scenario, in which the 2°C mean temperature target is achieved with a larger share of renewables to compensate for the potential slow development of carbon-capture-storage technologies and impediments in nuclear deployment [71].

As for CSP, in IEA's 2DS scenario, the share of CSP in the global electricity mix will account for 7%, while in their hi-Ren scenario it will increase up to 11% [71]. Even in the case that current trend continues (6DS), the IEA projects that CSP will continue growing to reach 1% of the global electricity mix (this scenario projects that only 8% will come from solar and wind). This is shown in Figure 19, as adapted from [2].

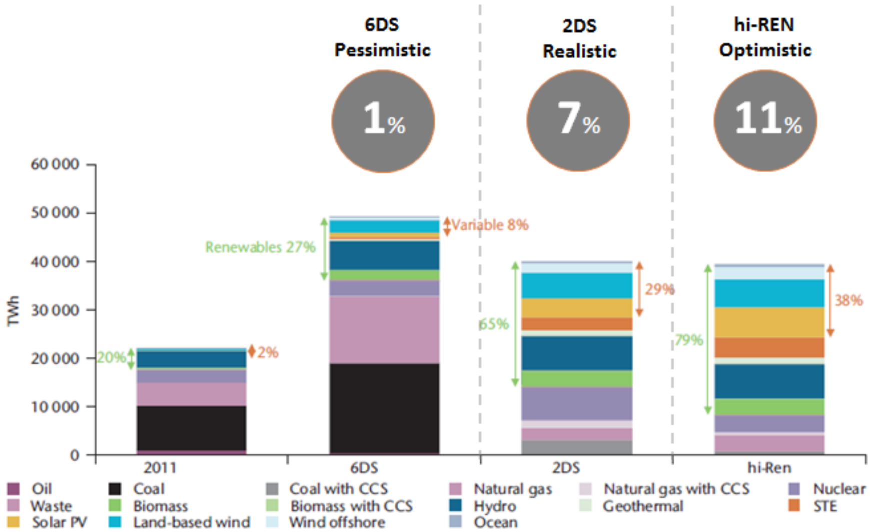

Figure 19 Global electricity mix in 2011 and in 2050 in three ETP 2014 scenarios [2]

In terms of installed capacity, the IEA projects that under the hi-Ren scenario CSP will be able to reach approximately 230 GW_e by 2030 and 980 GW_e by 2050. While these numbers might seem too optimistic they are a clear indicator that CSP technology is believed to increase rapidly in the coming years, even if considering that only a tenth of such targets are reached (23 GW_e and 98 GW_e by 2030 and 2050 respectively).

Another aspect highlighted by the IEA, is that CSP is expected to have an important role in markets such as the Middle East, Africa and the USA. Figure 20 shows the projected generation mix by technology and region under the IEA's hi-Ren scenario. Specifically, in terms of annual generation, IEA's hi-Ren scenario forecasts that CSP will represent the largest source of electricity in Africa and in the Middle East countries [71]. Worth noticing that the IEA estimates that CSP will have a larger generation share than PV in such locations even when projecting that the cumulative installed capacity will be less than a third of that of PV, this highlights again the value of TES.

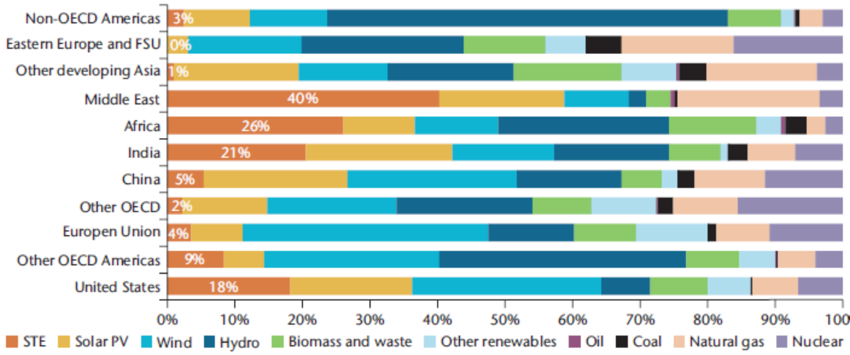

Figure 20 Generation mix by 2050 in the hi-Ren Scenario, by region [2]

Other studies from organizations in support of CSP development tend to show even more optimistic scenarios. In their 2016 outlook the European Solar Thermal Electricity Association (ESTELA) and SolarPACES estimate that, under current trends, CSP will reach the milestone of 11 GW_e of installed capacity by 2020 to provide 0.1% of the world's annual electricity demands [9]. Moreover, they predict that under current development trends CSP will reach 21 GW_e and 42 GW_e of installed capacity by years 2030 and 2050, respectively [9]. In addition, in their moderate scenario they project that CSP will reach 22 GW_e, 131 GW_e and 781 GW_e of installed capacity as of 2020, 2030 and 2050, respectively. Their projections are even more aggressive in their 'advance' scenario, where the world's total fleet of CSP capacity is expected to reach 1600 GW_e by 2050[9].

4.5. Summary: Main Challenges for CSP

Albeit the future for CSP seems promising, it is only possible provided a number of challenges are, or continue to be, addressed. It was shown earlier in this section that the main challenge for CSP, in general, is to reduce its LCOE and thereby be deemed 'competitive'.

On the technical side, new power plant components with improved efficiencies and lower costs can have a direct impact on the LCOE. The cost reduction potential for the solar field related components is still vast and, although it has been decreasing, it will continue to decrease as more projects are deployed [9]. Advanced research for development of new TES systems and hybridization, as well as for its suitable integration and operation, is also still needed. This last being understood that TES is a main differentiator for CSP amongst renewables. The shift towards power blocks with higher efficiencies can also make a big impact [2][9][13]. As the technology becomes more established, understanding also how to design and optimize the system when considering all the interconnected components and sub-systems becomes relevant. This last, is especially true when considering the particularities of each location, here included for instance the weather, policies and the project framework (structure).

One of the main challenges for CSP is that it is a high capital intensive technology. Some of the projects in operation today required investments of a USD billion magnitude [56]. Therefore, the financing structures become extremely important. In order to be able to continue the technology development and demonstration, adequate financial instruments are needed [9]. In addition, the realization of large projects requires that well-thought-out programs or policies are put in place for the structuring of new projects. The experiences learned from Morocco and South Africa, reducing the risk on the developer, have thus far proven successful in achieving fast cost reductions. Alternative instruments, such as the tax credit mechanism in the USA, have also yielded positive results.

Last, but not least, one of the main challenges for CSP is to focus the discussion on the value that CSP offers to the grid when cost-effective TES systems are integrated. CSP with TES shall be compared with other dispatchable technologies. Comparing on the basis of LCOE against PV or wind, might be incorrect, as the role of each technology in the system can be completely different. They can instead complement each other. It is then the main responsibility of policy makers to realize that.

5. Pre-Design of CSP Plants with TES

In order to assist the decision making processes for all stakeholders involved in the project development of a CSP plant, effective methods (e.g. fast and accurate) for the analysis of the whole system are needed. These should help to answer specific questions raised along the process with regards to the technology use, the system integration, the operation, and the financial aspects, among others. In practice, the development of a project should consider multiple dimensions. In this section, techno-economic analysis is briefly explained as a methodology to evaluate the performance of CSP plants. Then, the typical CSP plant techno-economic performance indicators are described in short. Lastly, a brief description of available commercial software for CSP plant pre-design is given, followed by previous examples involving techno-economic analyses of CSP plants with TES.

5.1. Techno-economic Analysis for CSP Plant Evaluation

As discussed in §4.2.1 techno-economic analysis can be an useful tool to assist the decision making processes along the complete value chain of power generation systems (i.e. their investment, design and operation). It is only possible through simultaneous technical and economic performance evaluation that stakeholders can agree on the design of a particular plant, best comprising among the often conflicting objectives of being financially attractive (either the least costly or most profitable), and at the same time being the best technical solution . Moreover, aside the potential conflicts between meeting financial and technical objectives, the design of power generation systems also involves the added complexity of meeting required environmental objectives in accordance to the needs of society [72][73]. Currently bearing in mind these three aspects is, in general, a must during the process of decision making towards a more sustainable future, especially for policy makers [74][75].

As an example, deciding upon a final design of a power generation system shall not be based solely on its technical performance. This can lead to designs that require sufficiently large investments to a point to which the systems are not financially viable (are not able to pay-off). Similarly, deciding upon the construction of a power plant based solely on cost and financial indicators, might lead to very inefficient designs often non-reliable and potentially harmful for the environment [76].

It is thus recommended that each of the actors along the value chain of a CSP plant (e.g. policy makers, project developers, investors, equipment manufacturers and plant operators) make good use of techno-economic modeling as a methodology for the analysis of the systems prior to decision making [14][77]. From a sustainable development standpoint it is important that these actors work close enough to guarantee that technical, financial and environmental aspects are considered along the lifetime of a power plant, and also that these projects are developed successfully in a beneficial way for society as a whole.

5.1.1. Techno-economic Performance Indicators

To be able to quantify (or estimate) the performance of a CSP plant it is necessary to define a number of appropriate performance indicators. The performance indicators introduced in this section are only a summary of those most commonly used in industry [6][13][63][64] and academia [14][77] to measure the performance of a CSP plant.

The Net Electrical Output (the 'Yield')

The most basic performance indicator is the net electrical output of the power plant during its first (or typical) year of operation, 'E_{net}', often referred to as the annual 'yield'. This is the basis for most of the other performance indicators, and is the main outcome of the dynamic simulation. It can be calculated as the sum of all the net power generated throughout a one year's worth analysis and is often measured in the units of [GWh_e] [14]. This being understood that the net power at every time step is calculated as the difference between the gross power generated and the parasitic electricity consumption of the power plant.

The Capacity Factor (CF)

Under its simplest definition, the capacity factor (CF) is the ratio between the net electrical output of the plant and the theoretical output that the plant would have reached if it had operated constantly at its nameplate capacity, for a given period of time (e.g. a year) [14][63]. It has no units and is thus often referred to in percentages. In principle, the CF should be less than 100%, but in practice it is possible to operate a power plant at a higher capacity than its nameplate one for a given period of time (at the cost of potentially damaging the equipment) [45]. Depending on the size of the TES system, if any, the annual CF of a CSP plant usually varies between 30% up to 85% [2][9][11][12].

PPA contracts are sometimes signed with a specific annual generation objective, the CF and the yield can thus be used as indicators to measure the generation objective in the proposal. The CF can also be used to measure the availability of the plant at specific key periods. This last is useful, for instance, to estimate the production during critical daily peak hours, which can also be a pre-condition of the tender.

In this thesis Paper V introduces a slight modification to the standard definition of CF by proposing a firm power CF calculation, applicable mostly to the hybrid concepts. Firm power refers to the ability of the plant to inject a constant firm net electrical output to the grid whenever in operation, as desired by the operators or defined by the tender. Firm power can be, in general, desirable in some locations out of a number of reasons. Two of these reasons can be to avoid sub-utilization of the grid-connection point, and to avoid un-predictable distribution congestion issues in weak grids. As discussed along the thesis, one of the intrinsic values of CSP plants with TES is their availability to supply controllable power on demand, which enables them to provide firm power on their own, but also to regulate their output to compensate for the output fluctuations from other renewables in hybrid schemes. Specifically, in Paper V the firm CF is introduced as a performance indicator to quantify the percentage of time that the hybrid CSP-PV plant was able to deliver a desired firm power objective set by a tender.

Lastly, although the techno-economic analysis of the CSP plants in this thesis focused on revenues from electricity sells only, the 'dispatchable' nature of CSP plants allows them to participate in capacity markets. In such markets, the CF can be an important performance indicator.

The Annual Solar to Electricity Efficiency

The annual solar-to-electricity efficiency '$\eta_{s\text{-}el}$' of a CSP plant is the ratio between the annual net electrical output and the total solar energy incident on the solar collector field. This definition though, neglects the use of a fossil-fuel back-up system for electricity generation. In a hybrid CSP power plant (including electricity generation from the use of fossil fuels), the overall annual efficiency of the system is understood as the ratio between the annual yield and the addition of the heat contained in the fuel and the incident solar energy on the solar collector field [14].

This performance indicator is used mostly only to compare among solar technologies. It must be acknowledged though that being the solar resource “free”, then this indicator is often dismissed as the efficiency of the system is already considered in the yield estimation, which is then used for calculating other financial or economic indicators of more interest for decision makers. In hybrid configurations the annual solar to electricity efficiency is also connected to the “solar share”, an indicator used to quantify the percentage of the electricity that was generated from solar power [14]. The solar share can be used to evaluate and compare different hybrid configurations. It can also be a pre-requisite of the tender (i.e. when the use of fossil fuel is limited).

The Specific CO_2 emissions

The most commonly used indicator to assess the environmental performance of a power plant is the specific CO_2 emissions [14][76], which refer to the ratio between the amount of carbon dioxide emissions emitted and the net electrical output over a period of time. It is usually measured in the units of [$kgCO_2/MWh_e$] and evaluated over a period of one year. It can be calculated by means of Eq. (1) [14], as a function of the quantity of fuel burnt annually Q_f (calculated based on the performance specifications of the power plant) and the carbon content of such fuel c_c.

$$F_{CO2} = Q_f c_c \cdot (E_{Net})^{-1} \tag{1}$$

The Capital Expenditures (CAPEX)

The investment costs or capital expenditure (CAPEX) of a CSP project is one of the key performance indicators used by some decision makers (i.e. developers and FIs). Although it does not measure the performance on its own, it is a relevant indicator as usually CSP projects require large investments [2][9][11]. Securing the investment, can delay the start of the construction, even if a PPA contract has already been signed. The CAPEX accounts for all the investment incurred along the development and construction of the project, including all direct and indirect costs. Direct costs refer mainly to all costs in connection to the purchase and installation of equipment. Indirect costs refer to all remaining costs incurred, for instance in connection to taxation and project development.

In order to estimate the CAPEX for a large number of power plant configurations, cost models are needed [13][14][76][77][78][79][80]. In this thesis, the cost models used for the analysis consisted of cost functions for component cost scaling based on cost values from reference plants and respective material and labor cost multipliers, to ensure that results are sensitive to the specific location considered [11][13]. A generic function for cost scaling is shown in Eq.(2), where the cost of equipment 'm' (or component 'm'), can be calculated based on n_1 reference cost values C_{ref}, which are sensitive to n_2 critical design parameters 'X', each in different degrees of relevance expressed by n_2 size scaling exponents 'y'. In its simplest form, Eq(2) is expressed as Eq.(3), where the cost of component (C_n) is calculated using a reference cost ($C_{ref,n}$) multiplied by the ratio between the component 'size' X_n and its reference size '$X_{ref,n}$', related through a cost-scaling coefficient 'y_n' [80][76]. In a simple split, the direct CAPEX of a CSP plant can be estimated by Eq.(4), as the addition of the CAPEX associated to the following components: power block 'C_{PB}', the solar collector field 'C_{SF}', the thermal energy storage block 'C_{TES}', the receiver 'C_{rec}', the site preparation and civil works 'C_{site}', the balance of power system 'C_{BOP}', and also some contingency costs 'C_{cont}'.

$$C_m = \sum_{\gamma=1}^{n_1} \left\{ C_{ref,\gamma} \cdot \prod_{\beta=1}^{n_2} \left[\left(\frac{X_{m,\beta}}{X_{ref,\beta}} \right)^{y_\beta} \right] \right\} \tag{2}$$

$$C_n = C_{ref,n} \left(\frac{X_n}{X_{ref,n}} \right)^{y_n} \tag{3}$$

$$CAPEX_{direct} = \begin{Bmatrix} C_{PB} + C_{SF} + C_{TES} + C_{rec} \\ + C_{BOP} + C_{site} + C_{cont} \end{Bmatrix} \tag{4}$$

In the appendix section of Paper II, a list of cost functions for each of the components are provided, as used in that particular analysis. The reference cost and plant data used were based on discussions with industrial partners or extracted from quotations and industry reports (i.e. [13]). Specifically, the cost functions used in Paper II were built as a combination from discussions with the industrial partners involved in the study and the cost models described in [13][14][79]. The research work of Rönnberg [81], supervised by the author of this thesis, shows the typical reliability scaling coefficients used in the STPP models and also provides a sensitivity analysis to the values used. It is clear that the setup of the cost model influences the performance estimation of the plants. It is thus recommendable that the decision maker, or user of the techno-economic framework, is carefully involved in the process of building such a cost model and that sensitivity analysis are performed to the optimum configurations with regards to key uncertainties.

