

University of Cape Town
Faculty of Engineering and the Built Environment



**Synthesis of Integrated Solar Thermal Networks
for Domestic and Industrial Utilization**

A thesis submitted for the degree of
DOCTOR OF PHILOSOPHY

by

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Abstract

This study involves the development of generic multi-period Mixed Integer Non-Linear Programming (MINLP) based design and optimization methods for integrating solar thermal with domestic and industrial heat networks over multiple time frames based on discrete time intervals/periods. The study also presents a new simultaneous multi-period modelling and design framework for increasing thermal output of an integrated solar thermal-heat pump system. Detailed MINLP superstructure-based design and optimization technique is used for the proposed designs while the synthesis of the heat networks was implemented and solved simultaneously in General Algebraic Modelling Systems (GAMS) using SBB solver.

The first aspect of the thesis deals with the development of design and optimization model for direct and indirect integration of feasibly attainable solar thermal with industrial heat network. In the model, periodic changes in demand and supply sides of the industrial heat network superstructure, including periodic changes in the amount of heat stored in thermal storage tank, are accounted for using discretized time periods. The developed model was then applied to three kinds of integration scenario for industrial heating which includes pre-heating of single cold stream, targeting of a definite cold stream among multiple industrial cold streams, and pre-heating of multiple cold streams within the heat network. The second part of the study introduces the developed design and optimization model for integrating solar thermal with the heat network of residential buildings. The residential heat network includes water and space heating, periodic heat storage and backup utility, while other essential attributes of the design are incorporated and accounted for periodically in the proposed model. The case study considered involves solar thermal integration with heat supply network of a cluster of buildings considering heat storage and the varying heat requirement profiles of each building in the network. In the case study, two heat storage design alternatives incorporating combined water and space heating networks for three different types of building designs in Slovenia were investigated for the proposed residential integration of solar thermal network. The third aspect of the study presents a multi-period mathematical programming approach for simultaneous design and optimization of a solar thermal source multi-stage heat pump cycle for low/medium temperature heat production. The proposed model accounts for the intermittent changes in solar irradiation and ambient temperatures, as well as their effects on heat output from the system, while the dynamic operating conditions and thermodynamic features of the integrated system are also accounted for according to diverse ambient temperatures. The conceptual framework for the combined solar thermal-heat pump design rests on the idea that the thermal output of solar heat network designs, such as those described in the first two parts of the thesis, could be further enhanced by incorporating heat pump technology with the solar thermal network.

The results obtained from the studies indicate good prospect for solar thermal integration with domestic and industrial heat networks; it also offers opportunities for enhanced solar heat output through systematic combination of solar thermal with heat pump cycle. For the case of industrial cold stream pre-heating, the results obtained show that the average attainable solar heat increases (i.e. by 80.9 W/m²) up to collector area of about 6,500 m², beyond which the average solar heat attainable increase dropped to 16.7 W per additional m² of collector area up to 10,000 m². However, for the selected case study of a dairy plant, an average solar heat output of about 75 W/m² of collector is obtained with linear increase in the average attainable heat load up to certain collector area (on case-

by-case basis), after which it is observed that further increase in collector area does not result in much increase in the obtained heat load. For the first design alternative in the integrated residential solar thermal with heat storage network study, the results show that about 7.4 % of the total heat required by the buildings (for water and space heating) in winter months could be satisfied by solar thermal while the total heat demand for water heating in summer months could be fully satisfied by solar. Whereas the result obtained from the second design with a single heat storage tank shows that for collector area of about 18.8 m², only 25% of the energy required in the buildings could be satisfied by solar while for a collector area of 601.2 m², up to 92% of heat demand could be satisfied by solar. The results for the integrated solar thermal and heat pump systems show relative operational stability in the heat output regardless of season with 4,904.9 kW and 4,714.8 kW of heat harvested from the system in March and August respectively at an average coefficient of performance of 1.68. The models developed in this thesis are generic in that the model equations are formulated independent of the data. Hence, they can be applied to any integrated solar heating network in any location with known geographical coordinates and meteorological information.

Author's Statement of Declaration

I, Semilore Ben Olaoluwa Abikoye, hereby declare that the report and series of research information provided in this thesis are true reflections of my thought. The thesis in its entirety was put together by me unaided and it is original for the intended purpose by which it is prepared. For the benefit of doubt, the thesis (either in whole or in part) has not been previously submitted for any degree or academic purposes except in few cases where similar contributions from other authors are discussed. Such areas are well cited and referenced accordingly while acknowledgements are also given where necessary.

The proposed study plan for this PhD research and the conduct of the study afterwards followed official procedure set by relevant authorities of the University while prior approval was also obtained from the ethics in research committee of the university of Cape Town before commencement of the research work reported in this thesis.

In conformity with all the published papers, numeric citations which correspond to the respective reference list entry for each of the chapters, are used for in-text citations in this thesis while the output styles of the references follow the recommended format by each of the Journals. The 'EndNote' commercial referencing management software package is used to compile the bibliographies and references for the thesis.

Declaration on Inclusion of Publications in the PhD Thesis

I confirm that I have been granted permission by the University of Cape Town's Doctoral Degrees Board to include the following publications in my PhD thesis, and where co-authorships are involved, my co-authors have agreed that I may include the publications:

- a. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja. Synthesis of Solar Heat Network for Preheating of Industrial Process Streams. Computer Aided Chemical Engineering (Elsevier). 2019, Vol. 46, Pp. 535–540. DOI: 10.1016/B978-0-12-818634-3.50090-4.
- b. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja. Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations. Energy (Elsevier). 2019, Vol. 182, Pp. 381–396. DOI: 10.1016/j.energy.2019.05.205.
- c. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja. Synthesis of Solar Heat Network for Domestic Heat Utilization. Chemical Engineering Transactions. (AIDIC) 2019, Vol. 76, Pp 1015-1020. DOI:10.3303/CET1976170.
- d. **Ben Abikoye**, Lidija Čuček, Danijela Urbancl, Adeniyi Jide Isafiade, Zdravko Kravanja. Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations. In print:- Computer Aided Chemical Engineering (Elsevier), accepted for publication on 10th January 2020.
- e. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja. Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating. To be submitted to Renewable and Sustainable Energy Reviews Journal
- f. **Ben Abikoye**, Lidija Čuček, Danijela Urbancl, Adeniyi Jide Isafiade, Zdravko Kravanja. Synthesis of Heat Pump Enhanced Solar Thermal Considering Multi-Period Design and Optimization Approach. To be submitted to the Journal of Cleaner Production.

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STUDENT NUMBER: **ABKSEM001**

Dedication

This thesis is dedicated to Almighty God, the giver of life and strength,

To my parents for their love and encouragement
and

To my Wife and Children for their support and level headedness throughout the period I was away from home in the course of my PhD research.

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- (v). the entire staff and students of Chemical Engineering Department and the EBE, UCT

Publications from the PhD research

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2. **Ben Abikoye**, Lidija Čuček, Danijela Urbancl, Adeniyi Isafiade, Zdravko Kravanja (2020): Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations. In print, accepted for Publication by *Computer Aided Chemical Engineering Journal*.
3. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja (2019): Synthesis of Solar Heat Network for Domestic Heat Utilization. *Chemical Engineering Transactions*. 2019;76:1015 - 20.
4. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade and Zdravko Kravanja (2019): Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations. *Energy* (2019). DOI: 10.1016/j.energy.2019.05.205.
5. **Ben Abikoye**, Lidija Čuček, Niyi Isafiade and Zdravko Kravanja (2019): Synthesis of Solar Heat Network for Preheating of Industrial Process Streams. *Computer Aided Chemical Engineering*. Vol. 46, Pp. 535 – 540. DOI: 10.1016/B978-0-12-818634-3.50090-4.
6. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade, Andreja Nemet, Zdravko Kravanja (2018): Retrofitting of Industrial Utility Systems Considering Solar Thermal and Periodic Heat Storage. Proceedings of the *1st International Conference on Technology & Business Models for Circular Economy*, 5th – 7th September 2018, Portorož, Slovenia. DOI: 10.18690/978-961-286-211-4.21.

Publications/Abstracts in Conference Proceedings

1. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade, Zdravko Kravanja (2019): Maximization of Attainable Heat and Coefficient of Performance of Solar-driven Heat Pump. 3rd SPIL Scientific Conference on Energy, Water, Emission & Waste Reduction in Industry and Cities. 21st – 22nd November, 2019, Brno, Czech Republic.
2. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade, Zdravko Kravanja (2019): Energetic performance of heat pump-enhanced solar thermal considering hourly-based meteorological data. International Conference on Technology & Business Models for Circular Economy, 24th – 25th October 2019, Portorož, Slovenia.
3. **Ben Abikoye**, Lidija Čuček, Adeniyi J. Isafiade, Zdravko Kravanja (2018): Synthesis of a Solar District Heating Supply Network Considering Heat storage and Biomass-based Boiler Backup. Proceedings of the 24th Annual Meeting of Slovenian Chemical Society, 19th – 21st September 2018, Portorož, Slovenia.
4. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade, Andreja Nemet, Zdravko Kravanja (2018): Retrofitting of Industrial Utility Systems Considering Solar Thermal and Periodic Heat Storage. Proceedings of the International Conference on Technology & Business Models for Circular Economy, 5th – 7th September 2018, Portorož, Slovenia. DOI: 10.18690/978-961-286-211-4.21.
5. **Ben Abikoye**, Lidija Čuček, Adeniyi Isafiade, Andreja Nemet, Zdravko Kravanja (2018): Hourly-based Integration of Solar Heat in Industrial Processes. 2nd SPIL Scientific Conference on Energy, Water, Emission & Waste Reduction in Industry and Cities. 30th – 31st August 2018, Brno, Czech Republic.
6. **Ben Olaoluwa Abikoye** and Adeniyi Jide Isafiade (2018): Integrated Design for Renewable Energy and Waste Heat Utilization in Multi-Period Plant Operations Including Periodic Heat Storage. Proceedings of the 21st Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction. 25th – 29th August 2018, Prague, Czech Republic.
7. **Ben Abikoye** and Adeniyi Isafiade (2017): Life Cycle Assessment Study of Integrated Renewable Energy Network; 2nd South African Life Cycle Assessment Colloquium. 31st October – 1st November 2017, Johannesburg.

Table of Contents

Abstract.....	iii
Declaration Statement	v
Declaration for Inclusion of Publications.....	vi
Dedication	vii
Acknowledgement	viii
Publication from This Thesis	ix
Table of Contents.....	xi
List of Figures	xvi
List of Tables	ixx
1 Introduction	1
1.1 General Background of the Study.....	1
1.2 Research Goals and Objectives	4
1.3 Scope of Study.....	7
1.4 Research Questions	8
1.5 Assumptions.....	9
1.6 Limitations.....	12
1.7 Thesis Structure	12
References for Chapter 1	15
2 Literature review.....	19
2.1 Introduction	19
2.2 Historical Development	19
2.3 Solar Thermal as Potential Source of Renewable Energy	21
2.4 Solar Collectors	22
2.4.1 Flat plate solar collector.....	22
2.4.2 Evacuated tube solar collector.....	23
2.4.3 Solar air collector	23
2.4.4 Parabolic trough solar collector/concentrator	24
2.4.5 Thermodynamic panels.....	24
2.5 Application and Thermal Analysis of Solar Collectors.....	25
2.5.1 Applications of solar collectors	25
2.5.2 Thermal analysis of solar collectors	26
2.6 Supporting Technologies for Solar Thermal Systems	27

2.6.1 Heat storage.....	27
2.6.2 Heat storage temperature	30
2.6.3 Heat pump	30
2.6.3.1 Hybrid heat pump system	31
2.6.3.2 Absorption heat pump system.....	31
2.6.3.3 Solar energy and heat pump system	32
2.6.4 Heat transfer fluids for solar thermal systems	37
2.7 Heat Integration.....	37
2.8 Solar Thermal Systems Modelling and Design.....	39
2.9 Heat Pump Systems Modelling and Design	41
2.10 Integrated Solar Thermal and Heat Pump System Design.....	43
2.11 Optimization of Solar and heat Pump System	44
2.11.1 Mathematical programming	45
2.11.2 Mixed integer non-linear programming	46
2.11.3 Solution algorithms for MINLP problems	48
2.11.4 Extensions to MINLP solution algorithms	49
2.12 Chapter Conclusions	51
References for Chapter 2	53
3 Methodology.....	67
3.1 Introduction	67
3.2 Methodology.....	67
3.2.1 Description of applied methodology	67
3.2.2 General problem statement	70
3.3 Implementation Strategy.....	73
3.4 Model Development and Mathematical Formulations	74
3.4.1 Parameter initialization and bounding	74
3.4.2 Considerations for detailed model formulations.....	75
3.5 Summary of Applied Methodology.....	76
3.6 Chapter Conclusions	79
References for Chapter 3	80
4 Industrial Integration of Solar Thermal Incorporating Periodic Heat Storage and Backup Utility	82
Background to Chapter 4	82
Part I: Integration of Solar Thermal for Preheating of Industrial Process Streams	84

Synthesis of Solar Heat Network for Preheating of Industrial Process Streams.....	85
4.1 Introduction	86
4.2 Methodology.....	87
4.2.1 Solar heat network design for industrial utility retrofit.....	87
4.2.2 Model development.....	87
4.3 Case Study.....	89
4.4 Conclusions and Future Work	91
4.5 Acknowledgements.....	92
4.6 References for Part I	92
 Part II: Integration of Solar Thermal with General Industrial Heat Network Involving Multiple Cold Process Streams	 93
Integrated Design of Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations	94
4.7 Introduction	98
4.8 Description of Solar Heat Network Design for Industrial Application	101
4.9 Model Development and Optimization Approach.....	103
4.10 Detailed Model Formulation.....	104
4.10.1 Solar collector	105
4.10.2 Heat storage tank	106
4.10.3 Industrial process.....	109
4.10.4 Objective function.....	112
4.11 Case Study.....	112
4.12 Results and Discussion	117
4.13 Conclusions and Recommendations	125
4.14 Acknowledgements.....	126
4.15 References for Part II	127
Appendix 4A: Supplementary Material for Part II	130
Chapter Conclusions	149
 5 Integration of Solar Thermal with Periodic Heat Storage and Backup Utility for Domestic Utilization	 150
Background to Chapter 5	152
Part I: Domestic Integration of Solar Thermal Incorporating Multiple Heat Storage Tanks and Backup Boiler	153
Synthesis of Solar Heat Network for Domestic Heat Utilization.....	153

5.1 Introduction	153
5.2 Methodology.....	155
5.2.1 Description of solar heat network design for applications in buildings	155
5.2.2 Model approach.....	156
5.3 Case Study.....	157
5.3.1 Results of the first scenario (winter months)	159
5.3.2 Results of the second scenario (summer months).....	160
5.4 Conclusion to part I.....	161
5.5 Acknowledgement	162
5.6 References for Part I	163
Part II: Domestic Integration of Solar Thermal Incorporating Single Heat Storage Tank and Backup Burners.....	165
Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating	166
5.7 Introduction	169
5.8 Outlook on Energy Consumption in Buildings	171
5.9 Overview of Domestic Solar Thermal Utilization and Methodologies.....	173
5.10 Domestic Solar Heat Network Architecture and Description of the Integrated System	177
5.11 Methodology and Model Development	180
5.12 Case Study.....	182
5.13 Conclusions	192
5.14 Acknowledgements.....	193
5.15 References for Part II	194
Appendix 5A: Supplementary Material for Part II	202
Chapter Conclusions	220
6 Design and Optimization of Heat Pump-Enhanced Solar Thermal for Improved Thermal Performance	222
Background to Chapter 6	222
Synthesis of Heat Pump Enhanced Solar Thermal Considering Multi-Period Design and Optimization Approach.....	225
6.1 Introduction	228
6.2 Description of Integrated Heat Pump Enhanced Solar Thermal System	232
6.2.1 Selection of refrigerant	232
6.2.2 Description of Heat Pump Enhanced Solar Thermal Cycle	233
6.3 Methodology and Model Development	236

6.3.1 Correlations for thermodynamic properties.....	236
6.3.2 Model formulations	238
6.3.2.1 Solar collector	239
6.3.2.2 Heat pump circuit	240
6.3.2.3 Heat recovery section	240
6.3.2.4 Objective function.....	241
6.4 Case Study and Results	242
6.5 Conclusions and Future Research Directions.....	247
6.6 Acknowledgements.....	248
6.7 References for Chapter 6	249
Appendix 6A: Accepted Paper in Computer Aided Chemical Engineering Journal	254
Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations. Chapter Conclusions	264
7 General Conclusions and Future Research Directions.....	265
7.1 Concluding Remarks.....	265
7.2 Recommendation for Future Research Directions	269
Compilation of Bibliography	271

List of Figures

Figure 1.1: World energy outlook: Global energy consumption by source	1
Figure 1.2: Global solar resource map: Radiation insolation distribution	2
Figure 1.3: Total global energy consumption	3
Figure 1.4: Thesis structure.....	13
Figure 2.1: Global solar thermal installed capacity in operation and annual yield	20
Figure 2.2: Installed capacity of annual grid-connected solar energy	20
Figure 2.3: Types of heat storage suitable for solar thermal systems.....	30
Figure 2.4: Stages and components for basic vapour compression heat pump cycle.....	34
Figure 2.5: Summary of systematic methodologies for heat exchanger network synthesis	38
Figure 3.1: Implementation strategy for the proposed solar thermal integration scheme	73
Figure 3.2: Summary of methodology applied in Chapter 4.....	77
Figure 3.3: Summary of methodology applied in Chapter 5.....	77
Figure 3.4: Summary of methodology applied in Chapter 6.....	78
Figure 4.1: Integration of solar heat network for industrial stream pre-heating.....	87
Figure 4.2a: Average DH^{solar} with different sizes of solar collectors	90
Figure 4.2b: Average T^{solar} with different sizes of solar collectors	90
Figure 4.3: Average values of variables for the case when $A_{\text{panel}}^{\text{UP}} = 1000 \text{ m}^2$	90
Figure 4.4: Average values of variables for the case when $A_{\text{panel}}^{\text{UP}} = 10,000 \text{ m}^2$	91
Figure 4.5: Integration of solar thermal for heating of industrial process streams.....	102
Figure 4.6: Integration of solar thermal for multiple industrial process streams.....	103
Figure 4.7: Summary of applied methodology	104
Figure 4.8: Schematic representation of heat storage tank	107
Figure 4.9: Schematic representation for heating single industrial process streams.....	110
Figure 4.10: Location of the case study	113
Figure 4.11: Monthly and daily hourly irradiation for typical winter month.....	113
Figure 4.12: Monthly and daily hourly irradiation for typical summer month.....	114
Figure 4.13: HEN with stream-stream matches and external utility requirement on each stream...	115
Figure 4.14: Grand composite curve.....	116
Figure 4.15: Values of variables for the first scenario $5,000 \text{ m}^2$ for time period M1, D1, H3.....	119
Figure 4.16: Values of variables for the first scenario $5,000 \text{ m}^2$ for time period M7, D1, H3	120
Figure 4.17: Values of variables for the second scenario $5,000 \text{ m}^2$ for time period M1, D1, H3.....	121

Figure 4.18: Values of variables for the second scenario 5,000 m ² for time period M7, D1, H3.....	121
Figure 4.19: Solar heat supply to the cold stream C ₃ with solar collector area of 500 m ²	122
Figure 4.20: Solar heat supply to the cold stream C ₃ with solar collector area of 5, 000 m ²	122
Figure 4.21: Solar heat supply to the cold stream C ₃ with solar collector area of 10, 000 m ²	123
Figure 4.22: Solar heat supply to the storage tank when solar collector area is 5, 000 m ²	124
Figure 4.23: Temperature of the fluid in the storage tank when solar collector area is 5, 000 m ² ...	125
Figure 4S1: Schematic representation of heat storage tank	138
Figure 4S2: Schematic representation of solar heating of single industrial process stream	142
Figure 4S3: Schematic representation of solar heating for multiple process streams	145
Figure 5.1: Representation of solar thermal integration for heat utilization in buildings.....	156
Figure 5.2: Share of end-use energy consumption in buildings for cold and temperate climates.....	172
Figure 5.3: Global total energy consumption in buildings	173
Figure 5.4: Integration of solar thermal for domestic hot water and space heating	178
Figure 5.5: Summary of applied methodology	181
Figure 5.6: Location used as case study.....	182
Figure 5.7: Discretized irradiation data as used in the model	183
Figure 5.8: Discretized data for ambient temperature for the reference location	183
Figure 5.9: Temperature of fluid in the storage tank when V_{fluid}^{UP} is 50 m ³	185
Figure 5.10: Temperature of fluid in the storage tank when V_{fluid}^{UP} is 1, 000 m ³	186
Figure 5.11: Heat transfer of solar thermal to storage tank when V_{fluid}^{UP} is 50 m ³	187
Figure 5.12: Solar thermal utilization when V_{fluid}^{UP} is 50 m ³	188
Figure 5.13: Heat transfer of solar thermal to storage tank when V_{fluid}^{UP} is 1, 000 m ³	188
Figure 5.14: Solar thermal utilization when V_{fluid}^{UP} is 1, 000 m ³	189
Figure 5.15: Details of result for the period M1,D1,P2 when V_{fluid}^{UP} is 1, 000 m ³	190
Figure 5.16: Details of result for the period M7,D1,P2 when V_{fluid}^{UP} is 1, 000 m ³	190
Figure 5S1: Schematic representation of heat storage tank model	208
Figure 6.1: Schematic representation of multi-stage heat pump cycle.....	234
Figure 6.2: Integrated heat pump-enhanced solar thermal system.....	235
Figure 6.3: Summary of applied methodology for heat pump-enhanced solar thermal integration.	236
Figure 6.4: Schematic diagram of heat pump enhanced solar system in Aspen Plus.....	238
Figure 6.5b: Changes in mass enthalpy with varying temperature and pressure for liquid phase	238
Figure 6.6: Periodic solar heat supply to the evaporator with solar collector area of 50 m ²	243

Figure 6.7: Periodic solar heat supply to the evaporator with solar collector area of 5,000 m²..... 244

Figure 6.8: Values of variables in selected period and collector area (A = 5,000 m², M3, 8-10am)... 244

Figure 6.9: Values of variables in selected period and collector area (A = 5,000 m², M3, 8-10am)... 245

Figure 6.10: Average heat output with different sizes of solar collector 246

List of Tables

Table 2.1: Different types of solar collectors and their temperature range	27
Table 4.1: Stream data for milk powder plant	115
Table 4.2: Main results for the first scenario for different sizes of solar collector.....	117
Table 4.3: Main results for the second scenario for different sizes of solar collector	118
Table 5.1: Baseline scenario for energy consumption in VSS1, ESS1 and ESS2 buildings.....	158
Table 5.2: Allocation of energy consumption on hourly basis for the three buildings (%)	158
Table 5.3: Average volumes of variables for the scenario considering 4 winter months.....	160
Table 5.4: Average values of variables for the scenario considering 4 summer months	161
Table 5.5: Baseline scenario for energy consumption in VSS1, ESS1 and ESS2	184
Table 5.6: Solar potential for varying volume of fluid in the tank and respective collector sizes	192
Table 5S1: Share of energy consumption on an hourly basis for the three buildings in different months	217
Table 5S2: Energy consumption for space heating on a period basis for the three buildings	218
Table 5S3: Energy consumption for water heating on a period basis for the three buildings	218
Table 6.1: Average values of some integration variables for different solar collector areas	246

CHAPTER ONE

Introduction

1.1 General Background of the Study

Increasing concerns about global climate change, energy security, and other recent environmental challenges associated with energy production from fossil fuels, is propelling global transition from fossil-based resources towards a more sustainable and climate resilient energy systems [1]. The global energy system is dominated by various fossil fuels until the oil crisis of the mid- to late- 70s when global oil shocks and trade embargo triggered the thought for alternative sources of energy. Moreover after the crisis, the exponential increase and instability in the price of oil, as well as the stringent environmental regulations enacted by various institutions with respect to greenhouse gas emissions, have further helped to dislodge the global dominance of fossil fuels [2]. Several individual and institutional plans aimed at facilitating the transition towards a more sustainable energy system have been put forward over the past few decades. These range from rational usage of energy (energy efficiency) for existing conventional energy systems [3], to newer technology options such as the various renewable systems [4]. More than 5 decades after the first energy/oil crises the reality is that global energy production and supply is still largely dominated by non-renewable energy resources such as oil, natural gas, uranium and coal which together account for about 80% of the global primary energy consumption [5, 6], see also Figure 1.1.

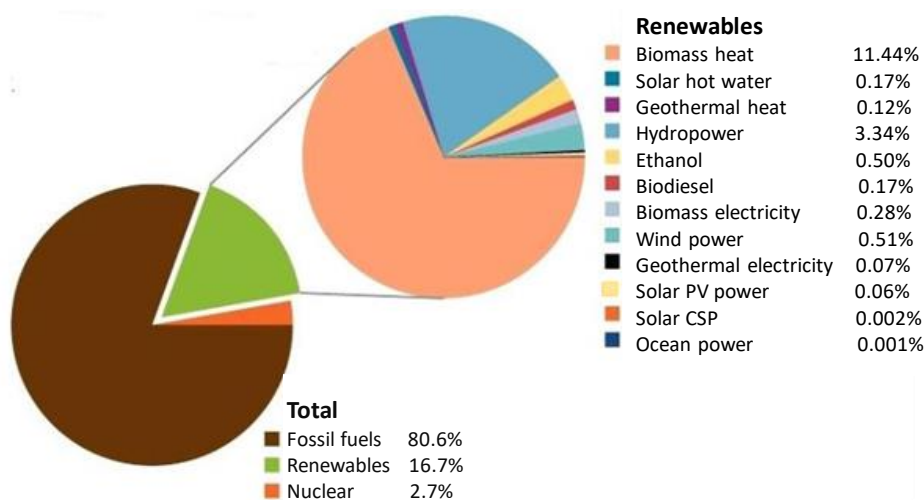


Figure 1.1: World energy outlook: global energy consumption by source (Source: IEA, 2018 [6])

The global demand for energy continues to be on the increase, and this is accompanied by increased CO₂ emissions. Residential and industrial sectors are part of the key sectors contributing heavily to global energy consumption. While the industrial sector is responsible for about 40% of global energy consumption [7], residential and commercial buildings jointly account for between 32% [8] and 40% [9] of total energy consumption. With projected increase of about 50 % between 2019 and 2050 [10], further increase in both energy demand and emission level is most likely [11] considering the persistent growth in global population, industrialization and economy, and its impact on energy demand [12]. Expanding the capacities of existing conventional energy architecture to meet current demand for energy, as well as future demand projections may not be a viable option due to issues bordering on sustainability and environmental pollutions [13, 14]. In this regard, sufficient deployment of various renewable energy resources to supplement the carbon-intensive fossil-based system has been propounded as a sustainable means of achieving energy security and simultaneously mitigating the threat of climate change [15].

Solar thermal is a renewable and sustainable source of heat with great potential to offset substantial amount of energy from conventional fossil fuels. The natural availability of solar at ambient temperature levels without any mechanical work input also makes it a unique source of heat suitable for domestic and industrial applications, especially for low- and medium- temperature applications. Besides, solar thermal is available in various parts of the world in considerable amount that is profitable to be harnessed for use as shown in Figure 1.2.

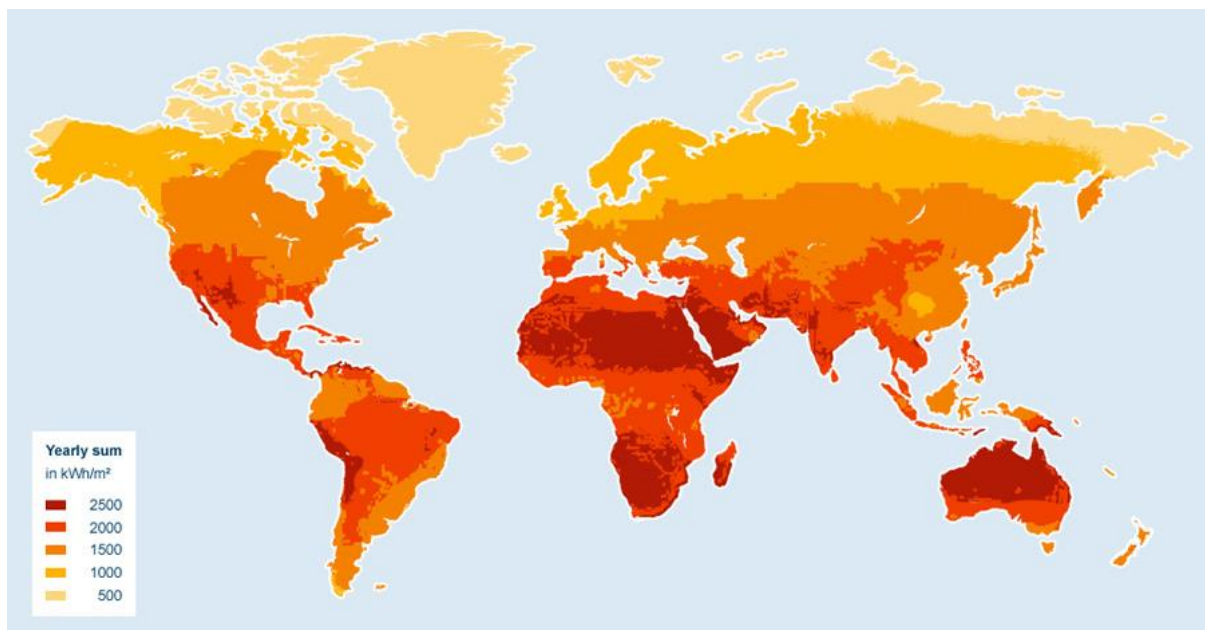


Figure 1.2: Global solar resource map: radiation insolation distribution (Source: Solar informative [16])

Basically, domestic hot water and space heating temperatures which lie between 50°C – 120°C can be satisfied by simple solar thermal designs [17], while a number of low/medium temperature industrial operations (such as cleaning, washing, drying, raw material processing and cold streams pre-heating) which account for about 52% of the total industrial energy use (i.e. see Figure 1.3) can also be satisfied with solar.

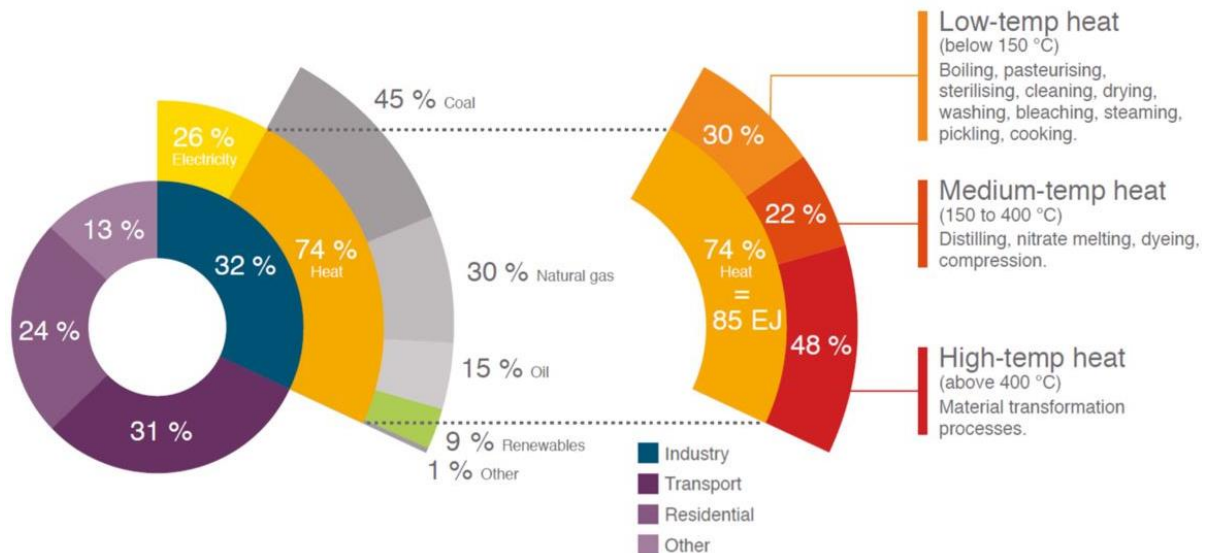


Figure 1.3: Total global energy consumption: 340 exajoule (adapted from [18] based on IEA statistics)

Several applications of solar thermal for integration with domestic/commercial buildings [19, 20] and industrial processes [21] have been reported in the literature. These range from individual efforts for direct and indirect solar thermal utilizations [22], solar thermal design for policy redirection towards energy savings and emission reduction [23], domestic solar thermal designs for single household and community district heating networks [24, 25], to various industrial applications such as presented by Atkins et al. [26], Isafiade et al. [27] and Quijera et al. [28]. Other available designs include the combination of solar with other technologies such as heat pumps [29] and various combi-systems for efficiency and capacity enhancement [30]. Regardless of the type of design and integration pattern, the main contending issues affecting the growth of solar thermal utilization include: the intermittent nature of solar availability, the influence of fluctuating weather conditions on solar heat networks and lack of suitable storage facilities/materials of high energy density. Though incorporating appropriate heat storage technique(s) could circumvent some of these problems by bridging the gap between energy supply and demand [31]. An important aspect which is often neglected is that the heat storage should be designed to optimally match the fluctuations in attainable solar heat and the profile of energy demand with minimal use of a backup energy source [32].

More so, the benefits of the synergy between energy efficiency technologies (such as heat pump) and solar thermal have been well documented as part of the strategic measures to improve the performance of solar systems. However, since the properties and features of the integrated system are subject to changes according to the fluctuating solar irradiation and ambient temperature; coupled with the changing profile of heat demand, integration framework for combining solar and heat pump technologies should reflect the transient behaviour and multi- period dynamics of design parameters.

In similar perspective, since the potential of solar resources varies from region to region, it is also pertinent that the design framework for solar thermal utilization should be generic, such that it can be adapted to similar case studies in other locations [22]. Though, it is worth noting that obtaining an energy design framework incorporating all the above highlighted features is not trivial, considering the computational complexities resulting from the technical difficulties and thermodynamic constraints involved. Nonetheless, optimum performance of any solar thermal and heat pump design could only be guaranteed when the integration scheme is formulated with utmost consideration given to the aforementioned features, as well as the changing meteorological conditions, together with the actual daily and seasonal variabilities in the profile of heat demand.

To the best of the authors' knowledge, a comprehensive design and optimization method for direct and indirect integration of solar thermal, where all these features are accounted for in a multi-period manner, is still lacking. Therefore, unlike what is commonly found in most previous solar thermal and heat pump designs methods where some/all the aforementioned issues are either neglected or addressed using a simplified/non-comprehensive approach, this study provides additional contributions to existing knowledge, given that all the aforementioned features (which are considered to be essential for a robust solar thermal design), are rigorously accounted for in a comprehensive design and optimization framework. Integrating these details in a flexible structure that is applicable to different case studies located in any part of the world is yet another unique contribution of this study.

1.2 Research Goals and Objectives

One of the most important pathways to achieving the sustainable development goals is sustainable energy developments to reduce greenhouse gas emissions. A key contribution to this is sufficient deployment of renewable energy (such as solar thermal) as substitute and alternative to the carbon-intensive fossil energy. It has been widely proven that solar thermal (a renewable source of heat) can

be used to supply heat for both industrial and domestic uses. Albeit, the low and slow penetration of solar energy designs contradicts the social and environmental significance of solar technologies. Therefore, the main goal of this PhD thesis is to proffer solution to the slow uptake of solar thermal systems. This is done through development of generic models for the most feasible design of direct and indirect integration of solar thermal with domestic and industrial heat networks using mathematical programming approach. The proposed designs incorporate strategies for periodic storage of harvested solar heat (which is later regarded as indirect solar thermal integration in the heat supply network), and opportunities for backup utility system to satisfy the heat demand of the networks. Implementing the design and optimization framework for industrial and domestic heat networks involve maximization of the attainable direct and indirect solar heat across the entire networks.

The industrial solar heat supply network considered in this study comprises solar collector panel and its features, heat storage tank and the industrial heat network which function in three closed loops. The loops are: i) solar collector – heat storage – solar collector loop; ii) solar collector – industrial process stream(s) – solar collector loop; and iii) heat storage – industrial process stream(s) – heat storage loop, representing the three possible heat flow directions for the direct and indirect solar thermal integration. On the other hand, the domestic solar supply network comprises solar collector field and its features, heat storage tank, space heating radiators and feed water/hot water supply lines to the participating heat demand points. In this network, two closed loops are involved which are, i) solar collectors – heat storage tank – solar collectors loop, ii) space heating radiators – heat storage tank – space heating radiators loop. The domestic supply network also includes an open loop feed water – domestic hot water use loop.

A subsequent obligation of this PhD research is to develop a comprehensive synthesis method for extending the above introduced models in order to combine the solar thermal designs with heat pump technology. The integrated system will operate as a continuous non-steady state system where the multi-period ambient and meteorological conditions (hourly changes in solar irradiation and ambient temperatures) are considered on the heat source side of the heat pump while the extended model allows the simultaneous optimization of all essential design features according to discrete time intervals. The optimization of the combined solar thermal and heat pump network involves maximization of the recoverable heat. In this case, the network consists of solar collector panels and its features, heat pump circuit and the heat recovery side of the integration where low/medium temperature heat is harvested. These design blocks are incorporated to form three separate but interconnected loops which are:- i) a closed loop involving solar collector – heat pump – solar collector

loop; ii) a closed loop heat pump (comprising of just the heat pump cycle); and iii) an open loop involving a circulating cooling water – heat pump – industrial process. The industrial process represents potential heat sink while all the loops operate with different working fluids.