The Operational Expenditures (OPEX)

The operational expenditures (OPEX) as a performance indicator, relates to all operational and maintenance (O&M) costs incurred in the normal operation of the power plant throughout a period of time, usually a ‘typical’ year. By ‘typical’, it is understood a year with no unexpected power plant shortages or failures, and for which all expected minor and major overhauls throughout the lifetime of the power block are in some way pondered or included (not always). The typical annual OPEX of a CSP plant refers to utility costs, service costs, labor costs, insurance costs and other miscellaneous (contingency)[13][14][79]. Utility costs relate to external water, electricity and sewage use, for instance. Service costs relate to all normal maintenance included in the service agreements with the OEMs. In the case of a hybrid configuration (or presence of a backup unit), the annual OPEX includes the cost of fuel, which is a function of the amount of fuel utilized [14]. In order to accurately estimate the OPEX, similar cost models to that used for the CAPEX are needed. In the appendix section of Paper II, the OPEX equations used for the analysis of STPPs can be seen. OPEX cost models are sensitive to reference cost values and scaling coefficients. The study performed by Rönnberg [81] also includes a sensitivity analysis to the OPEX assumptions and their impact on other financial indicators. As for the CAPEX, it is recommendable that the decision maker is involved in the process of building the cost models and that subsequent sensitivity analysis are performed with regards to key uncertainties.

A simpler representation of the OPEX assumes the addition of a variable and fix OPEX figures, as a function of the net generation and the installed capacity, respectively [63].

The Levelized Cost of Electricity (LCOE)

The LCOE is one of the main performance indicators used to measure the economic performance of power plants in industry. The LCOE is a measure of cost per unit-energy produced over the course of the lifetime of a power plant. The LCOE is often used to compare between different energy technologies even if the scales of operation and level of investments are different [1][63][67][70][71]. In its simplest form, the LCOE is calculated as the ratio between the lifetime cash outflows of the project and the lifetime electricity yield, as shown in Eq(5). Here '*lifetime cash outflows*' relate to all CAPEX, OPEX and decommissioning costs incurred throughout the plant's lifetime. Similarly, the lifetime electricity yield relates to the addition of the total net electrical output generated by the plant throughout its lifetime.

$$LCOE = \frac{Lifetime\ \ Cash\ \ Outflows}{Lifetime\ \ Electricity\ Yield} \qquad (5)$$

Eq. (6) shows a simplified methodology for calculating the LCOE of CSP plants. In this equation, the LCOE is estimated as a function of the annualized overnight CAPEX, the annual OPEX, and the annual net electricity output E_{net}. In most cases, when this simplified methodology is used then the E_{net} value assumed is the net annual electricity output estimated for the first year of operation, often calculated from performing dynamic power plant simulations using typical meteorological year (TMY) data. In Eq.(6) the CAPEX is annualized through use of the capital return factor α, often calculated using Eq.(7), where i stands for the real interest rate, n for the power plant lifetime and k_{ins} for the insurance rate, with values tailored to the location of the project [67].

$$LCOE = [\alpha \cdot CAPEX + OPEX] \cdot (E_{Net})^{-1} \qquad (6)$$

$$\alpha = i \cdot (1+i)^n \cdot [(1+i)^n - 1]^{-1} + k_{ins} \qquad (7)$$

Another methodology for calculating the LCOE is shown in Eq.(8) as introduced in [13]. This approach is based on a discounted cash flows analysis where all the financial flows are discounted to present value. In Eq.(8) the time value of money is considered by use of the weighted average capital cost (WACC) as a discount rate. The *WACC* can be understood as the aggregated required return on all sources of long-term capital [13]. In Eq.(8), the E_{net} can be assumed as the first year net output and is multiplied by the system degradation rate *SDR*, which is often negligible for CSP [82]. In Eq.(8) *N* stands for the operational lifetime of the project. The *WACC* can be calculated using Eq.(9), as a function of the equity-debt ratio ($Eq_{\%}$-$Debt_{\%}$), the debt interest rate i_{debt}, the expected rate of return for the equity part IRR_{eq}, and the corporate tax T_{corp}; with values tailored to the location of the project.

$$LCOE = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX_n}{(1+WACC)^n}}{\sum_{n=1}^{N} \frac{E_{net} \times (1-SDR)^n}{(1+WACC)^n}} \tag{8}$$

$$WACC = Eq_{\%} \times IRR_{eq} + Debt_{\%} \times i_{debt} \times \left(1 - T_{corp}\right) \tag{9}$$

It is worth highlighting that the methodologies briefly described here for the calculation of the LCOE are focused only on the operational lifetime of the plants. In reality the construction of a CSP plant takes approximately 2 to 3 years, and interest begins to accumulate on the money that was raised to finance the project. The longer the construction phase takes, the more interest that is accumulated. To account for such effect, the equation of the capital return factor (Eq.(7)) can be multiplied by a construction factor as explained in [14]. Similarly, at the end of the operational lifetime of the plant, the project owner is owed to incur in costs related to the decommissioning of the plant. An analogous factor could also be introduced in Eq.(7) to account for such effects [14].

For all the analyses performed in this thesis the LCOE comparisons were made considering overnight CAPEX. While it is acknowledged that such correction factors would impact on the calculated values, it should be stated that the trends and discussions raised throughout the analyses, as well as the comparisons performed, would still hold true.

The Net Present Value (NPV) and the Internal Rate of Return (IRR)

In order to be able to estimate and compare the profitability of distinct projects, financial performance indicators are used in techno-economic analyses [77]. Typical ones are the internal rate of return of the project (IRR) and the net present value (NPV). The NPV is the sum of the discounted cash-flows over the lifetime of the project, and can be calculated by use of Eq.(10). This equation is a function of the annual revenues calculated as the sum of the hourly product between the electricity price λ_h and the yield [14]. Eq.(10) is also a function of the years of plant construction n_{con}, years of operation n_{op}, and the decommissioning time and costs, n_{dec} and C_{dec}. Importantly, the NPV is a function of the discount rate i, for which the WACC can be used [13].

$$NPV = \left\{ \begin{array}{l} -\sum_{t=0}^{n_{con}-1} \frac{CAPEX}{n_{con}(1+i)^t} \\ +\sum_{t=n_{con}}^{n_{con}+n_{op}-1} \frac{\sum_{h=1}^{8760} \lambda_h \cdot E_{net,h} - OPEX}{(1+i)^t} \\ -\sum_{t=n_{con}+n_{op}}^{n_{con}+n_{op}+n_{dec}-1} \frac{C_{dec}}{n_{dec}(1+i)^t} \end{array} \right\} \qquad (10)$$

The IRR can be calculated as the interest rate, i, that would make the NPV equal to zero over the project lifetime. In financial terms, the IRR is the discount rate for which the present value of revenues and costs of the project are equal [83]. It is a measure of the profitability of a project and is used mainly by developers and financial institutions (creditors) for making investment-related decisions. A project is acceptable if the IRR exceeds the required target return. For comparing projects, it is generally accepted that the one with the higher IRR is a better choice.

Importantly to state that the IRR of the project should not be confused with the return of the equity, IRR_{eq}, used in Eq.(9) for the calculation of the WACC. The IRR_{eq} refers only to the expected IRR on the equity part of the capital, not the overall project IRR. Moreover, and depending on the tariff schemes, Eq.(10) can be used to calculate the bidding PPA price that is required to meet a desired project IRR target (i.e. by solving Eq.(10) for the electricity price λ_h that meets an NPV of zero for an assumed IRR).

Lastly, and as mentioned before, the financial performance indicators shown in this section, and used in the analyses, considered only revenue streams from the selling of electricity. In reality there are a number of additional revenue streams that a CSP plant could have by addressing, for example, several other markets such as a capacity market and the market for ancillary services (e.g. frequency stability).

5.2. Previous Research

Previous work has been performed both in the use of techno-economic analysis for the pre-design of CSP plants, and also in the evaluation of TES system integration through techno-economic performance modeling. This section first provides an overview of the tools commercially available for the pre-design of CSP plants. Then a brief overview of the previous work concerning the pre-design of CSP plants with TES is given.

5.2.1. Tools for Techno-economic Evaluation of CSP Plants

To date there exist several simulation software commercially available to evaluate the performances of CSP plants. The most commonly used software are here below mentioned, including key advantages and cons.

First, and foremost, the most common tool for the pre-design of CSP plants is the System Advisor Model (SAM) from the US based National Renewable Energy Laboratory (NREL). This tool incorporates economic and energetic hourly simulation of CSP plants and many other renewable energy technologies. The key advantage of SAM is that it is made freely available on the internet and accounts for a very detailed power plant cost (economic) model [78]. Another important advantage is its integrated graphical user interface, which makes it very easy to use. Moreover, SAM integrates a sensitivity analysis toolbox to simultaneously perform sensitivity studies with regards to multiple design parameters. One of its main disadvantages, though, is that it only accounts for a number of rigid CSP plant layouts (e.g. molten salt tower CSP plants) thus making it complex to use for evaluating new concepts (either new components or hybrid schemes). Another disadvantage is that while focus is placed on the accurate modelling of the solar components, the modelling of the power blocks is rigid and the power block design parameters are limited.

Another tool used for the analysis of CSP plants is the Green Energy System Analyses Tool (Greenius) developed by the German Aerospace Center (DLR) [84]. Greenius has both a free and a private version. The free version, FreeGreenius, is similar in structure to SAM, in the sense that it allows evaluating only rigid plant layouts, it offers a combination of fast technical and economical calculations and comes with an interface. The main disadvantages are similar to those of SAM, these being the impossibility to develop own new models and the level of detail in the power block design. Besides, it does not incorporate optimization models.

Another tool used for the pre-design of CSP plants is OPTISIM, developed in 2009 by the Fraunhofer Institute [85]. Information about this tool, though, is scarce and the tool was never made publically available. Available information states that it incorporated a single-objective multi-variable optimization routine based on biological evolution for identifying 'optimum' parameter configurations for each of the sub-systems in CSP plants (e.g. the solar field and the power block). A differentiator, with regards to SAM and Greenius, was that it seemed to consider more details of the power block components. OPTISIM was developed for parabolic trough plants based on the "Andasol I" configuration, from which the user could propose new designs only by varying some specifications (not allowing for customized designs either).

Several of the key companies providing power plant design software have begun to include CSP plant components in the tools. This is the case for Thermoflex [86] and Ebsilon Professional [87], for instance. Even though these software offer detailed power plant block models, the solution to quite complex equations is slower than for other tools (i.e. SAM). Furthermore, the integration of new components is not yet possible and the solar field related component models (technical and economical) are less detailed than in SAM. This is why SAM is still the preferred choice for studies concerning the pre-design of CSP plants.

5.2.2. Previous work on Pre-Design of CSP plants with TES

A number of studies have been performed dealing with the optimization of TES integration and operation in existing CSP plants. They are of different nature, some are oriented towards the benefits of CSP in the design of the energy system, at grid level, others at power plant level and some others are more detailed at component level.

Most of studies focused at grid level (e.g. energy system scenarios) are based on linear power plant models in order to quickly make a fair representation of multiple power plants with different technologies at the same time. In the context of CSP, these studies are focused on highlighting the value of CSP with TES at system level [65][66][88]. To ease and speed calculation, they require a fixed TES and solar field technology, and in some cases even to fix their size. Also, the power block models in these analyses are simple. As such, to fulfill their purpose most of these studies use a representative plant configuration from previous sensitivity studies performed at power plant level.

A large number of studies deal with the analysis of CSP plants with TES at power plant level (e.g. [89][90]). In most of these studies, all the main power plant blocks are modeled for a given CSP plant layout, and sensitivities to critical design parameters (i.e. the size of the solar field and the TES) are performed to ultimately identify 'best' configurations from quantifying key specific performance indicators, such as the LCOE. These studies are often based on the use of the available tools mentioned in the previous section. This means that they are limited to a number of already existing layouts and decision variables to optimize from. They also lack a number of details in the power block design. Moreover, these studies regularly employ sensitivity analysis techniques, instead of optimization algorithms. The outcome from these studies, though, has helped the research community to understand that:

- There exists an interrelation between the desired operation and the 'optimum' solar field, power block and TES sizes.
- That TES, despite increasing the investment, can lower the LCOE.
- That, although the main benefit of a CSP plant with TES is the increase in electricity sales, the integration of TES also enables additional revenue streams (i.e. ancillary services).

An issue missing in most of these studies is the use of detailed techno-economic power plant optimization models to analyze the interrelation between key performance indicators, and the usefulness of such performance indicators for a given project structure (e.g. comparing LCOE, IRR, CAPEX and others when considering specific price schemes or operating hours set by the tender). Similarly, there is a lack of studies focused at optimizing the integration of the power plant sub-systems when considering multi-variable parameter optimization in each of the sub-system designs (such as in [77][85]). Also, in most of the models, the operating modes and the use of smart dispatch strategies (e.g. for peaking) are dismissed (mainly because the focus is on the LCOE).

Specifically, in [77] Augsburger describes a thorough thermo-economic analysis of MS-STPPs with focus on identifying optimum plant configurations that lower the LCOE. In [77] the Gemasolar plant [12] is taken as a reference and multi-objective optimization is also performed to identify the optimal size and layout of the sub-systems involved. New configurations with regards to multi-tower analysis and a combination with parabolic troughs are also proposed and evaluated on the basis of minimizing the LCOE. One differentiator with regards to the work described in [77] is that in this PhD thesis the focus is to a great extend placed on reinforcing the value of a CSP plant in being dispatchable. In this work new comparative analyses between the LCOE and other financial indicators under different pricing schemes are introduced, when coupling TES dispatch strategies. Moreover, in this thesis the techno-economic tool is used to introduce, and to evaluate, for the first time new TES components and hybridization concepts.

Similarly, in [85] and [91] Morin introduces a techno-economic optimization framework for the design of solar thermal power plants. In this case, the work was mostly focused on parabolic trough plants to which multi variable sub-system optimization was performed to identify optimum plant configurations lowering the generation costs. Likewise [77], although it is shown that there exists an interrelation between the optimum design of the sub-systems in the plant, the scope of the analyses were limited to minimizing the LCOE (on the economic calculation side) and no hybridization with other technologies were considered.

Lastly, previous research have used techno-economic modeling for the evaluation of new TES concepts. In most cases the focus of these studies has been on the modeling of the TES technology itself, often validated against experimental data, and not on its impact at power plant level. In the studies where the TES concept is evaluated at plant level, then either most of the other key design parameters in the system are fixed, or the study focuses on a single performance indicator (e.g. [31]).

6. The TESCONSOL Project

This thesis emanates from a research project titled “Thermal Energy Storage for Concentrating Solar Plants” (TESCONSOL) [93][94][95]. The project has been funded by the European Institute of Innovation and Technology with the main objective of proposing strategies for the reduction of the high capital and maintenance costs in TES systems for CSP plants, by developing unique engineering analysis tools, optimum designs and innovative solutions. It aimed at providing a number of new products and services as deliverables by its conclusion in 2015, including:

1. Proposal of a cost-effective design for sensible TES in CSP plants.
2. Proposal of a cost-effective design for latent TES in CSP plants.
3. Pre-design tool and engineering services for decision making and optimization of TES integration in CSP plants.
4. Pre-design tool and engineering services for decision making and optimization of CSP plants.

Specifically, the work performed in this thesis is motivated on the successful accomplishment of deliverables 3 and 4: a pre-design engineering tool for CSP plants which, once developed, was used to evaluate different plant operating strategies and TES concepts in connection to deliverables 1 and 2. This is explained in each paper and shall also help to clarify the underlying motivations for the research questions formulated in each of the appended papers.

The TESCONSOL project was a consortium formed by a number of partners from industry and academia, all with expressed interest and complementary expertise in the field. The relation of the partners with the author of the thesis, and their contributions to each of the papers appended, are also explained in chapter 9. The partners in the TESCONSOL project were (in no specific order):

- KTH Royal Institute of Technology, *a university in Sweden.*
- UPC Polytechnic University of Catalonia, *a university in Spain.*
- Tecnalia, *an applied research and technology center in Spain.*
- Gas Natural Fenosa Engineering, *a subsidiary engineering firm of a multinational utility company under same name.*
- Total New Energies, *the renewable energy branch of a multinational oil and gas company under same name.*

7. The Dynamic Energy Systems Optimizer

In this thesis a comprehensive techno-economic methodology for analysis of CSP plants with TES is presented based on the application and further development of the Dynamic Energy Systems Optimizer (DYESOPT) software [14]. DYESOPT is an integrated tool capable of performing power plant design, performance evaluation and equipment costing that has been previously developed at the Energy Department of KTH Royal Institute of Technology [14]. To all of the research articles appended to this work a modified version of DYESOPT was applied in order to allow answering specific research questions concerning the integration of TES in CSP plants. These research questions and the specific implementation works required for each of the articles are briefly described in Chapters 8 and 9, respectively.

Prior to this work, DYESOPT was developed as a new software tool with the objective of being able to implement a techno-economic analysis process carefully described in the works of J. Spelling [14]. In following sections §7.1 and §7.2 the techno-economic process implemented in DYESOPT and the study cases previously considered are briefly described, respectively, as background information to the reader.

7.1. Techno-economic analysis process in DYESOPT

This section is a short summary of the description available in the work of J. Spelling [14] about KTH's modeling tool for techno-economic analysis, which has been further extended though this thesis.

The techno-economic analysis implemented in DYESOPT can be broken down into a number of modeling processes, as synthetized in Figure 21. The power plant analysis process in DYESOPT begins with its steady state design. A number of key design parameters of the power plant are used for performing steady-state calculation routines with the aim to determine the nominal operating point of the plant, as well as to design and size its equipment. This process is performed using standard numerical models of the involved components. These models are often used as previously developed by other authors, unless new models (or changes) are required, in which case they are developed, validated and implemented in the tool, as explained both in [14] and in Chapter 9.

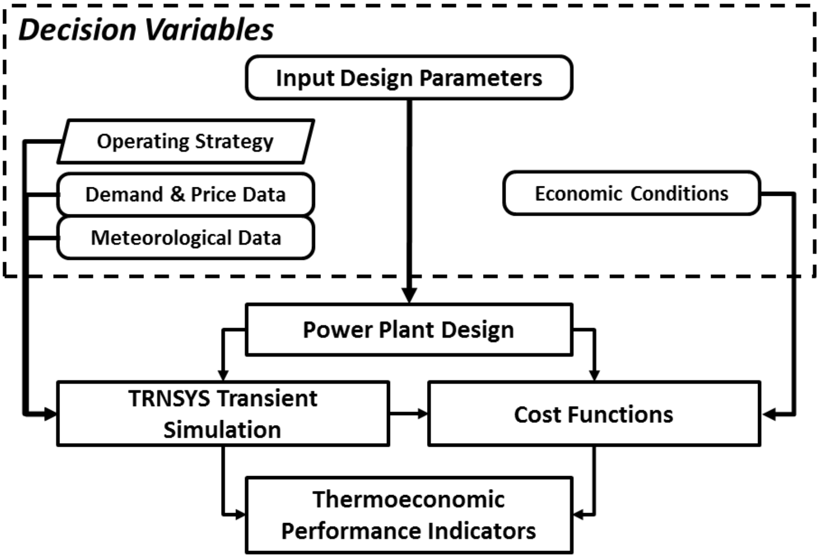

Figure 21 Sub-sections and information flows within the techno-economic analysis process implemented in DYESOPT [14]

Having determined the nominal size of the power plant components, this information is then sent to a transient simulation studio to simulate an entire year's worth of operation of the power plant. This is deemed possible provided that a dynamic model of the plant is previously developed and set in the simulation studio. This dynamic simulation is performed based on a set of time-dependent location input data (e.g. weather and price) and for a given operating strategy. The operation is defined by the user and might require the design and implementation of suitable controllers in the dynamic model (e.g. for peaking). This explains why the 'operating strategy' box has a different shape in Figure 21.

In fact, the dynamic simulation of a solar power plant is a necessity to obtain a representative evaluation of its performance. This mainly given that its output, and the operation of its components, are highly dependent on the solar resource and weather conditions. These are not only variable throughout the course of a day, but also very different along the year, which is the reason why a complete annual simulation is preferred. In DYESOPT this process is performed today using the commercial software TRNSYS [96] (as can be seen in Figure 21).

The power plant steady-state design data and the output from the dynamic simulation are used to determine the CAPEX and OPEX of the power plant through the use of dedicated cost functions tailored to the plant layout and based on location reference data, as explained in §5.1.1.

The results from the dynamic modeling and cost estimation processes are combined to produce a set of techno-economic performance indicators that can be used by decision makers for plant evaluation, such as those presented in §5.1.1 (e.g. the LCOE).

By varying key design parameters and repeating the techno-economic modeling process described in this section, it is then possible to compare different plant configurations and thereby to simultaneously assess a vast range of designs before decision making. The same applies to uncertain or sensitive input data. To simplify this process, DYESOPT incorporates a sensitivity analysis mode in which key design parameters are automatically varied within a specified range and respective performance indicators and plant data are stored.

As the design objectives for a CSP plant can be conflicting, DYESOPT can be coupled to a tool for multi-objective optimization that allows the users to determine the optimal trade-off curve that exists between the given conflicting objectives [14]. This is achieved by the notion of Pareto-Optimality [97] based on evolutionary algorithms and the optimization process described in detail in the works of Leyland [98] and Molyneaux [99]. In DYESOPT this process can be performed through the use of the Queuing Multi-Objective Optimizer (QMOO) tool developed at the Swiss Federal Technology Institute in Lausanne [99].

The choice of performing a sensitivity analysis or an optimization study will depend on the number of decision variables to simultaneously consider, the available resources (e.g. computational and time), and ultimately of the specific objective of the particular analysis. For all publications appended to this thesis, the techno-economic analysis process hereby described has been used, either in the form of a sensitivity analysis or of an optimization study. The specific performance techno-economic analysis process followed and respective performance indicators considered in each paper, are briefly explained for each case individually in Chapter 9. Finally, all relevant information about the core structure of the tool, the data treatment, and about the information exchange processes among the commercial software interconnected are found and explained in detail in the work of Spelling [14].

7.2. Previous power plant case-studies in DYESOPT

Power plant models available in DYESOPT prior to this thesis relate to the research work of Spelling [14]. The scope of the work of Spelling was to evaluate and compare a wide spectrum of hybrid solar fueled gas-turbine power plant configurations to ultimately provide decision makers with a useful tool for assessing the design of such systems. Although the scope of the present thesis is focused on the integration of TES in CSP and not on solar-gas turbine hybridization, the power plant models developed by Spelling (and especially their related subcomponents) well served as an inspiration and reference for the development of the power plant models shown in the appended papers (and discussed later in this thesis). This section is aimed at shortly describing the power plant performance models presented in [14] and to comment which sub-models have been used in the present work, as well as to which of them the author of this thesis has contributed to, when applicable.

Simple-Cycle Hybrid Solar Gas-Turbine Power Plants

The basis for all power plant models developed in the work of Spelling relates to the simple cycle hybrid solar gas turbine power plant model, which consisted of five main sub-components, namely: the compressor, the heliostat field, the central tower receiver, the combustion chamber and the turbine. The power plant layout and respective sub-component models are thoroughly described in [100]. Out of these, only the heliostat field model, both the dimensioning approach and the TRNSYS type, was used for the power plant case-studies considered in this work.

The algorithm deployed for the dimensioning of the heliostat field was based on the works of Klister [101] and Collado [102]. It takes into account the annual performance of each individual heliostat cell, to only select best cells showing highest annual specific power output and guarantees that the required thermal power by the central receiver at design conditions is met. This methodology allows calculating an off-design solar field efficiency matrix which is required as input to the TRNSYS component Type 394 [103], used for the dynamic model.

Hybrid Solar Gas-Turbine Power Plants with TES

The integration of TES into the simple-cycle hybrid solar gas turbine power plant model briefly described in the previous section represented the development of models for the steady-state sizing, off-design dynamic performance (including new power plant controllers), and respective cost functions of the proposed TES concept. The TES concept introduced was applicable only for direct integration into hybrid solar fueled gas-turbine cycles with an air mixture as HTF and it was not considered for any of the power plant models developed and analyzed in this thesis. However, the author of this thesis contributed to the integration of such TES component in the TRNSYS plant layout by performing first preliminary off-design controlling strategies and tests based on existing TRNSYS types as available in the TRNSYS STEC library [103]. The detailed techno-economic modeling of the hybrid solar gas-turbine power plant with TES, including results and underlying assumptions, can be found in [104] (a research paper also co-authored by the author of this thesis).

Hybrid Solar Gas-Turbine Combined Cycle

A conventional bottoming Rankine steam-cycle [45] was added to the simple-cycle hybrid solar gas-turbine power plant model with the objective of increasing the thermal efficiency of the system. In doing so, Spelling developed and implemented thermodynamic models for the sub-components of the steam-cycle. Some of these sub-component models have been used in this thesis. These are all described in [14]. The off-design models were based in the STEC library TRNSYS components [103]. Same approach was followed in this thesis, as explained and properly referred to in each of the publications hereto appended.

Hybrid Solar Gas-Turbine Combined Cycle with TES

This model relates to an advanced solar gas turbine hybrid cycle that combines the advantages of both TES integration for solar share augmentation, and also the addition of a bottoming steam cycle for increased fuel-use efficiency. Aside the required new controllers to meet the designated operation of the new proposed layout, no further model development was performed.

8. Summary of Research Questions

In alignment with the objectives listed in §2.1, and based on the challenges described in §4.5, as well as in order to build from the previous research mentioned in §5.2 and §7.2, a number of research questions were defined and addressed by the studies performed throughout this PhD Thesis. The main research questions in connection to the papers appended were:

- Can the optimization of the sub-systems in a solar tower plant, and their relation, impact its performance?
  - What are the key decisive parameters and how does each influence the performance?
  - How much is the performance affected by the way the sub-systems are sized and operated (i.e. the size and dispatch of the TES system)?
- Is it possible to identify a single-optimum configuration when designing a solar tower plant?
  - What is the criteria to decide so?
  - Are the performance indicators used valid?
  - Is there a better methodology to assess the designs?
  - How do the hour of generation and the hourly electricity price impact on the decision?
- Can a new TES concept enhance the competitiveness (e.g. in terms of IRR, CF, and LCOE) of a solar tower CSP plant? If so:
  - Can we estimate by how much?
  - What are the challenges for it to be deployed?
- Can new hybrid schemes enhance the competitiveness (e.g. in terms of IRR, CF, and LCOE) of a solar tower CSP plant? If so:
  - Can we estimate by how much?
  - What are the challenges for it to be deployed?
- What impact does TES integration have on the operational requirements of the power block in CSP Plants (in terms of size and dispatch strategy)?

9. Results and Discussions

This chapter provides a brief description of each of the research articles appended to this thesis. The aim is to provide the reader with an overview of the results, the interrelation between the articles and their contributions with respect to the state of the art. As explained in §2, the work carried in this thesis can be split in four parts: multi-parameter techno-economic optimization of contemporary MS-STPPS; techno-economic feasibility evaluation of new TES concepts in contemporary MS-STPPs; techno-economic feasibility evaluation of new hybrid schemes based on contemporary MS-STPPs; and other related studies on the added value of TES. This chapter is therefore split in four sections, each grouping papers in connection to the mentioned topics. Each paper is addressed individually, and the contributions from the author of the thesis to each of them are also explicitly mentioned.

9.1. Evaluation of Contemporary CSP plants

In order to support the decision making processes along the development of a CSP project, it was first deemed necessary to develop and establish a flexible pre-design techno-economic modeling tool that allowed to quickly and accurately evaluate the performance of the plants. The underlying research goal of such, was to being able to understand how the integration of the sub-systems could be designed to yield a better optimized plant configuration, on the basis of the 'typical' performance indicators (§5.1.1). To add to the state of the art, work is focused in particular in the conventional MS-STPP layout and is aimed at understanding the interrelations between the TES sizing and dispatch strategies with regards to the design of the PB and the SF.

This section summarizes the works and results from Papers I and II. Paper I presents the first approach of the thesis towards a flexible pre-design tool for assessing the design of MS-STPPs. The approach proposed is based on multi-variable parameter optimization used to address multiple design objectives at the same time. The multi-variable parameter approach included as decision variables a set of key parameters in the sub-systems (i.e. design parameters in the SF, the PB and the TES blocks) and also a developed TES peaking 'smart-dispatch' script at pre-design. Paper I builds from the work presented in [105], another study performed and published by the author of this thesis (Paper A – not appended).

Paper II, builds from the flexible model presented in Paper I. In this study the model is further enhanced and applied to specific boundary conditions. In Paper II the model presented in Paper I is enhanced by improving the dynamic response (i.e. transients and dispatch strategies) and also by adapting it to allow the coupling of specific electricity hourly pricing schemes. A case-study is set for South Africa to compare the optimum plants resulting under the different pricing schemes. Moreover, an analysis with regards to the validity of using solely one performance indicator is discussed, and also how the relation between the different performance indicators varies for each scenario considered.

9.1.1. Multi-variable Parameter Optimization of MS-STPPs (Paper I)

In this study, a flexible techno-economic model for the analysis of a MS-STPP with a layout similar to that shown in Figure 13, and briefly described in §3.5.1, was developed. A specific case-study for a suitable location for deployment of this technology in southern Spain was setup to assess the usefulness of the tool and to analyze the interrelation among the key sub-systems when considering multiple objectives at pre-design stage (i.e. minimizing LCOE, maximizing IRR and minimizing CAPEX).

The objective of the work was to introduce for the first time the techno-economic methodology when applied to MS-STPP, and to show its efficacy for identifying the true optimum trade-off curves between costs, profitability and investment by simultaneously considering TES dispatch strategies together with SF and PB design (i.e. size). The goal was to show that when multiple design objectives are addressed there is no single optimum MS-STPP configuration, instead by identifying the trade-off curves then a wide range of 'optimums' can be presented to decision makers (e.g. FIs and developers), who can at last choose a configuration that best satisfies their needs (e.g. in terms of investment and profits).

Remarks about the Modeling Work

The MS-STPP model was developed and setup in DYESOPT (§7). The individual steady state models for each of the components existing in the power plant were implemented. The equations governing these models were extracted from [14] (as gathered from [101][102] and [106]) for the SF, from [78] for the HTF cycle, and from [107][108] for the PB.

For the dynamic model, each of the blocks in the MS-STPP: the SF, the TES-HTF cycle and the PB, were modeled in detail in the TRNSYS simulation studio [96]. Within TRNSYS, the SF was modeled using STEC Types 394 and 395 for the heliostat field and central receiver respectively [103]. The TRNSYS Type 39 variable volume tank was used to model both the hot and cold tanks of the two-tank direct TES system, with additional HTF fluid properties data obtained from [78]. Concerning the PB, the transient model calculates the steam mass flow input to the turbine based on the conditions of the hot molten salts at the inlet to the steam-generator heat exchanger train, using components from the TRNSYS STEC and Heat Exchangers libraries, as described in [103]. All of these components have been validated in previous studies for the transient modeling of Rankine cycles in CSP plants [109]. Off-design performance of the PB considered variations in efficiency and mass flows as a function of the turbine inlet conditions using the Stodola ellipse law [110].

In this study, two TES dispatch strategies were introduced together with their respective logical variables. The choice of the TES dispatch was set as an input to be defined by the user. Specifically, new controllers were set to satisfy a "peaking" operating strategy (i.e. to prioritize production hours based on the hourly electricity price and the available energy forecasted in the TES), different from that of a 'continues' strategy where electricity is always produced as long as the hot tank does not meet its minimum operational level (input). The implementation of this "*Pre-defined Dispatch Strategy*" (PDS) required the development of new data–processing structures in the pre-design stage. The dispatch control strategy and decision variables are shown in Paper I.