The loops in each of the networks described above represent the building blocks of the various design options. They are modelled over multiple time periods using a simultaneous multi-period mixed integer non-linear programming (MINLP) approach. Due to computational complexity resulting from the multidimensional and nonlinear nature of the proposed solar thermal and heat pump networks (wherein the transient features of parameters and variables are systematically captured), the simultaneous design and optimization framework for the problems described above are formulated as an inter-related trifecta wherein the major tasks are executed in three successive steps with each step having its unique statement of the problem to be addressed. Accordingly, the objectives of this PhD research are as follows:

- To develop a generic design approach for direct and indirect utilization of solar thermal in industrial heat network considering periodic heat storage, backup utility and simultaneous optimization of design and operating features over multiple timeframe based on discrete time intervals/periods.
- To develop a generic design approach for integrating solar thermal with domestic water and space heating of a multi-building heat demand network considering periodic heat storage, backup utility and simultaneous optimization of design and operating features over multiple timeframe based on discrete time intervals/periods.
- To develop a comprehensive generic design and optimization approach for combining solar thermal and heat pump technologies for low and medium temperature level heat generation considering variabilities in meteorological and ambient conditions as well as the multi-period dispositions of the thermodynamic state functions based on discrete time intervals/periods.

The integrated features of the proposed designs will enhance flexibility of the system and this potentially leads to cost savings, improved efficiencies and less environmental impact when compared to the stand-alone solar design(s).

1.3 Scope of Study

Depending on the nature and scope of study, there are many criteria that can be implemented to perform the optimization of energy systems such as the one presented in this thesis. To mention just a few, some of these criteria include the following:

- maximizing efficiency of the entire system
- maximizing the total heat output of the system
- minimizing the amount of certain types of energy consumed over a period of time
- minimizing the global warming potential and environmental footprint of the system
- minimizing pay-back period of investment
- minimizing installation and / operating cost

Generally, researchers have grouped the major criteria for performing the optimization into four broad categories: environmental, economy and energy/exergy, and social criteria. One or a combination of these criteria can be implemented in optimization, but compromise towards a particular objective and trade-offs are of essence again, depending on several exogenous and endogenous factors because a decrease in total investment cost or an increase in the energy or exergy performance of a system can be found in a design that has very high environmental impact and vice versa.

However, since most renewable energy systems (such as solar thermal presented in this thesis) involve the use of non-conventional technologies (either in solitary or combinations), as well as set of new/emerging energy conversion techniques and systems lay-out, it often of high importance to first provide novel modelling and optimization framework for a design option that enhance energy output of the collector and the entire systems under time varying meteorological conditions and fluctuating profiles of energy demand. This is so because simultaneously optimizing the variables involved on both the supply and demand sides of an integrated solar thermal system alongside with any of the other earlier mentioned criteria is not trivial. Therefore, the modelling and optimization procedures in this thesis focused on maximization of thermal output of the systems described in Section 1.2 and does not include the cost implication of the designs and the environmental impact. Though, it is worth noting that renewable technologies are said to be characterized by high initial cost of investment which fizzles out overtime with considerably reasonable economic pay-back period and gainful utility rate profile [33]. It is also widely known that renewable energy designs are poised with less environmental footprint as compared to the conventional energy technologies, especially if the lifecycle emissions index of the conversion technologies are not considered. Applicable and relevant

knowledge to establish these with respect to the proposed designs are part of the schemes of how other work could evolve to advance the contributions made in this thesis.

Furthermore, rather than implementing a full-scale control framework which will definitely add to the complexity of the optimization problem, this thesis considers the development and implementation of simple temperature control measures (such as the “big M ” constraint and upper bound on fluid temperatures) in the developed models so as to activate some form of control actions using integer variables according to specified constraints when the need arises. For instance, in order to circumvent the dangers and challenges of boiling which are more likely to occur in active solar heating periods, the “big M ” constraint (which is later discussed in Chapters Two and Four) is developed for the temperature of fluid in the storage tank for thermal control and overtemperature monitoring. Moreso, bound tightening (within lower and upper extreme values) was also accommodated and implemented for selected variables such as flowrates and temperatures of heat transfer fluids across the loops (including the solar collector). This is also further described in detail in Chapter Three, and according to previous studies (Sawaya and Grossmann [34], and Floudas [35]), such simple logic control does not have any effect on the results of the model but rather improves the approximation of convex relaxation for reasonable convergence.

Therefore, within the scope of this thesis, it is believed that the proposed integrated designs will offset substantial amount of conventional fossil-based fuels in that maximum attainable solar heat is harvested and the collector provides thermal energy at diverse temperature levels based on the ambient conditions without any mechanical work input and at no direct cost. The incorporated heat pump also provides additional support to the solar thermal system by increasing the efficiency and thermal performance of the system.

1.4 Research Questions

In pursuing the goals highlighted above, the following research questions are addressed as guides to achieving various objectives of the designs:

- What is the maximum attainable solar heat based on a set of discrete time intervals for each of the proposed designs?
- How much of the annual heat demand of the process/ domestic heat demand can be satisfied by solar thermal, and what are the potential gains in terms of energy savings due to reduction in external utility?

- What are the most feasible sizes of the solar collector and heat storage tank required to achieve maximum attainable solar heat supply to a multi-building heat network as well as an industrial process?
- Which heat pump design features, including the type of refrigerant, number of stages, components arrangement and design features, are necessary to achieve maximum recoverable heat output with respect to multi-period changes in meteorological conditions?
- What is the mutual gain, in terms of quantity of heat, harvestable from the integrated system with respect to the total heat output when solar thermal is combined with the heat pump features?

1.5 Assumptions

Implementing the design and optimization framework of a complex system comprising of large-scale nonlinear variables and intertemporal features requires suitable and reasonable assumptions, and some form of simplifications that is precise enough to not undermine the overall result(s) of the problem. Thus, the following general assumptions are considered in the developed models:

- Heat losses across solar network in the proposed systems are neglected;
- Variabilities in meteorological features and ambient conditions in the proposed designs (i.e. changes in solar irradiation and ambient temperature) are discretized on an hourly basis;
- The minimum temperature difference (ΔT_{\min}) for heat transfer in the storage tank and process streams across the year is the same and fixed;
- The content of the storage tank is assumed to be continuously perfectly mixed, such that the temperature of the exiting stream is the same as the temperature of the fluid in the tank;
- Specific heat capacity and density of heat transfer fluids are assumed to be constant to reduce the computational complexity;
- Lower and upper bounds on temperatures for space heating radiators and hot water are the same for all building types considered.

The first stated assumption relates to heat losses across the heat networks in the proposed systems (i.e. along the distribution pipes and storage tanks in the proposed design). In the proposed design, harvested solar heat from the rooftops is channelled directly for use at short distances within the

process (i.e. for the industrial case) or within the multi-building heat network (for domestic case study). Even when the harvested heat is stored for later use, the storage points are also strategically located at proximity within the integrated system. In order to satisfy the interest of whether or not there is temperature gradient between the temperature of the fluid at two different time step, the storage tank is modelled with circular or equilibrium leads and lags [36] as presented in Section 2.6.2. Meanwhile, thermal losses from the proposed storage units are restricted to the sensible heat effects which are usually very small (in the order of 1% of the stored capacity) according to Prieto [37], although this may also be dependent on lagging in the tank.

Moreso, when the data size of a model is too large, the already complex and difficult problems (i.e. due to nonlinearity) becomes much more compounded. Hence, the second assumption was considered to minimize the computational complexity and resource utilization of the developed model. This entails clustering of the large set of hourly, daily, and monthly time data into a set of discrete-time periods. For variation of data of this nature during the daytime, Varbanov and Klemeš [38], suggest that the use of time slices can provide an accurate result. But in the case of seasonal variation, a multiperiod approach is of essence. According to Mercenier [39], the intertemporal optimization models for time aggregation have shown to be inefficient because it presents a dependency of the solution steady state for a specific choice of sequence of time intervals. In this thesis, a mathematical model reduction technique, which was earlier presented by Lam [40], was used to discretize the hourly, daily and monthly time periods as presented and discussed in Section 4.S1 in Chapter 4. This technique established sufficient conditions for numerical accuracy of the aggregated time approximations and could be applied to different types of complex multidimensional and multiperiod models like the case presented in this thesis. Accordingly, meteorological data (such as hourly solar irradiation and ambient temperature for each hour of the year) were discretized following the order of a reduced multiperiod time approach.

The third assumption has to do with the minimum temperature difference approach (ΔT_{\min}) between two streams exchanging heat within the system. Typically, temperature difference of about 10 °C is generally taken to be suitable for feasible heat transfer at both moderate and high temperature systems (except for selected cases of refrigeration systems) [41]. This ΔT_{\min} condition may not be entirely fixed as a consideration for time is also important when considering heat transfer in transient systems, while the exchanging surface area is also crucial in steady state. However, for heat transfer systems involving solar thermal heating, a ΔT_{\min} of between 5 to 10 °C is said to be sufficient across the loops [42].

Furthermore, the thermal storage design presented in this thesis is modelled as a cylindrical heat storage tank. The heating coils of the tank (through which the hot solar fluid flows) runs through almost the entire length of the tank (i.e., from the topmost part of the tank to its base). This design technique was implemented in order to provide maximum flow contact between water in the tank and hot solar fluid circulating through the coil. In the compendium of techniques for the design of thermal storage for solar systems, Sarbu et al. [43] and Razo et al. [44] substantiated that improvement in heat storage tank designs and sufficient exchange of heat between two streams could be achieved when the heat transfer area is considerably large enough. In the same vein, perfect mixing and evenly distributed heat transfer can be achieved within the storage tank if water inlet to the tank is strategically positioned in a manner that maximizes flow-contact and exchange of heat between water and the circulating hot solar fluid flowing through the heating coil of the tank (McLinden and Klein [45]). This is the scenario for the case presented in this thesis, justifying the assumption that the content of the storage tank is continuously perfectly mixed such that the temperature of the exiting stream is the same as the temperature of the fluid in the tank.

The next assumption considers constant values for the specific heat capacity and density of heat transfer fluid to reduce the computational complexity of the developed model. This is done despite the fact that the properties respond slightly to changes in temperature. However, the change has little or no effect on the system except for very extreme temperature change towards a particular direction (i.e., towards extreme freezing or boiling). At such condition, a constant value (e.g., 1000 kg/m^3) as used for the density of water would no longer be valid for acceptable results. This is not so in the presented case studies. Hence, the specific heat capacity and density of heat transfer fluids are assumed to be constant in the developed models.

With respect to the assumption relating to the lower and upper bounds on temperatures for space heating radiators and hot water use, it is good to note that 3 different building designs were considered for the domestic solar thermal integration as presented in Chapter 5. However, irrespective of the building design, space heating (through the radiators) and hot water supply through the taps in all buildings come from the same source. Therefore, the same flow conditions apply to these source of heat demands on the building. Thus, this condition was upheld while modelling for the allowable minimum and maximum values for the inlet and outlet stream temperatures to the building.

1.6 Limitations

Solar energy is widely known for considerable intermittency. This feature presents a level of complexity and uncertainties to the proposed model and by extension the results obtained.

Furthermore, estimation of harvested solar heat in the model for the considered case studies (i.e. industrial and domestic integration of solar thermal and its combination with heat pump) is based on the assumption that the entire collector heat yield (according to its efficiency) is delivered to the system because heat losses from the heat networks are considered to be negligible. Although this assumption is valid for the considered cases presented in this thesis. This is the case since the harvested solar heat from the rooftops is channelled directly for use at short distances within the process (i.e. for the industrial case) or within the multi-building heat network (for domestic case study). Even when the solar heat is stored for later use, the storage points are also strategically located at proximity within the system. Thus, the estimated potential might not be too far from what could actually be obtained in reality. However, some school of thought may argue that losses and drop in heat quality is expected in heat transport. Further extension of the models to explore this attribute is beyond the scope of this study.

Despite these limitations, the proposed models are formulated in a generic manner such that the model equations are written independent of the data. Thus, the model can be applied to any related case study in any region of the world with known geographical coordinates and meteorological information.

1.7 Thesis Structure

The case study applications of the various models developed in this study (i.e. solar heat network for industrial, solar heat network for residential sector, heat pump-integrated solar heat network) have been published in peer-reviewed journals while other contributions from the thesis are either undergoing review process or awaiting final submission. Accordingly, the presentation style of relevant chapters of the thesis are in conformity with the requirements of the respective journals. The only changes are the cosmetics applied to section identifications in order to maintain the requirements for the thesis presentation. The inclusion of publications within the thesis and the thesis presentation format was approved by the Doctoral Board of the University of Cape Town.

The entire thesis (including the publications) is made up of seven chapters. Figure 1.4 outlines the general structure of the thesis and link between all the seven chapters presented. In order to accommodate the structure of the thesis presentation style, each chapter is treated as separate entity

having its own introduction, survey of relevant literature, main contributions of the chapter, concluding remarks and references. This chapter presents the general background of the study stating the research goals, key research questions and limitations. After which a detailed outline of the thesis structure and the main contributions of each chapter is provided.

Chapter 2 presents a comprehensive literature review of essential concepts related to this thesis. The chapter could be broadly divided into two sections. The first part deals with the theories relevant to solar thermal designs and supporting technologies. The second part presents the state-of-the-art of modelling and optimization techniques in relation to solar thermal and heat pump networks synthesis, with special focus on MINLP problem formulations and solution algorithms.

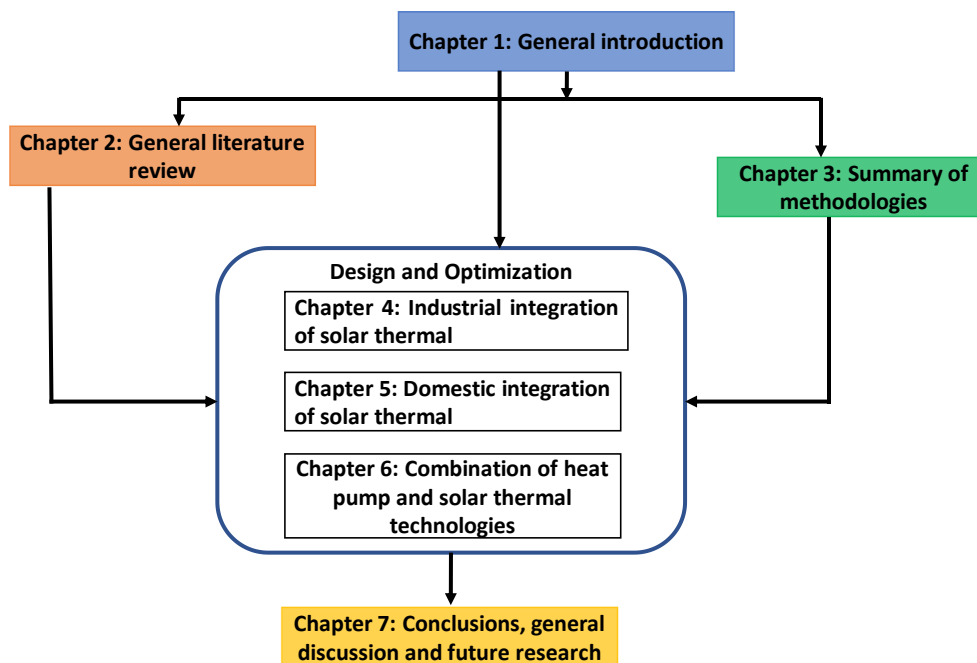


Figure 1.4: Thesis outline

The summary of the general methods proposed in this thesis is presented in Chapter 3. The chapter also describes the problem statement for each of the objectives and summary of the approaches developed to solve the problems based on simultaneous multi-period MINLP models. The main contributions of this thesis are covered in Chapters 4, 5 and 6.

Chapter 4 presents the design and optimization framework for direct and indirect integration of optimally attainable solar thermal with industrial heat network incorporating periodic heat storage and backup utility. The contributions of the chapter is presented through the direct “word-for-word”

reproduction of papers titled “Synthesis of Solar Heat Network for Preheating of Industrial Process Streams” published on 25th July 2019 in Volume 46 of *Computer Aided Chemical Engineering* book series, and another paper published on 1st June 2019 in Volume 182 of *Energy Journal* which is titled “Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations”.

Chapter 5 presents the design and optimization framework for the integration of solar thermal with multi-building water and space heating network incorporating periodic heat storage and backup utility. Contributions presented in this Chapter is also a direct “word-for-word” reproduction of the papers published on 20th October 2019 in Volume 76 of *Chemical Engineering Transactions Journal* titled “Synthesis of Solar Thermal Network for Domestic Heat Utilization”, and another paper titled “Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating” invited for the Special Issue with *Renewable and Sustainable Energy Reviews Journal*.

Chapter 6 presents the design and optimization framework for integrating solar thermal and heat pump for enhanced thermal performance. The chapter features a paper contribution titled “Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations” accepted for publication in *Computer Aided Chemical Engineering Journal* on 10th January 2020, and another paper titled “Synthesis of Heat Pump Enhanced Solar Thermal Considering Multi-Period Design and Optimization Approach” to be submitted to the *Journal of Cleaner Production* as an extension of the first paper publication developed from this Chapter.

Chapter 7 presents the general concluding remarks of the thesis highlighting the summary of the major contributions and significance of the research work, followed by recommendations for future research. The thesis ends with an aggregation of all the bibliography used for the research.

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Literature Review

2.1 Introduction

This chapter presents theoretical background and overview of the review of major concepts relevant to this thesis. First, an historical overview of solar heating is presented to show the trend of development over the years. Thereafter, the current installed capacity and level of adoption of solar thermal technology are provided to highlight the current global market potential and economic prospect of solar heating. The remaining part of the chapter covers literature relevant to various aspect of the thesis in entirety including supporting technologies for solar thermal designs (significantly thermal storage and heat pump) and mathematical modelling methods deployed for design and optimization of related systems. However, since Chapters 4, 5 and 6 are direct reproduction of collection of papers developed by the author during the study, relevant literature on the state-of- the- art that applies to specific case studies for the different stages of the research is also presented in the respective chapters.

2.2 Historical Development

The use of solar for heating has been known as early as recorded history. In 214 BC, Archimedes generated hot water with solar radiation through the use of concave mirrors [1]. It was also reported that the ancient Greek empire used incident radiation from the sun to heat up their homes, water and other edible substances as far back as 4th century BC [2]. These earlier solar heating methods continue up to the 19th century when the use of black metal tanks placed on the roof tops for domestic solar water heating became more prominent [3]. The years that follow witnessed different stages of transformations and improvements in the use of solar energy (especially for heating) [4]; from the inefficient techniques of the early time (when water heating with the sun required long time and then cooled down again as soon as the sun disappears), to the modern solar heating systems which make use of better heat transfer fluids with higher heat absorption rate and improved storage technologies to retain/preserve harvested solar heat over a long period of time. Currently, the various technologies for solar utilization and their supporting components have penetrated the global market with cumulative installed capacity of only solar thermal in operation recorded to be about 480 GWth (686 million square meters) as at the end of 2018 as shown in Figure 2.1 [5], while the total amount of grid-

connected solar energy as at the end of 2017 is said to be approximately 99.1 GW [6] (see also Figure 2.2).

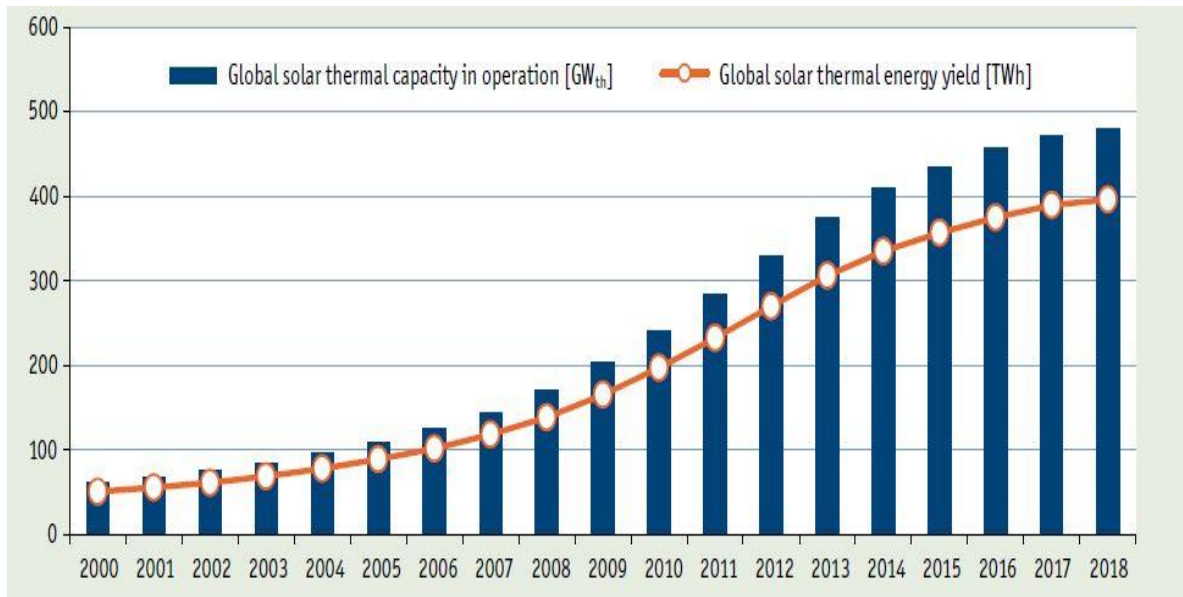


Figure 2.1: Global solar thermal installed capacity in operation and annual yields 2000 – 2018 (Source: IEA SHC, [5])

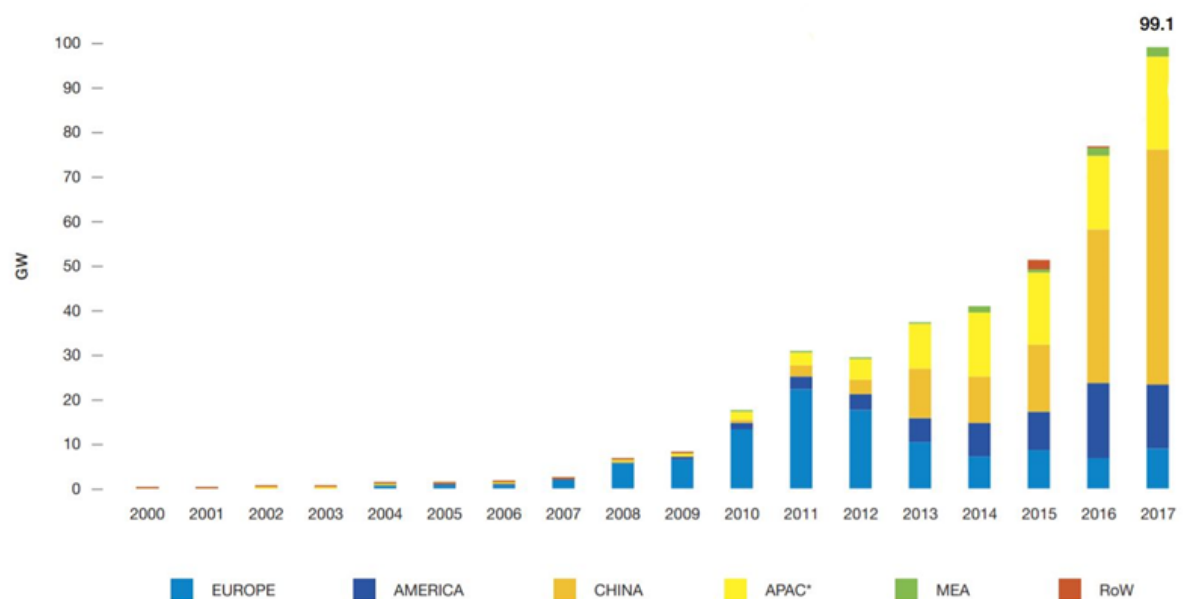


Figure 2.2: Installed capacity of annual grid-connected solar energy 2000 – 2017 (Source: Solar Power Europe, [6]).

- APAC represents the Asia pacific countries and Australia, MEA represents the middle East and African Countries while RoW represents the rest of the World.

Despite the level of developments over the years, the expanding global population and increased demand for energy have necessitated the need for further improvements in available methods for solar utilization. A key technical issue at the crux of most solar designs still lies in uncertainties in energy supply and demand considering the intermittent nature of solar radiation, unpredictability in the harvestable quantity of energy from solar per period of time, variability on the demand side and the implications of these uncertainties during energy planning and decision making process.

Furthermore, as the world's population increases, escalating resource utilization is increasingly becoming an issue of concern, especially with respect to energy use. Having recognized solar as a cutting edge renewable energy source [7], several performance improvement measures and technological combinations have been proposed to enhance the performance and efficiency of solar systems because of its inherent supply gaps. Thus, another critical part of solar energy utilization which requires more research efforts is the aspect of technology hybridization in order to increase the thermal potential of the solar energy system with the aim of matching the exponential population growth resulting in increased energy demand. If these aforementioned limitations of solar thermal utilization are surmounted, the global energy demand (which is estimated to be about 6×10^9 toe/y [8]) can potentially be satisfied through solar energy. Therefore, a study of this nature has become necessary.

2.3 Solar Thermal as Potential Source of Renewable Energy

With about 86,000 TWe solar energy reaching the earth in one year, the sun is considered to be the main source of energy for the earth. Meanwhile, considering the annual global energy consumption which is estimated to be around 15 TWe [9], solar energy remains an inexhaustible source of energy with reference to the total documented global energy need.

Solar energy can be utilized in its various forms such as: solar power/electricity (photovoltaic conversion system and solar concentrators for power generation), solar thermal energy (direct solar radiation collection for water heating, process heat, space and air heating) and solar fuels (direct and indirect solar synthetic fuels). Solar has also been reported to be pivotal in the production of bioenergy (i.e. through photosynthesis), [10]. All the above (with the exception of bioenergy) could be achieved using different types of solar radiation absorbing techniques such solar collectors and solar panels [11] with the basic idea of converting energy from the sun (which are mostly in the form of radiating photons) to different forms of usable energy. As will be shown later in Chapters 4, 5 and 6 (where the main contributions of this thesis are covered), this work is concerned with the use of roof-top solar

thermal collectors for harvesting and converting solar radiation to thermal energy and subsequent transfer of the harvested heat energy via different kinds of heat transfer fluids for domestic and industrial utilizations as presented in [12], [13], [14] and [15]. Solar thermal is naturally available in various region of the world at diverse ambient temperature levels without need for any mechanical work input and the energy resource is self-regenerating. Thus, it is a renewable source of energy that is relatively in abundance with unlimited availability in every parts of the world.

2.4 Solar Collectors

Solar collectors are special type of heat exchanger which absorb solar radiation, convert the absorbed radiation to heat energy and transfer the useful heat to a medium (air, solar fluid or water) within the solar system. Collector technology is critical to solar thermal system designs. Depending on intended purpose of the design, there are several established solar collector technologies readily available in the global market. These range from simple collector designs to more advanced and sophisticated systems which are designed for much higher temperature heat demand. Some of the commonly used solar collector designs are described next.

2.4.1 Flat plate solar collector

Flat plate solar collectors are the oldest type of solar heat collection technology. They are regarded as the traditional means of thermal collection that is commonly in used. This is perhaps due to the simplicity of its structure and possibility of locally sourcing for replacement to defective parts. Essential parts of the collector include a flat plate absorber (usually dark in colour for higher absorbency efficiency and enclosed inside the collector housing), an insulated transparent cover (to prevent heat loss) and heat transfer fluid (mostly a mixture of water and antifreeze) [16]. Collector plates are generally made from aluminium or copper with special heat coating and colour for better heat absorption and retention [17], while absorber tubes are mostly copper or silicon tubes [18]. Though it is worth noting that some special types of flat plate collectors where plastics and polymers are used as replacement or alternative to metal have been developed [19]. Generally, in all available collector designs, the absorber converts the incident solar radiation to thermal energy and transfers the heat (through solar fluid within the absorber tubes) to a secondary working media (usually water in tanks or geysers).

2.4.2 Evacuated tube solar collector

The design of evacuated tube solar collectors rests on the principle that by allowing a vacuum between the collector cover and the absorber in the collector, the amount of conventional heat losses resulting from movements of air inside the collector can be minimized [20]. According to previous studies, this design technique gives the collector a rated efficiency of about 70 % [21] simply because it allows better insulation and the effects of air temperature on heat losses are significantly reduced [22]. Though the cost of evacuated tube collector is still currently high when compared with other simple solar collector designs (such as flat plate).

Evacuated tube collectors are essentially made up of an array of well insulated and firmly locked tubes inside which the metal absorber and heat pipes are centrally fitted. Most designs also contain specific chemical formula (mainly temperature-sensitive medium e.g. methanol) which ensures rapid heating of the metal rod in each tube. Condensation of heated pipe fluid takes place at the other end of the pipe array which serves as the heat exchanger between the heated fluid and secondary working media.

The tubes of an evacuated solar collectors are of two types: (i) glass-to-glass [23] and (ii) glass-to-metals [24, 25]. The former uses two layers of glass designed and bonded together at both ends. It is known for its very reliable vacuum design but features a reduction in the amount of radiation that eventually gets to the absorber. On the other hand, the glass-metal combination permits more ray of light to the absorber and reduces the chances of corrosion since there is no form of condensation at the non-evacuated part of the tube [26].

2.4.3 Solar air collector

Solar air collectors make use of ambient air as heat transfer medium [27]. The air is absorbed and heated directly in the collector. The collector is then subsequently used as a pre-heating or main heating source for ventilation air and space heating in buildings [28]. Their use in other sectors especially for drying agricultural products has also been reported [29] and the technology represent one of the most widely used solar thermal air heating in commercial buildings.

Solar air heater can be either glazed or unglazed. The top metal sheet of a glazed solar air heater is made up of a transparent top with an insulated frame and a back panel around its surroundings that prevents heat loss to its immediate environment. An unglazed solar air heater comprises an absorber plate which allows passage of air while heat is transferred to the air from the absorber along the process.

2.4.4 Parabolic trough solar collector/concentrator

Parabolic trough collectors or concentrators feature solar thermal collection designs that are straight in one dimension and curved like a parabola in the other two directions with polished metal mirror lining. With the help of the mirror coating on the curved reflectors (which is parabola-shaped), radiation from sunlight is concentrated on the tube (usually called Dewar tube) which is filled with oil. Thermal energy is eventually made available by the tube through the heated oil. Parabolic solar collectors are particularly designed to generate more higher temperatures with considerably good thermal collection efficiency [30]. The design topology allows them to capture direct solar radiation over a wide range of surface area and then concentrate the radiation towards small area called the focal point, thereby increasing the amount of radiation (and by extension the amount of energy produced) with over a factor of two. Moreover, in order to further increase the thermal efficiency, a number of available parabolic trough solar collector systems are mounted/installed with solar radiation tracking device which makes it possible for the solar collector to track and follow solar radiation as the earth rotates [31].

2.4.5 Thermodynamic panels

Thermodynamic panels appear to be one of the newest innovations in solar thermal collection systems. It is closely related to an air-sourced heat pump but unlike most solar panels, thermodynamic panels does not use only solar radiation for heating the heat transfer media as they have the ability to gather energy from ambient air, the sun and rain, for space/water heating all through the day (24 hours) [32]. Although it is currently predominantly used for water heating and contribution from the sun in thermodynamic panels hugely outweighs that of ambient air and rainwater. Notwithstanding, the technology can function in extreme weather conditions even with sub-zero temperatures.

The operational mode of a thermodynamic panel is like that of a vapour compression heat pump. Inside the panel are different types of refrigerants which absorb heat in the process of passing through the panel and then turn to gas. Currently available designs are mounted on the rooftop or walls incorporated with hot water cylinder where immersed heating coils are used to transfer heat from the hot refrigerant gas to water. The hot water can then be channelled across the connected units. This technology is currently undergoing the final review for micro generation certification in the United Kingdom and its performance shows ability to generate hot water at a minimum of 55 °C all year round [32].

2.5 Applications and Thermal Analysis of Solar Collectors

2.5.1 Applications of solar collectors

Solar collectors are mostly used for space and water heating systems with water heating being the most common area of its utilization [33]. According to a recent survey by Renewable Energy Policy Network, various designs of solar water heating systems have been installed and are now being used in over 70 million houses across the world [34].

Solar water heating designs can be either active or passive systems [35]. Active solar water heating technology works with different types of electric pumps and circulation controllers to move water around the collectors and the water supply network. Production of hot water in active solar water heating could also be direct and indirect. In the direct circulation type, pressurized portable domestic hot water is produced directly through the collector with the use of pumps. This type of system is applicable in regions where freezing is not a problem and the water circulating through the collector is not acidic or hard. The indirect circulation systems on the other hand use different heat transfer fluids in the collector and then transfer the absorbed solar heat to water through an intermediate heat exchanger.

The other form of solar water heating systems relies on the theory of gravity and the tendency of water to circulate naturally when heated. These are referred to as passive solar water heaters. Since the technology requires no pumping system and other electric components that goes with the active heating systems, the passive solar water heating systems is generally considered to be more affordable (in terms of cost), less complex, easy to maintain and most often more reliable. The two most widely utilized passive solar water heating systems are the thermo-syphon system and what is called the integral or combined collector-storage system.

The use of solar thermal for space heating in buildings is also becoming more relevant in a bid to increase the contribution of renewable energy and to reduce energy-related emissions in buildings. Technologies for solar space heating can either be liquid-based or air-based systems [36]. The liquid-based systems are similar to those found in solar water heating systems and the harvested solar heat is supplied to buildings through the radiator [37]. On the other hand, there are different types of air-based solar space heating systems [38]. However, the main technique of the air-based system involves the use of fans to circulate ambient air through the collector in order to produce hot air.

The general design procedure for various types of solar water and space heating systems are well documented [39-41], including economic evaluation of the most widely used designs [42] and design

considerations for better thermal performance [43]. This thesis considers the use of solar collectors for generating heat for low temperature industrial processes, its combined utilization for domestic water and space heating as well as its integration with heat pump.

2.5.2 Thermal analysis of solar collectors

The most important parameter for consideration in solar collector design is its thermal efficiency. This is considered as a relation between the ratio of thermal energy harvested from solar heated fluid flowing through the collector and the incident radiation or solar flux (i.e. thermal energy) reaching the aperture of the collector [44].

The incident radiation (solar flux) reaching the collector consists of the diffuse and direct solar radiation [45]. When the rays from the sun hit the atmosphere, parts of the beam of light are scattered according to the covering by the cloud. A portion of the scattered light reaches the Earth as though it comes from “all over” the sky. This is referred to as diffuse radiation. On the hand, a portion of the beam of light which appears to come directly from then sun (generally referred to as ‘sunshine’ is called direct solar radiation. It is regarded to be of very high temperatures and its power density on typical clear days is about 1 kW or 1000 watts per square meter. Thus, the ability of solar collector to absorb useful energy from these radiations is a measure of its efficiency. This depends largely on the collector design and properties of the system in which the collector is an integral part.

Section 2.4 presents the commonly used solar collector designs in low/medium temperature level solar heating for both domestic and industrial applications. However, the list is not exhaustive and a more comprehensive listing of available solar thermal collectors/panel designs and the temperature levels in which they are used is provided in Table 2.1. According to the standard of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the thermal performance of collectors in most solar thermal applications is determined by incident radiation, the ambient temperature, as well as the inlet and outlet temperatures of the fluid around the collector [46]. These factors are considered in the modelling and optimization framework presented in this thesis. Being the most utilized types of solar collectors [47], the mathematical model developed in this thesis for the solar collector is applicable to flat plate and evacuated tube collectors. The next section highlights the various supporting technologies deployed with solar thermal systems in order to enhance its efficiency.

Table 2.1: Different types of solar collectors and their temperature range

Collector	Temperature limit (°C)
Uncovered absorber	Up to 40
Air collector	Up to 50
Flat plate	Up to 100
Evacuated tube	Up to 120
Evacuated/vacuum tube CPC	Up to 150
Small parabolic trough	Up to 250
Concentrating dish	Up to 350
Large parabolic trough/large concentrating dish	Above 500

*Table compiled from Solar Server, 2019 [48] and IEA Task 49 IEA | SHC [47]

CPC: compound parabolic collector

2.6 Supporting Technologies for Solar Thermal Systems

It is widely known that energy supply in most solar designs (and indeed all renewable energy systems) are characterized by considerable intermittency [49]. Hence, apart from combining different primary sources of energy with solar, there are several supporting/accompanying technologies (i.e. [11, 50, 51]) deployed in tandem with solar energy systems as a complementary strategy to enhance efficiency and thermal performance of the system. This study considers the incorporation of periodic heat storage technique with solar thermal design as well as the synergy between solar thermal and heat pump technologies for improved performance.

2.6.1 Heat storage

Heat storage remains a fundamental part of solar heating applications (water and space heating) in domestic/commercial and industrial sectors. Storage of heat energy could be described as temporary preservation or holding of hotness of thermal energy for later use. Supply of solar thermal as well as demand for heat vary periodically in cycles [52] (i.e. day and night (24 hour time horizon), weekly time

periods (i.e. 7 days of the week) and based on seasons (winter, autumn, spring and summer)). Hence, heat storage in solar energy network designs is to create opportunity to buffer and normalise the disparity imposed by the fluctuations in solar radiation and demand for energy. Essentially, the technique deployed for storing the heat should also have capacity for the intermittencies for uniformity and consistency, thereby bridging the gaps between supply and demand.

Several heat storage materials, methods and technologies have been examined over the years [53]. A review of technologies featuring the use of advanced storage concepts in solar energy system of IEA Task 32 projects have been presented for general solar thermal utilization [54, 55], and specifically for integration of solar thermal with domestic/residential buildings [56, 57]. A generalised school of thought categorized all available thermal storage technologies as: chemical heat storage systems (sorption and thermochemical) [58], latent heat storage [59] and sensible [60] heat storage technologies.