The cost model was set up using as a reference the model described in [79] and [80] with input data for the location taken mainly from [13]. A sensitivity analysis with regards to the cost functions and reference input data was performed later in the study of Rönnberg [81], supervised by the author of this thesis. Moreover, the ability of the model to accurately estimate the techno-economic performance of the MS-STPP was also verified in a later stage, throughout the work performed by Schiessl [111], also supervised by the author of this thesis. Schiessl compared the results between the MS-STPP model and an equivalent one set up in SAM for a number of reference cases, showing in average a mismatch of less than 5% for LCOE and yield predictions. Both [81] and [111] contributed to verify the accuracy of the MS-STPP model as a pre-design tool.

The MS-STPP model was coupled to the QMOO Multi-Objective Optimizer [98][99] and used to evaluate the performance of the MS-STPP for a location in Spain. The choice of Spain was based on the fact that Gemasolar [12] was the only demonstrated large-scale MS-STPP by then. The optimization was setup to allow varying critical design parameters for each of the key blocks, as explained in Paper I (including the choice of operating strategy), with the objective of finding optimum plant configurations maximizing the project's IRR and minimizing the CAPEX. While the choice of maximizing the project's IRR is obvious, the selection of minimizing CAPEX as a design objective was based on the fact that, being MS-STPP a new technology then the larger the CAPEX, the higher the associated risk and difficulty for reaching financial closure. Simultaneously, other performance indicators such as the LCOE and the CF were calculated. At this stage, the IRR was calculated using historical annual electricity price data for the location, not a fixed scheme.

Highlights from the Analysis

An example of the main results from the optimization is seen in Figure 22, which shows the trade-offs between maximizing IRR and minimizing CAPEX when compared to a design parameter (i.e. PB capacity) and to a performance indicator (i.e. LCOE). In these plots, each point represents a specific plant configuration resulting from the particular combination of inputs chosen by the optimizer. The use of such discretized plots for showing the optimization results with regards to its decision variables, was also for the first time introduced in this work. This was deemed as advantageous by the industrial partners of the project.

Discretizing the trade-off plots as a function of the input critical design variables (or vs. other performance indicators such as in (b)) was deemed useful for understanding the influence that each parameter had on the results. Such a representation of the results would allow the users of the tool (e.g. decision makers) to visually understand the influence of critical parameters in order to rapidly decide which configurations should be further investigated. For the specific case considered in the study, Paper I shows that although the highest profits were reached for larger PBs with 'continuous dispatch', a project with a smaller SF and a smaller TES (and thus way less capital intensive) would have being able to achieve only slightly lower IRR values when coupled to a peaking dispatch strategy.

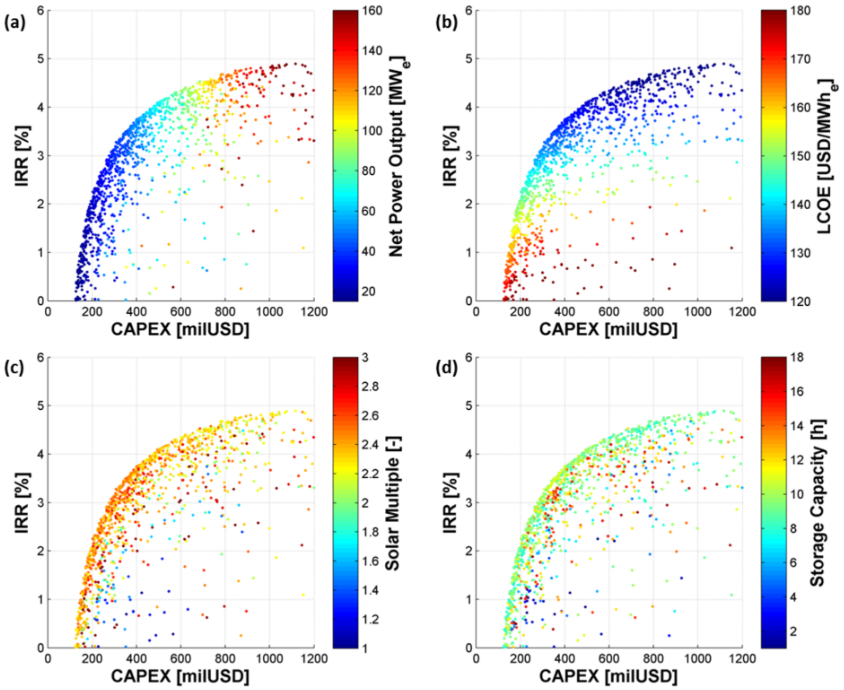

Figure 22 Multi-variable IRR-CAPEX Optimization trade-offs in Paper I

Paper I also shows that by tracing back the influence that decision variables had on the objectives' trade-offs it was possible to further tune the analysis by fixing, for instance, one of the resulting key variables and then performing a second optimization. In this study, this was done so for the PB Capacity, which seemed to drive the results (as shown in Figure 22 (a)). For a fixed PB capacity the influence of other key variables such as the operating strategy, the solar field size (measured using the SM as defined in [78]), and the TES size was possible to be seen (Figure 23). The methodology allowed to derive correlations with regards to the decision variables for later use in even faster models, if desired, though only applicable to the specific case-study (layout and location).

Lastly, for the specific case-study, results showed that there is a clear connection between how each sub-system is designed with regards to the other (e.g. the size of the SF, the TES capacity and the PB capacity) and how the choice of such would impact the overall power plant performance, which could be assessed using different indicators at once.

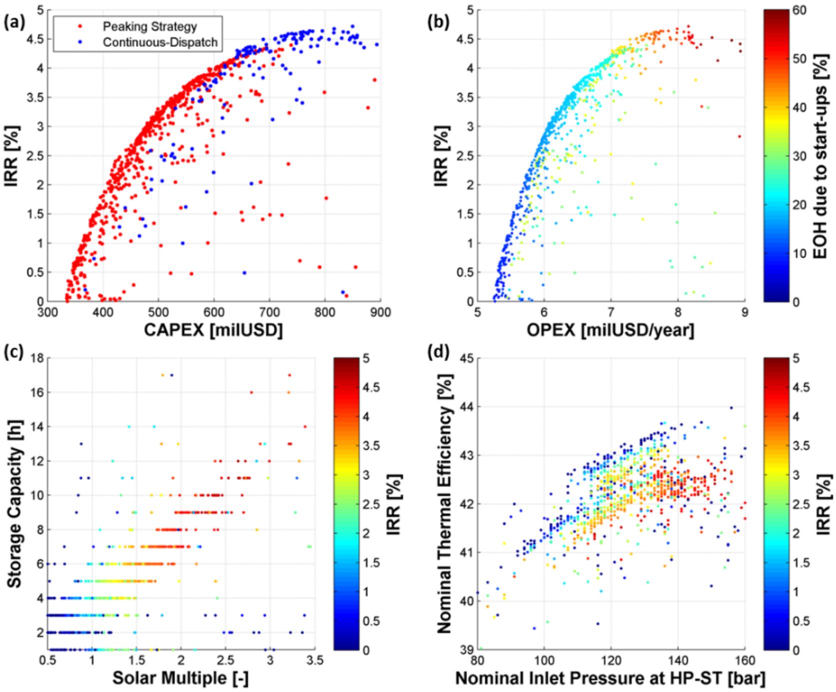

Figure 23 Paper I results (cont.): optimization trade-offs for fixed PB capacity

9.1.1.1. Contributions to state-of-the-art

- A new multi-variable techno-economic optimization model for the analysis and pre-design of MS-STPPs is introduced.
- For the first time, peaking strategies are included in techno-economic performance models of MS-STPPs. A pre-defined dispatch strategy routine is presented and proven to have an impact in the financial performance (i.e. IRR) of MS-STPPs.
- A new methodology for the assessment of MS-STPPs is suggested to decision makers by evaluating CAPEX vs. IRR and CAPEX vs. LCOE trade-offs.
- Discretized plots for better and quick interpretation of the techno-economic optimization results are introduced.

9.1.1.2. Author contributions to the paper

All model development, implementation and verification work, as well as the analyses, were performed by the author of this thesis. Similarly, all sections of the paper were also written by the author of this thesis.

Co-author M. Topel supported by co-supervising the sensitivity analysis to the cost models shown in [81]. Co-authors J. Spelling and B. Laumert proof-read the paper and provided feedback to the structure and discussion in the analysis section of the paper.

9.1.2. Electricity price influence on designing MS-STPPs (Paper II)

In Paper II the MS-STPP model introduced in Paper I was further developed and adjusted through cross-verification at industry, before its application to three case-studies using the same location (i.e. Upington in South Africa), but with different electricity pricing schemes. The goal of such was to at last discuss the influence of pricing tiers in the choice of optimum plant configurations, in terms of size and dispatch strategy. In addition, the case-study is used to bring forward the discussion about the usefulness of a sole performance indicator when comparing power plants (i.e. LCOE). The study also provides detailed suggestions to decision-makers about the use of the proposed techno-economic methodology when evaluating CSP plants under different off-taker pricing schemes.

Remarks about the Modeling Work

In Paper II the steady-state part of the MS-STPP model introduced in Paper I was cross-validated with commercial software for power plant design. In order to perform such cross-validation work it was deemed necessary to develop a simple graphical user interface for the tool. This was done so that the industrial partners of the Tesconsol project could use the model as a third-party user. For a number of reference cases, one included in the paper, the model was compared against commercial software ([86]) and the results were deemed as satisfactory. In addition, by doing so, the industrial partners were able to corroborate the reference cost data and helped tuning the cost model by providing real power plant component costs, as made available through quotations.

In Paper II the Pre-defined Dispatch Strategy is further explained. The paper shows a schematic representation of the logical controller routine set prior to the dynamic simulation, and also of the dispatch controller used in the dynamic model itself. The start-up and ramp-down response was also enhanced by, for instance, including fixed steam turbine start-up schedules based on cooling-down time [103]. In this study, the cost model was extended and explained in more detail in the Appendix section, based on experiences learned from [81] and at industry.

The choice of the location for the model was based on the use of Solar Reserve's Redstone project as a reference [55]. The choice of South Africa was also based on the fact that different pricing structures (i.e. tariff tiers) have been used by the government in the distinct tenders launched within their Renewable IPP Procurement Program (REIPPPP) [62].

Three pricing scenarios were implemented in the tool. The first scenario, S1, assumed a two-tier pricing scheme similar to that resulting in the 3.5 round REIPPPP, with a 'Time of Use' multiplier of 2.7 for energy generated in the evening. The second scenario implemented, S2, resembled the pricing tiers found in the South African Power Pool, a power market in the region [112]. This is also a scheme similar to one previously used by the local utility ESKOM [113]. The third scenario, S3, was based on the results from Round 1 of the REIPPPP [92][114], with a fixed price under certain hours. For all these scenarios, the optimizer was set to determine the trade-offs: maximizing IRR vs. minimizing CAPEX.

Highlights from the Analysis

Key results from the optimization can be seen in Figure 24, which shows the trade-offs between maximizing IRR and minimizing CAPEX for all three scenarios. In the discretized plots, each point represents a plant configuration from the combination of the decision variables. Figure 24 shows the influence of critical design parameters (i.e. PB capacity, SF size and TES size) and also the influence of the choice of a peaking operating strategy. Optimum configurations 'A', 'B' and 'C' in scenarios S1, S2 and S3 respectively, are highlighted in Figure 24, for the sake of comparison and discussion. In this figure, plant "D" is an 'optimum' configuration when the optimizer is set to minimize LCOE for S1 instead of maximizing IRR, as discussed later in this section (Figure 25).

The results confirmed that the pre-design of CSP plants is subject to location and, more importantly, to project structure boundaries (i.e. pricing tiers and operating schemes defined by tender). From which it can be inferred that projects are to be treated on a one-by-one basis, and that comparing plants resulting from different conditions might not yield useful conclusions, even if in the same country or location.

In the discussion section of Paper II an exhaustive analysis is provided to explain how an 'optimum' plant configuration for a specific pricing scenario would not necessary be 'optimum' under other conditions. The relevance of allowing multiple design parameters to vary in each of the key blocks of the MS-STPP at early design phase is discussed, as it is shown that some parameters would be more decisive than others depending on the scenario (i.e. a peaking dispatch strategy for S1).

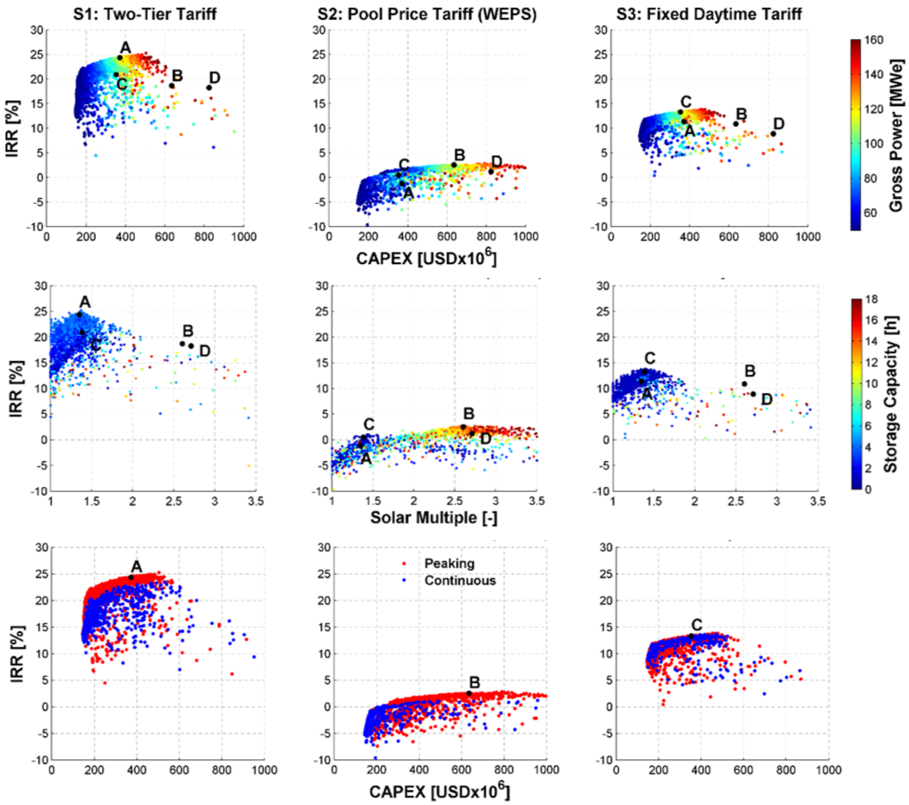

Figure 24 IRR vs CAPEX trade-offs for all three scenarios considered in Paper II

The resulting performance of the ‘optimum’ power plants under distinct scenarios is used to provide the reader with a comprehensive strategy for applying the techno-economic modeling in order to evaluate risks prior to the decision making. The results are also briefly analyzed under the perspective of different key-actors (i.e. tender designers and developers), to whom recommendations are addressed at last.

To complement the study, another optimization was set using also S1 as a basis, but with the objective to minimize LCOE instead of maximizing IRR (keeping minimizing CAPEX as a second objective). The purpose of such second optimization was to show the difference in the resulting ‘optimum’ configurations and thereby the need for the decision maker to understand the context of the analysis, the meaning of the performance indicator, and how to use each of them to compare power plant designs.

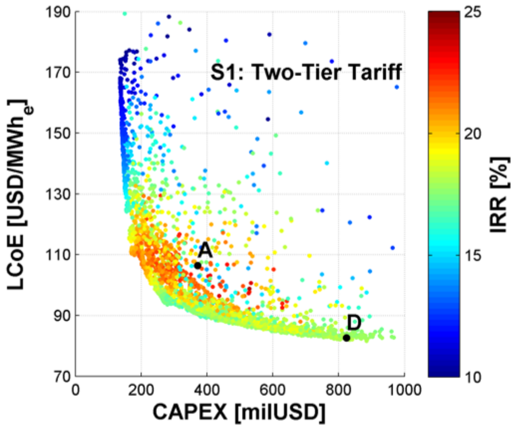

Figure 25 CAPEX vs. LCOE trade-offs for S1 (Paper II)

Figure 25 shows the trade-offs between minimizing LCOE and minimizing CAPEX for S1. In this figure results are discretized with regards to the IRR. In Figure 25 plant 'D' is highlighted from the Pareto Front. In Paper II, optimum plant 'D' is compared against plant 'A' (an optimum for maximizing the IRR) and used as an example to stress that the LCOE does not value the time of generation. It is discussed that optimum plant configurations minimizing the LCOE would not necessary be deemed as optimum from a 'maximizing IRR' standpoint.

Conclusively, the study recommends decision makers to, in practice, use the LCOE as a performance indicator together with the CF, often restricted by the tender (e.g. by imposing operation hours), and compare it to the IRR. This last, especially if hourly variations are seen in the electricity price, for which models that incorporate 'smart' dispatch strategy controllers should be used. It is lastly suggested that the LCOE under its standard definition shall be 'valid' to use as a single-indicator only in the case when the off-taking contract is based on a single tier fixed-price (e.g. FiTs or fixed-price PPAs) and, preferably, when the contract is signed on a generation amount (i.e. the annual net output), regardless the time of production. The LCOE would thus be suitable for analyzing baseload-like plants, for example.

9.1.2.2. Contributions to state-of-the-art

- The MS-STPP CSP model, introduced in Paper I, was further extended by adding improved dynamic controllers, new location data and pricing schemes.
- First work using detailed sub-system multi-variable techno-economic optimization analysis to assess the relevance of TES dispatch strategies under different pricing schemes.
- A methodology for assessing CSP plant configurations under different pricing schemes, simultaneously, is provided.
- First study that applies techno-economic optimization to specific tender-like CSP project requirements to provide suggestions to key actors along the project development chain.
- First time that multi-variable parameter optimization is used to argument the validity of comparing power plants on the basis of LCOE and to show the importance of coupling LCOE with CF and IRR calculations for assessing CSP plants.

9.1.2.3. Author contributions to the paper

In Paper II all model development and implementation work was carried by the author of this thesis. Similarly, the choice of the case-study and the analysis of the results was performed, mostly, by the author. All sections of the paper were likewise written by the author of this thesis.

Co-author M. Topel supported the work by providing information to the cost models used. Co-authors I. Conde, F. Ferragut, and I. Callaba supported by contrasting the results from the model with other standard software for a large number of cases, in cooperation with the main author of the thesis. They also provided cost data and reviewed cost models. Co-authors Z. Hassar and C.D Pérez Segarra provided feedback concerning the choice of the case-study, the paper structure and the discussion of the results. Co-authors B. Laumert and J. Spelling proof-read the complete paper and provided final suggestions with regards to the presentation of the results and structuring of the discussion section.

It is worth mentioning that during model implementation, setup of the case-study, verification of the model, and also while analyzing the results, the author of the thesis re-located to the offices of the industrial partners within Tesconsol with whom discussions were held frequently. Only by doing so the co-authors at industry were able to contribute as mentioned.

9.2. Feasibility of new TES concepts

Aside the optimization of the integration of the sub-systems in a CSP plant (i.e. SF, PB and TES), as discussed in the previous section (§9.1), another alternative that could drive LCOE down is the development, and at last deployment, of new TES concepts. As such, in this thesis a new TES concept was proposed and evaluated through techno-economic analysis. The goal of doing so, was two-fold:

- To assess the usefulness of the techno-economic methodology presented in Papers I and II when applied to the feasibility evaluation of new components in the system (i.e. TES).
- To quantify the impact that integrating a new TES concept in a contemporary CSP plant layout could have for reducing its LCOE or else enhancing its profitability (i.e. in terms of IRR).

The TES concept introduced and evaluated in this thesis consists of a single-tank thermocline TES concept comprised by multiple layers of solid fillers and encapsulated PCMs for integration in a MS-STPP. Paper III presents the concept and describes the modeling steps and the main findings from the feasibility analysis, including future research work suggestions. In this section a summary of Paper III is provided. The paper is put into context of the PhD work, and also key findings and remarks on the methodology followed are provided. The contribution of the author of the thesis to the study is also explicitly mentioned.

9.2.1. Multilayered Solid PCM Tank TES for MS-STPPs (Paper III)

In Paper III a multi-layered solid-PCM (MLSPCM) tank TES concept for MS-STPPs is for the first time introduced and evaluated through setup of a specific techno-economic case-study. The performance of the MS-STPP with the new concept is also compared against the performance of the more conventional MS-STPP based on the two-tank direct TES system. At the end, Paper III highlights the challenges and opportunities for the concept proposed and suggests future research paths.

The choice of the concept was based on the fact that one of the main drawbacks of the two-tank TES system is that it requires two equally-sized tanks to act as buffers, each one with a volume capacity enough to store the whole TES media, which means that the tanks themselves are not effectively used (at no point both tanks are full in a MS-STPP). Therefore, a solution based on a single-tank was perceived by the authors of Paper III as a potential alternative to decrease the TES costs significantly while guaranteeing the plant performance, if properly designed.

The layout of the MS-STPP using a single-tank is shown in Figure 26. As can be seen in Figure 26, a single-tank is integrated in parallel to the receiver, altering only the TES-HTF block of the layout. Single-tank TES concepts receive the name of thermocline TES systems. These are systems in which in one single container both cold and hot HTFs are stored simultaneously and forced to pass through a packed bed of solid filler material (TES media). This creates a steep temperature gradient in the heat-exchange region, called the thermocline.

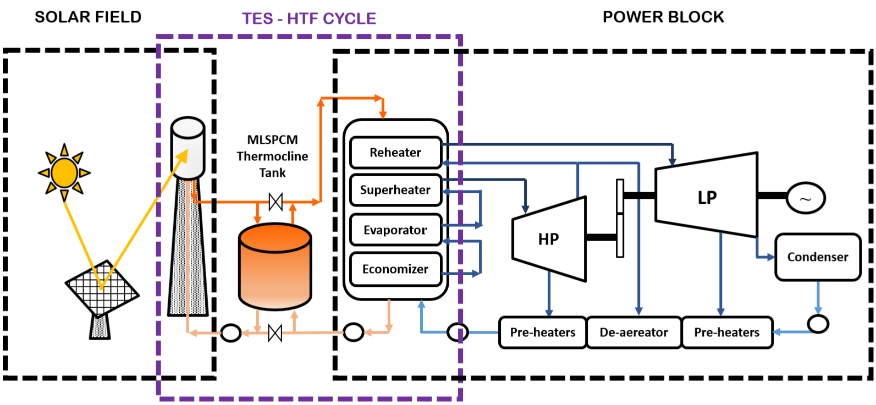

Figure 26 MS-STPP layout with a Multi-layered Solid PCM Thermocline TES (Paper III)

The thermocline region of a single-tank is what prevents the hot and cold fluids from mixing and it travels along the tank during the TES charging and discharging processes. Usually, solid sensible TES media is used as filling material, as it is deemed as less costly. The use of such S-TES media though represents multiple challenges. Then, in order to come up with an interesting single tank concept for MS-STPP worth evaluating, the authors identified the main drawbacks and challenges of the more conventional solid-filled single-tanks, and proposed potential solutions to tackle each of them based on an exhaustive literature survey work [115] and in previous work of the co-authors [116][117].

After doing so, it was proposed to evaluate the feasibility of a single-tank combining both S-TES and L-TES fillers in different layers to create a porous medium, similar to that previously proposed for PT-CSP plants by two of the co-authors of Paper III. In this case the search for new suitable materials and the related operational challenges were needed to be addressed, as higher temperatures are handled in the MS-STPP.

A simple schematic representation of the concept is shown in Figure 27. Specifically, the design consisted of a 'packed bed' formed by two layers of encapsulated-PCM (E-PCM) L-TES fillers (PCM 2 and PCM1 at top and bottom of the tank respectively), and a large layer of S-TES fillers for which quartzite and silica sand were considered. The same 'solar salt' used in the two-tank system was considered as HTF to ease integration.

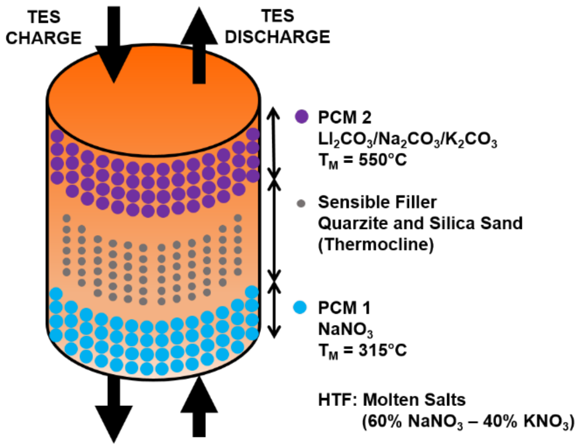

Figure 27 Schematics of the Multi-layered Solid PCM Thermocline TES Tank (Paper III)

In the study developed by Ferruzza [115], all design criteria considered for the choice of the materials and final geometry are provided, in some cases as resulted from several sub-component optimization analysis. Similarly, the details of the modeling work, the case-study and the comparative analysis versus the more established two-tank concept can also be found in [115], as implemented by Ferruzza under guidance of the main author of the thesis. The author of this thesis actively contributed throughout all the steps of the work: defining research questions, concept evaluation, model implementation, model cross-validation, integration in the MS-STPP performance model and, especially, in the analysis.

Paper III, is a condensed version of the work described in [115], including the key findings, as they are later described in this section. Worth mentioning that this work builds on the modeling work and experiences described in Papers I and II of the author. Conclusively, the study shows that the concept is technically feasible (in theory), and that it could certainly help increase the cost-competitiveness of CSP with regards to the ‘conventional’ two-tank system. Specifically, for the test case set it was found that the MLSCPM concept was able to enhance the profitability of ‘peaking’ MS-STPPs with small TES units (3-6 hours).

Remarks about the Modeling Work

The modeling work carried out for the feasibility evaluation of the proposed TES concept can be split in two: the modeling and validation of the TES concept itself, and the multi-variable optimization model of the MS-STPP with the new concept integrated.

First, in order to be able to test the concept and its impact in the MS-STPP, an accurate representation of the physical phenomena occurring in the proposed geometry during the charging and discharging processes was needed. A numerical model was developed based on mass and energy conversion equations between the HTF and the filler capsules, based on the geometry proposed. The model deployed conventional finite volumes method for solving the differential equations, to which simplifications were made as described in Paper III. This model was cross-validated in three different aspects: the PCM-HTF temperature evolution, the thermocline profile evolution and the dynamic response of the multi-layered concept. To do so, works from Nallusamy et al. [118], Pacheco et al [119], and Galione et al. [116] were respectively used. Results from the validation can be seen in Paper III, as found in more detail in [115].

Once validated, a methodology was defined in order to implement the TES component model in the performance model of the MS-STPP. As the component model was highly computational demanding, a strategy was set to ultimately define a valid interpolant function with correlations dependent on the working conditions of the thermocline tank (i.e. inlet mass flows and temperatures), for which a number of simulations of the TES model in isolation were needed.

Based on such interpolant function, a new dynamic component was developed and implemented in TRNSYS, and later integrated in the dynamic model of the MS-STPP in DYESOPT. In order to evaluate the impact of the TES concept in the model, new controllers for the TES dispatch were created (e.g. to allow for reversible flows) and the peaking dispatch strategy was slightly modified to account for the difference in dynamic response between the two-tank TES and the new concept. Moreover, in order to implement it in DYESOPT, a detailed cost model of the new TES concept was set based on discussions and data provided from the research partners of the Tesconsol consortium [120].

At last, two multi-variable techno-economic optimization analyses were performed for the same location and conditions used in Paper II. The key parameters of the MS-STPP with the new TES concept were varied to find optimum configurations in terms of maximizing IRR and minimizing CAPEX, as well as in terms of minimizing LCOE. From these trade-offs two optimum configurations were selected, both of 110 MW_e capacity, and used as a basis for a subsequent comparative analysis against the performance of an equivalent MS-STPPs with a two-tank system. The comparative analysis was made by means of a sensitivity analysis with regards to the SF and TES size for both MS-STPP layouts, while keeping the same PB size and design specs yielded from the optimizations.

Highlights from the Analysis

Figure 28 summarizes the results from the comparative analysis amongst the performance of the MS-STPP with the conventional two-tank system and with the new TES concept proposed.

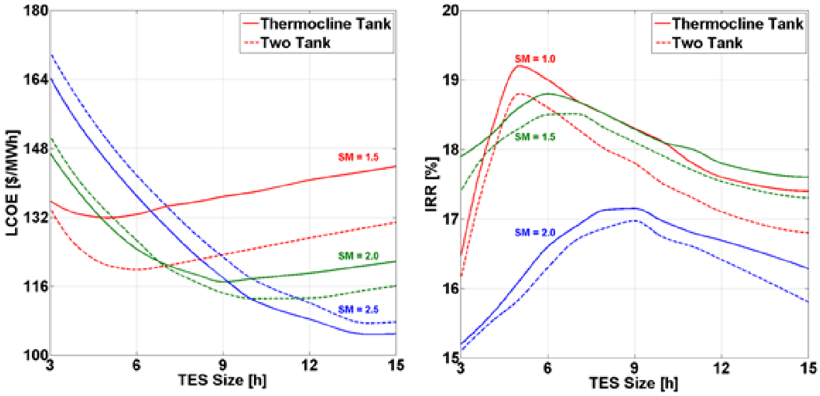

Figure 28 Sensitivity analysis between a two tank and a single-tank MLSPCM (Paper III)

To put the work into context, it is worth highlighting that the price-scheme used for the IRR optimization was the same as the S1 scenario in Paper II, a two-tier tariff scheme with a clear 5 hour premium in the evening. Figure 28 (right) shows that, under such market conditions and cost assumptions, the MS-STPP with the new MLSPCM TES concept would be more profitable.

In reality, results from the analysis carried in Paper III showed that there was no clear better solution amongst the two technologies for the particular case-study considered. For instance, results in Figure 28 (left) also showed that a conventional MS-STPP with two-tank TES would be more competitive on the basis of LCOE, except for the plants with large SFs and TES systems. Nevertheless, with a large potential for cost reduction on the PCM material and in the encapsulation process, the scale could weight in favor of the proposed single-tank concept. However, it is acknowledged in the study that for the proposed MLSPCM concept to be deployed, first an analysis on the impact of cycling and degradation of the components is needed. This is critical, especially for the E-PCM, as the capsules could suffer from failure while being exposed to daily charging and discharging processes. Failure of the capsules would ultimately force the plant to stop, for instance, because of the complexity of the system, which would also make difficult the maintenance.

9.2.1.1. Contributions to state-of-the-art

- A multi-layered solid-PCM single-tank TES concept for MS-STPPs is for the first time introduced.
- A component model of the multi-layered solid PCM single-tank TES concept was developed, validated and implemented in a techno-economic performance model.
- Through a case-study, competitive advantages of the new TES concept are highlighted and future research work is proposed.

9.2.1.2. Author contributions to the paper

The research questions and methodology of the study were defined by the author. Similarly, the author actively contributed to the analysis of the results and to the model implementation of the TES concept into the existing MS-STPP performance model. The author proposed the structure for the paper, reviewed it and applied modifications to the introduction, analysis and conclusions sections directly.

Co-author D. Ferruzza performed the literature survey, as well as the implementation and validation work of the new TES model. D. Ferruzza also prepared the first draft of the paper, which was then reviewed by the author and subsequently distributed to all other co-authors. The work in Paper V corresponded to a condensed version of the MSc. Thesis work of Ferruzza, performed under supervision of the author.

Co-author M. Arnaudo provided support to the validation of the TES model and also to the development of the TES component in TRNSYS.

Co-authors I. Rodríguez and C.D. Pérez-Segarra contributed to the work by sharing their experiences of previous research work [116][120] in the field and by discussing the concept prior to the model development. Both co-authors also reviewed the final version of the paper.

Co-authors Z. Hassar and B. Laumert provided feedback to the final draft of the paper prior to its submission to SolarPACES 2015.