- **Sensible heat storage systems:** Sensible heat storage systems store energy by raising the temperature of the storage medium (a liquid or solid) with high heat capacity and releasing the stored energy when it is required [61]. There is a change in the temperature of the medium and the temperature change can be “sensed”. In order to determine the amount of stored energy, the temperature change is multiplied by the mass of the medium and the heat capacity. Thus, it is important that the materials used for sensible heat storage should have a relatively high heat capacity, boiling point and melting point. It is also recommended that the storage medium should be thermally insulated to reduce heat losses. A popular example of sensible heat storage system is hot water tank [62, 63].
- **Latent heat storage systems:** Unlike the sensible heat storage system, for the latent heat storage systems, energy storage occurs without a sensible change in temperature of the storage medium. The charging and discharging takes place by changing the phase and state of the storage medium (usually solid to liquid). However, other phase transition such as liquid – gas and solid – solid have also been reported in literature [64]. Latent heat storage is widely referred to as phase change material (PCM) thermal energy storage systems [65], with the advantage over the sensible heat storage arising from the fact that the solid to liquid phase change technique (i.e. the melting and solidification cycle) stores more heat energy per unit volume than the sensible heat storage methods [66]. The techniques are such that when there is an increase in temperature above the melting point of a phase change material, the material melts and receives energy corresponding to the latent heat of the material. The material

subsequently solidifies again when temperature decreases below the melting point of the material and the same latent heat is released. These features give phase change materials the ability to function as heat storage medium in both heating and cooling systems.

Phase change materials for latent heat storage includes organic compounds (mostly paraffins with varied melting temperatures depending on the composition of the materials), inorganic compounds (i.e. salt hydrates mostly referred to as molten salts with calcium chloride hexahydrate and sodium sulphate decahydrate as the commonly utilized examples), and mixed compounds called eutectics (which is a combination of two or more compounds, mostly organic or inorganic compounds) [67]. Common examples of eutectic compounds include myristic acid for inorganic, palmitic acid for the organic and stearic acid for the combination of organic and inorganic compounds [68, 69].

- **Chemical heat storage systems:** Chemical heat storage systems include thermochemical and sorption reactions. Thermochemical heat storage systems store energy through thermo-reversible chemical reactions by breaking chemical bonds. Energy storage occurs through a dissociation reaction and subsequently recovered via chemically reverse reaction. Charging of the storage system occurs through endothermic reactions by subsequent absorption of the enthalpy while energy discharge occurs through the exothermic reactions. The reversible thermochemical reaction can be utilized for heat storage with high energy density. On the other hand, the sorption heat storage systems are built on a chemical process. The sorption process could be absorption or adsorption by nature. Absorption occurs when storage medium is distributed into a liquid or solid and then forms a solution while adsorption occurs through the accumulation of an adsorptive at the exterior of an adsorbent and subsequently shapes an atomic or molecular layer. The adsorptive can either be in gaseous or liquid phase while adsorbent could be in liquid or solid phase.

Highlighted above is a summary of all available thermal storage techniques. For low/medium temperature solar thermal applications such as the one presented in this thesis, sensible heat storage technology using water tank is very common [70]. Nowadays, the use of aquifer storage techniques and underground heat storage methods are also becoming more popular in the application of solar thermal especially for domestic/residential and general application in buildings [71]. A thermally insulated sensible heat storage technique which reflects the periodic changes in the quantity of solar heat supply to the system, as well as variabilities in the quantity of heat pushed to the supply network from storage according to the time horizons is considered in this thesis.

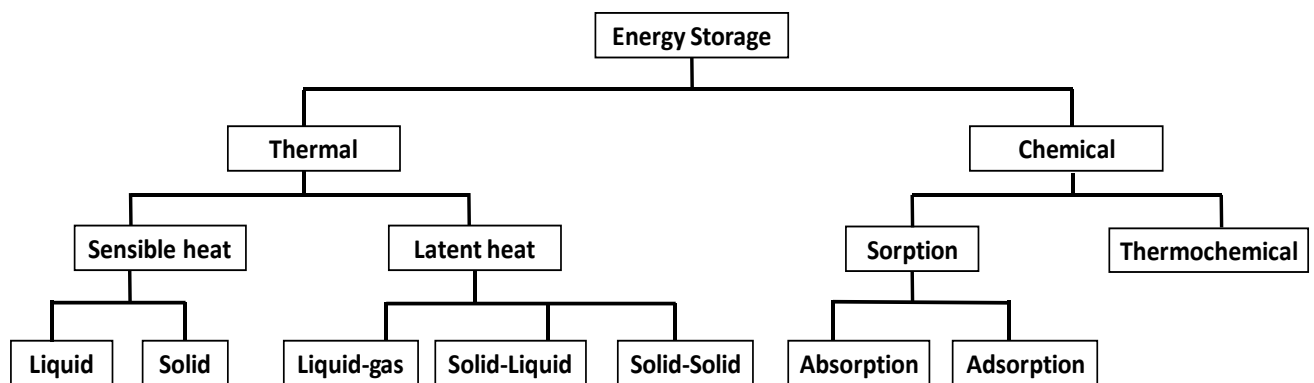


Figure 2.3: Types of heat storage suitable for solar thermal systems

2.6.2 Heat storage temperature

One of the critical aspects of sensible heat storage system is temperature of the storage medium and how to maintain temperature levels in the tank in every time period. This is in addition to other design parameters such as materials of construction, shape and volume of the tank, insulation methods as well as the charging and discharging methods (to and from the tank). In sensible heat storage system, temperature in the tank should be monitored and controlled in order to prevent backward heat flow from storage medium in the tank to the circulating heat transfer fluid, especially for systems in continuous operation [72]. Moreso, the heat storage system should also be in quality conditions to maximize the potential of the stored energy and the amount of heat duty that could be obtained from the tank as the storage system changes from a reference condition to a state of equilibrium with respect to temperature variation between the heat storage fluid in the tank and the circulating heat transfer fluid(s).

In the proposed thermal storage for the integrated solar design, the system is modelled to be in continuous operation such that there is always a momentary temperature level of the fluid in the tank before receiving another temperature lift from hot solar fluid passing through the coil in the tank across different operational time periods. In order to account for the intermittent changes in temperature of the tank, the temperature of fluid in the tank is calculated as temperature of fluid in storage tank in previous time period (which is modelled with circular or equilibrium leads and lags as described in Abikoye et al. [12]) plus the change in temperature of the fluid in storage tank for each time period.

Furthermore, it should be noted that the heat storage system in solar thermal designs are also prone to challenges and danger relating to boiling. This is more likely to occur in active solar heating periods when the quantity of attainable solar heat exceeds both the heat demand and the level that can be accommodated in storage. As indicated in most previous research work, the most widely utilized techniques of collector refilling [73] and water draining [74, 75] for thermal control and overtemperature monitoring in solar thermal storage system have not been very effective [76, 77]. Hence, this thesis considers the development and implementation of a constraint (called the big M constraint) on the temperature in the storage tank. As will be shown later in the thesis, this constraint is to ensure that heating of the fluid in heat storage tank occurs only when temperature in storage tank is lower than outlet temperature of the heat transfer fluid returning to solar collector. The constraint is however relaxed on the tank when there is no heat transfer (no flow) to the tank from hot solar fluid. A detailed information and mode of operation of the big M constraint introduced in the design and optimization is described in Abikoye et al. [12] and also presented in Chapter 4 of this thesis.

2.6.3 Heat Pump

One of the supporting technologies used to enhance the performance of solar thermal systems is the heat pump [78]. Heat pump is an energy efficient technology that is used to upgrade a relatively low-temperature heat source and eventually deliver more heat energy to the system than the total work input [79].

There are different types of heat pump and several methods have been used by many authors to categorise the various types of heat pumps. These include the categorization based on the source of heat to the heat pump or classification according to the combination of heat source and delivery media. The former classified heat pump as ground source heat pump system, water source heat pump system and air source (ambient air/ exhaust air) heat pump system [80, 81]. Other extended categorization according to the orientation of heat/energy source also exist in literature. These include hybrid heat pump system (combination of two or more heat sources e.g. combination of ground and air source heat pump systems), solar heat pump system (photovoltaic, solar thermal or photovoltaic-thermal) and absorption or gas fired heat pump system [82].

2.6.3.1 Hybrid heat pump system

A hybrid heat pump system is basically a combination of heat pump alongside with other energy source (e.g. gas or boiler), using their combination to provide a more constant and reliable source of warmth or heat at a higher level of efficiency as a dual fuel system. Its advantage rests on the fact that radiators in existing source of heat generation such as the traditional gas, liquified petroleum gas (LPG) or oil heating needs not to be changed while combining it with hybrid heat pump system. An alternative type of hybrid configuration is to also have a mixed-technology of both air source- and ground source- heat pump systems operating at different times in the day (or performing all through the year) at separate highly rated efficiencies. The technique is such that when the temperature of outside air is warmer and ideal for it operation, it draws on the energy from the air and when the air is colder, it operates in the reverse order, providing constant source of warmth to the building [83].

2.6.3.2 Absorption heat pump system

Absorption heat pumps are heat pump systems driven by a source of thermal energy such as steam, natural gas, propane, solar-heated water, air or geothermal-heated water. Some literature referred to absorption heat pump systems as gas fired heat pumps [84], because natural gas is the most common heat source being utilized. Different configurations of absorption heat pumps exist [85, 86]. However, depending on the preferred configuration, the heat pump system may require larger units than the conventional set up in order to accommodate the added units such generators and absorbers [87], and / refrigerators in the case of a reverse operational mode [88, 89].

Due to the distinct attributes of solar energy resource among all naturally available and environmentally friendly energy resources (i.e. as a clean and sustainable energy source), the utilization of various forms of solar in combined mode with other established technologies for providing clean and affordable domestic/industrial heating and cooling is currently receiving increased research attention. Unlike the most utilized conventional absorption heat pumps, the current trend utilize thermal energy from a low temperature heat source in combination with reasonable amount of energy in the form of electricity to convert heat from the low temperature source to higher temperature level of various capacities [90].

2.6.3.3 Solar energy and heat pump system

A combined solar energy-heat pump system could be described as a machine that represents the incorporation of a heat pump and energy output from solar panels in a single integrated system. In the combined system, solar energy (in this case solar thermal) performs the function of a low temperature heat source and the available heat is linked to the heat pump through an evaporator [91]. It can also be in form of direct conversion of solar radiation to electricity through photoelectric effects (solar photovoltaic) to directly power the heat pump, while it can also involve a combination of both solar thermal and the photovoltaic (Solar photovoltaic/thermal) systems [90].

Apart from the above classifications and categorization, heat pumps can also be described based on the combination of heat source and delivery media. Using this naming nomenclature, the heat source is usually first mentioned followed by the energy/heat delivery technique without emphasis on the system in which it operates. The following are the major categories available in the market and in the literature:

- (1) Air-to-Water heat pump system
- (2) Air-to-Air heat pump system
- (3) Water-to-Water heat pump System
- (4) Water-to-Air heat pump system

Regardless of the orientation used to describe the heat pump system, the basic idea remains the same, i.e. to upgrade and move heat from a colder source (low temperature source) to a hotter level (heat sink). In this sense, solar thermal at shady or lean periods (i.e. periods with low solar irradiation and ambient temperature) is considered to be a relatively low temperature heat source while a circulating cooling water is considered as the working fluid on the heat recovery side of the heat pump unit. Incidentally if appropriate refrigerant (i.e. relative to the source temperature) is used within the heat pump circuit, the temperature of the solar capture fluids within the lean/shady solar periods should be good enough to overcome the start-up problem usually experienced in most heat pump applications thereby enhancing the performance of heat pumping cycle. Therefore, the combined technology of solar thermal and heat pump systems is a win-win synergy which has the potential to increase the thermal performance of the integrated system. An integrated system showcasing such technology amalgamation is addressed in Chapter 6 of this thesis.

The components and techniques in basic heat pump cycle (i.e. evaporator, compressor, condenser and expansion valve with the refrigerant circulating through the components in closed circuit) is like refrigeration cycle. The only exception is the fact that heat (which is the product of the cycle) is added

to the system (or reservoir) as against the removal of heat from the system (or cold reservoir) as in the case of the refrigeration cycle.

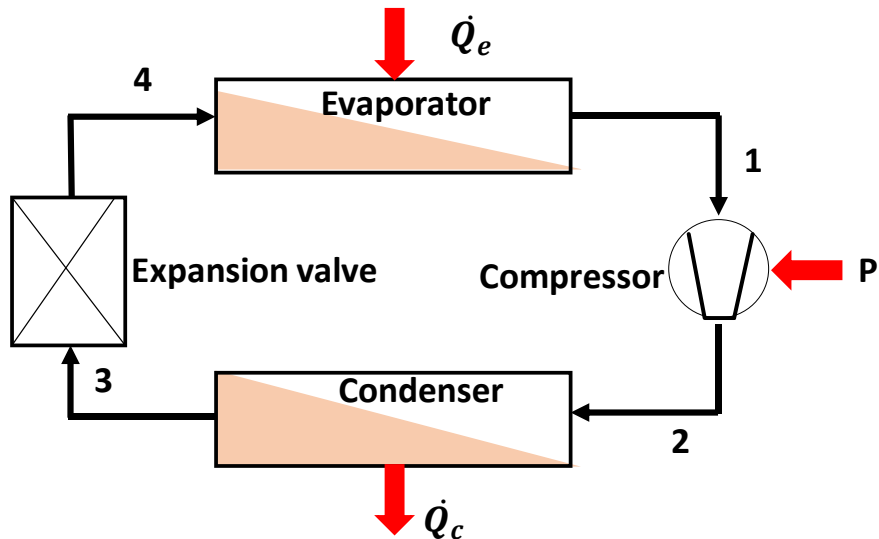


Figure 2.4: Stages and components for basic vapour compression heat pump cycle

- Evaporator:** The heat needed to vaporise the refrigerant (\dot{Q}_e) is added to evaporator as shown in Figure 2.4. The heat could be sourced from any of the aforementioned, but this thesis considers the heat from solar capture fluid. The refrigerant leaves the evaporator as superheated vapour at low pressure to ensure that no liquid (which could cause damage to the compressor) leaves the evaporator.
- Compressor:** The compressor receives the hot refrigerant gas and compresses it. The compression raises the pressure of the gas leading to further increase in its temperature. The refrigerant is thus released at high temperature and high pressure to the condenser. To achieve this, power (P) is applied to the compressor and this is also referred to as the work done (W) by the compressor. Hence, it is the point in the integrated system where energy is converted from one form to the other. The compressor also ensures that there is constant flow of refrigerant across the heat pump circuit. Therefore, one of the utmost targets in heat pump designs is to get the required or needed heating capacity with the barest minimum power on the compressor.
- Condenser:** Condenser is the heat recovery part of the heat pump circuit. It receives hot refrigerant gas at a very high temperature and pressure. While flowing through the condenser,

the hot refrigerant gas rejects some of the heat (\dot{Q}_c) via condensation. The refrigerant gas is expected to be cooled below its unique bubble point temperature in the condenser such that none of the stream leaves the condenser as vapour. The design of the heat recovery part should also aim at extracting more heat from the refrigerant gas to reduce the temperature of the stream (liquid refrigerant at high pressure) flowing through the expansion valve.

- **Expansion valve:** The stream sent to expansion valve by the condenser is expected to be in liquid phase but still with high pressure, after heat rejection through condensation. The pressure is dropped to evaporation pressure as the refrigerant flows through the expansion valve. The expansion device can be operated electronically, thermostatically or even manually. Considering the pressure drop in the expansion valve, the mass flow of refrigerant flowing to the evaporator is determined by the flow area across the expansion valve. Thus, for the manually operated device, the pressure on the gauge and temperature of the stream must be read by someone who will then change the settings on the valve by twisting (depending on the valve design) the handle.

The above are the basic components found in heat pump circuits. However, when a high temperature lift is desired for the heat pump cycle, a multi- stage compression cycle is essentially required. This is due to the wide difference between evaporator and condensing temperatures. Thus, more than one compressor are usually needed to fulfil the thermodynamic and technical requirements of such heat pumping task. Moreover, when the temperature lift is eventually achieved, another challenge is how to extract more useful heat from the condenser side of the integration. While examples of heat pump systems incorporating the series connection of condenser and desuperheater/sub-cooler for higher heat extraction exist in literature [92, 93], such application cannot be found for the combined design of heat pump and solar thermal technologies. The above stated issues are also addressed in this thesis by proposing a comprehensive and generic modelling approach for combining solar thermal and heat pump technologies considering simultaneous optimization of the integrated design features under the multiperiod changes in meteorological conditions. A two-stage vapour compression heat pump cycle with successive condensation and subcooling is considered on the heat pump side of the integration. The two-stage vapour compression is implemented for strategic higher temperature lifting of low grade solar heat while the incorporation of sub-cooler in series with the condenser is conceptualised for improved heat recovery from hot refrigerant gas of the heat pump cycle. Further details on the integrated system are provided in Chapter 6 of the thesis.

Other important point to consider in heat pump designs is the type of refrigerant to be used in the circuit and performance rating of the system.

- **Refrigerants:** Refrigerants are the working medium used in most heat pump systems. The refrigerants undergo transitions (phase change) from liquid to gas (superheated vapour) and then back to liquid again in each cycle.

There are different types of refrigerants suitable for different applications. The choice of refrigerant could be based on the thermodynamic requirements of the systems e.g. stability and suitability at high temperature (especially in high temperature lift), suitable working pressure (for evaporation and condensation), heat retention and thermal conductivity [94]. Other factors include economic considerations (costs) as well as environmental and safety criteria such as global warming potential (GWP), ozone depletion potential (ODP), non-toxicity, non-corrosivity and non-flammability [95].

For utility system linked with solar energy resource however, the uncertainties in meteorological and ambient conditions also comes to mind especially as the condition approaches the extreme (either minimum or maximum). In this regard, comprehensive information on the behaviour of various working fluids under varying conditions is essentially required. Detailed analysis and description of various refrigerants used in absorption and vapour compression heat pump systems have been presented by Zhang et al. [96]. This study considers the use of R-245CA as the refrigerant in the heat pump circuit. The decision criteria and other detail information regarding the operational mode of the heat pump are provided in Chapter 6 of the thesis.

- **Performance indicator:** The performance indicators in heat pump systems are heating capacity, heat upgrade/conversion efficiency, heat collection/recovery efficiency and the heat pump's performance. A common heat pump performance measure which include all the aforementioned performance indicators is termed coefficient of performance (COP). This is defined as the ratio of useful heat output of the heat pump cycle to the work input (electrical energy input) i.e. $\frac{\dot{Q}_c}{W}$, where W is the work done by the compressor which is equal to the electrical power input. For a multi-stage and multiple heat recovery units as in the case considered in this thesis, the ratio of net heat recovered from the system and the net work done by the compressors is used to evaluate the performance of the system. This is further discussed and presented in Chapter 6.

2.6.4 Heat Transfer Fluids for solar Thermal Systems

Heat transfer medium takes part in transforming natural solar radiation to heat energy. Technically, it serves as an intermediate medium for cooling one part of the system and transferring the heat energy to another part of the system. It also serves as a means of transporting heat to storage tank and storing the thermal energy till a later time. The most widely used heat transfer medium are basically fluids in the form of liquid and gas such as air, water/steam, molten salt and heat transfer oil [97]. Other heat transfer materials in solid phase (e.g. ceramic particles and heating stones) have also been reported in literature [98, 99].

For solar thermal heating systems specifically, heat transfer fluids transport heat from solar collectors through heat exchangers to storage tanks or directly to the heat sinks. Bearing in mind that some heat transfer fluids are exposed to freezing in cold climates and high temperatures (boiling) in the active solar heating periods or in desert climate, some essential criteria normally considered to select heat transfer fluid in solar systems include properties such as the material's coefficient of expansion, thermal conductivity/capacity, boiling point, freezing point, viscosity and flash point [100]. Commonly used heat transfer fluids for solar heating systems include water, water/ glycol mixture (ethylene and propylene glycol), air, hydrocarbon oils (e.g. paraffin hydrocarbons, aromatic oils, aromatic refined mineral oils and synthetic hydrocarbons), phase change materials and nano fluids (refrigerants). Different heat transfer fluids (i.e. water, mixture of water and ethylene glycol (50/50) and R-245CA refrigerant) are used in this thesis to achieve the various objectives pursued. Detail information on selected heat transfer fluids including where and how they are applied at different stages of the study is provided in Chapters 4, 5 and 6 of the thesis.

2.7 Heat Integration

Heat integration is a family of systematic methodologies for analysing, designing and optimizing the energy features of a system for optimum energy utilization [101]. Energy systems incorporate a large number of equipment such as boilers, furnaces, compressors and heat transfer equipment (mostly referred to as heat exchangers) involving several heating and cooling duties in single line of operations. Depending on nature and scale of the system, the complexity and associated costs resulting from interactions/connections among these series of equipment could be very high [102]. This is also the case for the total amount of energy consumed within the system. Hence, energy reduction as well as energy efficiency/ energy recovery measures are essentially employed to minimise cost and total energy required in the system. As it is known that heat exchangers are mostly used for the heating

and cooling utilities (such as hot oil, fuel, steam as well as cooling water), several sets of heat exchangers are usually connected to form a heat exchanger network (HEN). Therefore, energy audit and thermal performance improvement measures in process systems are conventionally referred to as heat exchanger network synthesis HENS [103]. Essentially, the procedure entails the appropriate placement or adjustment of heat exchangers for hot and cold streams within the process system in order to recover more energy from the process streams and to reduce energy consumption [104].

Traditionally, heat integration uses the concepts of composite curves, problem table algorithm/ grid diagram of process streams and the principle of pinch point to reduce energy use within the process, Linnhoff and Flower [105]. This is initially achieved using a sequential approach, whereby the best stream conditions (flow rate, pressure, temperature, density etc.) of a process are firstly identified while the heat integration is thereafter performed in the second stage. A further improvement in heat integration methodologies is the simultaneous approach developed by Duran and Grossmann [106]. Unlike the sequential approach, heat integration is performed concurrently with optimization of the process flowsheet in their [106] proposed method. Over the years, several heat integration modules have been developed in process integration such that the various techniques can be implemented directly and simultaneously in rigorous optimization models during process simulation. Figure 2.5 presents a summary of the various systematic methodological approach and procedure used for heat integration, especially those performed through heat exchanger network synthesis. The recent years have witnessed the application of all these heat integration techniques in renewable energy systems, especially in solar thermal and heat storage modelling and designs (Atkins et al. [107] and Baniassadi et al. [108]), as well as in heat pump designs extending to combined heat and power systems [109]

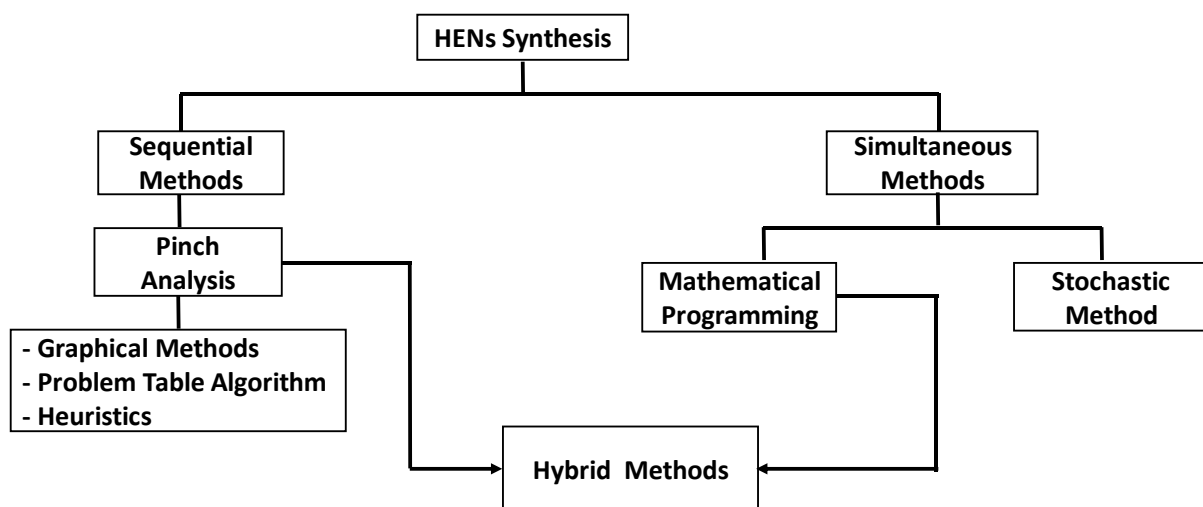


Figure 2.5: Summary of systematic methodologies for heat exchanger network synthesis (Extracted from Yoro et al. [110])

2.8 Solar Thermal Systems Modelling and Design

Uncertainties and inconsistency (referred to in this thesis as variability) are some of the major inherent challenges associated with solar energy systems. Therefore, appropriate planning tools that can increase stability and efficiency of the system are imperative. Besides that, proper sizing/dimensioning of components and supporting technologies are some of the complex tasks during planning of solar system design. This involves both the predictable aspects of the design (i.e. solar collector features and characteristics of other accompanying components and technologies), and unpredictable parts of the system (basically the meteorological dispositions and general information on prevailing weather condition for specific location). Since the latter (the unpredictable parts) is beyond immediate control of the modeller, modelling approaches which allow dynamic representation and transient behaviour of the system offer a great advantage for comprehensive analysis of solar thermal designs [111].

Different computer programs have been developed to model the dynamics and performance of solar energy systems. These include: Transient Simulation System (TRNSYS) [112] which was developed by Solar Energy Laboratory of the University of Wisconsin, WATSUN Design and Simulation Program [113] developed by the University of Waterloo in Canada, Artificial Neural Networks for solar system designs and other renewable energy applications put forward by Kalogirou [114], Polysun Simulation Program [115] developed by Vela Solaris AG in Winterthur, Switzerland and the F-Chart program and methodology for solar systems developed by Beckman et al. [116].

Due to computational complexities, the need to analyse more design data points in order to identify better system configurations, as well as the need to perform the optimization of the system which are somehow beyond the capacity of the aforementioned modelling approaches, has led to the development of other techniques to estimate the periodic (daily, monthly and annual) performance of solar systems [117-120]. Most of these methods are based on correlation of regression results obtained from the transient and dynamic analysis of the system. Klein et al. [117] presented a method where thermal performance of closed loop solar collector system and sensible heat storage is investigated using computer simulations. Based on the techniques of φf chart method, Suehrcke et al. [118] advanced a technique that uses the bimodal features of intermittent solar radiation to model the “on and off” operational mode of a solar system in correspondence with the actual “clear and cloudy” behaviour of time intervals, while the study of Gordon et al. [120] showcased a method that combined the design, analysis and optimization of solar thermal system in estimating the annual performance of the system.

More recently, the techniques that combine various process integration concepts with mathematical programming approach have shown more competence with respect to finding the perfect design that optimizes several desired objectives simultaneously. In such techniques, the design and optimization problems are initially classified/categorized as discrete and continuous based on whether or not discrete or integer decision variables are involved [121]. Thereafter, subclasses of the problems are identified according to the nature of the system and mathematical relations/functions involved [122]: e.g. linear programming, integer programming, non-linear programming, mixed integer linear programming, mixed integer non-linear programming, and generalized disjunctive programming. Ashouri et al. [123], Omu et al. [124], Wallerand et al. [125] and Steen et al. [126] presented diverse Mixed Integer Linear Programming (MILP) approaches for distributed energy models. Bühler et al. [127] and Fokaides et al. [128] presented different formulations of Non Linear Programming (NLP) approaches for solar thermal system design using particle swarm optimization and simplex algorithm respectively, While Pruitt et al. [129] and Isafiade et al. [130] developed Mixed Integer Nonlinear Programming (MINLP) techniques for optimal design and integration of solar thermal with heat exchange networks. Other studies on solar thermal system design and optimization using the mathematical programming approach include those of Alipour et al. [131], Bürger et al. [132], Farkas et al. [133], Mian et al. [134] for industrial applications of solar thermal, and Mertz et al. [135], Kohlhepp et al. [136] for the applications of solar thermal in residential/domestic buildings.

Despite the numerous contributions by various authors on sectoral integration of solar thermal, its impact in global share of energy is still yet to be visible [8]. This is an indication that further improvements are still needed on the established methods for the design, operation and optimization of solar thermal utilization with the goal of increasing the quantity of attainable solar heat that could be realized in practical applications. Such methodology improvements would be needed on both the demand and supply sides of the integration considering the discontinuous nature of solar thermal supply and the multi-period variability in attainable quantity of harvestable solar heat per period, multi-period variability in the profile of heat demand, as well as the implications of these uncertainties on residential and industrial heat supply networks.

The maximum obtainable heat in any solar thermal technology depends not only on the type of collector and its efficiency but also on momentary changes in the ambient conditions, particularly irradiation and ambient temperature. Thus, these important attributes, in addition to the influences of thermal storage on the heat network (which is also largely subject to periodic changes) should be considered in solar integration framework. This is essential in order to estimate the attainable solar heat and expected thermal performance of the entire heat network at the design level. Whereas most

previous studies in this line of research have focused largely on ways to circumvent or manage the discontinuous nature of the heat supply in solar thermal utilization, the periodic variabilities on both demand and supply sides of integration, along with its implications for the actual heat network, and optimization of the entire system, are often neglected in most previous studies.

Furthermore, after all the above underlying factors have been comprehensively considered in the integration framework, it is also crucial that the clustering techniques used in the model to represent the time intervals/periods should be realistic enough in comparison with the actual hourly, daily, monthly and seasonal time periods in reality. Unlike what is commonly found in most previous domestic solar thermal utilization methods, all the aforementioned features (which are considered to be essential for a robust solar thermal design), are rigorously accounted for in the design and optimization frameworks presented in this thesis.

2.9 Heat Pump Systems Modelling and Design

As earlier stated, the heat pump system is an energy efficient technology that is used to upgrade and transport heat from a relatively low temperature heat source and eventually deliver more heat to the heat sink than the total work input, thereby increasing efficiency of the energy system [79]. Modelling and simulation of vapour compression heat pump technologies (including refrigeration and air conditioning cycles) has been extensively researched in the past few decades. Accordingly, different techniques and methods have been proposed by several authors in line with the objective and nature of their studies. The following categorization seems to cover most of the available modelling methods:

- Simple/modest steady state models
- Steady state models with individual description and characterization of each components
- Steady state design models
- Simple/modest models with transient behaviour of the system
- Transient behaviour models with individual description and characterization of each components
- Comprehensive transient behaviour models

Yong et al. [137], Chua et al. [81] and Conde [138] present detailed and comprehensive reviews of the existing methods. Their reviews cover the above listed categorization and techniques as applied by various authors to achieve the objectives of their studies.

Due to the level of development in computer programs and advancement in mathematical models, integration of heat pumps with other heat networks operating at a relatively low temperature level is

currently considered to be less complex with matured technologies readily available across the world. However, the desire for higher thermal output have led to several capacity enhancements in heat pump designs which still require more research efforts [139], especially when higher temperature lift is desired [140]. To this end, different performance improvement measures for heat pump systems have been sought by various authors over the years. Shelton and Grossmann proposed different formulations of mixed integer linear programming (MILP) heat pump superstructure that minimizes costs [141] and another one that allows flexibility in systems with multiple temperature grids [142]. Kamalinejad et al. [143] presented a mixed integer non-linear programming (MINLP) approach for optimal synthesis of vapour compression systems considering economic trade-off, partition temperature and compression configuration.

Research interests in these earlier studies were oriented towards finding a robust but simplest possible heat network representation that reduces the complexities in the design of heat pump and general refrigeration systems, with steady state assumptions where the state of refrigerants and other thermodynamic features in the heat pump cycle (e.g. evaporation temperature and/ temperatures at the heat source and heat sink) are specified. Despite the level of advancement attained with the use of several equations derived from the steady state operation of the system, the series of assumptions and resulting simplifications make the characteristics of the system to deviate from what is obtainable in reality. Hence, development of a model that accounts for the dynamic and transient behaviour of the heat pump cycle from one component to the other is highly required. This is in addition to the optimization of the integrated system according to the different input temperature levels.

Though it is worth noting that modelling of the individual components of the heat pump have advanced to a reasonable level of sophistication. However, a design approach for combined solar thermal – heat pump systems incorporating multiple components in the heat pump circuit (i.e. multiple evaporators, multi-stage compressors, multiple condensers and desuperheaters/sub-coolers) together with simultaneous optimization of the integrated system is still an area that is yet to be extensively studied. This aspect is considered in this thesis in that the proposed heat pump cycle design involves a multi-stage vapour compression incorporated with successive condensation and sub-cooling of the vaporised refrigerant. Furthermore, the most widely used low grade heat sources for heat pump systems include waste heat from sewage water and industrial effluents (mostly referred to as wastewater) [144-147], ground water [147], sea water [148, 149], air (ambient air and exhaust air) [150, 151] and portable water [152, 153]. Rarely explored as potential heat source in vapour compression heat pump circuits is low grade heat from solar capture fluids. With the realization that the unique individual attributes of both solar thermal and heat pump systems provide a platform for

using the combined technology to circumvent the low energy output limitation of most solar thermal designs and to overcome the start-up problem in heat pump applications, the combination of solar thermal and heat pump technologies is currently attracting the attention of many authors. The analysis of possible configurations for the combined technology has been undertaken and presented in [154], the likes of which are comprehensively studied in order to develop and implement the combined solar thermal and heat pump design proposed in this thesis. Thus, the next section presents the summary of an outlook on combined solar thermal and heat pump designs and the contribution of this thesis towards that direction.

2.10 Integrated Solar Thermal and Heat Pump System Design

An integrated solar thermal and heat pump design is a synergy of energy efficiency technology (heat pump) and renewable energy system (solar thermal) where the design implementation of the two technologies and its analysis is treated as a single integrated system. Naturally, these technologies are mostly developed and used separately in their individual capacity to produce heat for space and water heating at different temperature levels. However, for the combined system, heat energy from solar collector/solar capture fluid functions as the low grade (low temperature) heat source for the evaporator unit of the heat pump cycle to initiate the heat upgrading cycle. The goal of such integrated system is to use a low temperature heat source to produce thermal energy at higher temperature levels than it is naturally available.

Several system configurations and design methods have been proposed by many authors to achieve respective design objectives [155]. The various categorization covering all available technologies combining solar thermal and heat pump systems in a single design outfit are provided in Chapter 6 of this thesis. Though the technological combination can be deployed for various purposes such as air conditioning, desalination, drying, water and space heating [156-159], Omojaro et al. [160] presented a review of recent research and applications of solar assisted heat pump systems where it was shown that the available designs are mostly focused on all kinds of heating operations. Regardless of the intended purpose of design, the techniques for improving the combined design of solar thermal and heat pump systems have advanced over the years with different performance improvement measures. Kuang et al. [161] examined the performance of multi-functional direct expansion solar/heat pump systems, and Yang et al. [162] analysed the characteristic features of indirect expansion solar-multifunctional heat pump design. As with several other studies in this research domain, an important aspect which is often neglected is simultaneous optimization of the design

features under multiperiod variability in meteorological and ambient conditions in order to ensure efficiency (stability) and optimal heat output from the system. This is a major challenge in the established methods for analysing the combined design of solar thermal and heat pump systems.

Thermal efficiency and general performance of heat pump systems depend largely on momentary operating conditions of the system. With this in mind, it should be noted that the operating conditions in the combined solar and heat pump systems vary significantly with the transient dispositions of ambient and meteorological conditions. Therefore, the performance of the heat pump cycle at designated thermodynamic state is not sufficient as the criterion for analysing whether or not the heat design is properly formulated since the properties and features of the integrated system is subject to changes over different time horizons. This thesis provides additional contributions to existing knowledge on heat pump system design methods given that a multi-period non-steady state ambient and meteorological conditions (hourly changes in solar irradiation and ambient temperatures) are considered on the heat source side of the integration while the design framework allows the simultaneous optimization of all essential design features according to discrete time intervals.

2.11 Optimization of Solar and Heat Pump System

Design of energy systems such as the combined operational mode of solar thermal and heat pump is a difficult task because it involves the complexities of accurately/reasonably predicting the thermal output of the system regardless of the uncertainties in the profile of the design and operating parameters. Application of a robust system analysis tool can be used to obtain such result.

Several system analysis techniques have been proposed to assist/guide in developing robust energy system planning, operation and control strategies. Among the available techniques, optimization methods have demonstrated some level of superiority due to their ability to provide a desired choice of alternatives while making decisions under several varying conditions [163]. Within the context of process design of physical systems, optimization problem has to do with the tasks of finding the best method or path (among several feasible alternatives) to achieving a desired result. Complimentarily, several approaches to perform the optimization of energy systems have also been developed [164, 165]. The pattern of the optimization methods is dependent upon the energy source(s), purpose/objective of the design, already known characteristics of the system (i.e. parameters and variables), types of constraints and intended environment in which the system is to operate.

Due to advancement in computing programs and level of development in mathematical models, optimization approaches oriented along mathematical programming techniques have shown more capability with respect to finding the ideal design that optimizes several desired objectives simultaneously [166]. The design and optimization methods applied in this study are based on the mathematical programming approach. Thus, the remaining part of this chapter describes the general understanding on the concept of mathematical programming within the context of energy systems design with concluding remarks which highlight the main contribution of this thesis.

2.11.1 Mathematical programming

Mathematical models are made up of sets of discrete and continuous variables representing the objective functions and constraints which may take the form of linear and/ non-linear relationship. An objective function is a quantitative measure which evaluates the performance of the system being modelled. Therefore, the goal in most optimization problems is to either minimize or maximize this quantitative measure subject to a number of constraints. In optimization problems, constraints are the functions that define and describe the boundaries by which both the parameters and variables of a system can function within the model (i.e. allowable values of parameters and variables).