9.3. Feasibility of new hybrid CSP plants

As mentioned in §3.4 and §4.5, one of the means for enhancing the techno-economic performance of a CSP plant, and ultimately its competitiveness, is by exploiting its capabilities for hybridization. Indeed, hybridization with more established and cost-competitive generation technologies can be seen as an intermediate step towards fully competitive CSP plants. As such, in this thesis two new hybridization schemes were proposed and evaluated through techno-economic analysis:

- A solar combined cycle composed of a topping gas-turbine (GT) plant and a bottoming MS-STPP. One of the most competitive fossil-fuel based technologies with one of the most promising CSP technologies. Paper IV presents the concept and describes the modeling steps and main findings from the feasibility analysis, including future research work suggestions.
- A hybrid CSP-PV power plant for a solar-only high-capacity factor power plant with firm output. Paper V presents the concept and describes the modeling steps and the main findings from the feasibility analysis, including future research work suggestions (i.e. main challenges for the concept)

In this section Paper IV and Paper V are put into context of the research work. A summary of each paper, including key findings and remarks on the methodology followed is provided. The contributions of the author of the thesis to each of the studies is also explicitly mentioned.

9.3.1. The integrated Salt Solar Tower Combined Cycle (Paper IV)

Paper IV deals with the techno-economic analysis of the ‘salt solar tower combined cycle’ (referred to as SSTCC), a new hybrid plant concept consisting of a MS-STPP supported by additional heat provided from the exhaust of a topping open cycle gas turbine (OCGT). The layout of the SSTCC can be seen in Figure 29. The layout of the SSTCC was designed by the author of this thesis and it aimed to fulfill the roles of both a large peaking and a medium-sized baseload-like plant in one single power plant. The OCGT part was aimed to operate only during specified peaking hours, while the bottoming STPP would be online as long as there was energy stored in the TES units, potentially behaving like a baseload plant.

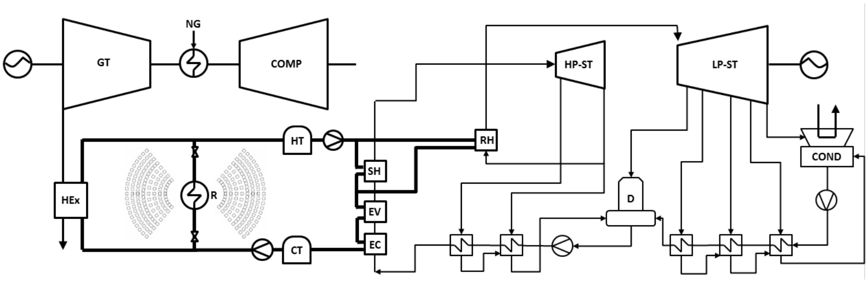

Figure 29 Layout of the proposed SSTCC hybrid concept (Paper IV)

Details from a case-study set around the proposed SSTCC are provided in the paper. The results show that most promising designs of the SSTCC can successfully fulfill both the roles of an OCGT and a baseload-like MS-STPP in a more effective manner. Moreover, these designs are also compared against conventional combined cycle gas turbine (CCGT) power plants and it is shown that, under specific peaking operating strategies, the innovative concept would be able to outperform the CCGT from both environmental and economical standpoints (i.e. in terms of the annual specific CO_2 emissions and the LCOE).

The study presented in Paper IV is presented as a new approach for the modeling and evaluation of new cycles. Specifically, the conclusions highlight the importance of encompassing different operating strategies, plant configurations and design parameterization when evaluating new hybrid plants on the basis of conflicting objectives such as being economically competitive (e.g. low LCOE) and more environmentally friendly (e.g. low specific CO_2 emissions). Special emphasis is placed on the operating strategy of the power plants, shown to be a decisive factor for the results. A reason to why the paper concludes also highlighting the need for coupling power plant models with price and operating schemes.

Conclusively, the study ends by assuring that because of the results, and from the analysis, it was possible to state that hybrid configurations such as the SSTCC are worth continue investigating for increasing the competitiveness of CSP. This last, mainly as they can represent an economically viable intermediate step towards meeting future needs in a sustainable way by lowering the specific CO_2 emissions whilst simultaneously driving forward the deployment of CSP, which ultimately can continue to bring down the costs and promote the research of more advanced CSP technologies and concepts.

Remarks about the Modeling Work

In Paper IV the model of the SSTCC is explained as it was developed and implemented in DYESOPT (§7). A specific case-study was setup for a location nearby Seville, Spain, for which hourly weather and price data were gathered. Two different 'Peaking Operating Strategies' (P-OS) were set to define the role of the SSTCC in the market. P-OS1 set the OCGT to operate only for 5 hours during the evening peak (6:00 PM – 11:00 PM), while P-OS2 set the OCGT to run for 12 hours similar to a mid-merit plant (11:00 AM to 11:00 PM). The choice of such is explained in the paper.

For each P-OS a number of cases were evaluated on the basis of a techno-economic sensitivity analysis with regards to critical design parameters such as: the ratio of the OCGT capacity to the MS-STPP's, the TES size and the SF size. Three cases were considered in terms of the OCGT to MS-STPP installed capacity ratio, in all them the OCGT was assumed to have an installed capacity of 100 MW_e. The MS-STPP was set to 15 MW_e, 30 MW_e and 60 MW_e in PC1, PC2 and PC3 cases respectively. The choice of such is also explained in the paper. The TES size varied from 1 to 15 hours, and the SF varied from 1 to 3.5 solar multiple.

Each SSTCC case was evaluated on the basis of the LCOE (referred to as LEC in this study) and the Specific CO_2 emissions. From all cases, most promising SSTCC configurations were selected to be subsequently compared against other more 'conventional' solutions fulfilling the same market role. Comparisons were made on the basis of LCOE, CF, IRR and the specific CO2 emissions between the selected SSTCC and an equivalent CCGT (in capacity). The performance of the SSTCC was also compared against the performance of two equivalent co-located OCGT and CSP plants. At the end, a further sensitivity analysis with regards to the air-to-salt heat exchanger design and to the NG costs assumed was performed.

It is worth mentioning that the MS-STPP model used in Paper IV corresponded to a simpler version of that described in Paper I. Apart from serving the purpose of showing the viability of the SSTCC power plant, the experiences from Paper IV contributed to the setup of the more sophisticated model of the MS-STPP, as introduced in Paper I, and later improved in Paper II. Indeed, Paper IV served as a clear example of the relevance of developing modeling dispatch strategies that would allow the plants to operate 'smartly' at peak hours when considering the available and the day-ahead forecasted energy resource.

Highlights from the Analysis

Figure 30 summarizes the best SSTCC designs resulting from the combination of TES size and SF size for each of the cases of OCGT to MS-STPP capacity ratios considered (PC1, PC2 and PC3), and for each of the operating strategies considered (P-OS1 and P-OS2). These designs are compared in Figure 30 on the basis of the LEC and the annual specific CO_2 emissions (values shown). SSTCC-PC3 configurations for the P-OS1 and P-OS2 strategies (shown in blue) were deliberately selected for further comparison against other technologies, as shown in Table 8.

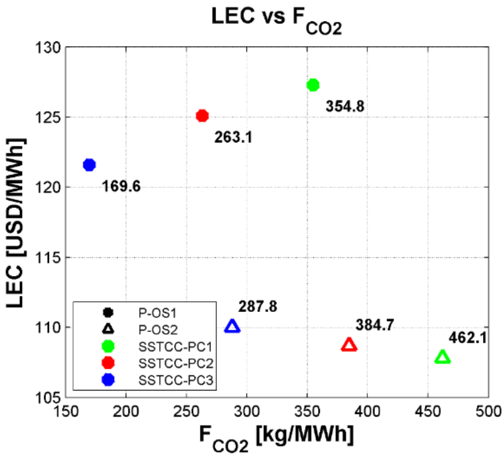

Figure 30 LGC vs. Specific CO_2 emissions for all scenarios (Paper IV)

Table 8: Comparative analysis between SSTCC and other power plants (Paper IV)

Power Plant	Op. Strategy	IC [MW_e]	CF [%]	LEC [USD/MWh]	IRR [%]	F_{CO2} [kg/MWh]
SSTCC -PC3	P-OS1	160.0	45.9 (88.2)	121.6	2.89	169.60
	P-OS2	160.0	65.1 (90.6)	110.1	2.50	287.80
OCGT+ CSP (A)	P-OS1 + Baseload	100 + 60	44.4 (84.2)	128.0	-1.17	176.62
OCGT+ CSP (B)	P-OS2 + Baseload	100 + 60	62.7 (84.2)	121.4	-4.58	300.29
CCGT	P-OS1	143.6	20.8	130.0	-2.31	419.45
	P-OS2	143.6	50.0	98.3	4.64	419.45

The results in Table 8 confirmed that the chosen SSTCC configurations outperformed their equivalent independent OCGT and MS-STPP plants under all performance indicators, with the difference being due to the capabilities of harvesting the energy from the exhaust of the OCGT. Importantly, it is shown that the SSTCC completely outcasts the CCGT in terms of specific CO_2 emissions regardless the P-OS. However, in terms of cost and profits, the SSTCC would be deem as an interesting option only in case the OCGT is used exclusively during the evening peak, but the STPP instead is allowed to operate as a baseload-like plant (the STPP was found to reach CF as high as 90%). Lastly, the study also shows that with remaining heat leaving the SSTCC at approximately 250°C, the potential integration of additional industrial heat processes (e.g. water desalination) could further improve the performance and, thus the competitiveness, of the SSTCC.

9.3.1.1. Contributions to state-of-the-art

- The SSTCC hybrid concept is for the first time introduced and evaluated through techno-economic analysis.
- First study coupling operating regimes, electricity prices and multi-variable parametrization in the evaluation of fossil-fuel hybrid CSP plants.

9.3.1.2. .Author contributions to the paper

All model development, implementation and verification work, as well as the analyses, were performed by the author of this thesis. Similarly, all sections of the paper were also written by the author of this thesis.

9.3.2. Hybrid CSP-PV Plants for Firm Power Generation (Paper V)

Paper V evaluates the optimum configurations and storage dispatch strategies of hybrid CSP and PV plants in terms of minimizing the LCOE for a suitable location in Morocco, when meeting specific tender-like requirements such as constant 400 MW_e injection into the grid during operation, and two sets of hour-operating regimes. In this study, a detailed techno-economic model of the hybrid CSP-PV plant (H-CSP-PV) was developed and implemented in DYESOPT based on the advanced multi-variable optimization model of the MS-STPP introduced in Papers I and II. The layout of the proposed H-CSP-PV is shown in Figure 31.

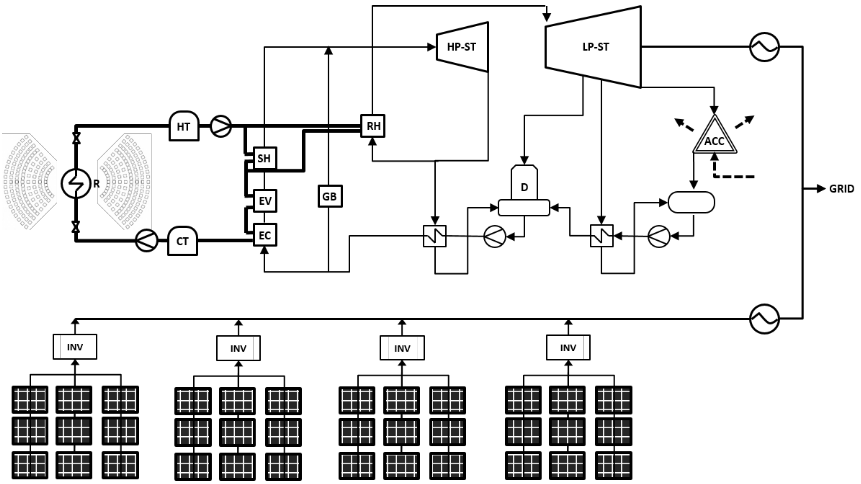

Figure 31 Layout of the proposed H-CSP-PV hybrid concept (Paper V)

In order to be able to meet the 400 MW_e firm capacity requirements, the layout was needed to be composed of several MS-STPP instead of one (e.g. due to physical limits being reached regarding the receiver rating capacity and due to large attenuation losses). The number of MS-STPP and the design of each were part of the optimization process. The operation modes of the proposed hybrid concept and the advantages for achieving firm output at high capacity factor are described in the paper.

Results in Paper V show that H-CSP-PV plants are able to achieve higher firm CFs than an equivalent 400 MW_e CSP only or PV-BESS plant, for which models were also developed and set correspondingly. Results also confirmed that, under current cost estimates, hybridization enables a lower cost solution for a given high CF objective than what is achievable with stand-alone CSP plants. This served to confirm that the 'cost-competitiveness' of CSP can indeed be enhanced in the near term through hybridization, although as cost continue to decrease then it might no longer be needed. The analysis section also highlights the synergies among the technologies and shows the relation and influence between sizing and operation of their critical components. The main challenges for successful hybridization of CSP and PV for firm operation are at last raised together with future work suggestions to address them.

Lastly, optimum configurations found for the two tender conditions are compared and a brief discussion section at the end is introduced to highlight the relevance of adequate policy design and its impact on the work of project developers for proposing the most competitive solutions. By doing so, Paper V is directly addressed to key actors along the project structure, especially tender-designers and project developers.

In such regards, it is worth mentioning that the work performed in Paper V was done with input from active key actors in the CSP industry. Specifically, the modeling work and analysis was performed by the main author with input from Solar Reserve, one of the global MS-STPP lead developers ([50][61][55]). Moreover, the setup of the cases was partly based on discussions with fellow R&D colleagues at the Moroccan Agency of Solar Energy (MASEN), Morocco's publically owned company in charge of designing the solar tenders. Lastly, the concept proposal and the research work was also built from discussions with Total, an active solar power project developer and owner [49]. In this way, another relevant outcome of Paper V, and in line with the specific objectives of this thesis, is that it served to demonstrate the usefulness of the proposed techno-economic methodology in the form of an engineering tool for the pre-design and feasibility evaluation of CSP plants and new concepts.

Remarks about the Modeling Work

Paper V builds from the modeling knowledge acquired in Papers I and II, and it is also based on the experiences from previous work performed, and also supervised [51], by the author of the thesis. Chronologically, it is the last paper written the author among the ones appended to this thesis. As such, and as mentioned in the previous section, the modelling work was thoroughly discussed with the involved co-authors, who supported to the setup of the optimization cases and also by providing input data.

The work required the development, implementation and verification of a utility scale PV power plant (and BESS) model in DYESOPT. To a great extend the setup of such models was based on previous research work ([121][122][123][124][125]) with input data extracted, mostly, from the works shown in [126][127][128][129]. The MS-STPP model was based on that described in Paper II. The integration of the models required the development of new logical dispatch operating schemes and related dynamic controllers. A PID controller was implemented and tuned in the dynamic model for regulating the TES dispatch load as a function of the forecasted PV output, as explained in Paper V.

The performance of the power plants was evaluated on the basis of the firm CF, introduced in the Paper, and the LCOE. Optimizations were setup for each technology with the objective of finding optimum configurations maximizing the firm CF and minimizing the LCOE. At last, seven multi-objective optimization cases were required in total in order to perform the comparative analysis. Specifically, optimizations were set for each technology (the H-CSP-PV, the stand-alone CSP, and the PV-BESS) under each hour-operating regime (baseload and mid-merit 8:00 to 22:00), and in addition a PV only (no storage) optimization case was setup for sake of comparison and to support the discussion section.

Highlights from the Analysis

Figure 32 summarizes the optimization results for all optimization cases set in the study (except the PV only case). In Figure 32, each subplot corresponds to an optimization case, as specified. In each sub-plot an optimum configuration is highlighted to be used in the discussions. The choice of such is explained in Paper V. In general, the results confirm that on the basis of LCOE, optimum H-CSP-PV plants can be deemed as most competitive for generating firm power output and meeting specific CF values. Moreover, CSP plants (STPPs) were found to be the second best option for both dispatch cases, with LCOE values only 3% higher, approximately. Optimum PV-BESS configurations (E and F) fell far behind the optimum H-CSP-PV and CSP plants in terms of LCOE. A comprehensive discussion and analysis of the results with regards to the decision variables is provided in the study, where the trade-offs are discretized accordingly to the key parameters, for the sake of discussion.