Optimize: $f(x_1, x_2, \dots, x_n)$

$$\text{Subject to } g_j(x_1, x_2, \dots, x_n) \begin{cases} \leq \\ = \\ \geq \end{cases} b_j ; j = 1, 2, \dots, m \quad (2.1)$$

The general mathematical formulation for optimization problems is described in Eq. (2.1) where x_1, x_2, \dots, x_n represent the set of decision variables. $f(x_1, x_2, \dots, x_n)$ is the objective function of the optimization problem which is expressed in terms of the decision variables. $g_j(x_1, x_2, \dots, x_n)$ are the set of constraints which describe the performance of the system. As shown in Eq. (2.1), the constraints can take the form of inequality (\geq or \leq) or equality ($=$) relationships. Depending on the nature and focus of the optimization task, the term 'optimize' as used in the equation can either be to minimize or maximize the objective function.

There are basically two major steps in approaching problems of this nature[167]:

1. Development of a superstructure which embeds all (or as many as possible) candidate structures for a feasible and optimal/near optimal design of the system to be analysed.

2. Modelling of the superstructure as an optimization problem using mathematical programming models, after which relevant solver(s) can then be engaged to optimize the superstructure in order to find the best (optimal) solution that satisfies the objective function of the problem subject to certain constraints.

There are different forms of mathematical programming models. The general classification of systems to be modelled based on the nature of the system and mathematical functions involved has been discussed in Section 2.8 of this Chapter. For emphasis, they are described to be in either of the following order: linear programming, integer programming, non-linear programming, mixed integer linear programming, mixed integer non-linear programming, and generalized disjunctive programming.

For the integrated system designs presented in this thesis, the basic equations that describes the relationships between parameters and variables across various parts of the system are better represented in the form of a mixed integer non-linear programming (MINLP) formulations. This stems from the fact that both flowrate and temperature of streams across the various units in the systems are periodically changing. Therefore, the mathematical programming representation of the proposed designs is a mixed integer non-linear programming (MINLP) design and optimization problem.

2.11.2 Mixed integer non-linear programming

An optimization problem essentially entails modelling of discrete and continuous variables of the system. This mostly results to mixed integer linear and non-linear programming (MILP/MINLP) problems [168]. When the objective function and / the constraints of an optimization model are non-linear, it is referred to as MINLP problem. The general form of MINLP problem is described in Eq. (2.2)

$$\begin{aligned}
 & \text{Minimize } f(x, y) \\
 & \text{Subject to: } C_i f(x, y) = 0 \quad \forall i \in E \\
 & \qquad \qquad C_i f(x, y) \leq 0 \quad \forall i \in I \\
 & \qquad \qquad x \quad \quad \in \quad X \\
 & \qquad \qquad y \quad \quad \in \quad Y \text{ integer}
 \end{aligned} \tag{2.2}$$

In Eq. (2.2), $f(x, y)$ and $C_i f(x, y)$ are all non-linear equations, E signifies the index for set representing equality constraints and I for the sets of inequality constraints. The equality constraints are used to satisfy the material and energy balance equations together with other essential design equations, while features such as process specifications are included in the inequality constraints.

MINLP design and optimization model formulations have found use in many engineering applications such as flow sheet problems in chemical and industrial processes, selection of design portfolios for batch and continuous processes, optimal design of heat and general transmission networks, as well as a host of other related chemical process design tasks. According to Grossman et al. [169], the MINLP formulations of optimization problems are generally considered to be more robust when compared with other optimization methods. This is because a wide variety of options for design representation are possible, thereby yielding more superior solutions for the design problem. However, it is also widely known that MINLP problems are generally difficult to solve because it combines the difficulties of solving non-linear functions in equations with the combinatorial complexities of performing the optimization task over discrete variable sets.

Several techniques have been developed by many authors to circumvent the difficulties encountered in MINLP design and optimization problem formulations. Atwa et al. [170] presented a method for optimal allocation of various types of renewable energy resources in energy generation and distribution networks. Their method is based on probabilistic generation-load model where all likely operating conditions of the potential renewable energy sources as well as their distribution units are combined. Herrera-León et al. [171] presented a MINLP design formulation for water desalination design where solar is considered as the source of energy. A multi-period MINLP optimization model for including direct solar utilization and storage option in combined heat and power systems is presented by Abdelhady et al. [172].

Short, in his study [173] argued that global optimisation techniques are needed in order to effectively solve optimization problems that are formulated as MINLPs. The author summarized the available options to achieve global optimization as stochastic methods [174] (e.g. genetic algorithm, simulated annealing) and the various deterministic methods [175]. Unlike the stochastic optimization which involve random objective functions and constraints [176], the deterministic methods use mathematical structures which are unique and inherent to specific problems as an advantage over the stochastic approaches [177]. This is because with such mathematical structures, a finite convergence with reasonable level of accuracy are always guaranteed, though with its own endemic problem as well [178]. However, in order to speed up and enhance the rate of convergence to solutions in deterministic approaches, the MINLPs are mostly formulated in a manner that specific solver

(algorithm) of choice can easily and satisfactorily handle the mathematical structure of the problem. This provides a recourse to a great extent.

2.11.3 Solution algorithms for MINLP problems

Different solution algorithms have been developed for solving MINLP formulations of design and optimization problems. According to Grossman [179], the major classification of these algorithms include branch and bound [180, 181], generalized bender's decomposition [182] and outer approximation [183] techniques.

- i. Branch and bound method – The branch and bound technique is a direct extension of the mixed integer linear programming solution approach to optimization problem. In this method, a search tree also referred to as binary tree is established to represent the binary variables of 0 and 1 combinations. The observed feasible region is partitioned and divided into nodes while a subset of 0-1 variables are successively solved at each respective node. The method thoroughly searches each branch of the tree for binary variables and the complexity of the problem rests on the size of the binary tree which depends on the number of binary (0-1) variables. However, the technique of saving the upper and lower bounds of the valid solutions eliminates the branches of the tree (solution space) where optimal solution does not lie, thereby improving the robustness of the method [184]. The branch and bound approach is widely described to be MINLP solver with the attribute of producing feasible solutions for very large problems, especially for problems poorly or wrongly formulated.

- ii. Generalised bender's decomposition – this solution approach is implemented by dividing the variables of the optimization problem into two subsets of NLP and MILP problems. In the method, both the NLP subproblems with fixed binary variables and the MILP master problems are solved in each iteration. The NLP subproblems function to optimize the continuous variables and provide upper bound to the optimal MINLP solution while the MILP master problem is made up of only discrete variables and it predicts a lower bound to the MINLP as well as the new 0-1 variable values for each iteration. The new configuration is subsequently solved as an NLP in the next iteration. If the lower bound is more than the upper bound, the resulting structure is considered as a global optimal solution, otherwise the procedure is repeated until it is so [185]. The method has the advantage of producing a unique solution in the NLP subproblems, however huge number

of iterations are usually needed between the MILP master problems and NLP subproblems to realise this.

- iii. Outer approximation algorithm – The technique involved in outer approximation method is like that of generalised bender’s decomposition (GBD) with respect to the sequential and alternate solution of NLP and MILP subproblems which generate upper and lower bounds to the objective function. The unique disparity in outer approximation (OA) algorithm is that contrary to the GBD method where the MILP master problem is composed of only integer variables, continuous variables are introduced to the MILP problems in OA algorithm and the outer approximations are at the solution point of NLP subproblem. This is to allow a master problem that is composed of linearization of non-linear constraints and objective function. Although since both the continuous and integer variables are retained in the master problem for the OA, a larger solution of the master problem is required in OA than in GBD. This potentially compounds the complexity of getting the solution especially when several iterations are needed.

2.11.4 Extensions to MINLP solution algorithms

In attempts to further increase the capability of the above described algorithms in solving non-linear equality constraints in MINLP problems resulting from structural optimization, an Equality-Relaxation strategy to the established methods was developed by Kocis and Grossmann [186]. Whereas the development presents no additional modification to the initial GBD method, an extension was derived for the branch and bound method by adding the non-linear equality constraints to the relaxed NLP subproblems solved at each node. Meanwhile, in the case of OA, the MILP equations of the master problems are solved with equality relaxation by adding the linearization from NLP subproblem to them and relaxing the equations based on the signs of Lagrangean multipliers. Hence the method is called Outer- Approximation/Equality Relaxation (OA/ER) algorithm.

Viswanathan and Grossmann [187] developed a different version of OA/ER algorithm called Outer- Approximation/Equality Relaxation/Augmented Penalty (OA/ER/AP). In this new method, an augmented penalty function is introduced in the master problem. Firstly, the relaxed NLP is solved, slack variables are then included in the MILP master problem. Short [173], stated that by combining the slack variables with the penalty function, the non-convex constraints could be violated in order to obtain feasible solutions to the MILP master problem. Hence, verification of non- convexities is no longer required with the algorithm. This is a feature that has enhanced the robustness of the method

and thus its utilization for non-convex problems as highlighted in the studies of Bogataj and Kravanja [188] and Li et al. [189].

The above is a summary of the stages of development in solving MINLP formulation design and optimization problems. By and large, extensive work has been done on the development of improved algorithms for robust solutions to MINLP problems arising from the design and structural optimization of physical systems. Each of the available techniques has its unique features that warrant it to be preferred above the remaining methods depending on the situation at hand. While the well-known limitation of both OA and GBD methods is that a number of conditions which are convex in nature must be satisfied in order to guarantee convergence to global optimality [190, 191], the complexities of numerous NLP subproblems (sometimes in hundreds or thousands) which may result from the branch and bound method in large problems is also a big challenge. Thus, there is no algorithm that is reliable and constantly superior above others in every applications [167].

Each of the developed algorithms has also been applied to several domestic and industrial integration of renewable energy systems combining solar thermal and heat pump technologies, including those that incorporate opportunities for thermal storage techniques, with the designs. However, a common feature in most MINLP representation of solar thermal and heat pump designs in literature is that the results to the design problems are obtained from simplified models. In such models, linearized equations are used to represent the relationships between the periodic profile of streams such as temperature, mass and energy flow across the system as is the case in the studies of Steen et al. [126], Omu et al. [124] and Wallerand et al. [192]. Whereas the relationship among these parameters are non-linear in actual sense. In this thesis, such relationships as described above, as well as other realistic description of essential features of the design are represented and accounted for without any form of linearization while convergence to optimality are pursued in all the proposed models using the branch and bound algorithm for solving MINLP model formulations. This is implemented as SBB in General Algebraic Modelling System (GAMS) which is the modelling and optimization environment used for this study.

The SBB solver works for Mixed Integer Nonlinear Programming (MINLP) models and it is based on the combination of the standard Branch and Bound (B&B) method (which is known for solving mixed integer linear programming modelling and optimization problems) and some other standard nonlinear programming (NLP) solvers which are already supported by GAMS. One major advantage of the SBB solver is that it can make use of all GAMS nonlinear programming solvers as its subsolvers but performs better with Conopt, Minos, and Snopt, which are NLP solvers that can utilize a near optimal point as a starting point.

2.12 Conclusions

Historical development of solar heating and an overview of the state-of-the-art survey of solar thermal and heat pump design methods have been discussed in this chapter. Important findings relevant to the objectives developed for this thesis are summarized in the following key points:

- Solar thermal and heat pump systems are essential renewable heat technologies with booming global market and increased utilization in domestic and industrial sectors.
- Due to considerable intermittency, solar thermal (and indeed all renewable energy systems) are better utilized using relevant energy storage technique and in combination with other suitable primary energy technologies.
- Extensive research works have been carried out on the various aspects (i.e. design, operation and optimization) of solar thermal and heat pump systems (with respect to their individual applications, their combined design and in tandem with the supporting technologies).
- Several modelling techniques have been used to analyse the performance of the system. However, accurate and realistic modelling of energy systems involving solar thermal and heat pump designs together with thermal storage and other primary energy technologies require the use of non-linear and non-convex equations and constraints for proper representation of interactions among the components that make up the system.
- The mathematical structure of the model for combined solar thermal and heat pump designs should capture the dynamic operating conditions and thermodynamic features of the system according to the varying meteorological conditions and diverse ambient temperatures. Furthermore, the clustering techniques for time intervals and periods used in the model should be realistic enough as a representation of the actual hourly, daily, monthly and seasonal time periods.
- Since the potential of solar resources varies from region to region, it is pertinent that the design framework for solar thermal utilization should also be generic, such that it can be adapted to similar case studies in different geographical locations.

Several research interests have been channelled towards the above presented key points. Results from different studies show that the integration of solar thermal and heat pump technologies into

heat networks are of immense benefits, both in their individual applications or as integrated system. However, regardless of the design pattern, further study is still needed on both the supply and demand sides of the heat network considering the intermittent nature of solar energy supply, the attainable quantity of harvestable solar heat per period and the implications of these uncertainties on the entire heat supply network system. This thesis considers all the above listed key points by proposing sets of generic multi-period design and optimization methods for integrating solar thermal with domestic and industrial heat networks. The thesis also features strategies to increase the thermal output of solar systems through the development and implementation of heat storage and heat pump modelling approach which allows simultaneous optimization of the integrated system according to different temperatures using discrete time periods.

The next chapter presents a summary of the methodologies developed to achieve the objectives of this thesis.

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Methodology

3.1 Introduction

This chapter presents an overview of the methodologies developed in this thesis for the synthesis of integrated designs of direct and indirect solar thermal utilization for both industrial and residential heat supply networks. Insights on the developed mathematical models for domestic and industrial sectors, as well as the description of strategies developed to implement the design and optimization framework for the heat pump-enhanced solar thermal, are introduced in this chapter. In addition to the broad overview of the method discussed in this chapter, detailed implementation of the proposed methods for integrating solar thermal with industrial and residential heat networks are provided separately in Chapter 4 and Chapter 5 respectively. On the other hand, Chapter 6 deals with the combination of heat pump and solar thermal technologies and integration of the combined technology with thermal storage. The implementation of the developed framework rests on the idea that the general thermal output from industrial and residential solar heat networks presented in Chapters 4 and 5 could be further enhanced for improved thermal performance when the designs are harnessed with heat pump system especially during the lean solar heating periods. An overview of how the initially proposed methods are extended to capture the features of combined solar thermal and heat pump design is also presented in this chapter. However, a comprehensive description of the method and approach developed to achieve this technology combination is presented in Chapter 6. The discussions on methodology provided in this chapter ends with a short concluding remark describing what the chapter entails. Thereafter, a prologue of what is discussed in Chapters 4 – 6 of the thesis (where the proposed methodologies have been applied) is presented.

3.2 Methodology

3.2.1 Description of applied methodology

The propensity to search for and obtain satisfactory solar heat network performance (with respect to the maximum heat harvestable including reliability of the network), under several design constraints is what is referred to as optimization in this thesis. Mathematical programming approach makes it possible to present explicit model for a wide range of complex optimization problems. However,

obtaining a single but comprehensive, technically feasible design and optimization framework for energy system that is built on renewable energy resources such as solar thermal, which are characterized with intermittent fluctuations in availability and supply variability, is not an easy task. In reality, such problem comes with numerous technical features and constraints that need to be satisfied. A key problem lies in the fact that the actual equations describing the relationships between several design parameters and variables can only be correctly represented in the form of a mixed integer non-linear programming (MINLP) formulations. This is due to non-linearity features of the state equations representing the dynamics and interactions among the units within the system and the respective streams flowing in and out of the units. The above problem is in addition to the uncertainties in availability of solar radiation and unpredictability of the demand side. Nonetheless, a detailed design with realistic representation of the design features is needed to achieve a robust design and optimization result, though this often makes the problem extremely difficult to solve.

It is widely known that the synthesis and analysis of MINLP representation of design and optimization problems is very complex [1]. The task is generally referred to as NP-hard combinatorial problem due to the linear and non-linear functions of integers for continuous and binary decision variables. Even at the sight of reasonable convergence for a problem, the computational complexity and resource utilization to arrive at such convergence point are mostly enormous. Moreover, It is widely acknowledged that there exist a limited number of MINLP solvers in most available system optimization platforms [2]. Comprehensive survey of the most recent software for MINLP problems and latest advances are available in [3-5]. Despite the advent of advanced synthesis techniques, obtaining global optimal or near optimal solutions for a problem such as the one undertaken in this thesis is still considered to be a major challenge. Therefore, since the strength of any design and optimization model depends on the feasibility of the design and how well the problem is formulated, it is better to first make a target for proper formulation of the problem before thinking on how the problem can be solved. With this in mind, the following information are considered to be extremely important in order to correctly model realistic solar thermal integration problems such as those presented in this thesis:

- detailed information on the spatial and temporal availability of solar resource as well as the transient nature of heat supply from solar
- adequate information on the multi-period changes in the profile of heat demand (i.e. changes in the quantity of heat demand per specific demand population over a specified period of time)

- detailed information on the types and sizes of equipment/component needed to satisfy specific minimum heat load target
- detailed information on the thermodynamic properties of various heat transfer fluids and refrigerants that can deliver the desired target temperature.

The above information are needed to properly represent the dynamic nature of the whole system, and to assist with accurate energy potential forecasting during planning and decision making process. However, it is worth noting that accommodating such information in the model further increases the size and complexity of the MINLP formulations, as well as the computational efforts and resources that is required to obtain solutions to the model. Most previous studies have used simplified relationships to account for interactions between the stream temperatures, flowrates and energy flows across the system, while the periodic variability on supply side of the integration are also often presented in time steps using various rules of thumb which eventually reduces the strength and practical application of the model. This thesis presents comprehensive generic methods that account for the dynamic behaviour (hourly changes) in solar thermal utilization design features, including the periodic changes in the amount of heat stored in the thermal storage tank (on hourly basis) and the amount of additional heat load that may be required from backup utility (on hourly basis) in order to satisfy the multi-period heat demand networks of industrial and residential case studies. These features are accounted for with the use of novel simultaneous multiperiod mixed integer non-linear programming (MINLP) approach, where variabilities on both heat demand and supply sides of the integration as well as the effects of these variabilities on the heat networks are adequately captured.

The approach is later further extended to include the design and operating features of combined heat pump and solar thermal technologies, as well as the simultaneous optimization of the design for improved thermal performance.

In each of the solar thermal integration objectives investigated in this thesis, the problem to be addressed is first defined and the boundaries for the design framework are set. Thereafter, necessary information required as input data to the model is gathered. Such information include the profile of heat demand of the process (i.e. supply and target temperatures, T_s and T_t respectively), heat capacity flowrates of hot and cold process streams (FC_p^{stream}) together with existing heat integration between the process streams (i.e. for the case of industrial integration of solar) discussed in Chapter 4. Other data includes information relating to the type of solar thermal collector, minimum approach temperatures considered in the design, and the selected heat transfer fluid for the various heat network designs presented. For the specific case of domestic solar thermal integration presented in Chapter 5, the profile of heat demand for space and water heating in residential buildings are included

in the model, while the data on hourly solar irradiation and ambient temperatures of the considered location are also included in each of the solar thermal integration methodologies developed. For the solar thermal and heat pump capacity enhancement discussed in Chapter 6, the entire model is also implemented in General Algebraic Modelling System (GAMS) environment by linking the hourly solar irradiation and ambient temperatures data with the heat pump flowsheet superstructure.

The main variables considered in the developed models are the area of solar thermal collector in m^2 , volume of fluid in the heat storage tank in m^3 , attainable heat duty (in kWh/period) from solar thermal and the backup utility (in kWh/period). Since the operating features of any solar thermal system is transient with intermittent changes in meteorological conditions, integration variables such as fluid flow rates, temperatures, and energy flows, are accounted for in the model on an hourly, daily and monthly periods basis. The efficiencies of the solar collector are also considered as variables that are also subject to change on an hourly basis. On the other hand, the area of solar collector and volume of heat storage tank, and other components, are considered as optimization variables that are time independent. This implies that the solar collector and storage tank are designed to be of the optimally possible maximum size to cater for the heat demand throughout the year (i.e. based on the attainable solar heat). These same principles are applied to the heat pump-enhanced solar thermal case study. However, it should be noted that in addition to the aforementioned variables, other variables such as mass enthalpies and pressure across the heat pump loop and efficiency of compressors are included in the model for the case involving the heat pump enhanced solar thermal design presented in Chapter 6. Further detailed description of the applied methodology for each of the objectives addressed in this thesis is provided in the respective chapters.

3.2.2 General problem statement

The industrial sector and buildings sector (residential and commercial buildings) contribute heavily to the global energy consumption [6], and the two sectors are the leading single contributors to energy-related emissions [7]. While the residential and commercial buildings jointly account for between 32 % [8] to 40 % [9] share of the total global energy consumption, energy use in the industrial sector also continue to be on the increase with the sector responsible for between 42 % - 52 % (depending on the scope and accounting criteria) of the world's total delivered energy [10]. Whether in the industrial or residential sector, significant amount of energy consumed goes for heating (as will be shown later in the thesis), and this is mostly satisfied with energy from non-renewable sources [11]. With the current pressing concern about global climate change and the fear that most conventional energy resources

are finite [12], the major challenge remains how to provide alternative sustainable source(s) of energy to meet current energy demand and satisfy future demand projections [13]. Solar thermal has been widely described as a promising and sustainable alternative to conventional energy sources with respect to meeting the current energy demand and satisfying future demand projections [14]. However, increased utilization and expansion of solar energy in energy systems is constrained by intermittent variability of solar intensity resulting from the fluctuating weather conditions. This leads to low energy output from solar systems especially in lean periods with very low solar irradiation and ambient temperature, a situation that presents some technical difficulties to planning and decision-making process in practical application of solar utility systems. As such supporting technologies that enhance efficiency such as heat pump have been recommended. Various methods for combining heat pump and solar thermal technologies for water and space heating have been reported [15]. However, apart from simulation and design, it is necessary to perform the optimization of the combined solar thermal and heat pump system in a manner that reflects the dynamics of variables in the system. This is currently a challenge in most established design methods. Therefore, a comprehensive solar thermal utilization technique, as well as an all-inclusive method for integrating solar thermal with heat pump considering the multi-period variability in solar energy resource and other meteorological influence while also exploring a novel process optimization approach is needed.

With the above understanding, the main focus of this thesis could be broadly viewed as integration of solar thermal with industrial and residential heat demand networks, as well as incorporation of accompanying technologies (such as periodic heat storage and heat pump units) for optimum performance of the integrated solar thermal system. However, the problems addressed are formulated as an inter-related trifecta wherein the major tasks are executed in three successive steps with each step having its unique problem statement.

Step I: Integration of solar thermal incorporating periodic heat storage and backup utilities in industrial heat network.

Problem statement for step I

Given a set of hot and cold process streams with known supply and target temperatures, and heat capacity flowrates at specified periods of operation, the goal is to synthesize an optimally integrated heat exchanger network (HEN) involving solar thermal collectors with heat storage tanks and backup hot utility.

In order to achieve the set goal, the following design questions are addressed:

- What is the maximum attainable solar heat for the process?
- How much of the heat demand of a process can be satisfied by solar thermal?
- What are the optimal sizes of the solar collector and heat storage tank required to achieve maximum attainable solar heat supply to an industrial process?

Step II: Integration of solar thermal incorporating periodic heat storage and backup utilities for domestic heat network.

Problem statement for step II

Given a cluster of buildings with differing roof areas differing building insulation, year of construction, and varied orientations for solar collector installation. Given also that the annual profile of heat demand for hot water and space heating for the buildings are known but varies from building to building across specific time of the day and periods of the year. The goal is to synthesize an optimally integrated heat supply network that involves solar thermal collectors, heat storage, space heating radiators, hot water consumption and backup utility system.

To accomplish the above stated goal, the following design questions and objectives are addressed:

- What percentage of the annual heat demand of the buildings can be provided by solar thermal and what are the potential savings in terms of reduction in external utility?
- What are the optimal collector areas and the matching centrally located storage tank size that will be suitable for the integrated solar thermal network considering the maximum realizable solar heat from the building rooftops?

Step III: Integration of heat pump with direct and indirect solar thermal utilization for enhanced thermal performance and improved efficiency.

Problem statement for step III

Given the above highlighted opportunities for improvement in solar thermal utilization the goal is to consolidate on the synergy between solar thermal and heat pump technologies through solar thermal-aided vapour compression cycle for enhanced thermal performance.

In order to achieve the goal, the following objectives are addressed:

- Flowsheet and superstructure development for the optimization of combined solar thermal and heat pump cycle considering the multi-period variability in solar irradiation and ambient temperature. These variabilities are accounted for on hourly, daily and monthly time periods.
- Development of a set of multi-period mixed integer non-linear programming (MINLP) equations for the synthesis of integrated solar thermal and heat pump heat network for producing low/medium temperature level steam.

3.3 Implementation Strategy

In order to address the problem statements highlighted above, the formulated framework for the developed methodology are implemented in three successive steps as shown in Figure 3.1. The first and second steps focused on the integration of solar thermal with industrial and domestic sectors respectively proving opportunities for periodic heat storage in each of the steps. Each of these steps are presented and discussed in separate chapters (i.e. Chapter 4 and Chapter 5 respectively) together with the detailed applied methodologies which is peculiar to each case in point.

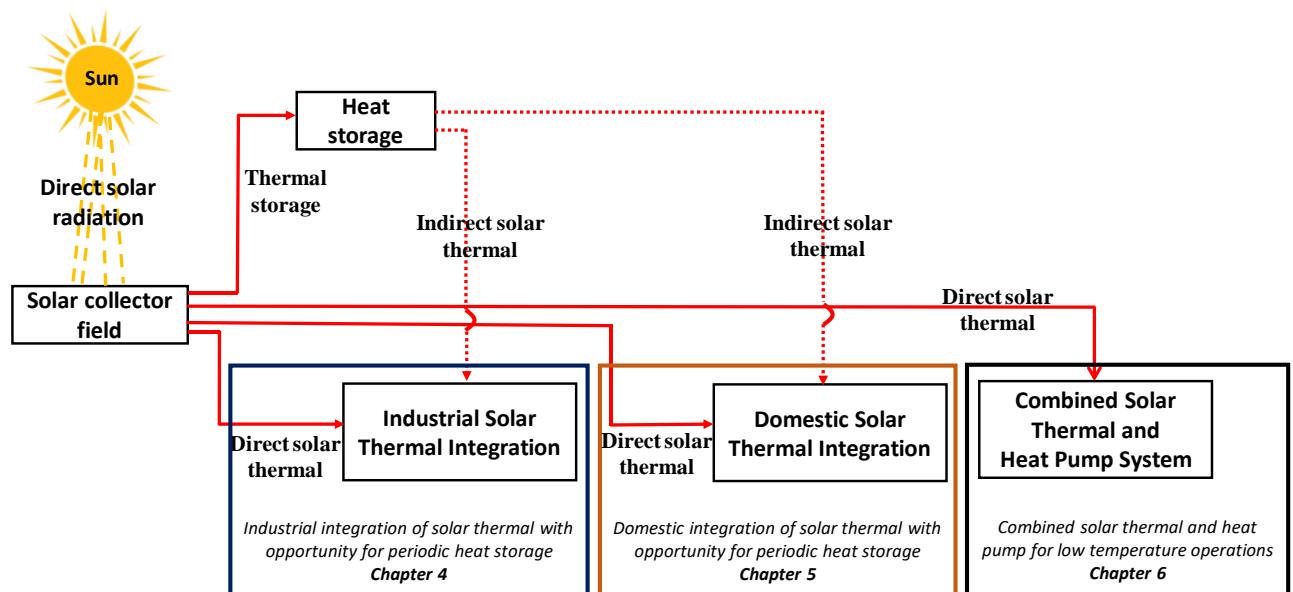


Figure 3.1: Implementation strategy for the proposed solar thermal integration scheme

Designing for the case where solar irradiation and ambient temperature might be too low for the desired temperature level of the captured solar heat and to investigate the synergy between renewable heat and energy efficiency technologies, the model is further extended to combine the direct solar heat with vapour compression heat pump cycle. This combination, which addressed the

third problem statement, is presented in Chapter 6 of the thesis. Figures 3.2, 3.3 and 3.4 provide overview of the applied methodologies while a step-by-step implementation of these methods are further discussed in detail within Chapters 4, 5 and 6 respectively.

3.4 Model Development and Mathematical Formulations

3.4.1 Parameter initialization and bounding

Accurate and realistic modelling of energy systems essentially require the use of non-linear and non-convex constraints for proper representation of the features of components within the system. However, non-convex and non-linear MINLP problems still remain the most difficult problems in Chemical Engineering till date [16]. Widely used concepts for solving problems of these nature in most deterministic design and optimization methods include parameter initialization and bound tightening [17].

Initialisation of model parameters are highly important in order to ensure fast convergence and to avoid infinite iterations, especially when the model contains implicit parameters. However, while selecting values for the parameters, the selection method should be realistic enough for practical applications as well as being in the range that will not automatically shut out some potential feasible solutions. For each parameter initialised, the likely values that underestimate the objective function are first determined. Subsequent iterations then proceed by including those values that underestimate the objective function such that large number of options are evaluated. In Chapters 4, 5 and 6 of this thesis, initial values are reliably selected for relevant parameters in the presented models. The values are selected through detailed design simulations and comprehensive review of the research area to predict and choose the possible region where the parameters may lie.

Furthermore, approximation of convex relaxations can be improved by tightening the bound(s) of selected features (variables) of the system represented in the model [18]. This involve assigning realistic lower and upper bounds for variables in the optimization problem in order to improve the solution [19]. Several techniques have been developed for setting bounds on optimization problems. These include the techniques developed for mixed integer linear programming problems Andersen et al. [20], and those for mixed integer non-linear problems such as that of Belotti et al. [17] and Messine et al. [21]. For MINLP problems, it is possible to maximize or minimize variables over the actual feasible region of the MINLP problem [16]. On the other hand, the variables can also be maximized or minimized based on the feasible region of convex continuous relaxation. This is referred to as

optimality-based bound tightening [22]. A common approach evaluates each constraint based on the reference bound(s) for the variables and then endeavours to improve the bound(s) by sustaining feasibility of the constraint. This is widely referred to as feasibility-based bound tightening [23]. The limitations and advantages of each of these techniques are analysed and presented in [16]. However, it should be noted that the feasibility-based bound tightening method is the fastest apart from the fact that more than two constraints cannot be evaluated at a time. In the presented case studies, the values of several parameters and variables present strong influence on the solution to the model. Hence, the models are solved considering different upper bounds as described in the next section and also in Chapter 4, Chapter 5 and Chapter 6.

3.4.2 Considerations for detailed model formulations

The developed models contain various material and energy balances across the basic components embedded in the superstructure of each case study presented. The components include: solar collector, splitters, mixers, heat storage tank, backup boiler (for step I), backup burner (for step II), heat network of the processing plant (only step I), space heating radiator (for step II), as well as the other units introduced in step III for the heat pump and solar thermal integration which include: evaporator, compressor, condenser, sun-cooler and expander. Since the results from the developed models are strongly dependent on the area of solar collectors, the model investigates different collector sizes which are recognized in the model as A_{panel} , where the upper bound of A_{panel} (A_{panel}^{UP}) was in the range between 500 m² to 10,000 m². In addition, upper bounds were set on flowrates ($F_{io,mp,dp,hp}^{u,UP}$) of 100 t/h and also on the heat load ($Q_{io,mp,dp,hp}^{u,UP}$) of 5,000 kW in Chapter 4 (step I of the objectives).

In step II (Chapter 5), upper bounds were also set on the flowrates (100 t/h), heat load (1,000 kW), volume of fluid in the storage tanks (between 50 and 10,000 m³), areas of solar collectors for each building (according to the baseline scenario described in Chapter 5 which is subject to available roof area) while the upper bound of temperature across the loops is taken to be 99 °C. Water is considered as the heat transfer fluid with specific heat capacity of 1.16 kWh/(t °C) and density of 1 t/m³. The inlet temperature of feed water to storage tank is assumed to be 20 °C, minimum temperature difference (ΔT_{min}) is 10 °C, minimum temperature for hot water use is 55 °C, while the lower bounds of the supply and return temperature to the radiators are set at 65 °C and 40 °C according to the standard limit for district heating networks described by Finish Energy (FE, 2019). The return temperature of heat transfer fluid in the radiators is assumed to be at least 20 °C lower than the supply temperature to the

radiators. Relevant equations describing all the aforementioned features are described in detail in the respective chapters.

In step III (Chapter 6), the upper bounds for solar collector range between 100 and 10,000 m². Other variables were also bounded within their feasible thermodynamic ranges considering suitability at high temperature, suitable working pressure as well as the critical and transcritical operating conditions of the refrigerant. Since the proposed design in this step comprises 3 loops (i.e. closed loop of solar collector – heat pump – solar collector loop, closed loop of heat pump alone and open loop of heat pump – industrial process – heat pump loop), the streams flow conditions (which is part of the main variables considered in the model) vary across the system while stream flow within the heat pump circuit is constant across the components as described in Chapter 6. The heat transfer fluid (HTF) that runs through solar collector – evaporator – solar collector loop (first loop) is a mixture of water and ethylene glycol. In the second loop (closed loop of heat pump cycle), R-245CA refrigerant is used as the working media, while circulating pressurized water is used to recover heat from the hot refrigerant gas which is then further used in the industrial process loop (third loop). The thermodynamic data for the refrigerant is obtained from Aspen Plus V10 using REFPROP property method (Aspen Technology, 2019) and correlations were derived for the changing values of mass enthalpy of the refrigerant as temperature and pressure change across the 2-phase medium of the compression cycles (i.e. liquid and vapour phase).

Since the operational features of a typical solar heating system are transient, the models are formulated as mixed integer non-linear programming (MINLP) problems in order to account for the time dependencies of the integration features. Additionally, the synthesis are implemented simultaneously to satisfy the objective functions formulated for each of the case studies presented as described in Chapter 4, Chapter 5 and Chapter 6. Overview of the applied methodology for in each of these chapters are presented in Section 3.5.

3.5 Summary of Applied Methodology

Summary of the applied methodologies for step I (Chapter 4), step II (Chapter 5) and step III (Chapter 6) are present in Figures 3.2, Figure 3.3 and Figure 3.4 respectively. Implementation of the basic steps involved could be categorized to three major steps: I): data collection II): data processing and computational framework (system resolution) and II):. Evaluation of model performance.

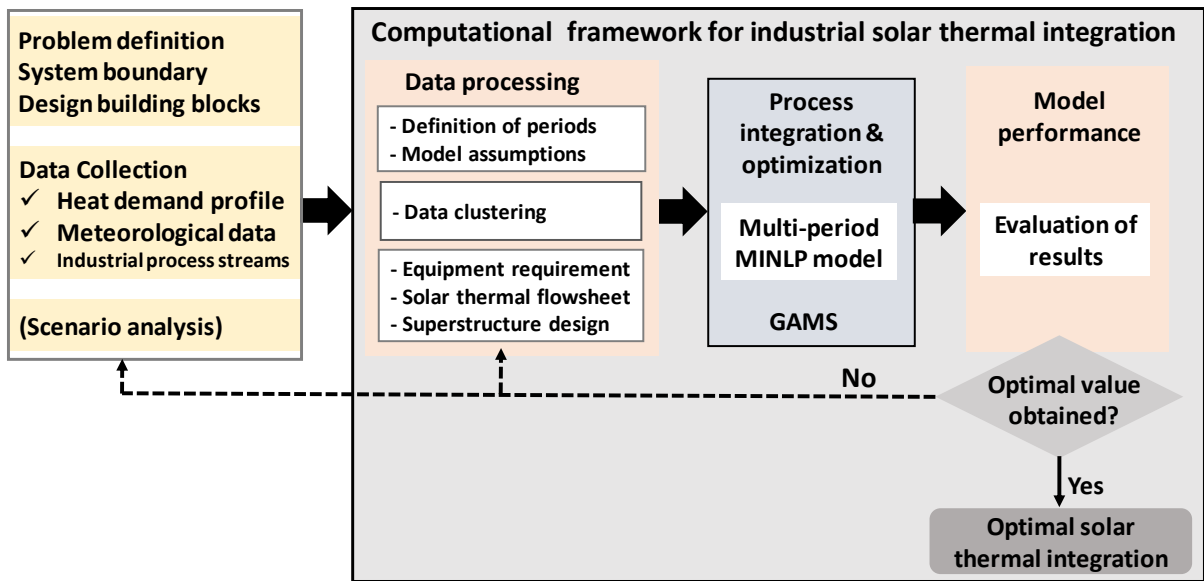


Figure 3.2: Summary of methodology applied in Chapter 4

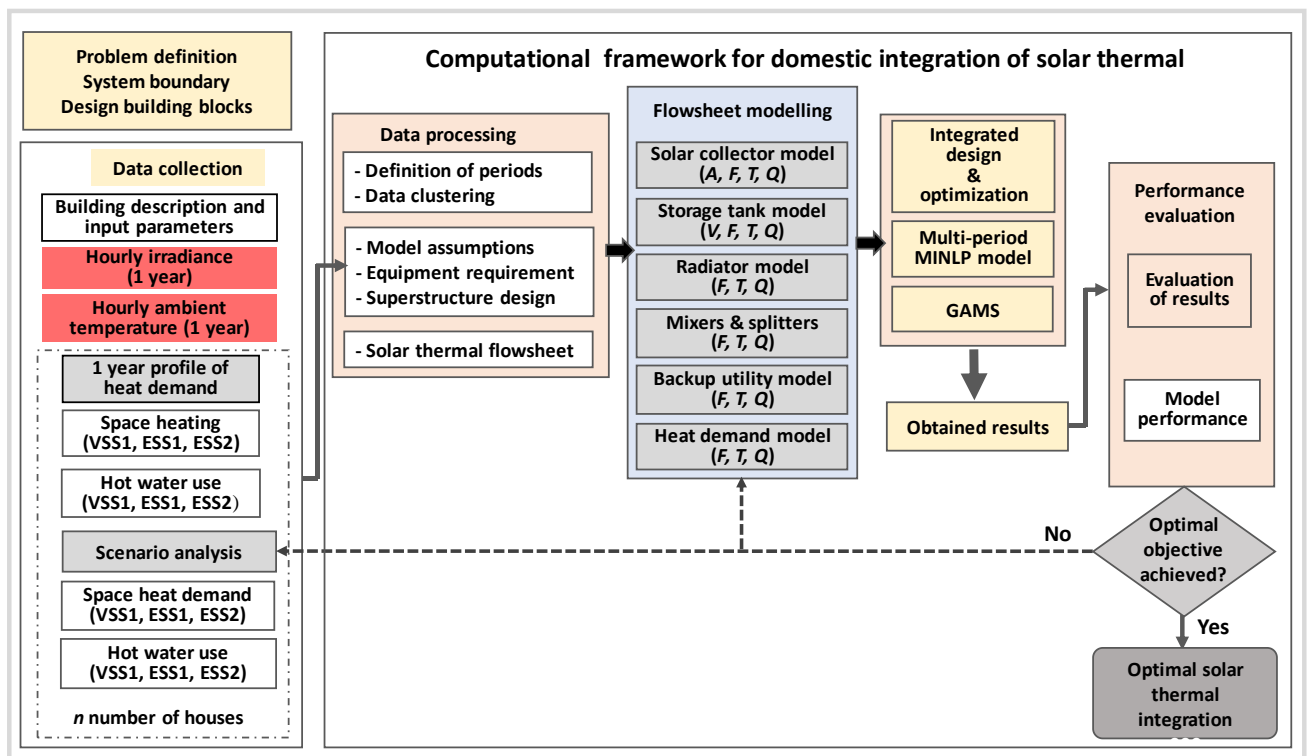


Figure 3.3: Summary of methodology applied in Chapter 5

Apart from the developed multi-period MINLP equations for representing the features of the presented technologies, sets of unique superstructures are developed to achieve realistic design and optimization in each of the proposed systems presented. In the case of the combined solar thermal and heat pump system presented in Chapter 6, the developed superstructure incorporates the features for multi-stage vapour compression cycle in addition to the successive condensation and subcooling techniques implemented for improved heat recovery. The design also accounts for multi-period changes in solar irradiation and ambient temperature and the impacts of these changes on the heat network. Incorporating these features in a flexible structure and simultaneous optimization of the design is considered to be an improvement to most available commercial simulation software.