The results from the study confirmed that the key technical benefit from hybridizing CSP and PV for firm power production is that higher CF can be reached when compared to stand-alone CSP plants (by approx. 5% absolute). In addition, it is shown that under the cost assumptions and cost model used, the H-CSP-PV concept would also deem more economically attractive for a same firm CF value. It is argued, though, that the economic results are sensitive to SF and PV cost values assumed, and the validity (in time) of the economic conclusions is thus dependent to cost development trends in the near future. Results also confirmed that, although technically viable (theoretically), the use of BESS systems for utility-scale PV farms is not competitive against CSP, highlighting that rather than competing, the two technologies can complement each other.

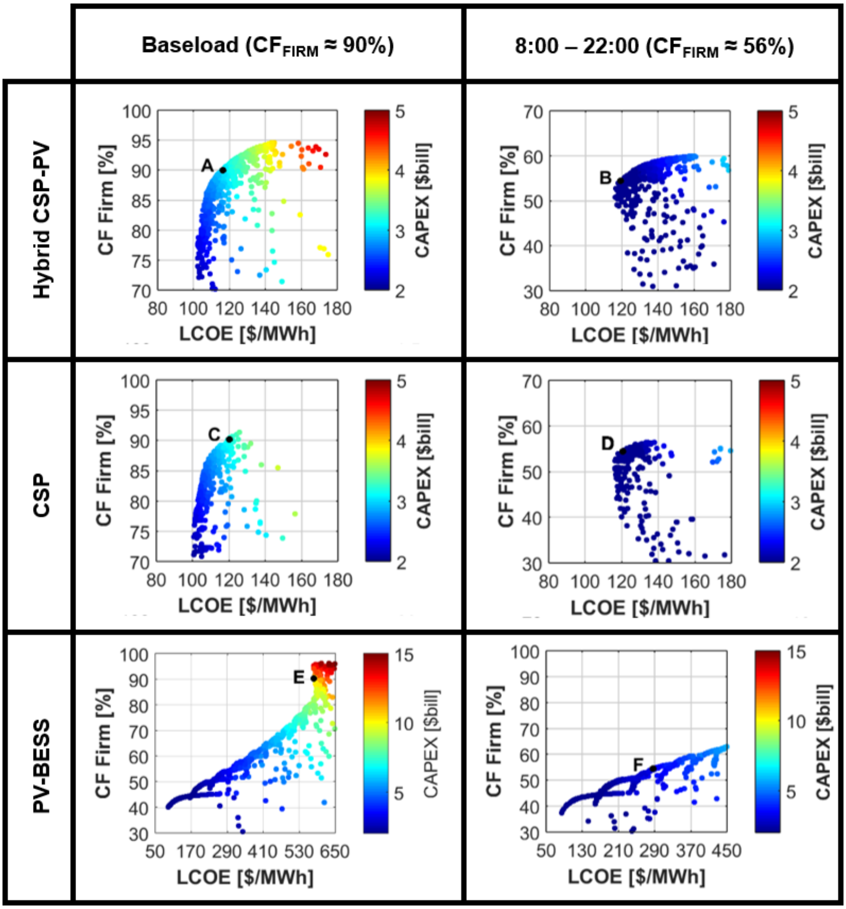

Figure 32 Paper V highlights from results section: H-CSP-PV vs. CSP vs. PV-BESS for baseload (CF ≈ 90%) and mid-merit (CF ≈ 56%) operation

9.3.2.1. Contributions to state-of-the-art

- A multi-variable techno-economic optimization model of the H-CSP-PV hybrid concept is for the first time introduced in open literature.
- For the first time the performance of the H-CSP-PV concept is compared against other technologies in response to specific tender-like conditions.
- For the first time multi-variable and multi-objective techno-economic optimization models are used to compare CSP plants to utility-scale PV plants with BESS.
- A methodology for assessing the impact of operating regimes on the choice of technology is suggested.

9.3.2.2. Author contributions to the paper

The definition of the research questions, the optimization cases and the proposal of the hybrid concept was performed by the author. The author also developed the MS-STPP model and set the basis for the PV model and the integration with the MS-STPP. The implementation of the combined dispatch strategy and required controllers was supervised by the author. The analysis of the results was performed by the author. The paper was entirely written by the author except for section 3.

Co-author K. Larchet implemented the additional models, and required controllers, in the already developed MS-STPP techno-economic tool under supervision and guidance of the main author. He also wrote section 3 (model description) of the study. Co-author K. Larchet also proof-read and reviewed the final paper.

Co-authors J. Dent and A. Green thoroughly reviewed the study, including the setup of the case-studies and the performance of the CSP and hybrid CSP-PV models. Co-author J. Dent provided feedback to the discussion section and was actively involved in the analysis of the results. Co-author J. Dent also proof-read and reviewed the final paper.

Co-author Z. Hassar helped to define the optimization cases and provided feedback to the structure of the analysis and to the framing of the recommendations to tender-designers. Co-author Z. Hassar also reviewed the final paper and approved it before submission.

Co-author B. Laumert proof-read the paper, reviewed it, and approved it before submission to Journal.

9.4. Additional TES integration benefits for CSP plants

Often the value of TES in a CSP plant is measured only from the perspective of the developer (i.e. how does TES allow a plant to increase its revenue). Nevertheless, and as mentioned earlier, the possibility of a plant to integrate TES could also add value to other stakeholders such as the grid operator and the plant operator. Like so, although not being the main focus of this thesis, other studies were carried out in connection to the additional value of TES for grid designers and plant operators during the setup of the techno-economic models previously presented. These are briefly explained in this section as addressed in Papers VI and VII.

In Paper VI, a simplified version of the model used in Papers I and II is used as a first attempt to show that, through a simple parametrization, CSP plants can be designed (i.e. be sized and operated) to be operated as a complementary source to other renewables by being able to generate the remaining un-met electricity demand for a grid in isolation. This because of CSP's TES and hybridization capabilities. In doing so, a NG-GB was integrated into the MS-STPP model and operating limitations for the hybrid-scheme with the GB were also introduced in the model.

In Paper VII the focus was placed on demonstrating the benefits that TES can bring to reducing the number of starts of the PB, this being understood from [130] that turbine start-up times represent one of the most critical issues for PT CSP plants. Paper VII is the only study in the PhD in which a PT-CSP plant is modeled. The choice of such is that it builds from previous work at KTH [130][131]. Paper VII quantifies the reduction in number of start-ups and introduces the Equivalent Operating Hours (EOH) concept to the analysis of CSP plants. This was the first paper, chronologically, and the findings and experiences were used to develop the more detailed MS-STPP model used and shown in papers I and II.

9.4.1. CSP to complement renewable intermittency (Paper VI)

Paper VI is aimed at underlining the value that a CSP plant can have in a grid with a high penetration of variable renewable electricity, referred to as "fluctuating renewable" (FR) in the paper. This, mainly because of the advantageous capabilities for CSP to integrate TES systems, and to enable hybridization with other fuels. The basic idea also consisted in showing that parametrization at power plant level, in this case for a hybrid CSP plant with TES, can also be used in the analysis at system level when, for instance, the modeling boundaries are determined by other technologies.

At the stage of writing Paper VI, which preceded Papers I and II, the author was investigating literature concerning the value of TES at system level and the impact of TES size in CSP plants. One of the motivations for the study was to understand why fixed TES and SF sizes were commonly assumed when evaluating CSP plants at system level, and also whether the TES-SF size choice would impact on the system performance results, for which 'new' system performance indicators were implemented.

Therefore, following a simple approach, Paper III compares the impact that a hybrid CSP plant would have at system level, in terms of system levelized generation costs and annual specific CO_2 emissions, against a combined cycle power plant (CCPP), for various TES and SF sizes.

In general, unlike Papers I and II, the work in Paper VI can be deemed as more useful for supporting the research of grid development and energy system scenario analysis, which in turn is more oriented towards grid operators and to policy designers than for the rest of the stakeholders in the project structure shown in §4.2.

Notes about the Modeling Work

The parametrization approach used at power plant level in this study is simpler than that introduced in Papers I and II. The CSP plant model was based on the MS-STPP layout shown in Figure 13, but modified to integrate a NG-GB in the TES-HTF cycle. Specifically, it was chosen to place the NG-GB in series between the receiver and the TES hot tank. By doing so, the NG-GB was able to complement the SF power in cases of insufficient radiation. As last resource, such a configuration also allowed the NG-GB to provide enough power to run the STPP on its own when no energy was available at all (neither from the SF nor stored).

Representative power plant models for the PV and wind farm were also implemented and coupled to the hybrid MS-STPP model. An isolated grid scenario for a location in the island of Mallorca was selected. For this location hourly demand, weather and cost data were gathered.

Three scenarios, in terms of installed capacity of PV and wind, were modeled. The electric net hourly generation from these systems was subtracted from the hourly demand to estimate the demand that shall be covered by the hybrid STPP or an equivalent CCPP. In order to realize this coupling, a set of operating modes with respective logical controllers were developed and implemented (as mentioned in Paper VI)

Different STPP configurations, only in terms of SF size and TES size, were evaluated through sensitivity analysis. The performance indicators used to assess and compare the performance of the system when integrating either the hybrid STPP or the CCPP, were the levelized generation costs (LGC), the specific CO_2 emissions of the system, and the share of renewable electricity. All introduced in the paper.

Worth highlighting that the MS-STPP model did not account for the same level of detail and dynamics shown in Papers I and II, and also the cost models for all plants were simpler. Also, as mentioned, a sensitivity analysis was performed instead of a multi-variable optimization.

Highlights from the Results and Analysis

A key message from the analysis is that, for the installed capacities and demand assumptions, irrespectively of the level of penetration of PV and wind, it was possible to design a hybrid MS-STPP to compensate for the un-met demand. This highlights the flexibility of the hybrid CSP plant and the value it can offer to the grid, being in turn potentially complementary to other cheaper but 'un-controllable' renewables.

Paper VI confirms that the choice of the TES and SF size does have an impact on the performance of the system. From this, it is recommended to consider different PB, TES and SF sizes when evaluating a CSP plant in system studies, especially if no previous work at plant level has been done using same location. In this regard, Figure 33 shows that the performance of the system is affected by the SF and TES size, regardless the scenario.

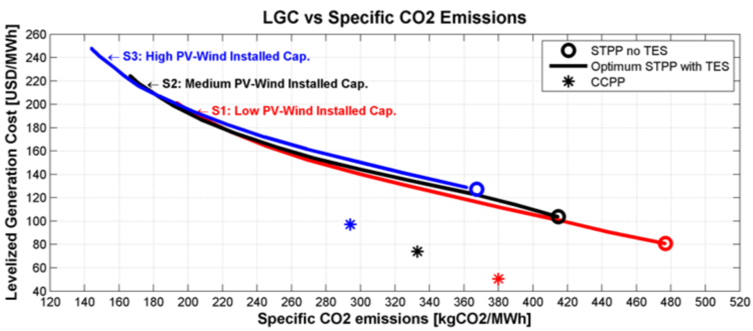

Figure 33 Paper VI results: LGC vs. Specific CO_2 emissions for all scenarios

Furthermore, the study shows that when compared to a conventional combined cycle designed to serve the same purpose (complement the other renewables), the hybrid CSP plant proposed was only advantageous if large SF-TES systems were considered. It is shown in Figure 33 that regardless the SF-TES size and the scenario, a hybrid CSP plant would yield higher system costs than its CCPP counterpart (on the basis of LGC). However, if large SF-TES systems were considered then the hybrid CSP plant could outperform the CCPP on the basis of yielding lower specific CO_2 emissions for the system in the overall. The study assumed no carbon taxation, which would have positively influenced the LGC results in favor of the hybrid CSP plant. Another relevant issue pointed out in Paper VI is the ineffectiveness of running a CSP plant from a GB installed in the HTF cycle, implying it should be avoided or used solely as back-up if needed.

9.4.1.2. Contributions to state-of-the-art

- The study shows the impact of considering different PB, SF and TES sizes for a CSP plant in system modeling.
- It is shown that a CSP plant with TES can be designed to complement other intermittent renewables in a grid.

9.4.1.3. Author contributions to the paper

All model development, implementation and verification work, as well as the analyses, were performed by the author of this thesis. Similarly, all sections of the paper were also written by the author of this thesis.

9.4.2. TES impact on the CSP plant cycling operation (Paper VII)

Paper VII provides an insight to the influence of TES integration on the cycling operation of contemporary CSP plants. The study shows that the integration of TES can lead to significant reductions in the annual number of turbine starts and can be thus beneficial to the turbine lifetime. This aside the obvious benefit of stabilizing operating conditions. Through setup of a specific case-study, Paper VII, shows that large TES capacities, can allow a CSP plant to be shifted from a daily starting regime to one where less than 20 plant starts occur annually. In addition, Paper VII provides a thorough explanation of the Equivalent Operating Hours (EOH) method and the operation and maintenance requirements of steam-cycles [132][133][134]. A comprehensive description of the process of turbine start-up and the types of start-ups is also provided. This is done so in order to relate the number of turbine starts to its maintenance requirements, and at last to its lifetime. In this way, it was possible to ultimately establish a relation between TES size integration and the PB maintenance requirements.

Prior to this study, no other research work was found dealing with quantifying the impact of TES integration on the cycling operation of CSP plants, neither were studies available interconnecting theories of PB operation and maintenance to a CSP plant model.

Furthermore, the study proposes a modification to the standard LCOE calculation methodology. It consisted of an 'availability factor' that would penalize the annual electric output to account for the productivity loss due to shutdown of the plant for scheduled turbine maintenance.

Remarks about the Modeling Work

Paper VII is the only study in this thesis in which the base power plant layout is a PT CSP plant and not a STPP. One reason for such was that the study built from the previous work of one of the co-authors [130][131], in which steam turbine start-up models were developed for PT CSP plants. The choice of the location was also limited to that of studies [130][131], a suitable location for CSP in Spain, for which data was already available.

It is worth mentioning that this was the first paper published by the author. As such, likewise Paper VI, in this study the techno-economic process is simplified to a lower level of detail in the dynamics than in Papers I and II, and a sensitivity analysis was performed instead of a multi-variable optimization. All model details and assumptions are including in the paper.

The level of model used, however, was proven enough to show the influence of TES integration in the cycling operation of CSP plants by yielding clear trends from which overall conclusions were extracted and recommendations provided to the research community in general.

Highlights from the Analysis

Figure 34 shows a summary of the result section of Paper VII. Herein the impact of TES integration on the cycling behavior of the PB is measured by means of four different performance indicators. All sub-plots in Figure 34 show the contour areas resulting from the sensitivity analyses with regards to the TES size and SF size. The upper plots refer to the impact on the annual number of starts (left) and the percentage of annual 'hot' starts (right). It can be seen that the integration of TES in CSP plants can lead to a significant reduction on the annual number of turbine starts, with the potential to pass from a daily shut-down regime for plants with no TES to less than 25 in a year for plants with large TES units (upper left plot). What is also interesting is that already at medium TES integration (7-8 hours of TES), it is possible to increase the percentage of 'hot' starts up to 90% (upper right plot). As explained in Paper VII, hot starts are beneficial for the operator as they can reduce turbine start-up time and also turbine lifetime consumption.