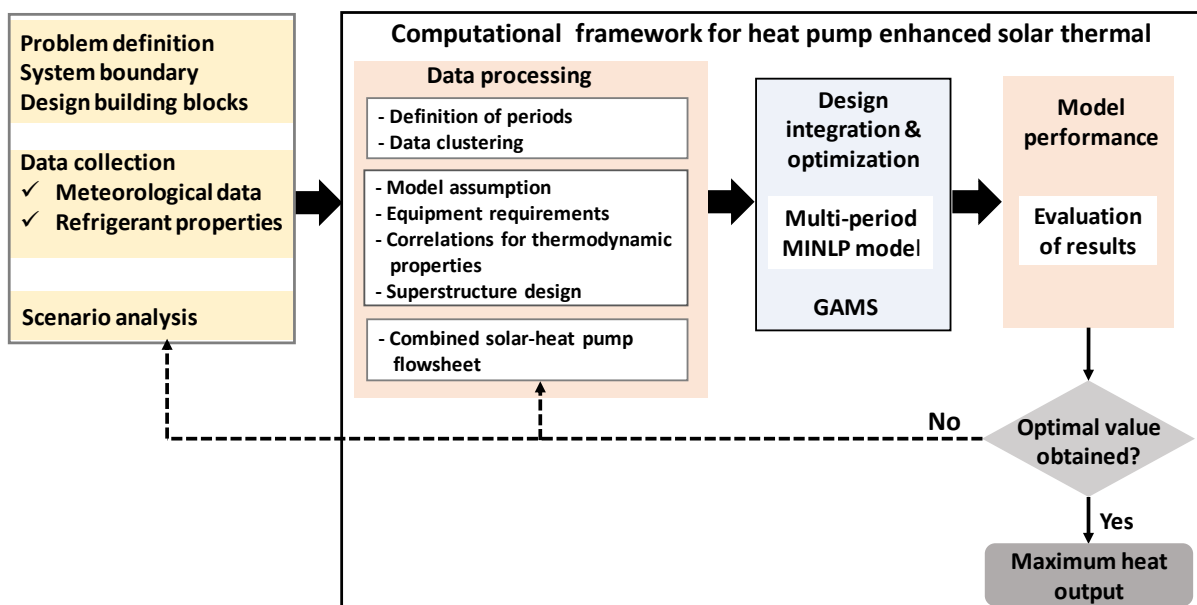


Figure 3.4: Summary of methodology applied in Chapter 6

In each of the presented designs, the multi-period changes in meteorological and ambient conditions are clustered according to the procedure presented in [24] which are also described in detail in Chapter 4. Furthermore, the development of the flowsheet as well as the computational framework for design and optimization in all the presented case studies are implemented in General Algebraic Modelling System (GAMS) environment using SBB solver. Detail description of each of the methods and the procedure followed to implement the design are provided in respective chapters (i.e. Chapters 4, 5 and 6).

3.6 Conclusions

Design and optimization of solar thermal systems is a multi-dimensional problem involving complex multi-period meteorological, technical and state variables for ideal representation of the problem. The synthesis and comprehensive analysis of the problem typically employs mathematical models which present a number of difficulties for most established methods. New multi-period design and optimization methodologies which seek to improve the performance of the system are proposed in this thesis. This Chapter provides general insights into the proposed MINLP solution methods. Rather than a simplified representation of the problem due to complex iterations and computational difficulties, the MINLP approach introduced in this thesis accommodates detailed information for proper representation of components within the systems modelled.

Subsequent chapters present implementations of the proposed methods to specific case studies. Due to specific contributions of each the chapter, full published research articles relevant for each chapter are included according to the structure designed for the thesis. Hence, each chapter includes its specific introduction, literature reviews, methodologies, results and conclusions for ease of reference.

In Chapter 4, applications of the proposed methodology in industrial heat networks is demonstrated with illustrative case studies of direct and indirect solar thermal integration strategies. In Chapter 5, the methodology is modified to capture the features for domestic heat supply network for water and space heating. The modified and extended model is then demonstrated with two illustrative case studies of solar thermal integration with domestic heat network. Chapter 6 presents further modification to the developed model. In the modified framework presented in Chapter 6, a combined design of solar thermal and heat pump technologies is presented for improved thermal performance. The resultant heat produced could then be integrated with relevant heat network at any potential heat demand points.

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Industrial Integration of Solar Thermal Incorporating Periodic Heat Storage and Backup Utility

Background to the Chapter

Industries and other energy-consuming chemical/process plants have been under intense pressure to reduce the rate by which energy is sourced from fossil resources, and to adopt relevant energy efficiency measures in order to mitigate climate change. In the wake of this global consciousness, it is a common opinion that sustainable solution to achieve energy security and reduced emission will require enough deployment of various renewable energy resources into energy supply-mix of the industrial sector. Hence, manufacturers and industries across the world are increasingly developing strategies to strengthen rationale use of energy in individual processes and maximize the use of clean energy alternatives in various industries. Despite this awareness, industrial energy-related emissions continued to be on the increase. To forestall further increase in the level of energy-related emissions, the Intergovernmental Panel on Climate Change in the fifth assessment report of the working group III proposed that a minimum of 25% of the emission level could be cut-off if the various renewable energy resources are well harnessed with industrial energy systems, in addition to wide scale technological upgrading, energy efficiency and replacement or retrofitting of best available energy technologies¹.

Solar thermal utilization in industrial processes is a promising renewable energy technology application for emission reduction in industrial sector. The technology is an evolving market that has created new business environment and opportunities. Depending on the reference geographical location and economy of scale, substantial amount of heat demand in most industrial processes (especially for low- and medium- temperature operations) could be satisfied with solar thermal. In order to promote its rapid growth, the International Energy Agency (IEA) has presented series of procedure to guide engineers, technicians and installers on the methods to integrate solar thermal with industrial heat networks². The applications range from technology retrofitting and process re-arrangement for existing designs (i.e. by identifying the best economic and technological point of integration options), while it involves the inclusion of essential constraint(s) to realize the maximum

attainable solar heat potential together with other technical and thermodynamic requirements of the heat transfer network in the case of grassroots designs.

Several integration possibilities involving the aforementioned strategies are presented in this chapter to demonstrate the suitability and application of the developed methodology for industrial integration of solar thermal. This chapter presents direct “word-for-word” reproduction of papers published in Volume 46 of *Computer Aided Chemical Engineering Journal* on 25th July 2019 titled “Synthesis of Solar Heat Network for Preheating of Industrial Process Streams”³ and the one published in Volume 182 of *Energy Journal* on 1st June 2019 titled “Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations”⁴. The presentation styles of the papers and the way they appeared in this chapter are in conformity with the Journal requirements. The only changes are the cosmetics applied to section identifications in order to maintain the requirements for the thesis presentation.

¹Fishedick M., J. Roy, A. Abdel-Aziz, A. Acquaye, J. M. Allwood, J.-P. Ceron, Y. Geng, H. Khashgi, A. Lanza, D. Perczyk, L. Price, E. Santalla, C. Sheinbaum, and K. Tanaka, 2014: Industry. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

²Hassine I. B., Helmke A., Heß S., Kruppenacher P., Muster B., Schmitt B., Schnitzer H, 2015: *Solar Process Heat for Production and Advanced Applications: Solar Heating & Cooling Programme*. International Energy Agency Solar Thermal Integration Guideline, Deliverable B2.

³Abikoye B., Čuček L., Isafiade A., Kravanja Z: *Synthesis of Solar Heat Network for Preheating of Industrial Process Streams*. *Computer Aided Chemical Engineering*. 2019;46: 535 -40.

⁴Abikoye B., Čuček L., Isafiade A., Kravanja Z: *Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations*. *Energy*. 2019;182: 381-396.

Part I: Integration of Solar Thermal for Preheating of Industrial Process Streams

Preamble

Part of the preliminary steps prior to the actual integration of solar thermal with industrial heat networks is to determine the best point of integration with respect to the technical feasibility, thermodynamic considerations and economic viability. These are in addition to other specific design considerations which could proceed after these initial conditions have been satisfied. Accounting for these requirements satisfactorily is not trivial due to the complexity of the procedure involved in the task. This has been identified as one of the major challenges confronting industrial utilization of solar thermal. In order to circumvent this obstacle, an approach considered to be relatively less complex is the utilization of solar heat for streams pre-heating in industrial processes. In this sense, the selected cold stream(s) can be matched with resulting hot stream(s) from the solar field for heat transfer which could be isolated from the general (main) industrial heat networks. This forms the background for the first part of this chapter published in Computer Aided Chemical Engineering (Volume 46, 2019).



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Synthesis of Solar Heat Network for Preheating of Industrial Process Streams

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Synthesis of Solar Heat Network for Preheating of Industrial Process Streams

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Abstract

Industrial integration of solar for process heat applications with periodic heat storage and backup utility system ensures reliability and efficiency of renewable heat utilization, thus minimizing the dependence on fossil fuel and energy related emissions. Furthermore, by minimizing heat duty from backup utility, opportunities for matching solar thermal and solar heat storage could be fully explored. This study models the industrial application of solar thermal considering direct and indirect integration, periodic heat storage and backup utility. For the synthesis of the integrated design, a flowsheet superstructure is presented for multi-period heat supply network of industrial processes. The design and optimization of the integrated system is implemented and solved in GAMS with the objective of maximizing total heat output to the heat network. To demonstrate the performance of the model, the proposed solar heat network design for industrial utility retrofit is applied to an illustrative case study of preheating a cold industrial stream.

Keywords: Solar thermal, Solar heat, Thermal storage, Solar heat integration, Industrial solar integration.

4.1 Introduction

Over the past few decades, the global energy consumption has been on steady increase due to the rising of population and expanding economic activities. According to a recent report, heat consumption accounts for over 50 % of the annual global energy use [1]. Further analysis has revealed that as at 2014 about 75 % of this share of energy consumption (around 130 EJ) is currently sourced from fossil fuels [2] which negatively impacts the environment.

Solar thermal is a form of renewable energy with great potentials to substitute/ supplement the use of fossil fuels for various heating purposes because it is a low-carbon source of heat and power (electricity). Studies have shown that out of the total global industrial heat consumption of 85 EJ, 30 % is used for low temperature (<150 °C) heat operations [3]. Due to the wide range of industrial processes with low temperature heat operations, industrial solar utilization is believed to have great potentials.

Solar industrial utility retrofit in combination with periodic heat storage [4] is a demonstration of how a renewable source of heat can be effectively planned for and harnessed with industrial heat networks. Due to supply variability and low thermal value of solar over some time periods, an important feature which could further improve thermal performance in such designs is the inclusion of an effective backup utility system in the design framework.

While a significant number of research works has been carried out on solar thermal utilization, not much has been done on the application and optimization of solar technologies for industrial processes [5]. Even in some existing solar designs with thermal storage, managing the intermittent fluctuations of heat supply is still quite challenging due to the technical difficulties and large number of decision variables involved, especially when considering backup alternatives to circumvent the supply gaps in solar systems. In this study, an integrated design of a solar heat network is proposed for stream preheating in industrial processes in order to study attainable quantities of solar heat that can be harvested regardless of economics considerations which can vary significantly both temporarily and spatially. The design includes strategies that account for the multi-period variability in solar energy supply on hourly basis according to meteorological data obtained from [6] for the specific location considered. The synthesis method involves a balanced close-loop circuit of direct and indirect solar thermal system with periodic heat storage and backup utility.

integer non-linear programming (MINLP) problem. Also, the synthesis is implemented simultaneously with the objective of maximizing the average solar heat output to the network ($Q_{mp,dp,hp}^{solar}$) shown in Eq. (4.1).

$$\max \sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in HP} |_{(dp,mp) \in DPM} Q_{mp,dp,hp}^{solar} \quad (4.1)$$

where hp , dp and mp represent the hourly, daily and monthly periods and DPM stands for set of pairs of days and months.

The model takes into account variable flowrates, temperatures and energy flows across each unit within the entire system. Additionally, area of a solar thermal collector and its efficiency and storage tank volume are optimization variables. The data required to achieve this were retrieved as actual measured values of hourly global horizontal irradiation and ambient temperatures. Thermal energy provided by solar collector (in kWh/period) and the data for its calculation are based on the work by [7], however in this work equality constraint is used and is multiplied by the number of hours for specific period.

The MINLP model consists of linear and nonlinear equality and inequality constraints and additionally it includes discrete or binary decisions. The binary variables ($y_{mp,dp,hp}$) are associated with the temperature of heat storage tank and the heat energy provided by heat transfer fluid from the solar collector. Eq. (4.2) shows such a constraint which states that the temperature in storage tank ($T_{mp,dp,hp}^{storage\ tank}$) should be lower than the difference between outlet temperature of the heat transfer fluid returning to solar collector ($T_{mp,dp,hp}^{out-2, storage\ tank}$) and the minimum temperature difference (ΔT_{min}), in a case the flow is non-zero. On the other hand, when there is no flow, there is no specific constraint on the temperature in storage tank.

$$T_{mp,dp,hp}^{storage\ tank} \leq T_{mp,dp,hp}^{out-2, storage\ tank} - \Delta T_{min} + M \cdot (1 - y_{mp,dp,hp}), \quad \forall (mp \in MP, dp \in DP, hp \in HP) \quad (4.2)$$

Eq. (4.2) represents big M constraint, M being big enough scalar, and binary variable $y_{mp,dp,hp}$ is connected to the flow from solar collector to the tank and back to the collector ($F_{mp,dp,hp}^{in-1, storage\ tank}$). If binary variable is 1, the flow should be between a minimum (F^{min}) and a maximum value (F^{max}), and 0 otherwise. Such constraints are shown in Eq. (4.3).

$$F^{\min} \cdot y_{mp,dp,hp} \leq F_{mp,dp,hp}^{\text{in-1,storage tank}} \leq F^{\max} \cdot y_{mp,dp,hp}, \quad \forall (mp \in MP, dp \in DP, hp \in HP) \quad (4.3)$$

4.3 Case Study

The developed model is implemented and demonstrated on a specific location near Maribor, Slovenia as a case study, partly because low temperature industrial operations represent approximately 37 % of the total industrial heat demand in Slovenia [8]. This location was a reference point to obtain required meteorological data, such as hourly solar irradiation and ambient temperature. The data, which are based on the year 2016, were extracted from the EC JRC PVGIS (2017) [6], using coordinates 46.552 N: 15.676 E Latitude and Longitude, and an elevation of 267 m above sea level.

In the case study, solar thermal is integrated with an industrial heat network for process stream preheating as shown in Figure 4.1. As a heat transfer fluid, 50/50 water-ethylene glycol is considered. For simplicity, only 1 cold process stream is considered in this demonstrative example while opportunities for using backup utility is accommodated within the framework of the model (see Figure 4.1).

To reduce computational time, mathematical model reduction techniques based on an earlier procedure presented by Egieya et al. [9], which is a modification from presentation of Lam et al. [10], is adopted. The 24 hours of each day are discretized into 4 periods of different durations: H1: 9 pm – 7 am, H2: 8 am – 10 am, H3: 11 am – 4 pm, H4: 5 pm – 8 pm. The 29 – 31 days of a month are discretized into just one period, while 12 months are considered in total. The input data on an hourly basis were averaged as previously done by Egieya et al. [9]. The model consists of 4,504 single equations, 4,755 single variables, and 48 binary variables. It was solved using SBB solver in GAMS with 1 % optimality gap in up to few hours on a personal computer with an on Intel® Core™ i7-8750 H CPU @ 2.20 GHz processor with 8 GB RAM.

The results from the model show that the allowable volume of heat transfer fluid (V^{fluid}) in the storage tank and solar collector area (A_{panel}) have strong influence on the solution. Thus, the model has been solved considering different upper bounds for V^{fluid} and A_{panel} . Additionally, upper bound on flowrates of 100 t/h has been set. In almost all the solutions obtained (except for $A_{\text{panel}} = 100 \text{ m}^2$, where V^{fluid} was 56.6 m^3), both V^{fluid} and A_{panel} were set at their upper bounds. The graphs in Figure 4.2a and 4.2b show the relationship between the average heat load of solar thermal (Average DH^{solar}) exchanged with the cold process stream and the temperature of the stream achieved with solar (Average T^{solar}) for different values of A_{panel} between 100 and 10,000 m^2 .

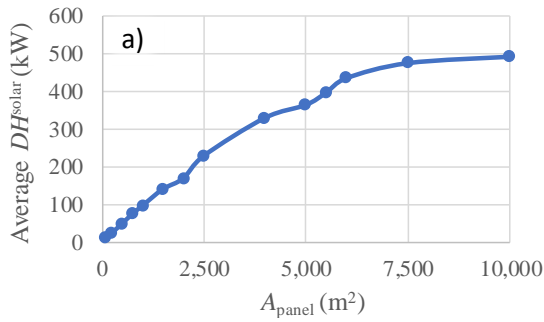


Figure 4.2a: Average DH^{solar} with different sizes of solar collectors

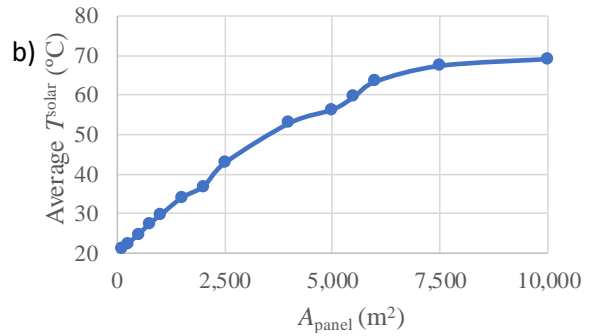


Figure 4.2b: Average T^{solar} with different sizes of solar collectors

From Figure 4.2a and 4.2b, it could be seen that both DH^{solar} and T^{solar} significantly increase up to A_{panel} value of 6,500 m^2 , DH^{solar} for 80.9 W/m^2 and T^{solar} for 0.008 $^{\circ}C/m^2$ in average. Beyond this A_{panel} value, the increase is lower, DH^{solar} is increased to about 16.7 W per additional m^2 of area and T^{solar} for 0.001 $^{\circ}C/m^2$.

Figures 4.3 and 4.4 show the flow sheet values obtained for cases where the upper bound of the solar collector size is set to 1000 m^2 and to 10,000 m^2 . Comparing these two figures, parameters such as the amount of heat captured by the solar collector, the amount of heat stored, and the quantity of heat that is ultimately exchanged between the solar heat transfer fluid and the cold process stream, are higher for the case where A_{panel}^{UP} is set as 10,000 m^2 . It can also be noted that solar thermal achieves a higher preheating temperature of 69.2 $^{\circ}C$ for the 10,000 m^2 case compared to the 1000 m^2 case which only achieves a preheating temperature of 29.65 $^{\circ}C$.

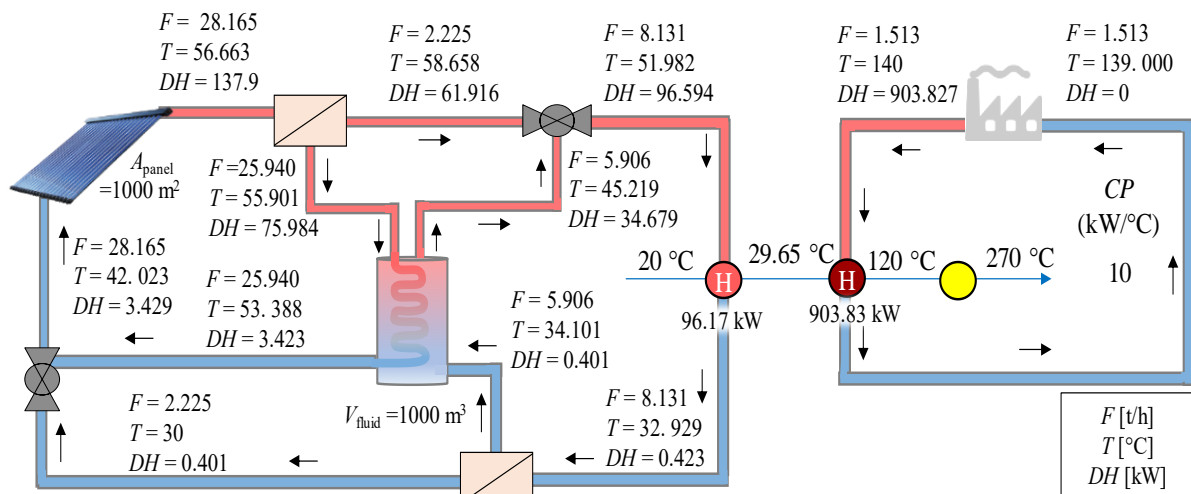


Figure 4.3: Average values of variables for the case $A_{panel}^{UP} = 1000 m^2$

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Part II: Integration of Solar Thermal with General Industrial Heat Network Involving Multiple Cold Process Streams

Preamble

The share of industrial energy use in the total global energy demand is very significant. Thus, enough deployment of renewable energy resources to industrial energy system will reduce the global dependence on fossil resources, environmental impact and promote the blue energy initiative in industries. Therefore, beyond the utilization of solar thermal for industrial stream preheating, a further step to maximize the quantity of heat delivered to the process from solar thermal is its extended integration with the general industrial heat networks. This will achieve more results in terms of reduced utility cost, emission reduction and sustainability. The above background influences the second part of this chapter which is an extension of the industrial solar thermal integration methodology developed in Part I to include the use of solar heat in industrial operations involving multiple cold process streams. The work reported in the second part of this chapter is a reproduction of the exact research article published in Energy Journal (Volume 182, 2019).



Energy

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Integrated design for direct and indirect solar thermal utilization in low temperature industrial operations

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Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations

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Highlight

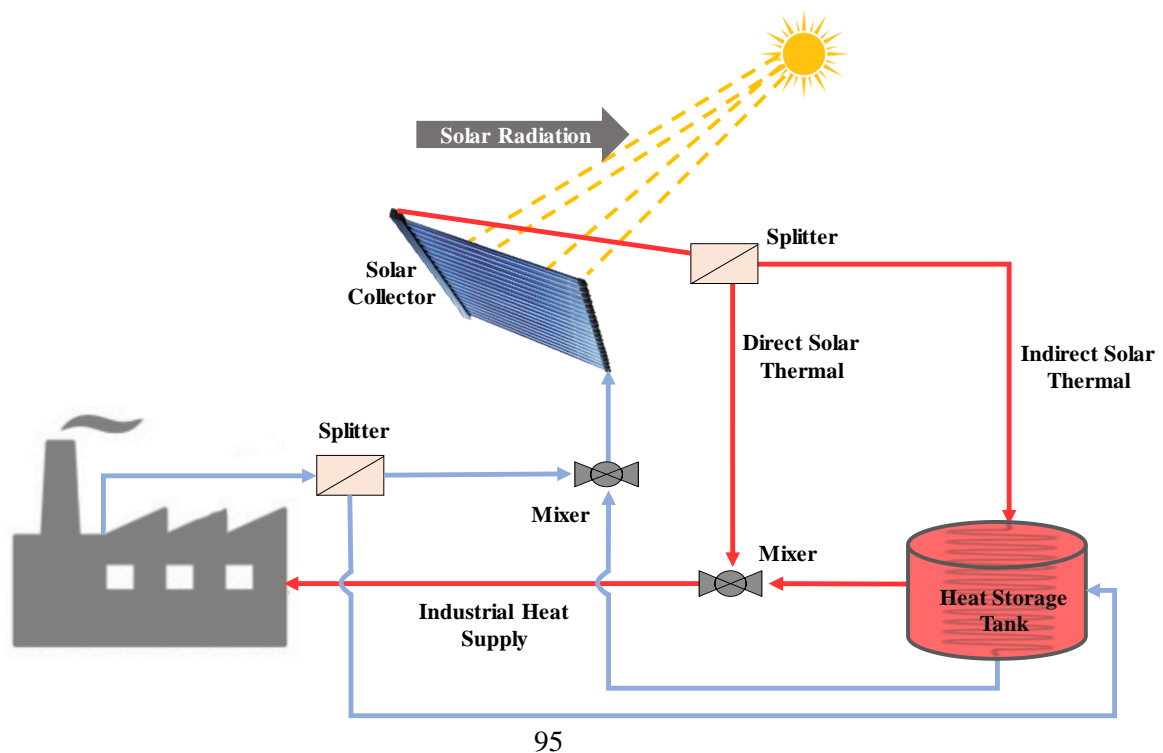
- Model for integration of solar thermal for industrial applications is proposed.
- Dynamic model includes periodic heat storage and backup utility.
- Design parameters and operating conditions are optimised by maximizing total heat output.
- Sensitivity analysis shows attainable heat load versus collector area.
- Two integration patterns involving one and multiple cold streams are considered.

Abstract

This work presents a flowsheet superstructure and integration possibilities for simultaneous optimization of the maximum share of attainable direct and indirect solar utilization through heat storage in industrial operations. Multi-period Mixed Integer Non-Linear Programming (MINLP) models were developed for this purpose and account for the dynamics in the profile of heat supply and demand using discrete time intervals/periods. The resulting models are applied to an industrial case study of a dairy plant for the two distinct integration alternatives of targeting one and multiple (two) cold stream utility requirements. The design and optimization of the integrated system is implemented and solved in GAMS. The results show good prospect for solar thermal utilization in industries with low temperature applications. Sensitivity analysis shows linear increase in the average attainable heat load up to certain collector area (on case-by-case basis), after which a break point is obtained where it is observed that additional increase in collector area does not result to much increase in the obtained heat load. For the selected case study of a dairy plant, average solar output of about 75 W/m² of collector is obtained.

Keywords: Solar thermal, Solar thermal utilization, Industrial processes, Heat exchanger network, Multi-period MINLP, Optimization

Graphical Abstract



Nomenclature

Abbreviations

EC	European Commission
GAMS	General Algebraic Modelling System
GHG	Greenhouse Gas Emissions
HEN	Heat Exchanger Network
JRC	Joint Research Center
MER	Maximum Energy Recovery
MINLP	Mixed Integer Non-Linear Programming
PVGIS	Photovoltaic Geographical Information System
SHC	Solar Heating and Cooling
UP	Upper bound

Sets

DP	Set of discretised or merged daily time periods with elements $dp \in DP$
HP	Set of discretised or merged hourly time period with elements $hp \in HP$
IO	Set of inlet and outlet streams with elements $io \in IO$
MP	Set of discretised or merged monthly time period with elements $mp \in MP$
U	Set of process units with elements $u \in U$

Subsets

$IN(IO)$	Set of inlet streams to process units with elements $in \in IN$
$OUT(IO)$	Set of outlet streams from process units with elements $out \in OUT$
$PANEL(U)$	Set of solar collectors with elements $panel \in PANEL$
$PROCESS(U)$	Set of industrial processes to be integrated with elements $process \in PROCESS$
$STORAGE\ TANK(U)$	Set of heat storage tanks with elements $storage\ tank \in STORAGE\ TANK$

Parameters

a_1, a_2	Experimental constants for thermal loss coefficient of solar collector (kW/(m ² °C))
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c_p^{fluid}	Specific heat capacity of the fluid water-antifreeze mixture (kWh/(t °C))
FC_p^{stream}	Heat capacity flowrates of the stream (kW/°C)
$I_{mp,dp,hp}$	Average solar irradiation in each time period considered (kW/m ²)
M	Large enough coefficient used as a "big M" constraint for temperature feasibility in storage tank
$T_{mp,dp,hp}^{ambient}$	Average ambient temperature in each time period considered (°C)
T_{s_i}, T_{t_i}	Supply and target temperature of cold streams (°C)
T_1^1	Stream temperature before entering the targeted heater (°C)
T_1^3	Stream temperature after exiting the targeted heater (°C)
$T_{mp,dp,hp}^2$	Variable stream temperature after exiting solar heat exchanger (°C)
ΔH_{vap}^{water}	Heat of vaporization of water (kWh/t)
ΔT_{min}	Minimum temperature difference (°C)
Π_0	Efficiency factor for solar collection
ρ^{fluid}	Density of water-antifreeze mixture (t/m ³)

Continuous variables

A_{panel}	Area of solar collector (m ²)
$F_{io,mp,dp,hp}^u$	Fluid flowrates in and out of a unit for each time period (t/period)
F^{min}, F^{max}	Minimum and maximum fluid flow constraint between the solar collector – thermal storage – solar collector loop
$\dot{Q}_{backup}^{process}_{mp,dp,hp}$	Quantity of heat exchanged between backup utility and specific cold stream in the plant (kWh/period)
$\dot{Q}_{io,mp,dp,hp}^u$	Quantity of heat flow in and out of a unit for each time period (kWh/period)
$\dot{Q}_{solar}^{process}_{mp,dp,hp}$	Quantity of exchange between solar heat and specific cold stream in the plant (kWh/period)
$T_{io,mp,dp,hp}^u$	Stream temperature in and out of a unit in each time period (°C)
$T_{mp,dp,hp}^{storage\ tank}$	Temperature in the storage tank (°C)
$V_{storage\ tank}$	Volume of fluid in storage tank (m ³)

Discrete variables (0, 1)

$y_{mp,dp,hp}$	Binary variable, if 1 heat transfer fluid flows from the collector to the heat storage tank, and 0 otherwise
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4.7 Introduction

The world is currently faced with several challenges resulting from increased energy demand [1], as well as growing concern for energy security and sustainability [2] which is caused by overdependence on fossil fuel resources [3]. Efforts aimed at resolving some of the problems relating to the rising cost of energy and security of supply, are increasingly being implemented through several energy efficiency techniques [4]. However, the frequency in occurrence of emission-induced environmental problems on a global scale suggests that strategies for minimising energy usage related emissions should be prioritized in energy systems [5]. In this regard, increased deployment of clean, renewable energy resources are essential in order to achieve improved environmental quality, sustainability and a lasting solution to the global threat of climate change.

Solar energy is a type of renewable energy with considerable potential to offset a substantial amount of energy from conventional fossil fuels, which have been described as highly carbon intensive [6]. The natural availability of solar at ambient temperature levels without any mechanical work input also makes it a unique source of heat suitable for industrial applications, especially for low- and medium-temperature industrial processes. Such processes include cleaning, washing, drying, raw material processing and pre-heating operations [7]. Although industrial applications of solar heat are still scarce [8], strategic and targeted integration of solar thermal to supply industrial process heat has proven to be technically feasible [5, 9 – 11] and economically viable [12] and is expected to become one of the main sources of renewable heat for industries in the not too distant future [13].

Several applications of solar thermal in industrial processes have been reported [14]. In the Solar Heating and Cooling (SHC) project, which falls within Task 49 of the International Energy Agency (i.e. IEA-SHC), over 150 solar thermal technologies were reported to have been installed for the sole purpose of providing industrial process heat [15]. These range from direct solar utilization, which is similar to the integration method of Atkins et al. [16], to indirect utilization through an intermediate heat transfer fluid and/ heat storage tanks [17 – 19]. It also includes other forms of solar thermal collector arrangements as described by Picón-Núñez et al. [20] and Muster [21]. Regardless of the integration pattern, the main contending issue as observed in all these solar thermal applications remains the intermittent nature of solar availability. While assessing the thermal performance of 134 solar installations from the IEA-SHC projects, Bunea et al. [22] reported that less than 0.1 % of the total installed capacity of solar thermal ($100 \text{ MW}_{\text{th}}$) is being realised as energy in the cases considered.

These issues show that there is a need for further improvement of the established integration strategies in order to raise the competitive edge of industrial solar thermal utilization, especially with

respect to thermal efficiency of harvestable solar heat, as well as the entire heat supply network. This is also supported by Martínez-Rodríguez et al. [23], where the importance of improving thermal efficiency of solar collectors has been well justified.

Whereas most previous studies in this line of research have focused largely on ways to circumvent or manage the discontinuous nature of the heat supply in solar thermal utilization, the periodic variability on the demand side of integration, along with its implications for the actual heat network, and optimization of the entire system, is often neglected [24]. However, it is worth noting that simultaneously optimizing the variables involved on both the supply and demand sides of integrated solar thermal network is not a trivial task. Nonetheless, an approach that could be used to overcome this challenge in retrofit scenarios is to first target the maximum attainable quantity of thermal energy on the collector side and thereafter identify the best integration location on the network considering thermodynamic, technical and economic constraints. For grassroots designs, however, the maximum harvestable solar heat potential can be determined alongside the technical and thermodynamic requirements of the heat transfer network, with or without economic considerations, which could also vary significantly both spatially and temporarily. Since the thermal performance and efficiency of a solar network is largely dependent on ambient conditions (which are constantly changing), implementing these strategies within the integration framework of industrial solar thermal design would require analysis of the dynamic behaviour and time-variant disposition of meteorological parameters. This work considers this aspect, together with the impact of thermal storage, as important areas to be addressed at the design level in order to improve the thermal efficiency of industrial solar utilization.

Globally, several research projects have been carried out to study the potential of solar thermal in industrial processes. Atkins et al. [16] investigated the potential for integrating an evacuated tube solar system with the process heat demand of a dairy plant in New Zealand. The authors found that about 14.4 % of the annual heat demand of the dairy process could be replaced with solar thermal. Walmsley et al. [25] presented four possible options involving heat recovery loops using variable and constant temperature heat storage approaches. The authors found that using heat storage tanks as a buffer could reduce the negative impact of large swings in temperature on the heat exchanger across each of the four integration options considered. Mauthner et al. [26] reported that around 20%, 45 % and 30 % of the thermal process energy demand in three European breweries could be met by a solar thermal system. Sing et al. [27] presented the trade-off between economic feasibility, system efficiency and solar utility temperature for industrial application of solar thermal. The authors identified the stream where solar thermal integration would have the maximum impact.

Apart from these case studies demonstrating the practical application of industrial solar thermal, there are a number of research contributions from various authors dealing with the development of methods and procedures for the design (retrofit/new design) and optimization of a particular quantity of the heat target from a relatively unpredictable energy source. Nemet et al. [28] presented a framework for solar heat integration in processes that are characterised by varying demand by using time slices with an assumed constant solar thermal supply for each slice. Baniassadi et al. [29] presented a procedure for an organic distillation plant that combines heat integration techniques with basic solar engineering methods to maximize available solar heat for direct heating of cold streams within industrial processes.

Despite the numerous contributions by various authors on industrial applications of solar thermal, there are still gaps in the literature with respect to the design, operation and optimization of an industrial solar system. Such gaps are particularly common on the supply side of the network considering the intermittent nature of solar energy supply, the attainable quantity of harvestable solar heat per period and the implications of these uncertainties on the entire heat supply network. The maximum obtainable heat in any industrial solar thermal technology depends not only on the type of collector and its efficiency but also on momentary changes in the ambient conditions, particularly irradiation and ambient temperature. Thus, these important attributes, in addition to the influences of thermal storage on the network (which is also largely subject to periodic changes) should be considered in any solar integration framework in order to estimate the attainable solar heat and expected thermal performance of the entire heat network at the design level. To the best of the authors' knowledge, a comprehensive design and optimization method for direct and indirect integration of solar thermal, where all these features are accounted for in a multi-period manner, is still lacking. Therefore, a new strategy for direct and indirect integration of solar thermal with process heat demand is proposed in this study. A simultaneous mixed-integer non-linear programming (MINLP) approach that accounts for the dynamic (hourly-based) behaviour of the design features, including potential periodic changes in the amount of heat stored in the thermal storage tank, is developed in this paper. The model is developed and tested using hourly-based, meteorological data from a geographical location in Maribor, Slovenia. Two different designs are considered: a design for heating a specific industrial cold stream, and a design for heating multiple industrial cold streams.

4.8 Description of Solar Heat Network Design for Industrial Application

The problem addressed in the study can be stated as follows:

Given a set of hot and cold process streams with known supply and target temperatures, and heat capacity flowrates at specified periods of operation, the goal is to synthesize an optimally integrated heat exchanger network (HEN) involving solar thermal panels with heat storage tanks and backup hot utility.

In order to achieve the set goal, the following design questions are addressed:

- What is the maximum attainable solar heat for the process?
- How much of the utility demand of a process can be satisfied by solar thermal?
- What are the optimal sizes of the solar collector and heat storage tank required to achieve maximum attainable solar heat supply to an industrial process?

Figures 4.5 and 4.6 outline the design framework used in this paper. The Figures illustrate the flow of harvested solar heat for direct and indirect (via heat storage tank) integration with an industrial process heat network. The superstructure of this integrated design comprises three closed loops representing three possible flow directions. The loops are as follows: i) solar collector – thermal storage – solar collector; ii) solar collector – industrial process stream(s) – solar collector; and iii) thermal storage – industrial process stream(s) – thermal storage. Between the solar collector and the industrial heat network, are splitters and mixers, which allow heat sharing and mixing across the integrated system. In each of these cases, the actual measured values of hourly global horizontal irradiation and ambient temperatures in a year are used to account for the dynamic nature of solar energy. This dynamic profile is modelled using a multi-period approach.

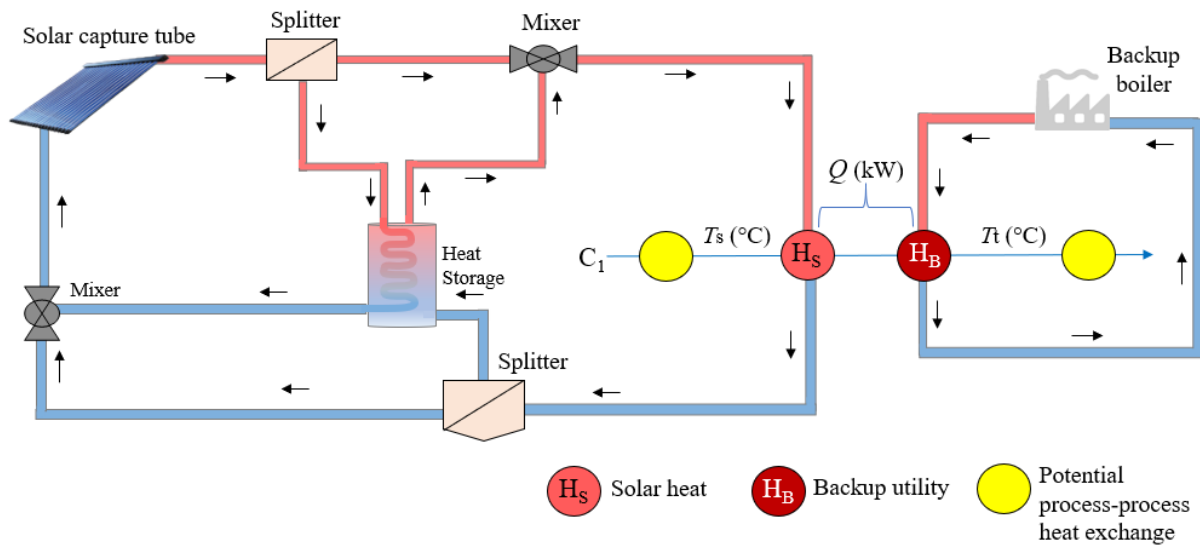


Figure 4.5: Integration of solar thermal for heating industrial process stream

Since the methodology of this paper addresses a retrofit scenario, the existing units in the industrial process whose heat demand is to be integrated with solar thermal through retrofitting are the process-process heat exchangers and backup utility heat exchanger (labelled as backup utility, H_B) in Figure 4.5. The goal is to reduce the heat load from backup utility to the cold process stream by retrofitting the existing network through inclusion of the solar thermal network. The solar network comprises a solar panel, a heat storage tank, splitters and mixers, and a solar utility heat exchanger, labelled as H_S in Figure 4.5. The heat captured by the solar thermal collector is directed to the plant through the splitter, which gives opportunities for both direct and indirect integration. Indirect integration through heat storage tank enables the utilization of stored solar heat in periods when there is no solar irradiation or as the need arises within the process. In cases where the total attainable direct and indirect solar heat may not fully satisfy the cold stream requirements in any of the specified time periods, heat from the backup utility is used to satisfy the remaining heat load through H_B .

Figure 4.6 differs from Figure 4.5 in that it involves multiple cold process streams; hence, an extra splitter and mixer are included in the solar section of the integrated network. This splitter provides an opportunity for the total available solar heat to be dispatched across more than one solar heat exchangers (H_S) within the process. The idea here is to first split the total available solar heat simultaneously across several heat demand zones within the process, before importing the balance of the heat deficit from an alternative heat source (the backup boiler) through H_B . It is worth stating that this second integration option is applicable to networks involving many process streams.

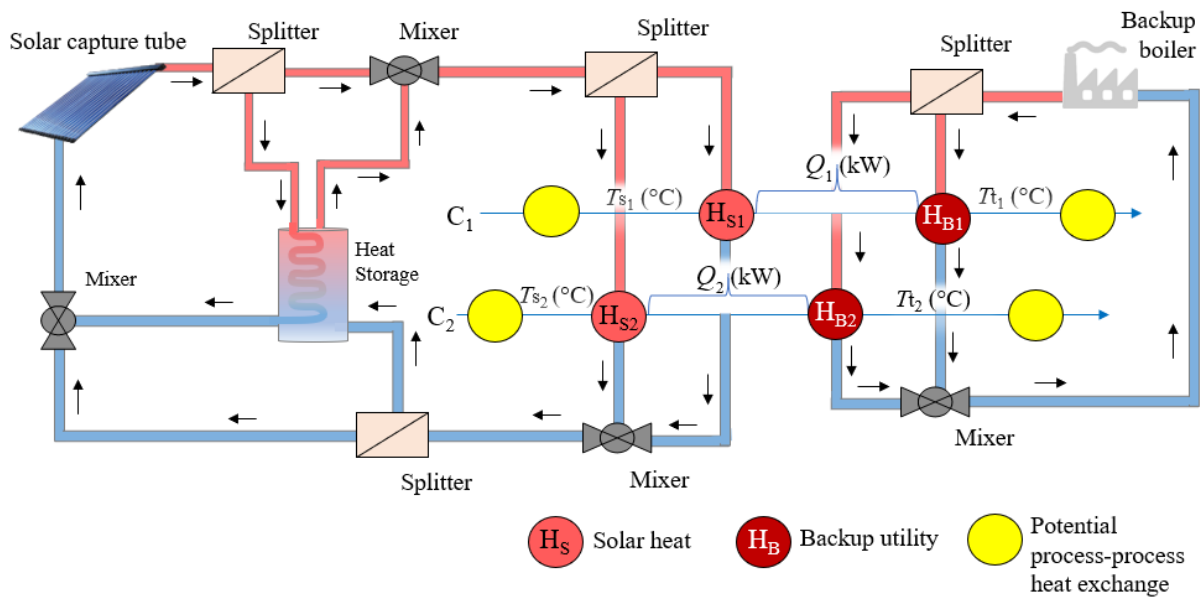


Figure 4.6: Integration of solar thermal for multiple industrial process streams

4.9 Model Development and Optimization Approach

The model and optimization framework presented in this paper seek to maximize the total solar heat output of the integrated closed-loop system as described in Figures 4.5 and 4.6. In order to implement the conceptual design and establish interaction among the participating nodes, the design building blocks are connected by a series of pipes, splitters and mixers, while the model takes into account the thermodynamic properties and material and energy balances. The main variables considered in the model are as follows: area of solar thermal collector in m^2 , volume of fluid in the heat storage tank in m^3 , attainable heat duty (in kWh/period) from solar thermal and the backup utility. As operating features of a solar thermal system are transient in nature and depend largely on the intermittent changes in meteorological conditions, the variables such as fluid flow rates, temperatures and energy flows are accounted for in the model on hourly, daily and monthly periods. The efficiencies of the solar collector are also considered as variables that are also subject to change on an hourly basis. On the other hand, the area of the solar collector and the volume of heat storage tank are also considered as optimization variables which would not change during the year. Thus, in order to account for the time-dependent uncertainties, the developed model is formulated as a multi-period mixed-integer non-linear programming (MINLP) problem. The models are solved using SBB MINLP solver in the General Algebraic Modelling System (GAMS), with the objective of maximizing the quantity of solar heat output to the network. A summary of the method is presented in Figure 4.7.

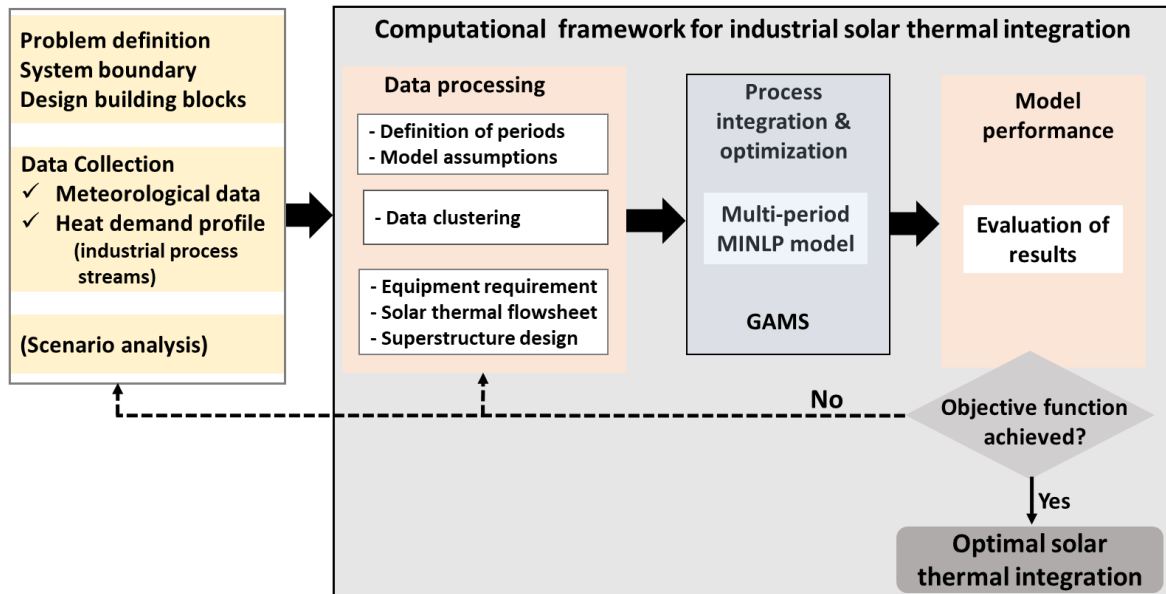


Figure 4.7: Summary of applied methodology

Firstly, the problem to be addressed is defined and the boundaries for the design framework are set. Thereafter, necessary information required as input data to the model is gathered. This includes the profile for the heat demand of the process (supply, T_s , and target temperatures, T_t , and heat capacity flowrates of hot and cold process streams, FC_p^{stream} , together with existing heat integration between the process streams), meteorological data (irradiation and ambient temperatures) of the location and specific data relating to the type of solar thermal collector, minimum approach temperatures considered in the design and the selected fluid for heat transfer within the network. In this study, hourly data for solar irradiation and ambient temperature for the selected location are considered.

In order to reduce the size of the problem, the data obtained, and the constraints formulated for the design are clustered into hourly, daily and monthly periods using model reduction techniques (see Section 4.5.1 in Supplementary material), similar to the work of Egieya et al. [32]. The remaining steps in the design methods shown in Figure 4.7 deal with the formulation of the optimization problem and corresponding constraints using the multi-period MINLP approach.

4.10 Detailed Model Formulation

In the model, parameters such as stream flowrate (t/period), temperature ($^{\circ}\text{C}$) and energy flow (kWh/period) are period dependent variables, and thus the relations are nonlinear. Additionally, the binary variable $y_{mp,dp,hp}$ is included in the model and relates the thermal energy of the heat transfer

fluid from the solar collector to the temperature of the heat storage tank, and thus the model is formulated as an MINLP problem. The following assumptions were also considered in the study:

- heat losses across the system are negligible;
- essential solar thermal integration parameters such as irradiation and ambient temperature are dynamic and change on an hourly basis;
- the minimum approach temperature between storage tank fluid and process streams is fixed;
- the content of the storage tank is assumed to be perfectly mixed, such that the temperature of the exiting stream is the same as the temperature of the fluid in storage tank.

The aim of the study is to assess the optimal potential of solar thermal utilization for industrial process heat demand, based on hourly changes in meteorological conditions at a selected location. Hence, the model is optimised with respect to the maximum attainable quantities of solar heat that can be harvested. The resulting model framework is generic, and equations are written independent of data, hence can be applied to any location or any industrial case study. The model equations are briefly presented next, while the details are described in Sections 4.S2-4.S6 in Supplementary material.

The model is formulated as a flowsheet superstructure, where global equations are used that connect the building blocks (process units). The relation for the flowrates (temperatures and heat flows) between the units is shown in Eq. (4.4):

$$F(T, \dot{Q})_{out,mp,dp,hp}^u = F(T, \dot{Q})_{in,mp,dp,hp}^{u1} \quad (4.4)$$

$$\forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP$$

where $F(t/\text{period})$ represents fluid flow rate from unit u to unit $u1$ in the integrated system for each monthly (mp), daily (dp) and hourly (hp) period. This implies that the flow rate at the outlet of unit u is equal to the flowrate at the inlet of unit $u1$ in each time period. In a similar manner, the relations for temperature and heat flow are provided, where T (°C) and \dot{Q} (kWh/period) represent the temperature and flow of heat from unit u to unit $u1$.

4.10.1 Solar collector

Based on the temperature levels of the proposed solar heat integration, an evacuated tube solar collector is considered for the design, where the temperature of the fluid leaving the collector is a direct function of the total irradiance on the collector, flowrate of the fluid and inlet temperature of the fluid entering the collector. Eq. (4.5) shows the mass balance; Eq. (4.6) describes the useful heat gain by the solar collector; and Eq. (4.7) describes the balance for heat captured by the fluid according to the monthly, daily and hourly period.

$$F_{out,mp,dp,hp}^{panel} = F_{in,mp,dp,hp}^{panel}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (4.5)$$

$$\begin{aligned} \dot{Q}_{out,mp,dp,hp}^{panel} = & A_{panel} \cdot (\Pi_0 \cdot I_{mp,dp,hp} - a_1(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient}) \\ & - a_2(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient})^2), \quad \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (4.6)$$

$$\begin{aligned} \dot{Q}_{out,mp,dp,hp}^{panel} = & F_{out,mp,dp,hp}^{panel} \cdot c_p^{fluid} \cdot (T_{out,mp,dp,hp}^{panel} - T_{in,mp,dp,hp}^{panel}), \\ & \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (4.7)$$

In Eq. (4.5), $F_{out,mp,dp,hp}^{panel}$ and $F_{in,mp,dp,hp}^{panel}$ are the outlet and inlet flowrates of heat transfer fluid from and to the solar collector. $\dot{Q}_{out,mp,dp,hp}^{panel}$ shown in Eq. (4.6) accounts for the attainable quantity of solar heat from the panel which is equal to the heat captured by the fluid as shown in Eq. (4.7), A_{panel} represents the area of the panel; c_p^{fluid} is the specific heat capacity of the solar heat transfer fluid, which is assumed to be constant to simplify the model (owing to the computational time required to solve such a dynamic system); $T_{mp,dp,hp}^c$ is the average of the inlet and outlet temperatures of the solar capture fluid in the solar collector in each time period ($\frac{T_{in,mp,dp,hp}^{panel} + T_{out,mp,dp,hp}^{panel}}{2}$); $T_{mp,dp,hp}^{ambient}$ is the ambient temperature in each time period; and $I_{mp,dp,hp}$ is the irradiation, which is also subject to change according to the monthly, daily and hourly periods; while Π_0 is the efficiency factor of the solar collector with a value of 0.764, and a_1 and a_2 are experimental constants with values of 1.53 W/(m²·K) and 0.0003 W/(m²·K), as adopted from Atkins et al. [16] and Isafiade et al. [17].

4.10.2 Heat storage tank

Heat storage is incorporated into the design to provide an opportunity for the accumulation of solar heat over time, to be used later. Heat transfer takes place through the walls of the heating coil as hot solar fluid flows through the coil in the tank and back to the solar collector in a closed loop. A schematic representation of the heat storage tank is shown in Figure 4.8. Considering *IN-1*, parameters F , T and \dot{Q} represent the variables for the solar heat transfer fluid, which comes from the solar collector to the tank; and *IN-2* is used to represent the variables associated with the heat transfer fluid flowing to the process from the storage tank. *OUT-1* represents the variables associated with heat supply from the

heat storage tank to the process (which implies that $T_{out-1,mp,dp,hp}^{storage\ tank}$ is the temperature of the fluid flowing out of the tank and transferring heat to the process, and is assumed to be the same as the temperature inside the tank $T_{mp,dp,hp}^{storage\ tank}$ in every period). *OUT-2* represents the variables associated with solar fluid returning to the collector from storage tank in each time period (see also Figures 4.5 and 4.6). The flows in and out of the heat storage tank from the solar collector (streams *IN-1* and *OUT-2*) and from the process cold stream(s) (streams *IN-2* and *OUT-1*) should thus be equal.

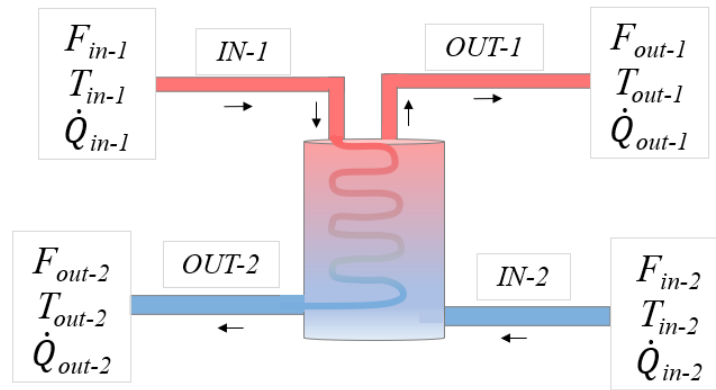


Figure 4.8: Schematic representation of the heat storage tank

The general energy balance equation for the storage tank is presented in Eq. (4.8), which shows that energy accumulated in the tank in each period is equal to energy added to the tank minus energy leaving the tank.

$$\begin{aligned}
 & V^{storage\ tank} \cdot c_p^{fluid} \cdot \rho^{fluid} \cdot \Delta T_{mp,dp,hp}^{storage\ tank} \\
 &= \dot{Q}_{solar,mp,dp,hp}^{storage\ tank} + F_{in-2,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{in-2,mp,dp,hp}^{storage\ tank} \\
 &- F_{out-1,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{out-1,mp,dp,hp}^{storage\ tank} \\
 &\forall mp \in MP, dp \in DP, hp \in HP
 \end{aligned} \tag{4.8}$$

where $V^{storage\ tank}$ is the volume of fluid in the tank, ρ^{fluid} is the density of the heat storage fluid which is assumed to be constant, and $\Delta T_{mp,dp,hp}^{storage\ tank}$ is the change in temperature of the fluid in the tank in each time period. Heat transferred to the tank from hot solar fluid, $\dot{Q}_{solar,mp,dp,hp}^{storage\ tank}$, is represented by the following equation:

$$\begin{aligned}
Q_{solar}^{storage\ tank}_{mp,dp,hp} &= F_{in-1,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{in-1,mp,dp,hp}^{storage\ tank} - F_{out-2,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \\
&\cdot T_{out-2,mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP
\end{aligned} \tag{4.9}$$

The temperature of fluid in the storage tank is calculated as the temperature of fluid in the tank in the previous time period (which is modelled with circular or equilibrium leads and lags; McCarl et al. [33]) plus the change in temperature of the fluid in the tank for each time period. This is because the system is modelled to be in continuous operation, such that there is always a momentary temperature level of fluid in the tank before it receives another temperature lift from the hot solar fluid passing through the coil in the tank across different operational periods:

$$\begin{aligned}
T_{mp,dp,hp}^{storage\ tank} &= \bigcup_{(mp_k)_{k \in K, k=1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp--1,dp--1,hp--1}^{storage\ tank} \\
&+ \bigcup_{(hp_k)_{k \in K, k>1}} T_{mp,dp,hp-1}^{storage\ tank} + \bigcup_{(dp_k)_{k \in K, k>1} \wedge (hp_k)_{k \in K, k=1}} T_{mp,dp-1,hp--1}^{storage\ tank} \\
&+ \bigcup_{(mp_k)_{k \in K, k>1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp-1,dp--1,hp--1}^{storage\ tank} \\
&+ \Delta T_{mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP
\end{aligned} \tag{4.10}$$

In Eq. (4.10) $T_{mp--1,dp--1,hp--1}^{storage\ tank}$ refers to the temperature in the storage tank at the beginning of January (first hour, first day and first month) which equals the temperature in the storage tank in the last hour of December (last hour, last day, last month). Similarly, $T_{mp,dp,hp-1}^{storage\ tank}$ refers to the temperature in the storage tank for each month and day, where the hour is not the first hour of the day, $T_{mp,dp-1,hp--1}^{storage\ tank}$ refers to the temperature in the storage tank for each first hour of the day, while the day is not the first day of the month, and $T_{mp-1,dp--1,hp--1}^{storage\ tank}$ represents the temperature in the storage tank for each first hour in a day and first day in a month for any month except January (first month).

To ensure that the tank fluid is heated only when the tank temperature is lower than the temperature of the heat transfer fluid returning to the solar collector (i.e. $T_{out-2,mp,dp,hp}^{storage\ tank}$) minus ΔT_{min} (minimum temperature difference), a constraint is introduced on the temperature in the tank. This constraint

should, however, be relaxed when there is no heat transfer (no flow) to the tank from hot solar fluid. Eq. (4.11) describes the concept of the big M constraint introduced for the temperature in the storage tank, with M being a sufficient scalar and the binary variable $y_{mp,dp,hp}$, which denotes the existence of the heat transfer fluid flow in the closed loop heat storage tank – solar collector. If the binary variable is 1, the fluid flow should be between a minimum (F^{min}) and a maximum value (F^{max}), as shown in Eq. (4.12); otherwise, a value of 0 is assigned.

$$T_{mp,dp,hp}^{storage\ tank} \leq T_{out-2,mp,dp,hp}^{storage\ tank} - \Delta T_{min} + M \cdot (1 - y_{mp,dp,hp}), \quad (4.11)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$F^{min} \cdot y_{mp,dp,hp} \leq F_{in-1,mp,dp,hp}^{storage\ tank} \leq F^{max} \cdot y_{mp,dp,hp}, \quad (4.12)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

4.10.3 Industrial process

As stated earlier, the quantity of solar heat exchanged with the process streams is linked to the industrial cold stream(s) by enabling a switch between direct or indirect solar integration. Using heat integration techniques [34], the external utilities requirement of the process can be pre-determined (i.e. after maximizing the available heat transfer between hot and cold process streams). Thereafter, the attainable direct and indirect solar heat is passed to the HEN process through the mixer or splitter (in the case of multiple process streams; see Fig. 4.6), before including other resources from backup utilities. In the following, the balances are presented for heating a single cold industrial stream, while the balances for multiple cold streams are presented in Section 4.56 in the Supplementary material.

The following equation describes the heat balance for the process, $\dot{Q}_{mp,dp,hp}^{process}$, which is obtained by the solar and backup utilities:

$$\dot{Q}_{mp,dp,hp}^{process} = \dot{Q}_{mp,dp,hp}^{solar,process} + \dot{Q}_{mp,dp,hp}^{backup,process} \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (4.13)$$

Heating of a single process stream by solar and additional heating by backup utility to reach its final temperature is shown schematically in Figure. 4.9.

$$\dot{Q}_{solar}^{process}_{mp,dp,hp} = F_{in-1,mp,dp,hp}^{process} \cdot c_p^{fluid} \cdot (T_{in-1,mp,dp,hp}^{process} - T_{out-1,mp,dp,hp}^{process}), \quad (4.16)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{backup}^{process}_{mp,dp,hp} = F_{in-2,mp,dp,hp}^{process} \cdot \Delta H_{vap}^{water}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (4.17)$$

In Eq. (4.16), $T_{in-1,mp,dp,hp}^{process}$ and $T_{out-1,mp,dp,hp}^{process}$ are the inlet and outlet temperatures of the heat transfer fluid from solar (mixer) to process HEN and from HEN back to the solar panel or storage tank. For the backup utility, it is assumed that the difference between inlet and outlet temperatures of the utility from the boiler to the process and from the process to the boiler, $T_{in-2,mp,dp,hp}^{process}$ and $T_{out-2,mp,dp,hp}^{process}$ is 1°C.

To account for changes in the temperature level of the cold process stream as it flows across the plant, variables T^1 , $T_{mp,dp,hp}^2$ and T^3 are defined, and these represent the inlet temperature of the cold stream from point 1 (before entering the heater targeted for solar heat integration), the intermediate temperature level of the cold stream at point 2 (after exiting the heater) and the final temperature of the cold stream at point 3 (after exchanging heat with the backup utility in the second heater), see also Figure 4.9. Temperatures T^1 and T^3 are assumed to be known, while $T_{mp,dp,hp}^2$ changes on an hourly-basis, depending on the heat available from solar. In the model, the equations accounting for feasibility of temperature changes across the process should be provided.

To calculate the variables for the backup utility and intermediate temperature, the following constraint is included, where $FC_p^{cold stream}$ is the heat capacity flowrate of the cold stream to be heated with solar and backup utilities:

$$\dot{Q}_{backup}^{process}_{mp,dp,hp} = FC_p^{cold stream} \cdot (T^3 - T_{mp,dp,hp}^2), \quad (4.18)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

4.10.4 Objective function

The integrated design for maximum attainable solar thermal utilisation in industrial operations is implemented with the objective of maximizing the solar heat output to the network in a year. To achieve the maximum solar integration with the minimum area of solar collectors and the fluid capacity of the storage tank, small weightings for the collector area and storage tank capacity are included, as shown in Eq. (4.19):

$$\max \left(\sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in hP} \dot{Q}_{solar_{mp,dp,hp}}^{process} - 0.001 \cdot A_{panel} - 0.01 \cdot V^{storage\ tank} \right) \quad (4.19)$$

4.11 Case Study

Using a reference point location in Slovenia (near Maribor, see Figure 4.10) to retrieve the needed meteorological data on hourly solar irradiation and ambient temperature for the whole year, the model was applied to an example selected from the literature [16] according to the two proposed integration options shown in Figures 4.5 and 4.6 and described in more detail above.

The heat transfer fluid used in this paper is 50/50 water-ethylene glycol with a specific heat capacity of 0.9478 kWh/(t °C), density of 1.05 t/m³ and a boiling point of 106 °C.

The EC JRC PVGIS project database [35] was used to obtain meteorological data of the selected location with coordinates 46.552 N: 15.676 E Latitude and Longitude, and an elevation of 267 m above sea level. Since Slovenia lies in a mixed continental-Alpine-sub-Mediterranean temperate zone, the impact of heat storage and backup boiler is logically demonstrated in this paper, especially during cloudy periods and the winter months when solar irradiation is limited, and ambient temperature is low.

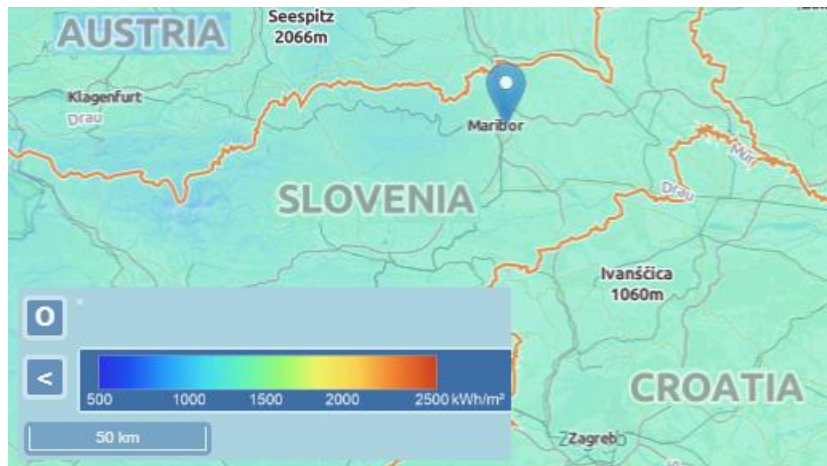


Figure 4.10: Location of the case study (from [36])

The data for the selected location were obtained for all the hours of 2016 (which is the most recent year for which data is available as of the study time). Figures 4.11 and 4.12 show the examples of irradiation on an hourly basis in the location considered for specific months and days in the winter and summer months.

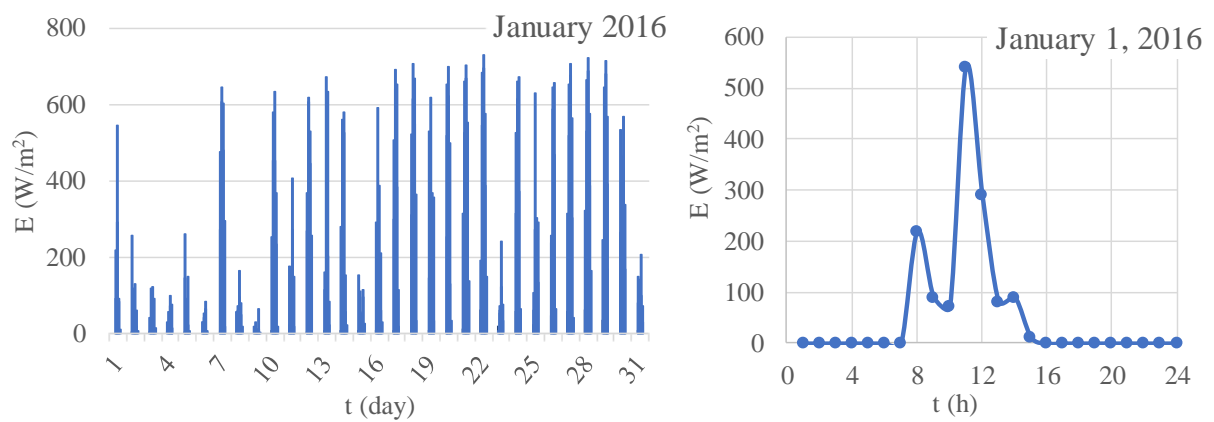


Figure 4.11: Monthly and daily hourly irradiation for a typical winter month (January 2016)

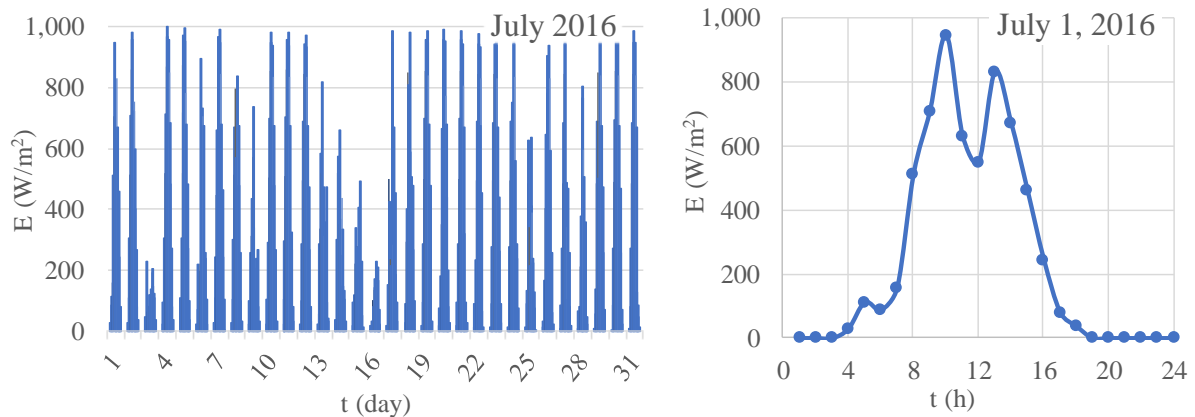


Figure 4.12: Monthly and daily hourly irradiation for typical summer month (July 2016)

The industrial process example adopted in this study is that of a milk powder plant having seven process streams (3 hot and 4 cold streams) [16]. The stream data for the process hot and cold streams for the example are shown in Table 4.1 (as adopted from [16]). The corresponding HEN is presented in Figure 4.13, while the net heat flow, temperature regimes and energy targets of the process are shown on the Grand Composite Curve in Figure 4.14.

Heat integration techniques [34] are first implemented to determine the amounts of external utility required by the process and to establish optimum process-to-process heat transfer within the HEN. An expanded transshipment model [36], which is a structural optimization method in process synthesis, was used to determine the stream matches and their heat transfer for maximum energy recovery (MER). Furthermore, modified stage-wise superstructure formulation of HEN [37] for multiperiod operation and utility selection at each stage [38] was applied with fixed heat contents as obtained from the expanded transshipment model [36] to obtain the HEN as shown in Figure 4.13. In this Figure, the external heating utility is needed in the process that is proposed to be provided by solar thermal and utility from the backup boiler.

Table 4.1: Stream data for the milk powder plant (after [16])

Stream Description	Stream Type	Supply Temperature (°C)	Target Temperature (°C)	Heat Capacity Flow Rate (kW/°C)
Skim milk	Hot	45	10	110.6
Cream A	Hot	80	10	4.8
Cow water	Hot	45	15	118.5
Raw milk	Cold	10	43	115.8
Cream	Cold	45	80	4.8
Cleaning (CIP)	Cold	15	80	25.1
Dryer feed (product)	Cold	48	80	21.0

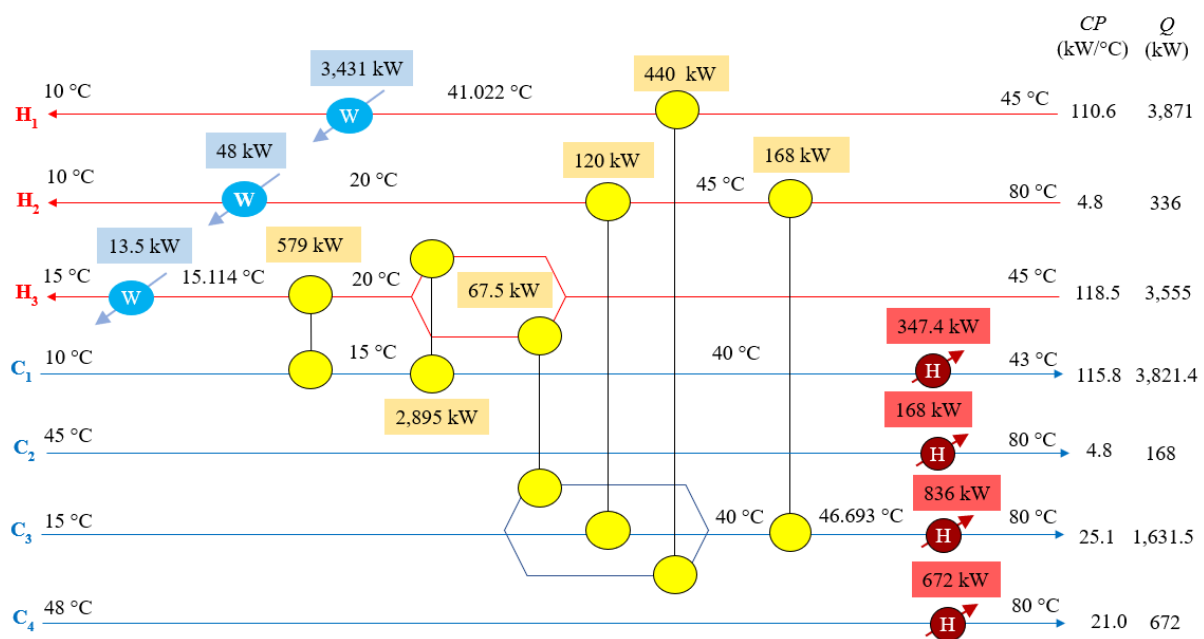


Figure 4.13: HEN with stream-stream matches and external utility requirements on each stream

Two scenarios are proposed for the integrated solar thermal design. The first scenario targets hot utility requirements of one industrial cold stream, while the second scenario targets hot utility requirements of two industrial cold streams. It should be noted that a similar procedure could be applied for targeting any number of cold streams (i.e. their hot utility consumption) in any industrial HEN.

- *First scenario:* Since stream C_3 has the highest hot utility consumption of all the cold streams (836 kW as shown in Figure 4.13), this hot utility exchanger is selected as a candidate unit for a reduction in external utility consumption. The temperature range of C_3 in this segment lies between 46.693 °C and 80 °C with a heat capacity flowrate of 25.1 kW/°C.
- *Second scenario:* Two cold streams are selected as candidates for solar heat integration. The first is C_3 while the second is C_1 . In the case of C_1 , an external hot utility of 347.4 kW is required to satisfy the heat demand within the temperature range of 40 to 43 °C with a heat capacity flowrate of 115.8 kW/°C (see Figure 4.13). It should be noted however that any set of cold streams could be selected as candidates for solar heat integration, and C_1 and C_3 were selected for demonstration purposes only.