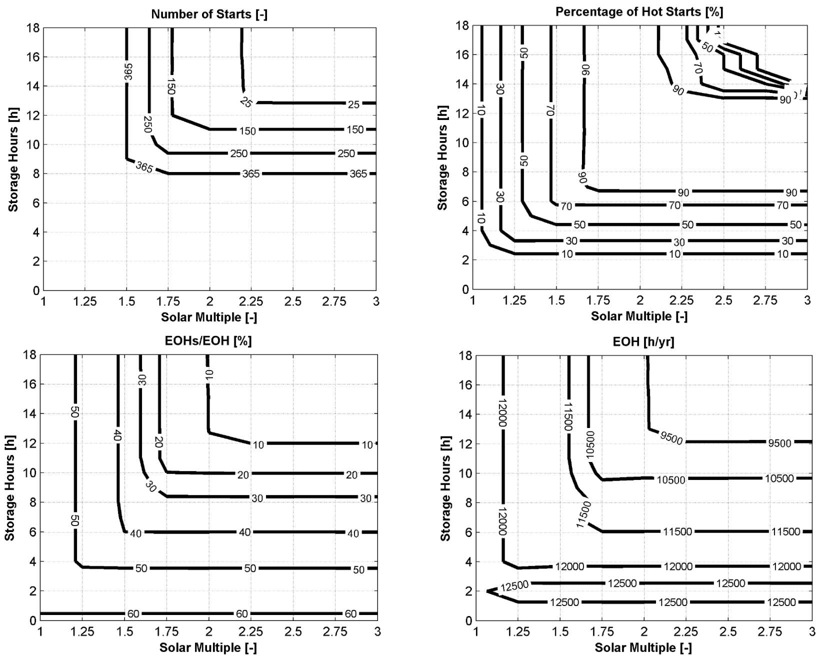

Figure 34 Paper VII results: TES integration impact of Cycling Operation

The lower part of Figure 34, refers to the EOH values. As explained in Paper4, the EOH can be calculated as the sum of the annual normal plant operating hours (NOH) and the equivalent operating hours due to the different turbine starts (EOHs). The value of the EOH determines when the PB requires a maintenance overhaul (thereby a plant shutdown).

What is worth highlighting from the results shown in the lower part of Figure 34 is that TES integration, not only increases the NOH by expanding the CF, but can also yield lower EOH (right). This is done so because the fraction of EOHs can also be reduced significantly (left). The latter implies that when TES is integrated in a CSP plant, the plant undergoes maintenance requirements mostly because of its normal operation, not because of its cycling behavior, which is the case when no TES are considered (or relatively small TES units).

9.4.2.1. Contributions to state-of-the-art

- First study quantifying the impact of TES integration (i.e. size) on the cycling operation of PBs in CSP plants.
- First study that introduces the concepts of EOH and maintenance requirements to the analysis of CSP plants.
- The study proposes a slight modification to the standard LCOE calculation by introducing a penalty factor to the annual net electricity output in order to account for scheduled maintenance requirements based on the EOH method.

9.4.2.2. Author contributions to the paper

All model development and implementation work, as well as the analyses, were performed by the author of this thesis. In doing so, discussions were held on a regular basis with co-author J. Spelling. Similarly, all sections of the paper, but the introduction (wrote by J. Spelling), were written by the author of this thesis.

Co-author B. Laumert actively participated providing feedback with regards to the structure of the paper, including figures and content disposition, and also to the final conclusions.

10. Conclusions

This thesis shows that the competitiveness of CSP plants can be enhanced in the near term by optimizing their capabilities to integrate TES and to be hybridized. In this work the analyses have been performed through the development and implementation of a new multi-variable techno-economic optimization model for CSP plants. This model was used to optimize the sub-system blocks available in contemporary CSP plants, in terms of component sizing and operating strategies. The model has also been used to evaluate the feasibility of new concepts, both at component level (i.e. TES concept) and at system level (i.e. new hybrid schemes), and their impact in the plant performance. Through a number of case-studies it is shown that both sub-system optimization and new concepts can help increase the economic competitiveness of CSP plants.

The analysis performed shows that there exists an interrelation between the design of each of the key component-blocks available in a CSP plant, namely the solar field, the power block and the TES system. It is also shown that the optimum design of these sub-blocks is very much dependent on the contractual electricity price schemes and the desired hourly operating regimes, besides the already known impact of the local meteorological conditions. In this thesis it is demonstrated that for every location, and for every specific tender-like requirements, techno-economic optimization can be used to determine the trade-offs of optimum plant configurations simultaneously satisfying potentially conflicting design-objectives. These objectives can be of technical, financial and environmental nature and were quantified in the case-studies by means of typical power plant performance indicators such as the IRR, the LCOE, the CF, and the annual specific CO_2 emissions. In this work it is discussed how these optimization trade-offs can be used to support the decisions of the key actors along the different steps of the project development value chain of a CSP plant.

More specifically, for the case of the MS-STPP layout, it is shown that the size of the solar field (and tower height), as well as the size and the dispatch strategy of the TES tanks are key decisive parameters influencing the performance of the plants. Another main decision variable is the power block capacity. The power block capacity is shown to be a competitive driver because of economics of scale, but this variable is often limited by the tender or by technical limitations imposed by given desired operation. Indeed when the CSP plant is desired to operate as a peaker plant, larger power block capacities can be accommodated (if allowed by the grid or tender), whereas if a plant is aimed at supplying high CFs then ‘smaller’ power blocks are to be considered. This is a consequence of the physical limitations imposed in the design of solar fields in tower plants.

In this thesis the size and the dispatch strategy of the TES are shown to impact the LCOE and, more importantly, the profitability (measured in terms of project’s IRR). The analyses show that TES integration, when coupled to sub-system optimization, can help decreasing the LCOE of the CSP plants, despite representing an additional investment. However, it is shown and discussed that the use of the LCOE as a single comparative indicator, under its standard definition (ratio of lifetime cash outflows to lifetime yield), shall only be effective when the contractual off-taking agreement is based on a fixed electricity price scheme and, preferably, on the whole annual generation (i.e. not limited to specific hours). It is suggested that when operating-hour regimes are imposed by the tender, then the LCOE shall be used together with the CF (limited in such case).

Furthermore, the analysis shows that when the off-taking agreement is based on multiple-tier prices then the use of the LCOE under its standard definition might lead to misleading and sub-optimized CSP plant configurations. Instead, plant configurations should be evaluated on the basis of the project’s IRR (for known price tiers like in the case of FiTs), or by calculating directly the power purchase agreement price that would guarantee the minimum acceptable project’s IRR for the owners. In this way the importance of the hour of generation is accounted for. This last, is especially decisive to determine the optimum TES size and dispatch strategy. The pre-defined dispatch strategy routine implemented in the techno-economic model of the MS-STPP is shown to have a positive impact on determining the optimum plant configurations maximizing profits when multiple price tiers and fixed operating-hour regimes are set by the tender. Indeed, for one of the specific case-studies considered in the thesis (in Paper II), it is shown that optimum plants on the basis of minimizing the LCOE would yield an IRR approximately 40% lower than plants optimized to maximize the IRR (relative values).

The MS-STPP multi-variable techno-economic optimization model was also demonstrated to be useful for the feasibility evaluation of the integration of new TES concepts and novel hybrid schemes. Specifically, new concepts were proposed and evaluated through model development, implementation and integration into the MS-STPP techno-economic model. More importantly, all of the concepts proposed showed the potential to enhance the economic competitiveness of MS-STPPs, either by means of reducing the LCOE or by increasing the IRR.

In the present research work a new TES concept based on a single-tank containing a packed-bed of solid and PCM TES media is for the first time proposed for application in MS-STPPs. The feasibility of the concept is evaluated by means of techno-economic modeling, for which detailed thermodynamic models were developed and cross-validated. Cost models were also built considering cost of materials, volumes and required engineering work. This model was at a later stage integrated in the MS-STPP techno-economic optimization model, for which suitable logical-control strategies were developed and implemented. At last, a test case-study was setup to evaluate the impact of the new concept on the performance of the MS-STPP and to compare it against the state-of-the-art two-tank TES system. It was shown that the new concept could potentially outperform the two-tank system on the basis of IRR by being able to achieve a similar technical performance for a slightly lower investment. For the specific case-study considered, the MS-STPP with the new TES concept was able to reach the same IRR values than the two-tank system despite the conservative cost values assumed. However, the added complexity of the single-tank and the encapsulation of the PCM are highlighted as a potential drawback that needs to be further investigated in terms of its durability and reliability, especially when exposed to multiple charging and discharging cycles.

The two hybrid concepts investigated were shown able to potentially enhance the competitiveness of CSP plants in the near-term, as a valid intermediate step towards more cost-competitive stand-alone CSP plants. Both concepts were based on the combination of the MS-STPP with another less expensive and more mature technology for electricity generation. The first concept was denominated the salt solar tower combined cycle (SSTCC) and it consisted on the combination of a topping open-cycle gas-turbine (OCGT) plant and a bottoming MS-STPP. The analysis of the SSTCC showed that most promising designs were able to successfully fulfill both the roles of an OCGT and a baseload-like MS-STPP in a more effective manner than stand-alone plants. It is shown that these SSTCC designs would also be able to outperform conventional combined cycle gas turbines (CCGTs) under fixed operating-hour regimes, from both environmental and economical standpoints (i.e. in terms of the annual specific CO_2 emissions and the LCOE). Specifically, the SSTCC hybridization was shown able to generate 60% and 31% lower annual specific CO_2 emissions than the CCGT, for the two respective power plant operating modes considered in the case-study.

The second hybrid concept evaluated in this thesis consisted of a solar-only concept composed of co-located MS-STPPs and PV power plants. In this concept the MS-STPPs are designed to regulate their load (i.e. the dispatch of the TES) in response of the PV output, mainly in order to meet a constant injection set-point into the grid at a higher CF objective than what can be achieved with CSP alone. The results for the case-study confirmed that the key technical benefit from hybridizing CSP and PV for firm power production was being able to increase by approximately 5% (absolute) the CF when compared to stand-alone CSP plants. In addition, it was shown that under the cost assumptions and cost model used, the hybrid CSP-PV concept would reach LCOE values approximately 3% to 5% lower for a same firm CF objective. It is discussed, though, that the economic results are sensitive to SF and PV cost values assumed, and the validity (in time) of the economic conclusions is thus dependent on cost development trends in the near future. Results also confirmed that the use of electric batteries in large utility-scale PV farms for firm extended production is not competitive against CSP, highlighting that today both CSP and PV can complement each other.

The techno-economic approach was also used in this thesis to show other additional value that TES can deliver to CSP plants from the perspective of grid and plant operators. The approach was first used to show the impact that sub-system optimization of the CSP plants, in terms of solar field and TES size and load regulation, could have on the system scenario analysis at grid level. It is discussed that the design of the tender, and thus the choice of the optimal TES size, should respond at the end to a need in the grid and be aligned with policy planning. Secondly, in this thesis the impact of TES integration in mitigating the negative consequences from cycling operation of the power blocks in CSP plants is also analyzed. TES integration is shown to significantly decrease the number of cold starts and thereby to improve the lifetime expectancy of the turbomachinery equipment. It is shown, and quantified for a case-study, that the turbomachinery in CSP plants with TES undergoes maintenance overhauls mostly because of their normal operation, not because of the impact of their start-up cycling behavior. The latter can also have an impact in the economic competitiveness of CSP plants, for which more detailed OPEX cost models would be needed in order to estimate such from pre-design stage.

Conclusively, the author believes that through the models, results, analyses and discussions presented, this thesis represents a stepping stone for further research in the field of CSP plant design optimization. The work highlights the value that TES integration and hybridization can deliver to increasing the competitiveness of CSP plants. Similarly, the multi-variable techno-economic modeling approach tailored to location boundaries introduced in this study is also proposed as a basis for new evaluation techniques to assess renewable power plants in general, and not only CSP (although especially for those with energy storage systems). The model and the methodologies proposed for evaluating MS-STPPs can support the decision making process of key actors along the project development value chain of a CSP plant (i.e. policy designers, project developers and plant operators). Like so, the methods and concepts investigated also serve as a basis to the scientific community to define research paths that can lead to increasing the competitiveness of CSP.

In the end, it is confirmed that CSP is a technology that through its cost-effective storage and hybridization capabilities offers an added value to the future electricity generation systems, being able to complement other nowadays cheaper technologies, reason for which it will likely continue to increase its market penetration and for which applied research work such as the one presented in this thesis is still needed.

10.1. Future Work

This doctoral thesis builds on work being performed at the CSP and techno-economic modeling research group at KTH. The results and conclusions drafted, add to the on-going work and do not represent the last efforts of KTH's research group in the CSP plant optimization field. Despite the advances made in terms of model development and concepts introduced, there are still a number of directions of research one can explore to follow up on the results and analyses performed in this thesis. It is possible to categorize such future work recommendations in two types: improvements on the modeling work, and new research questions.

With regards to improvements to the modeling work, several issues can be highlighted. First, the dispatch strategy routines implemented in this work can be further enhanced by incorporating more transient effects and day-ahead considerations into the dispatch-control, rather than a full year's worth pre-defined strategy. This could slow the calculation process but would potentially allow to reach higher accuracy. This future work is currently being carried out by the author (Paper F).

Furthermore, although the modeling work in the thesis has been focused on addressing 'typical' project structures where a technology-specific CSP tender has been defined, it is desirable to couple this techno-economic modeling work to broader system scenario models to ultimately extend the recommendations on how to design the tenders to policy makers. Similarly, it is acknowledged by the author that results are highly dependent on cost models and reference cost values, being the last ones in constant change for such a new technology. It is then suggested to perform an additional work summarizing all CSP cost models available and respective sources. It is also recommended to review OPEX cost models and to improve them to account for the influence of start-up. Like so, it shall be investigated if it is worth adjusting the models to accurately account for the off-time due to maintenance requirements. Given that the thermodynamic models were used as found in open literature, then the cost data represents the main uncertainty in the models. It is thus important to consider such uncertainties for future work, especially taking into account that costs are rapidly changing and that each owner and developer is very secretive with regards to their own cost figures.

In addition, although the solar field models used are valid as a first approach, it is worth investigating the coupling of more detailed models for the heliostat design and layout disposition. The same applies to the receiver design. An alternative for the solar field could be to consider simplified ray-tracing simulations to account for better estimation of the optical performance. Lastly, despite the model inputs and case setups were consulted with relevant industrial players, it would be of great value to cross-validate the model performance results against data from an existing case, i.e. Crescent Dunes. However, it should be stated that CSP industrial actors are very reserved with providing own operational and cost data for publication with academic purposes, especially for the new technologies such as the molten salt tower power plants.

In terms of future research questions, further work is suggested on the basis of extending the analysis to other CSP technologies, both established and also more advanced. Furthermore, it is desired to extend the methodology and model presented to incorporate other renewable technologies. In terms of the use of performance indicators, it is suggested to keep highlighting the value of the hour of generation when comparing the technologies by considering revenue streams. This can be by means of typical profit base financial indicators such as the IRR, but also by clarifying if the LCOE is used under its standard definition as the ratio of cash outflows to yield, or if instead if it is defined as the ratio of all lifetime cash flows to lifetime yield; in which case then it would be more assertive for comparative analyses. Furthermore, while the IRR can be useful for creditors and project developers, tender designers and governmental institutions should investigate the use of other indicators to evaluate the impact of a particular technology at system level. This can be done, for instance, by use of other macro-scale indicators such as the net system costs and the net emission costs besides the ‘typical’ LCOE.

Suggestions on future work for the new TES concept and the two new hybrid schemes proposed have been highlighted in the papers. However, and in summary, the new TES concept requires further investigation especially with regards to its reliability and lifetime expectancy, as well as more tuned cost models (or to include sensitivity studies). Likewise, it was identified that the integration of additional heat demanding processes, such as water desalination, to the hybrid SSTCC concept can be evaluated as a means to enhance its competitiveness in arid regions.

The hybridization of CSP with other cheaper renewables still remains as an interesting subject worth investigating while CSP continues to decrease costs. The main challenge of these systems lies on the control design and the transient considerations needed for a successful real operation. Several topics can be proposed for further investigation such as the analysis of hybrid wind-PV and CSP for baseload-like generation in very particular locations where the resources are favorable. Additionally, the analysis can be performed considering other CSP technologies not limited in capacity, such as the parabolic trough technology, or considering multi-tower systems instead.

When it comes to applicability of the tool to real cases, further work is suggested with regards to extending the level of detail of the financial models, and also with regards to making the tool friendlier for actors outside the academia to use. The last, for instance, by means of developing a new graphical user interface.

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Appendix

Paper I: "*Enhancing the Profitability of Solar Tower Power Plants through Thermoeconomic Analysis Based on Multi-objective Optimization*", Energy Procedia, Vol 69, Pages 1277-1286. 2015

Paper II: "*A Methodology for Determining Optimum Solar Tower Plant Configurations and Operating Strategies to Maximize Profits Based on Hourly Electricity Market Prices and Tariffs*", ASME Journal of Solar Energy Engineering, Vol. 138 (2). 2016

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