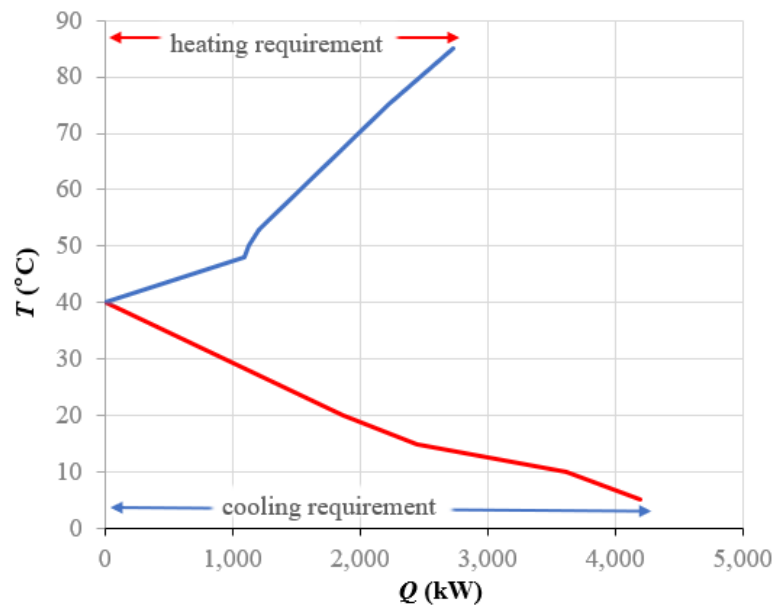


Figure 4.14: Grand Composite Curve for the case study

Since the results from the model strongly depends on the area of solar collectors, the model investigates different panel sizes, A_{panel} , where the upper bound of A_{panel} (A_{panel}^{UP}) was in the range between 500 m² to 10,000 m². In addition, upper bounds were set on flowrates ($F_{io,mp,dp,hp}^{u,UP}$) of 100 t/h and on the heat load ($Q_{io,mp,dp,hp}^{u,UP}$) of 5,000 kW.

Since the model is highly nonlinear and considers hourly, daily and monthly time dimensions, it presents certain difficulties to be solved for all the hours in a year. Thus, model reduction techniques as explained in Section 4.S1 of the Supplementary material, were applied to reduce the number of time periods in a year and thus reduce the computational efforts and model sizes. The twenty-four hours in a day were discretized into four periods of unequal duration according to the general trend of solar irradiation: H1: 9 pm – 7 am, H2: 8 am – 10 am, H3: 11 am – 5 pm and H4: 6 pm – 9 pm. The

29 – 31 days of the month were discretized into one period, while 12 months in the year were not discretized. Thus, 4 hourly, 1 daily and 12 monthly periods were considered in the examples.

4.12 Results and Discussion

The multi-period MINLP models were solved with a 1% optimality gap on Intel® Core™ i7-8750H CPU on 2.20 GHz 2.21 GHz processor with 8 GB installed RAM. The model for the first scenario consists of 4,504 single equations, 4,755 single variables and 48 binary variables and the solution was obtained in 44 minutes, while the model for the second scenario consists of 7,240 single equations, 7,395 single variables and 48 discrete variables and was solved in 80 minutes. The solution time for all other models ranged between 44 and 400 minutes, i.e. for both scenarios where A_{panel} varied between 500 m² and 10,000 m² (main results of scenarios are shown in Tables 4.2 and 4.3).

First, a series of cases was solved to analyse the influences of different maximum sizes of solar collectors (A_{panel}^{UP}) on available heat load from solar and raised temperature of the targeted stream segment(s) for the two integration options. Tables 4.2 and 4.3 show the results for the first and second scenarios.

Table 4.2: Main results for the first scenario for different sizes of solar collector*

Area of panel (m ²)	Volume of fluid (m ³)	Average heat load from solar (kW)	Average temperature achieved with solar (°C)
500	390.9	43.283	48.417
1,000	1,322.86	83.47	50.019
1,500	4,104.66	113.16	51.201
2,000	3,160.2	141.968	52.349
3,000	4,919	246.479	56.513
4,000	8,702.7	322.385	59.537
5,000	11,178.6	331.455	59.898
6,000	24,701.7	461.922	65.096
7,000	23,859.2	491.047	66.257
8,000	37,625.3	485.167	66.022
9,000	35,078.2	522.188	67.497

*The values when area of panel is greater than 9,000 m² are not shown as poor locally optimal solutions were obtained

The results include consideration of different sizes of solar collector (area of panel is always equal to A_{panel}^{UP}), and the corresponding values for the volume of fluid in the storage. Other results shown include the average quantity of heat that is ultimately exchanged between the solar fluid and the cold process streams, and the average temperature of the cold streams from where the backup utility will be required to take it to the target temperatures. Implementing this for the second case study, where more than one cold stream segment (heater) is targeted, the results for average heat load and average temperature achieved with solar thermal presented in Table 4.3 are shown for each targeted cold stream segment, C_1 and C_3 , while in Table 4.2 they are shown for the cold stream segment C_3 only (see also Figure 4.13). Linear increase in the average attainable heat load and volume of heat transfer fluid is shown up to 4,000 - 5,000 m² of collector for the case of single cold stream, and up to 8,000 m² for the case of multiple cold streams, and beyond that area, it is observed that additional increase in collection area and heat transfer volume do not increase the obtained heat load that much. It should be noted that the results (volume of fluid, average heat loads from solar and average achieved temperatures of the streams) do not exhibit a linear relationship with the increase in solar collector sizes. Such relationship is due to the significantly nonlinear nature of the problem and thus suboptimal local maxima obtained, which could also be a poor local maximum.

Table 4.3: Main results for the second scenario for different sizes of solar collector*

Area of panel (m ²)	Volume of fluid (m ³)	Average heat load from solar (kW)		Average temperature achieved with solar (°C)	
		C_1	C_3	C_1	C_3
		500	1,228.0	31.069	14.334
1,000	1,673.3	39.718	50.512	40.343	48.706
1,500	1,565.7	56.682	77.623	40.489	49.786
2,000	2,185.3	71.451	103.639	40.617	50.822
3,000	7,859.0	122.050	136.330	41.080	52.124
4,000	9,534.2	155.606	154.965	41.344	52.867
5,000	8,587.5	139.925	279.023	41.208	57.809
6,000	17,100.1	130.275	333.560	41.125	59.982
7,000	20,962.8	98.912	405.324	40.854	62.842
8,000	25,043.9	149.575	457.076	41.292	64.903

*The values when area of panel is greater than 8,000 m² are not shown as poor locally optimal solutions were obtained

The solution to the models identifies the transient changes in flowrates, temperatures and heat duties of the streams within the integrated system across each period. The total attainable solar thermal available to the process can thus be predicted for every hour in a year. Figures 4.15 and 4.16 are illustrative examples of the results obtained for typical months of January and July for the first scenario (C₃ is targeted) when maximum area of solar collector is 5,000 m² (average considered area). The Figures depict the performance of the system in period 3 of each of the months (i.e. M1, D1, H3 and M7, D1, H3).

There is no flow from the solar collector to the heat storage tank over the period displayed in Figure 4.15. This condition represents the case where the big M constraint (see Eq. (4.11) and Eq. (4.12)) is relaxed in the model. This condition will most likely occur on cloudy days or periods when the maximum attainable solar thermal from direct solar integration is barely enough to satisfy the heat requirement of the process, thus pushing all harvested heat into the process. According to the heat integration analysis, the hot utility required to lift cold stream 3 to its target temperature of 80°C is 836 kW. In period 3 (11 am – 5 pm) in January, approximately 485.65 kW of this energy is provided by solar, while the balance of the heat deficit (350.35 kW) is supplied by the backup boiler, as shown in Figure 4.15.

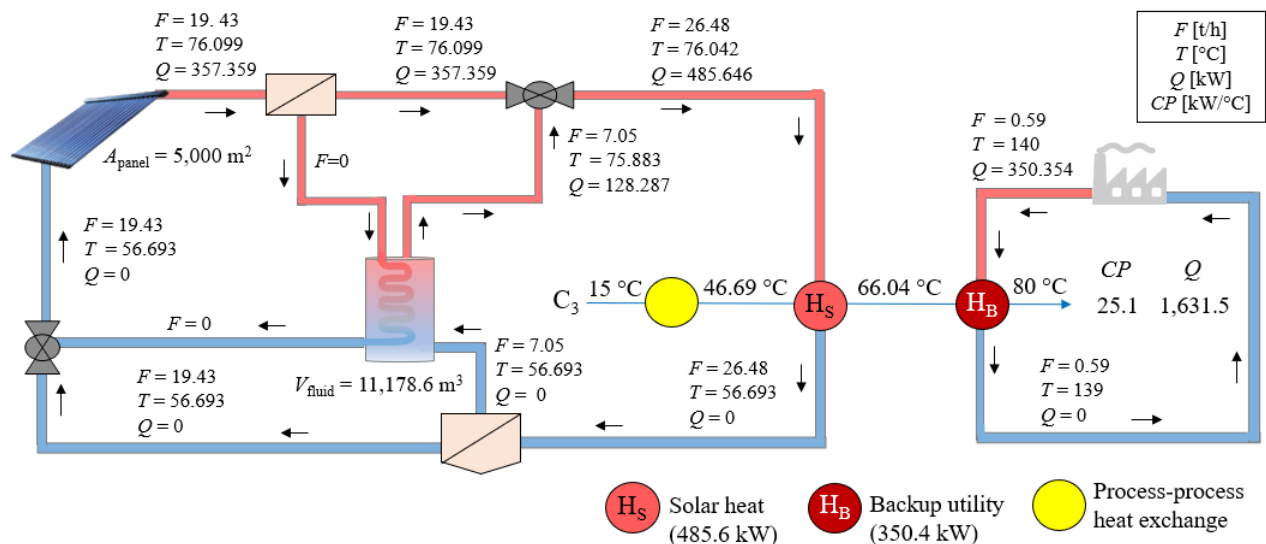


Figure 4.15: Values of variables for the first scenario with a solar collector area of 5,000 m² for time period M1, D1, H3 (January, 11 am – 5 pm)

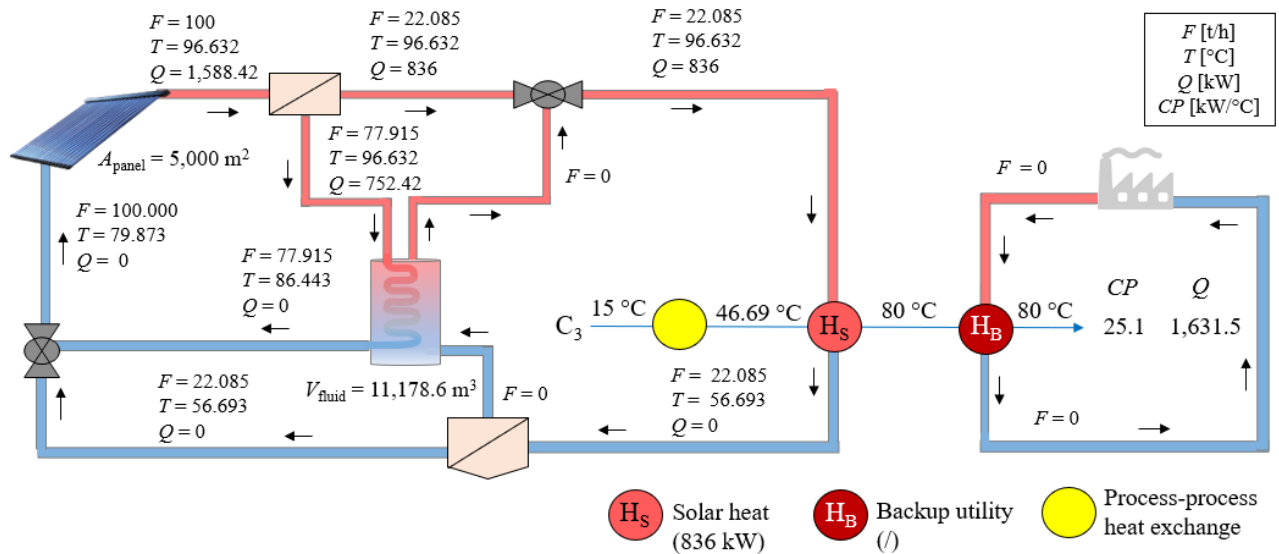


Figure 4.16: Values of variables for the first scenario with a solar collector area of 5,000 m² for the period M7, D1, H3 (July, 11 am – 5 pm)

On the other hand, the big M constraints are sustained in the case of a non-zero flow condition as obtained in July (Figure 4.16). Out of the 1,588.42 kW thermal energy obtained from solar, 752.42 kW (47.4 %) goes to heat storage for onward dispatch to the process at later time, and 836 kW (52.6 %) goes directly to the process for heating the process stream, C₃, as shown in Figure 4.16. Thus, all the external hot utility required by the cold stream could be completely met by solar in period 3 of July. In such periods of the year, once the ambient conditions are favourable and attainable solar thermal is sufficient to provide the heating required by the process, the flow between collector and storage is activated.

Figures 4.17 and 4.18 are examples of the results obtained for the second scenario where opportunity exists for the available solar thermal to split across several cold stream segments and exchange heat with more than one cold stream. The example is drawn from the same periods in the months of January and July (i.e. M1, D1, H3 and M7, D1, H3) when maximum area of solar collector is 5,000 m², as for the first scenario. Regardless of the ability of the solar heat to be able to split across several heaters, heat transfer and thermodynamic conditions should be satisfied as well, depending on the temperature level of the process and the profile of heat demand per period. This explains why even with the ability to split; no supply of solar heat occurs to cold process C₁ in Figure 4.17. This is unlike the case described in Figure 4.18 where the total available solar heat of 1,119.47 kW is shared as 347.4

kW and 772.07 kW among cold streams C₁ and C₃ before each of them obtains the balance of heat deficit from backup utility.

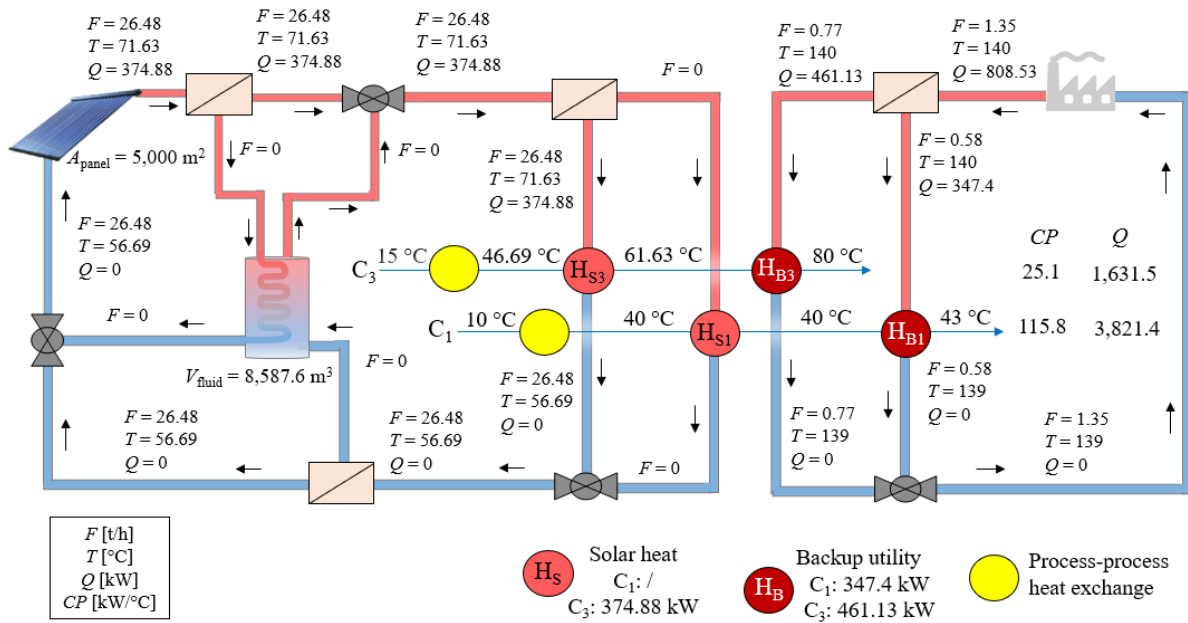


Figure 4.17: Values of variables for the second scenario with a solar collector area of 5,000 m² for the period M1, D1, H3 (January, 11 am – 5 pm)

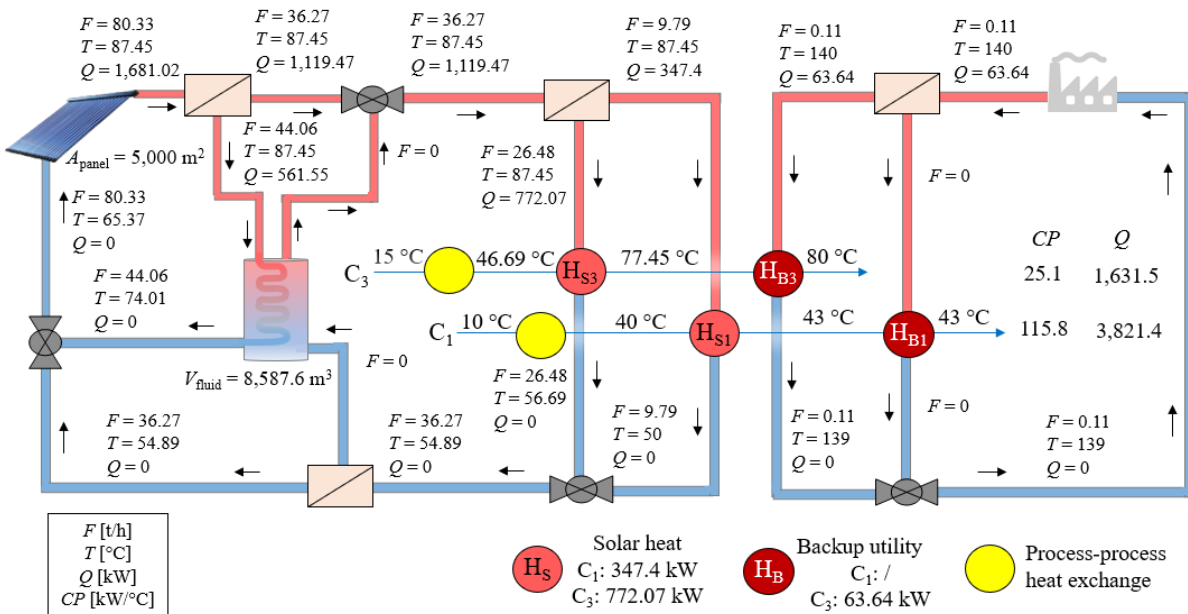


Figure 4.18: Values of variables for the second scenario with a solar collector area of 5,000 m² for the period M7, D1, H3 (January, 11 am – 5 pm)

Furthermore, the availability of both direct and indirect solar thermal across the discretized time periods were analysed to visualise the potential of solar heat supply to the process. The results of such analysis for the first scenario are presented in Figures 4.19 to 4.21 for collector sizes of 500 m², 5000 m² and 10,000 m².

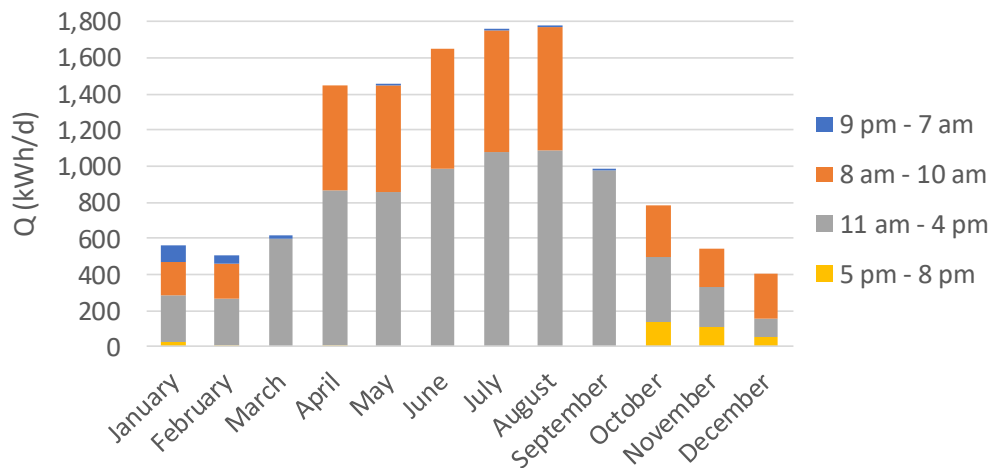


Figure 4.19: Solar heat supply to the cold stream C₃ with a solar collector area of 500 m²

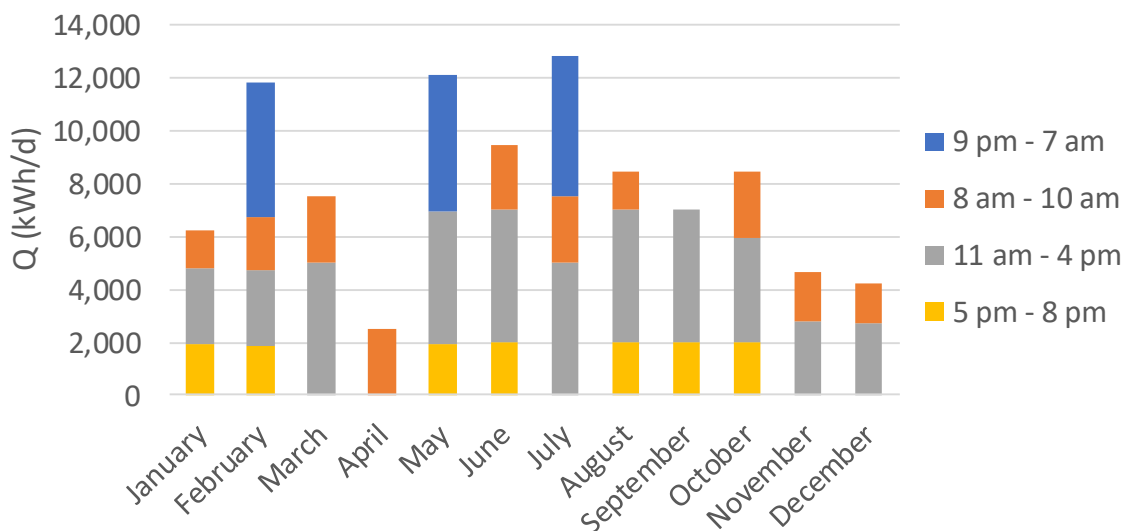


Figure 4.20: Solar heat supply to the cold stream C₃ with a solar collector area of 5,000 m²

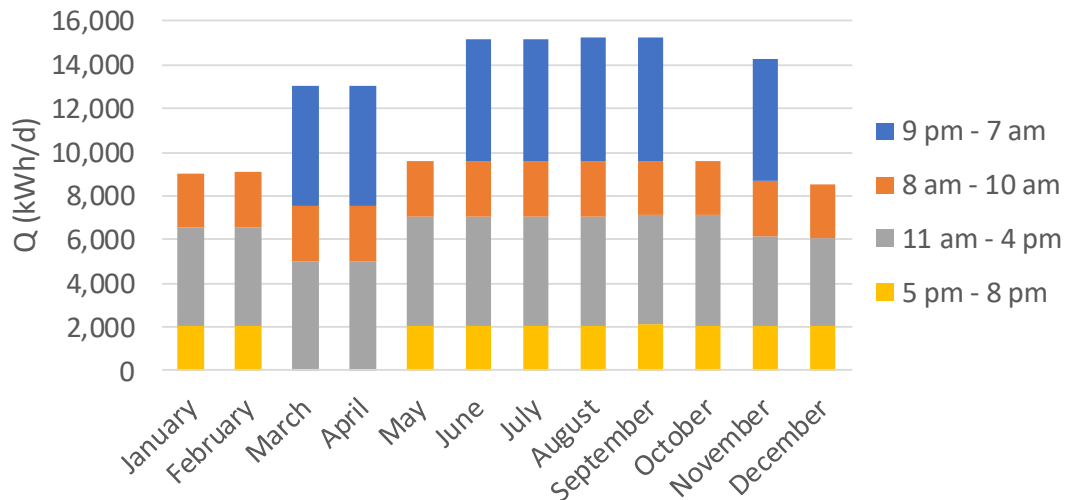


Figure 4.21: Solar heat supply to the cold stream C_3 with a solar collector area of 10,000 m²

From the Figures, the potential of solar heat supply increases with the increase in collector sizes, especially for the period between 11 am and 4 pm. Also, from the patterns of solar availability shown in Figures 4.20 and 4.21, it can be observed that more opportunities for solar utilization are given to period 1 (H1) of the day which is from 9 pm to 7 am. This is because as the size of the solar collector becomes larger, the system can push more excess solar heat to the storage which increases the potential of indirect solar utilization in the process even at night. Hence, the influence and importance of heat storage in solar thermal utilization is more significant when the collector is big enough to harvest more heat than required by the process over the peak periods.

While some of the available solar heat is supplied to the process through direct integration, part of the total solar potential is supplied through indirect integration via heat storage (especially during H1 (9 pm – 7 am) across the year and during H4 (5 pm – 8 pm) in the winter months). Such solar heat supplies (i.e. from direct and indirect integration) are merged together and captured as daily solar availability for each month in the year, as shown in Figures 4.19 to 4.21. It should be noted also that only 1 daily period is assumed for practical reasons explained above, and thus in each day of the month such a solar heat supply is obtained.

Some interesting situations can also be observed from the results, especially from Figure 4.20 for the month of April. A significantly lower quantity of direct solar heat supply is obtained than in all other months. This can be attributed to the fact that during this month, a greater fraction of the harvested solar heat is pushed into storage tank to raise the temperature level of the heat storage. These features can be seen in Figures 4.22 and 4.23, which show the solar heat supply to the storage tank

and temperature of the fluid in the storage tank for each period considered when the solar collector area is 5000 m².

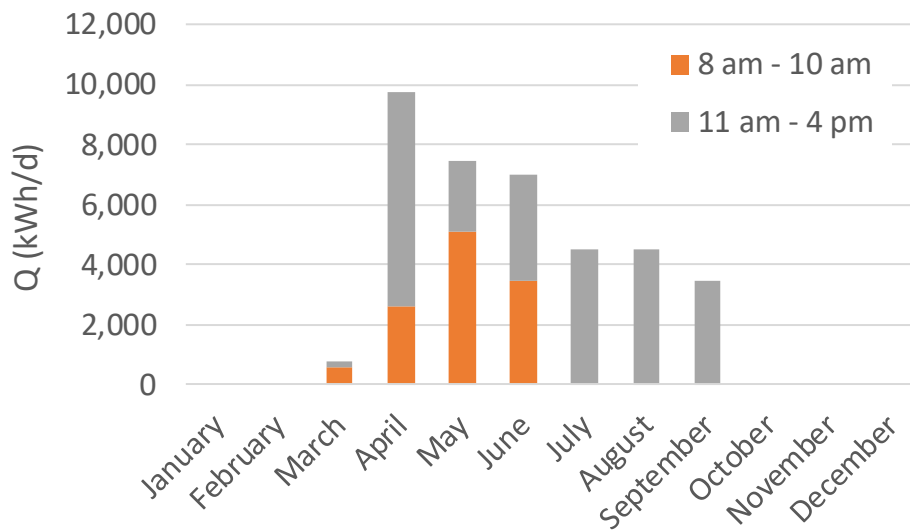


Figure 4.22: Solar heat supply to the storage tank when the solar collector area is 5000 m²

Figure 4.22 shows that in April the highest solar energy content is transferred to the fluid in the storage tank, mainly during period H3 (11 am – 4 pm). Some of the solar heat is also transferred between May and September, especially during period H3 (11 am – 4 pm) when the solar irradiation is the highest, while less in the morning hours during period H2 (8 am – 10 am). Another observation from Figure 4.22 is that no energy from solar is stored in the storage tank during the colder months (October - March). A similar pattern can be observed in Figure 4.23, which shows that the highest temperature rise in the storage tank occurs in the month of April, and some additional rise occurs till September, when the temperature in storage tank is the highest (76.8 °C). On the other hand, the temperature drops from October to March, with the largest decrease in the coldest month of January. Thereby, the lowest temperature (75 °C) in the storage tank occurs in February.

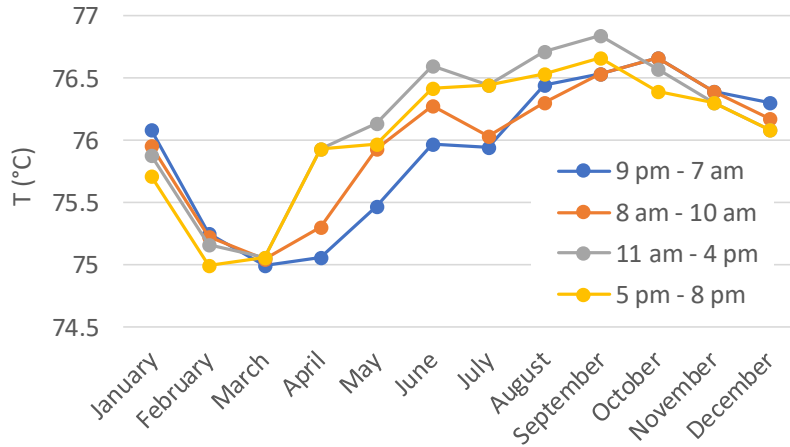


Figure 4.23: Temperature of the fluid in the storage tank when the solar collector area is 5000 m²

4.13 Conclusions and Recommendations

In this paper, a detailed procedure for integrating solar thermal with the heat demand of an industrial process has been developed and presented. The method, which is based on multi-period MINLP formulation, considers the dynamic behaviour of solar supply by accounting for the hourly-based values of meteorological parameters such as irradiation and ambient temperature. The method allows simultaneous optimization of direct and indirect (through heat storage) solar heat utilisation according to the formulated discrete time intervals based on hourly, daily and monthly time periods. Two design alternatives were presented, and a case study involving heat integration analysis of a milk powder plant is solved for the two scenarios.

The results obtained identified the dynamic changes in the flowrate, temperature and heat duty of both the direct and indirect integrated system at hourly, daily and monthly time intervals with substantial hot utility replacement and great potential for solar heat storage. In the first integration scenario, the results show that an average heat load of between 43.3 kW and 522.2 kW is attainable from collector sizes between 500 m² and 9,000 m². These values represent 5.2% and 62.5% of the total heat load required by the cold stream (C₃) to attain its target temperature. The temperature of this cold stream is increased from 46.69 °C to a maximum value of 67.5 °C with solar, and backup utility is used to heat the stream further, up to 80 °C. To achieve these temperature levels with solar (i.e. up to 67.5 °C), the volume of the storage tank should lie between 390.9 m³ and 37,625 m³. Sensitivity analysis indicated that, up to a collector area of 6,000 m², a linear increase in attainable heat load is observed, and beyond this size, the increase is less significant. Also, the volume of heat transfer fluid generally exhibits a linear relationship with the area of panel, while relationship with average attainable heat load is exponential (for collector area up to 9,000 m²).

For the second scenario, where hot utility requirements of multiple cold streams (i.e. C_1 and C_3) were targeted for solar thermal integration, an average heat load of between 45.4 kW and 606.7 kW is attainable representing 3.8% and 51.3% of heat required by the cold streams (i.e. for the case when area of collector(s) is 500 m² and 8,000 m²). The volume of the storage tank obtained for the indirect integration in the second scenario ranges between 1,228 m³ and 25,044 m³. Again, linear increase in the average attainable heat load (and the volume of heat transfer fluid) is obtained up to collector area of about 8,000 m². Additional increase in collector area again does not increase much the obtained heat load.

These results show that the two suggested integration possibilities are technically feasible and justified. In the case of larger industrial installations, using wider rooftops to yield a larger collector area would increase the solar heat output, thereby may provide an opportunity for offsite utilization in other commercial or residential buildings in close proximity.

The inclusion of sustainability criteria as an objective of the model could improve the robustness of the resulting method in that trade-offs are established among the many variables involved in the face of the multi-period profile of heat demand and supply. As MINLP model for such relatively small system requires significant computing efforts and provides only locally feasible (suboptimal) solutions, the use of metaheuristic algorithms (“modern optimisation techniques”) or a combination of classical and modern optimisation techniques, have the prospects of being more efficient in solving larger systems or systems with more time periods.

Future work will involve the afore-mentioned fields, such as sustainability criteria and metaheuristic algorithms, and linking the industrial heat supply network with residential heat demand to form an integrated system. Other issues that will be considered in future work include solar thermal integration with grassroot HENs, solar thermal integration for higher temperature industrial operations (evacuated tubes, molten salts heat transfer fluid, etc.), detailed retrofit scenarios where existing process-to-process heat exchangers are included in the optimization, heat pump integration to further increase the potential of solar thermal, especially in lean periods, and detailed analysis of the effects of long-term heat storage while considering heat losses.

4.14 Acknowledgements

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Appendix 4A: Supplementary Material

Integrated Design for Direct and Indirect Solar Thermal Utilization in Low Temperature Industrial Operations

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This supplementary material consists of:

- Part A – Nomenclature
- Part B – Detail mathematical model
- Part C – References

Part A - Nomenclature

Sets

<i>DPO</i>	Set of maximal number of days in a month (31 days) with elements $dpo \in DPO$
<i>DPOD</i>	Set of pairs of original daily period dpo and merged daily period dp , $(dpo, dp) \in DPOD$
<i>DPM</i>	Set of pairs of original durations which regularizes the number of days in a month since the months contains different number of days $mp \subseteq MP$, $dp \subseteq DP$, $hp \subseteq HP$, $(dp, mp) \in DPM$
<i>HPO</i>	Set of all hours in the day (24 hours) with elements $hpo \in HPO$
<i>HPOH</i>	Set of pairs of original hourly periods hpo and merged hourly periods hp , $(hpop, hp) \in HPOH$
<i>IO</i>	Set of inlet and outlet streams with elements $io \in IO$
<i>MPO</i>	Set of all months in a year with elements $mpo \in MPO$
<i>MPOM</i>	Set of pairs of original monthly period mpo and merged monthly period mp , $(mpo, mp) \in MPOM$
<i>U</i>	Set of process units with elements $u \in U$

Subsets

<i>BACKUP (U)</i>	Set of external utility required by cold process streams to arrive at the target temperature with elements $backup \in BACKUP$
<i>DP(DPO)</i>	Set of discretised or merged daily time period with elements $dp \in DP$
<i>HEAT STORAGE (U)</i>	Set of heat storage tanks with elements $heat\ storage \in HEAT\ STORAGE$
<i>HP(HPO)</i>	Set of discretised or merged hourly time period with elements $hp \in HP$
<i>IN(IO)</i>	Set of inlet streams to process units with elements $in \in IN$
<i>MIXER (U)</i>	Set of mixers with elements $mixer \in MIXER$
<i>MP(MPO)</i>	Set of discretised or merged monthly time period with elements $mp \in MP$

$OUT(IO)$	Set of outlet streams from process units with elements $out \in OUT$
$PANEL(U)$	Set of solar collectors with elements $panel \in PANEL$
$PLANT(U)$	Set of industrial process to be integrated regarded as industrial plant with elements $plant \in PLANT$
$SPLITTER(U)$	Set of splitters with elements $splitter \in SPLITTER$

Parameters

a_1, a_2	Experimental constants for thermal loss coefficient of solar collector (kW/(m ² .°C))
C_p^{fluid}	Specific heat capacity of the fluid water-antifreeze mixture (kWh/t °C)
FC_p^{stream}	Heat capacity flowrates of the stream (kW/°C)
$I_{mp,dp,hp}, I'_{mp,dp,hp}$	Average solar irradiation and hourly solar irradiation for each hour of the year (kW/m ²)
$L_{mp,dp,hp}^{period}$	Length of each monthly, daily and hourly time period
M	Large enough coefficient used as a "big M" constraint for temperature feasibility in storage tank
$T_{mp,dp,hp}^{ambient}, T'_{mp,dp,hp}$	Average ambient temperature and ambient temperature for each hour of the year (°C)
TS_i, TT_i	Supply and target temperature of hot streams (°C)
TS_j, TT_j	Supply temperature and target temperature of cold streams (°C)
T_1^1	Stream temperature just before entering the targeted heater regarded as inlet temperature (°C)
T_1^3	Target temperature of cold streams (°C)
$T_{1mp,dp,hp}^2, T_{2mp,dp,hp}^2$	Variable stream temperature for cold streams 1 and 2 just at the exit of the targeted heater before reaching the final target temperature (°C)
ΔH_{vap}^{water}	Heat of vaporization of water (kWh/t)
ΔT_{min}	Minimum temperature difference (°C)
Π_0	Efficiency factor for solar collection
ρ^{fluid}	Density of fluid water-antifreeze mixture (t/m ³)

Continuous variables

A_{panel}	Area of solar collector (m ²)
$F_{io,mp,dp,hp}^u$	Fluid flowrates in and out of a unit for each time period (t/period)
F^{min}, F^{max}	Minimum and maximum fluid flow constraint between the loop solar collector – thermal storage – solar collector
$\dot{Q}_{backup}^{process}_{mp,dp,hp}$	Quantity of heat exchanged between backup utility and specific cold stream in the plant (kWh/period)
$\dot{Q}_{io,mp,dp,hp}^u$	Quantity of heat flow in and out of a unit for each time period (kWh/period)
$\dot{Q}_{solar}^{process}_{mp,dp,hp}$	Quantity of exchanged between solar heat and specific cold stream in the plant (kWh/period)
$T_{io,mp,dp,hp}^u$	Stream temperature in and out of a unit in each time period (°C)
$T_{mp,dp,hp}^{storage\ tank}$	Temperature in the storage tank (°C)
$T_{2\ mp,dp,hp}^1, T_{2\ mp,dp,hp}^2$	Intermediate temperature of first cold stream and second cold stream considered for solar thermal integration (°C)
$V_{storage\ tank}$	Volume of the fluid in storage tank (m ³)

Discrete variables (0, 1)

$Y_{mp,dp,hp}$	Binary variable showing whether or not there is existence of flow of heat transfer fluid from collector to heat storage tank
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Part B – Detail Mathematical Model

4.S1. Model reduction techniques

Since the model accounts for variable flowrates, temperatures and energy flows across each unit within the entire system (subject to change on an hourly basis), a systematic procedure is needed to manage the input parameters and constraints in the model (which are somewhat large) so as to curtail the problem size and reduce computational time. To achieve this, a model reduction technique was applied similar to the earlier methods presented by Egieya et al. [1] and Lam et al. [2]. Instead of using hourly data for the entire year as available in EC JRC PVGIS [3], the 24 hours of each day could be discretized into periods of equal [1] or different durations (e.g. 4 periods: H1: 9 pm – 7 am, H2: 8 am – 10 am, H3: 11 am – 5 pm, H4: 6 pm – 9 pm). The 29 – 31 days of each month could further be discretized into one or more periods (e.g. into days of the week such as in [1]), while 12 months could also be discretized into one or more periods (e.g. seasons) or considered in total. Accordingly, the length of the period could be equal or could vary (e.g. January has 31 days or 774 h, February has 28/29 days or 672/696 h and so on) and M1, M2, M3, ..., M12 represent the 12 months of the year from January to December. Based on the discretization, the length of each period is calculated as follows:

$$\begin{aligned}
 L_{mp,dp,hp}^{period} = & \sum_{mpo \in MP} \bigwedge_{(mpo,mp) \in MPOM} |mpo| \cdot \sum_{dpo \in DP} \bigwedge_{(dpo,dp) \in DPOD} |dpo| \\
 & \cdot \sum_{hpo \in HP} \bigwedge_{(hpo,hp) \in HPOH} |hpo|, \\
 & \forall mp \subseteq MP, dp \subseteq DP, hp \subseteq HP, (dp, mp) \in DPM
 \end{aligned} \tag{S1}$$

where $MPOM$, $DPOD$ and $HPOH$ represent set of pairs of maximal number of time periods in a year (mpo , dpo and hpo) and merged time periods (mp , dp and hp). $HPOH$ discretizes the 24 hours in a day into any number of merged hours (with equal or different durations), $DPOD$ discretizes the 28 – 31 days in a month into the same or a smaller number of merged days (with equal or different durations); and $MPOM$ discretizes 12 months into 12 or fewer merged months, also with equal or different durations. In order to appropriately consider the useful heat gain by the solar collector and to consider the duration of hourly periods, Eq. (S8) is multiplied by the length of each hourly period $\sum_{hpo \in HP} \bigwedge_{(hpo,hp) \in HPOH} |hpo|$. Similarly, heat required for the plant ($\dot{Q}_{mp,dp,hp}^{process}$) and backup utility requirement ($\dot{Q}_{mp,dp,hp}^{backup,process}$) are also multiplied by $\sum_{hpo \in HP} \bigwedge_{(hpo,hp) \in HPOH} |hpo|$.

DPM in Eq. (S2) – Eq. (S3) stands for the set of pairs of days and months (January has 31 days, February has 28 days and so on). In order to appropriately consider different merged periods, all Eqs. (S4) – (S52) are calculated for each $mp \subseteq MP, dp \subseteq DP, hp \subseteq HP, (dp, mp) \in DPM$.

Additionally, the data on an hourly basis are discretized (averaged) into considered periods. Such discretized data include those for solar irradiation and ambient temperature shown in Eq. (S8), where $I'_{mp,dp,hp}$ and $T^{ambient'}_{mp,dp,hp}$ are the data as obtained from EC JRC PVGIS [3]:

$$I_{mp,dp,hp} = \frac{\sum_{mpo \in MP} \sum_{dpo \in DP} \sum_{hpo \in HP} \bigwedge_{(mpo,mp) \in MPOM, (dpo,dp) \in DPOD, (hpo,hp) \in HPOH, (dpo,mpo) \in DPM} I'_{mp,dp,hp}}{\left(\sum_{mpo \in MP} \bigwedge_{(mpo,mp) \in MPOM} |mpo| \cdot \sum_{dpo \in DP} \bigwedge_{(dpo,dp) \in DPOD} |dpo| \cdot \sum_{hpo \in HP} \bigwedge_{(hpo,hp) \in HPOH} |hpo| \right), \forall mp \subseteq MP, dp \subseteq DP, hp \subseteq HP, (dp, mp) \in DPM} \quad (S2)$$

$$T^{ambient}_{mp,dp,hp} = \frac{\sum_{mpo \in MP} \sum_{dpo \in DP} \sum_{hpo \in HP} \bigwedge_{(mpo,mp) \in MPOM, (dpo,dp) \in DPOD, (hpo,hp) \in HPOH, (dpo,mpo) \in DPM} T^{ambient'}_{mp,dp,hp}}{\left(\sum_{mpo \in MP} \bigwedge_{(mpo,mp) \in MPOM} |mpo| \cdot \sum_{dpo \in DP} \bigwedge_{(dpo,dp) \in DPOD} |dpo| \cdot \sum_{hpo \in HP} \bigwedge_{(hpo,hp) \in HPOH} |hpo| \right), \forall mp \subseteq MP, dp \subseteq DP, hp \subseteq HP, (dp, mp) \in DPM} \quad (S3)$$

4.S2. Global equations

The relation for the flowrate is shown in Eq. (S4):

$$F^{u}_{out,mp,dp,hp} = F^{u1}_{in,mp,dp,hp}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (S4)$$

where F (t/period) represents the fluid flow rate from unit u to unit $u1$ in the integrated system for each monthly (mp), daily (dp) and hourly (hp) time periods. This implies that the flow rate at outlet of unit u is equal to flowrate at the inlet of unit $u1$ in each time period.

In a similar manner, the relations for temperature and heat flow are shown in Eq. (S5) and Eq. (S6) where T and \dot{Q} represent the temperature and flow of heat from the unit u to the unit $u1$.

$$T_{out,mp,dp,hp}^u = T_{in,mp,dp,hp}^{u1}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (S5)$$

$$\dot{Q}_{out,mp,dp,hp}^u = \dot{Q}_{in,mp,dp,hp}^{u1}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (S6)$$

4.S3. Solar collector

Based on the temperature levels of the proposed solar heat integration, an evacuated tube solar collector is considered for the design where the temperature of the fluid leaving the collector is a direct function of the total irradiance on the collector, flowrate of the fluid and inlet temperature of the fluid entering the collector. Eq. (S7) shows the mass balance, Eq. (S8) describes the useful heat gain by the solar collector and Eq. (S9) the balance for captured heat by the fluid according to the monthly, daily and hourly time period.

$$F_{out,mp,dp,hp}^{panel} = F_{in,mp,dp,hp}^{panel}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S7)$$

$$\dot{Q}_{out,mp,dp,hp}^{panel} = A_{panel} \cdot (\Pi_0 \cdot I_{mp,dp,hp} - a_1(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient}) - a_2(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient})^2), \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S8)$$

$$\dot{Q}_{out,mp,dp,hp}^{panel} = F_{out,mp,dp,hp}^{panel} \cdot c_p^{fluid} \cdot (T_{out,mp,dp,hp}^{panel} - T_{in,mp,dp,hp}^{panel}), \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S9)$$

In Eq. (S7) $F_{out,mp,dp,hp}^{panel}$ and $F_{in,mp,dp,hp}^{panel}$ are the outlet and inlet flowrates of heat transfer fluid from and to solar collector. $\dot{Q}_{out,mp,dp,hp}^{panel}$ shown in Eq. (S8) accounts for the attainable quantity of solar heat from the panel which is equal to captured heat by the fluid as shown in Eq. (S9), A_{panel} represents area of the panel, c_p^{fluid} is specific heat capacity of the solar heat transfer fluid which is assumed to be constant for the simplicity of the model (due to computational time required to solve such dynamic system), $T_{mp,dp,hp}^c$ is the average of the inlet and outlet temperatures of the solar capture fluid in solar collector in each time period ($\frac{T_{in,mp,dp,hp}^{panel} + T_{out,mp,dp,hp}^{panel}}{2}$), $T_{mp,dp,hp}^{ambient}$ is ambient temperature in each time period and $I_{mp,dp,hp}$ is irradiation which is also subject to changes according to the monthly, daily and hourly time periods, while Π_o is efficiency factor of solar collector with value of 0.764 and a_1 and a_2 are experimental constants with values 1.53 W/(m²·K) and 0.0003 W/(m²·K) as adopted from the method of Isafiade et al. [4].

4.S4. Heat storage tank

Heat storage is incorporated into the design to provide opportunity for accumulation of solar heat in some time period to be used at a later time with lean or zero solar irradiation. The placement of a splitter in between the exit of the HEN and storage tank also provides the means of utilizing useful excess heat from the process to buffer the temperature level of the fluid in the storage tank thereby providing additional benefit of energy efficiency for the integrated system. Heat transfer takes place through the walls of the heating coil as hot solar fluid flows through the coil in the tank back to solar collector in a closed loop. Schematic representation of heat storage tank is shown in Figure 4S1. Considering *IN-1*, the variables F , T and \dot{Q} represent the variables for the solar heat transfer fluid which comes from the solar collector to the tank, *IN-2* variables are represented for the heat transfer fluid returning back from the process to the storage tank, *OUT-1* represents the main heat supply from heat storage tank to the process (which implies that $T_{out-1,mp,dp,hp}^{storage\ tank}$ is the temperature of the fluid out of the tank transferring heat to the process, which is assumed to be the same as the temperature inside the tank $T_{mp,dp,hp}^{storage\ tank}$ in every period), while *OUT-2* represents variables of solar fluid returning back to the collector from storage tank in each time period as shown in Figure 4S1.

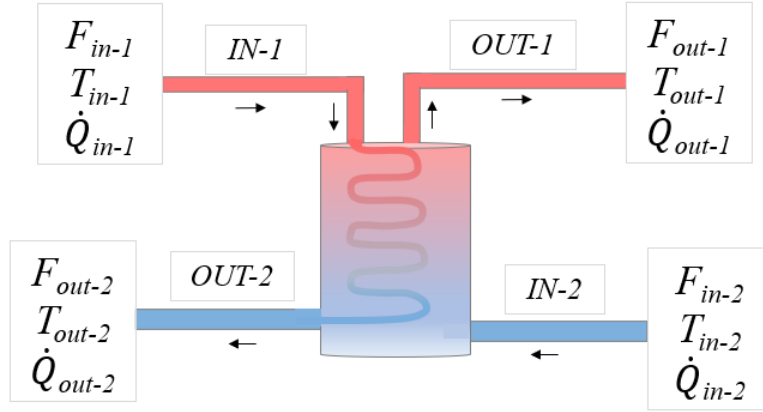


Figure 4S1: Schematic representation of heat storage tank

Eq. (S10) and Eq. (S11) account for the flows in and out of the heat storage tank from the solar collector and from the process cold stream(s). The subscripts $in - 1/in - 2/out - 1/out - 2, mp, dp, hp$ attached to each of the flows follow the same naming as earlier described for the streams entering and leaving the storage tank and shown in Fig. 4S1:

$$F_{out-2,mp,dp,hp}^{storage\ tank} = F_{in-1,mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S10)$$

$$F_{out-1,mp,dp,hp}^{storage\ tank} = F_{in-2,mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S11)$$

The general energy balance equation for the storage tank is presented in Eq. (S12) which shows that energy accumulated in storage tank in each time period is equal to energy added to the storage tank minus energy leaving the storage tank:

$$\begin{aligned} & V^{storage\ tank} \cdot c_p^{fluid} \cdot \rho^{fluid} \cdot \Delta T_{mp,dp,hp}^{storage\ tank} \\ &= \dot{Q}_{solar,mp,dp,hp}^{storage\ tank} + F_{in-2,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{in-2,mp,dp,hp}^{storage\ tank} \\ &- F_{out-1,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{out-1,mp,dp,hp}^{storage\ tank} \end{aligned} \quad (S12)$$

$\forall mp \in MP, dp \in DP, hp \in HP$

where $V^{storage\ tank}$ is volume of the fluid in storage tank, ρ^{fluid} is density of the heat storage fluid which is assumed to be constant for simplicity of the model and calculation, and $\Delta T_{mp,dp,hp}^{storage\ tank}$ is the change in temperature of the fluid in storage tank in each time period. Heat transferred to the tank from hot solar fluid, $\dot{Q}_{mp,dp,hp}^{solar,storage\ tank}$, is represented by the following Equation:

$$\begin{aligned} \dot{Q}_{mp,dp,hp}^{solar,storage\ tank} &= F_{in-1,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \cdot T_{in-1,mp,dp,hp}^{storage\ tank} - F_{out-2,mp,dp,hp}^{storage\ tank} \cdot c_p^{fluid} \\ &\cdot T_{out-2,mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (S13)$$

Temperature of fluid in the storage tank is calculated as temperature of fluid in storage tank in previous time period (which is modelled with circular or equilibrium leads and lags; McCarl et al. [5]) plus the change in temperature of the fluid in storage tank for each time period since the system is modelled to be in continuous operation such that there is always a momentary temperature level of the fluid in the tank before it received another temperature lift from hot solar fluid passing through the coil in the tank across different operational time periods:

$$\begin{aligned} T_{mp,dp,hp}^{storage\ tank} &= \bigcup_{(mp_k)_{k \in K, k=1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp--1,dp--1,hp--1}^{storage\ tank} \\ &+ \bigcup_{(hp_k)_{k \in K, k>1}} T_{mp,dp,hp-1}^{storage\ tank} + \bigcup_{(dp_k)_{k \in K, k>1} \wedge (hp_k)_{k \in K, k=1}} T_{mp,dp-1,hp--1}^{storage\ tank} \\ &+ \bigcup_{(mp_k)_{k \in K, k>1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp-1,dp--1,hp--1}^{storage\ tank} \\ &+ \Delta T_{mp,dp,hp}^{storage\ tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (S14)$$

In Eq. (S14) $T_{mp--1,dp--1,hp--1}^{storage\ tank}$ refers to the temperature in storage tank at the beginning of January (first hour, first day and first months) which equals temperature in storage tank in the last hour of December (last hour, last day, last month). Similarly, $T_{mp,dp,hp-1}^{storage\ tank}$ refers to temperature in storage tank for each month and day where hour is not first hour of the day, $T_{mp,dp-1,hp--1}^{storage\ tank}$ refers to temperature in storage tank for each first hour of the day while the day is not first day of the month

and $T_{mp-1,dp--1,hp--1}^{storage\ tank}$ for temperature in the storage tank for each first hour in a day and first day in a month for any month except January (first month).

In order to ensure that heating of the fluid in heat storage tank is performed only when temperature in storage tank is lower than outlet temperature of the heat transfer fluid returning to solar collector (i.e. $T_{out-2,mp,dp,hp}^{storage\ tank}$) minus ΔT_{min} (minimum temperature difference), a constraint is introduced on the temperature in the storage tank. This constraint should however be relaxed on the tank when there is no heat transfer (no flow) to the tank from hot solar fluid. Eq. (S15) describes the concept of big M constraint introduced on the temperature in the storage tank with M being a big enough scalar, and binary variable $y_{mp,dp,hp}$ which denotes the existence of the heat transfer fluid flow in the closed loop solar collector, i.e. storage tank – solar collector loop. If the binary variable is 1, the fluid flow should be between a minimum (F^{min}) and a maximum value (F^{max}) as shown in Eq. (S16), otherwise 0 is assigned.

$$T_{mp,dp,hp}^{storage\ tank} \leq T_{out-2,mp,dp,hp}^{storage\ tank} - \Delta T_{min} + M \cdot (1 - y_{mp,dp,hp}), \quad (S15)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$F^{min} \cdot y_{mp,dp,hp} \leq F_{in-1,mp,dp,hp}^{storage\ tank} \leq F^{max} \cdot y_{mp,dp,hp}, \quad (S16)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

4.S5. Mixers and splitters

Generally, the basic function of the mixers and splitters is to provide opportunities for stream mixing and splitting across units within the system. However, stream flow across these units, as well as the temperature and heat content, must be adequately accounted for in the model. Based on the aforementioned model assumptions, the set of equations that describe the flow, temperature and heat balances across the splitters is presented in Eq. (S17) to Eq. (S20) while the equations that describe balances across the mixers are presented in Eq. (S21) to Eq. (S23).

$$\sum_{out \in OUT} F_{out,mp,dp,hp}^{splitter} = F_{in-1,mp,dp,hp}^{splitter}, \quad (S17)$$

$$\forall splitter \in SPLITTER, mp \in MP, dp \in DP, hp \in HP$$

$$T_{out,mp,dp,hp}^{splitter} = T_{in-1,mp,dp,hp}^{splitter}, \quad (S18)$$

$$\forall splitter \in SPLITTER, out \in OUT, mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{out,mp,dp,hp}^{splitter} \cdot F_{in-1,mp,dp,hp}^{splitter} = \dot{Q}_{in-1,mp,dp,hp}^{splitter} \cdot F_{out,mp,dp,hp}^{splitter}, \quad (S19)$$

$$\forall splitter \in SPLITTER, out \in OUT, mp \in MP, dp \in DP, hp \in HP$$

$$\sum_{out \in OUT} \dot{Q}_{out,mp,dp,hp}^{splitter} = \dot{Q}_{in-1,mp,dp,hp}^{splitter}, \quad (S20)$$

$$\forall splitter \in SPLITTER, mp \in MP, dp \in DP, hp \in HP$$

Since temperature and heat loss is negligible across the integrated system and c_p^{fluid} is assumed to be constant, the following conditions apply for each mixer in every monthly, daily and hourly time period:

$$F_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} F_{in,mp,dp,hp}^{mixer}, \quad (S21)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

$$F_{out-1,mp,dp,hp}^{mixer} \cdot T_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} F_{in,mp,dp,hp}^{mixer} \cdot T_{in,mp,dp,hp}^{mixer}, \quad (S22)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} \dot{Q}_{in,mp,dp,hp}^{mixer}, \quad (S23)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

4.S6. Industrial process

The quantity of solar heat exchanged with the process streams is linked to the industrial cold stream(s) through one of the mixers (which provides opportunity for the plant to switch between direct or

$$F_{in-2,mp,dp,hp}^{process} = F_{out-2,mp,dp,hp}^{process}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S26)$$

$F_{in-1,mp,dp,hp}^{process}$ and $F_{out-1,mp,dp,hp}^{process}$ represent the flows of solar fluid in and out of the process for every monthly, daily and hourly time period while $F_{in-2,mp,dp,hp}^{process}$ and $F_{out-2,mp,dp,hp}^{process}$ represent flows of the backup utility in and out of the process for every time period as well. The equation for solar heat exchanged with the process ($\dot{Q}_{solar,mp,dp,hp}^{process}$) is presented in Eq. (S27), while the total heat supply to the process from backup utility ($\dot{Q}_{backup,mp,dp,hp}^{process}$) as shown in Fig. 4S2 is described by Eq. (S28).

$$\dot{Q}_{solar,mp,dp,hp}^{process} = \dot{Q}_{in-1,mp,dp,hp}^{process} - \dot{Q}_{out-1,mp,dp,hp}^{process}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S27)$$

$$\dot{Q}_{backup,mp,dp,hp}^{process} = \dot{Q}_{in-2,mp,dp,hp}^{process} - \dot{Q}_{out-2,mp,dp,hp}^{process}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S28)$$

The model equations that ensure heat balance of the cold process stream by solar and backup utility across the network are presented in Eqs. (S29) – (S30). It should be noted that since the backup alternative for hot utility is assumed to be superheated steam from the backup boiler, the change in heat of vaporization of water (ΔH_{vap}^{water}) is considered in order to evaluate the heat supply to the process from backup utility as described in Eq. (S30).

$$\dot{Q}_{solar,mp,dp,hp}^{process} = F_{in-1,mp,dp,hp}^{process} \cdot c_p^{fluid} \cdot (T_{in-1,mp,dp,hp}^{process} - T_{out-1,mp,dp,hp}^{process}), \quad (S29)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{backup,mp,dp,hp}^{process} = F_{in-2,mp,dp,hp}^{process} \cdot \Delta H_{vap}^{water}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S30)$$

In Eq. (S29), $T_{in-1,mp,dp,hp}^{process}$ and $T_{out-1,mp,dp,hp}^{process}$ are the inlet and outlet temperature of heat transfer fluid from solar (mixer) to process HEN and from HEN back to the solar panel or storage tank. For backup utility it is assumed that the difference between inlet and outlet temperature of the backup utility from the boiler to the process and from the process back to the boiler, $T_{in-2,mp,dp,hp}^{process}$ and $T_{out-2,mp,dp,hp}^{process}$ is 1 °C.

In order to adequately account for changes in the temperature level of cold process stream as it flows across the plant, variables T^1 , $T_{mp,dp,hp}^2$ and T^3 are defined which represent the inlet temperature of the cold stream from point 1 (before entering the heater targeted for solar heat integration), the intermediate temperature level of cold stream at point 2 (after exiting the heater) and the final temperature of the cold stream at point 3 (after exchanging heat with the backup utility in the second heater), see also Figure 4S2. Temperatures T^1 and T^3 are assumed to be fixed temperatures (in case the plant is operating at fixed or steady-state conditions), while $T_{mp,dp,hp}^2$ is changing on hourly-basis depending on heat available from solar. Accordingly, the following equations account for feasibility of temperature changes across the process.

$$T_{in-1,mp,dp,hp}^{process} \geq T_{mp,dp,hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S31)$$

$$T_{in-2,mp,dp,hp}^{process} \geq T^3 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S32)$$

$$T_{out-1,mp,dp,hp}^{process} \geq T^1 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S33)$$

$$T_{out-2,mp,dp,hp}^{process} \geq T_{mp,dp,hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S34)$$

In order to calculate the variables for the backup utility and intermediate temperature, the following constraint is included where $FC_p^{cold\ stream}$ is heat capacity flowrate of the cold stream to be heated up with solar and backup utilities:

$$\begin{aligned} \dot{Q}_{backup,mp,dp,hp}^{process} &= FC_p^{cold\ stream} \cdot (T^3 - T_{mp,dp,hp}^2), \\ &\forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (S35)$$

Heating of multiple industrial streams

The rationale behind the second industrial solar integration possibility proposed in this paper is to allow simultaneous utilization of available solar heat across more than one heater on several cold process streams to be heated up, as shown also in Figure 4S3.

The technique proposed to achieve this involves the placement of a splitter between the mixer (which aggregates all available heat from direct and indirect solar integration) and HEN and another splitter at the backup utility side of the integrated system such that the individual heater gets a certain amount of either solar heat or backup utility simultaneously. In order to complete the close-loop, the heat transfer fluid for the solar returning from the plant (i.e. $T_{out-1,mp,dp,hp}^{process}$ and $T_{out-2,mp,dp,hp}^{process}$), as well as the backup utility streams flowing out of the plant ($T_{out-3,mp,dp,hp}^{process}$ and $T_{out-4,mp,dp,hp}^{process}$), leave the plant through two separate mixers and the cycle continues as described above.

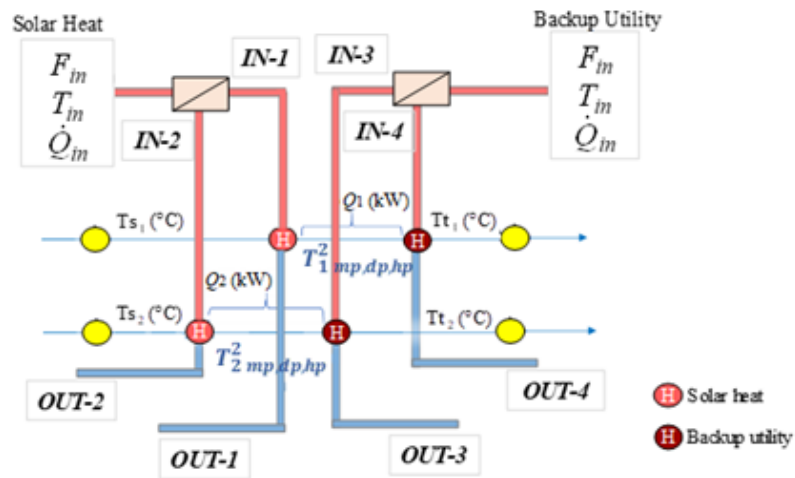


Figure 4S3: Schematic representation of solar heating in multiple industrial process streams

To account for changes in the temperature level of the streams in and out of the targeted heaters and the entire process, subscripts 1, 2, ..., n are added to the temperature variables (i.e. T^1 , $T_{mp,dp,hp}^2$ and T^3 described in the previous section) according to the number of streams to be heated up (or simply according to the number of heaters to be integrated with solar thermal) such that T_1^1 , $T_{1mp,dp,hp}^2$ and T_1^3 become the inlet temperature, intermediate temperature and outlet temperature of cold stream 1 while T_2^1 , $T_{2mp,dp,hp}^2$ and T_2^3 represent the inlet temperature, intermediate temperature and outlet temperature of cold stream 2, and so on up to the n^{th} numbered stream. The solution method and model equations developed to implement the integration possibility for multiple industrial streams (Eq. (S36) to Eq. (S43) follow the same procedure as described in Eqs. (S31) - (S35) with the introduction of subscripts (1, 2, ..., n) according to the number of cold process.

$$T_{in-1, mp, dp, hp}^{process} \geq T_{1, mp, dp, hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S36)$$

$$T_{in-2, mp, dp, hp}^{process} \geq T_{2, mp, dp, hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S37)$$

$$T_{in-3, mp, dp, hp}^{process} \geq T_2^3 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S38)$$

$$T_{in-4, mp, dp, hp}^{process} \geq T_1^3 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S39)$$

$$T_{out-1, mp, dp, hp}^{process} \geq T_1^1 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S40)$$

$$T_{out-2, mp, dp, hp}^{process} \geq T_2^1 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S41)$$

$$T_{out-3, mp, dp, hp}^{process} \geq T_{2, mp, dp, hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S42)$$

$$T_{out-4, mp, dp, hp}^{process} \geq T_{1, mp, dp, hp}^2 + \Delta T_{min}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (S43)$$

Since more than one heater is involved in the integration (and by extension more than one cold stream to be heated), the constraints presented in Eq. (S44) to Eq. (S46), are included to evaluate the backup utility and intermediate temperature within the process. Accordingly, the following constraints were included in the model equation to implement the second integration possibility that was proposed. Constraints, $FC_{p1}^{cold stream 1}$ and $FC_{p2}^{cold stream 2}$ represent the heat capacity flowrates of the two cold streams to be heated up around the heaters targeted for solar heat integration.

$$\begin{aligned} \dot{Q}_{solar}^{Stream 1}_{mp, dp, hp} &= F_{in-1, mp, dp, hp}^{Stream 1} \cdot C_p^{fluid} \cdot (T_{in-1, mp, dp, hp}^{Stream 1} - T_{out-1, mp, dp, hp}^{Stream 1}), \\ &\forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (S44)$$

$$\begin{aligned} \dot{Q}_{solar}^{Stream 2}_{mp, dp, hp} &= F_{in-1, mp, dp, hp}^{Stream 2} \cdot C_p^{fluid} \cdot (T_{in-1, mp, dp, hp}^{Stream 2} - T_{out-1, mp, dp, hp}^{Stream 2}), \\ &\forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (S45)$$

$$\dot{Q}_{mp,dp,hp}^{solar\ Process} = \dot{Q}_{mp,dp,hp}^{solar\ Stream\ 1} + \dot{Q}_{mp,dp,hp}^{solar\ Stream\ 2}, \quad (S46)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{plant} = \dot{Q}_{mp,dp,hp}^{solar\ process} + \dot{Q}_{mp,dp,hp}^{backup\ process}, \quad (S47)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{backup\ process} = \dot{Q}_{mp,dp,hp}^{backup\ Stream\ 1} + \dot{Q}_{mp,dp,hp}^{backup\ Stream\ 2}, \quad (S48)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{backup\ Stream\ 1} = FC_p^{cold\ stream\ 1} \cdot (T_1^3 - T_{1\ mp,dp,hp}^2), \quad (S49)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{backup\ Stream\ 2} = FC_p^{cold\ stream\ 2} \cdot (T_2^3 - T_{2\ mp,dp,hp}^2), \quad (S50)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{plant} = F_{in-4\ mp,dp,hp}^{Stream\ 1} \cdot \Delta H_{vap}^{water}, \quad (S51)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$\dot{Q}_{mp,dp,hp}^{Stream\ 2} = F_{in-3\ mp,dp,hp}^{plant} \cdot \Delta H_{vap}^{water}, \quad (S52)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

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Chapter Conclusions

As shown in the presented case studies and other recent research contributions, solar thermal is an excellent sustainable means to offset substantial amount of conventional fossil-based process heat in the industrial sector. However, the integration and utilisation of solar thermal in industrial processes has always been a very difficult task. This is especially the case if the multi-period variability in the availability and fluctuations in solar potential are to be considered along with the multi-period changes in the profile of heat demand of industrial process. In this chapter, design and optimization strategies which adequately account for these complex uncertainties via direct and indirect integration with industrial heat network were introduced.

The developed methods are based on the simultaneous multi-period mixed integer non-linear mathematical programming approach. Apart from the fact that the methods account for the dynamic behaviour of the design features (such as the intermittent changes (on hourly basis) in meteorological conditions, streams temperature levels, heat duties, flowrates as well as the periodic changes in the amount of heat stored in the thermal storage tank and changes in heat demand from the backup utility source), the methods can also be applied to any case study in any locations in the world because the model equations were developed independent of the data. Case study analysis of the developed model on several solar thermal integration possibilities show good prospect for solar thermal utilization in industries especially with low temperature industrial processes/applications.

In part 1 of the chapter, the author made a case for the use of solar thermal for preheating operations in industrial process. Where the integration of solar thermal with the process stream is presented in form of a retrofit and the synthesis of the solar heat network is isolated from the general industrial heat network by targeting a predefined cold stream for pre-heating outside the main network.

Different solar thermal integration possibilities, which are integrated with the entire industrial heat network, are presented in part 2 of the chapter. Here, a splitter is introduced along the path of flow of the hot solar field. This provides opportunity for the total available solar heat to be dispatched to more than one solar heat exchangers within the process such that multiple cold streams are targeted. The solar heat splits simultaneously across several heat demand zones within the process totally utilized before importing the balance of the heat deficit from an alternative heat source (the backup boiler) through the dedicated heat exchanger for backup utility. The solar thermal integration strategies proposed in this chapter provides several solar thermal integration possibilities based on need assessment and demand preference.

Integration of Solar Thermal with Periodic Heat Storage and Backup Utility for Domestic Utilization

Background to the Chapter

Apart from the industrial sector, energy use in residential and commercial buildings represents a significant part (about 33 %) of the total global energy consumption¹, majority of which are met using energy from non-renewable sources². Hence, in order to reduce the overdependence of global energy system on fossil fuels and cut down on energy-related emissions, clean and alternative energy sources need to be integrated with the energy networks of the building sector. Moreover, access to affordable energy in remote or isolated areas is often challenging, unreliable and very expensive (with respect to high cost of facilities for distribution), even in developed and developing countries. These are essential premise upon which renewable energy sources (such as solar thermal) are often considered to be of great benefits due to the distributed nature of their supply³ and environmental significance of their technologies⁴.

Major household energy use include lighting and heating (water heating, space heating and cooking). According to a recent report by International Energy Agency (IEA), this share of energy use accounts for about 75% of the total energy consumed within single and multi-family apartments across the world⁵. This shows that energy use for heating in homes constitutes the major part of the building energy consumption and thus presents an important integration area for renewable heat such solar thermal. At the moment, solar energy is majorly used for domestic water heating and sometimes electricity, with less consideration for space heating and opportunity for heat storage. In order to increase the contribution and impact of renewable energy in global energy production, more opportunity needs to be derived by increasing the utilization of renewable energy (such as solar energy and its accompanying technologies) in residential and commercial buildings.

This chapter presents two integration possibilities for utilizing solar thermal in domestic heat supply network. The generic design and optimization method used for the presented case studies is based on the multi-period mixed integer non-linear programming approach where both the design and optimization of the system are implemented simultaneously. The proposed method incorporates strategies for periodic storage of excess harvested solar heat in active solar periods, and inclusion of

backup utility features in the design framework with the objective to maximize the heat supply to the heat networks from solar thermal across the year.

The content of the chapter is a direct reproduction of the papers published in Volume 76 of Chemical Engineering Transactions, Journal of the Italian Association of Chemical Engineering titled “Synthesis of Solar Thermal Network for Domestic Heat Utilization”⁶ on 20th October 2019 and a second paper titled “Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating”⁷ invited for Special Issue with Renewable and Sustainable Energy Reviews Journal. The presentation styles for each of the papers and the way the papers are presented in this chapter are in conformity with the Journal requirements. The only changes, which are cosmetic in nature, applies to section identifications in order to maintain the requirements for the thesis presentation.

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Part I: Domestic Integration of Solar Thermal Incorporating Multiple Heat Storage Tanks and Backup Boiler

Preamble

In order to demonstrate the potentials and possibility of utilizing solar thermal in various part of the world, several solar thermal design topologies and integration strategies have been developed. To achieve a relatively satisfactory system performance (even in extremely cold climates), task 26 of the International Energy Agency (IEA) has compared 21 different solar system combinations with other technologies. In all, heat storage and improved storage tank insulation stand out as important measures to achieve most realistic thermal delivery from solar energy designs especially in the cold regions. Therefore, depending on the geographical location, hourly solar irradiation and level of demand, domestic solar thermal system can come in several designs and with diverse combination of technologies. Part I of this chapter presents a type of domestic solar thermal design where the use of two separate but inter-connected heat storage tanks are incorporated with the design in order to provide heat energy for water and space heating needs of a cluster of buildings. A summary of the results has been published in a journal of the Italian Association of Chemical Engineering "Chemical Engineering Transactions (Volume 76, 2019).

1015



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Synthesis of Solar Thermal Network for Domestic Heat Utilization

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Abstract

Strategic and systematic integration of solar thermal in the building sector can lead to energy security and emission reduction. The impact of such renewable energy application could be boosted when an integration scheme is formulated by considering the changing meteorological conditions and periodic variabilities in the profile of heat demand. The efficiency of such networks could be enhanced by incorporating heat storage technology and backup utility system to form an integrated design. In this paper, a new approach based on multi-period Mixed Integer Non-Linear Programming (MINLP) which captures such features is developed for integrating solar thermal with the space heat and hot water supply network of a cluster of buildings. The integration scheme is implemented and solved in GAMS and considers the hourly changes in solar irradiation and ambient temperatures, together with the effects of these changes on integration variables across different time horizons. Two scenarios are considered, the first involves four winter months while the second entails four summer months. The results obtained shows that solar thermal satisfies 7.4 % of the total heat required in the winter months, while it fully supplies the total heat demand in the winter months.

5.1 Introduction

Apart from the industrial sector, the building sector has a major share in global energy consumption, and by extension, it is one of the largest single contributors to climate change and CO₂ emissions. Energy use in buildings currently has a share of about 32 % of the total global energy consumption [1]. Between 60 – 80 % (depending on specific climate zone) of this share of energy is used for heating hot water, space dwellings and for cooking. A large portion of these heating is currently being accomplished using energy from non-renewable sources [2]. Going by the trends, it is predicted that the share of carbon emissions in the building sector will likely increase by the end of the current decade [3]. A great opportunity exists for emission reduction in the building sector by integrating renewable energy technologies to either supplement or substitute the use of fossil energy in meeting various thermal needs.

Solar thermal is one of the most proven renewable energy sources that could be useful for hot water and space heating in residential and commercial buildings. Its strategic integration in buildings, especially for hot water supply, has been described as one of the most feasible and economical means of utilizing solar energy [4]. To this effect, several techniques for integrating solar thermal in buildings have been reported in the literature with a demonstration of diverse mature technologies which have been advanced and commercialised over the years.

Various aspects of the most recent applications of solar hot water systems have been presented Kee et al. [5]. Several design implementations and applications of solar thermal for space and water heating in buildings could also be found in the literature, especially for moderate temperature levels such as those required in residential and commercial buildings [6]. To the best of author's knowledge, the profiles of hot water and space heat demand/consumption, as well as the general thermal energy supply patterns, have been based on assumptions using synthetic demand profiles or arbitrary values derived by some rule of thumb. This is also supported by Fuentes et al. [7], where similar submissions were made in their study on the review of domestic hot water consumption profiles for buildings. However, factors such as seasonality and specific period/time of day play vital roles in space heating and hot water demand.

A better understanding of energy use patterns (which is also subject to changes) and the influence of the changing meteorological conditions are crucial to establish a more robust solar energy integration model. Another notable observation from the literature review is that design and optimization methods which combine space heating and solar hot water supply system with thermal storage in a multi-building heat demand network are still lacking, especially in the case where the multi-building

heat demand network is also characterized by varied individual profile of heat demand from one building to another. Within the framework of the European Renewable Energy Research Centres Agency [8], and supported by the solar heating and cooling (SHC) project document on space heating and domestic hot water [9], building-integrated solar thermal concepts such as the one proposed in this paper has been identified as one of the paths to achieving more energy-efficient buildings and emission reduction.

In this paper, an integrated inter-building solar heat network design is presented with opportunities for periodic storage of solar thermal and backup utility system to satisfy hot water and space heating needs of the buildings. The work is formulated as a simultaneous multi-period MINLP by adapting some of the features from the study on the integration of solar thermal for industrial applications [10]. In this current contribution, solar collectors installed on the rooftop of different types of buildings (ranging from a single-family home to multi-family apartments) generate heat energy to satisfy the thermal needs of the buildings. In the likely event that solar radiation may not be enough or available, an additional source of heat is provided for the storage tank to either heat up the fresh water from its supply temperature or to raise the temperature level of solar pre-heated water to the target temperature required in the buildings.

5.2 Methodology

5.2.1 Description of solar heat network design for applications in buildings

The framework for the integrated solar thermal network for utilization in residential sectors presented in this paper is developed to demonstrate the possibility of using harvested solar thermal to provide hot water, and space heating in three buildings denoted as VSS1, ESS1 and ESS2 (see Figure 5.1). Solar collectors absorb the incident flux from the sun through its surface, and in the process, raise the temperature of the heat transfer fluid. In this study, water is considered as the heat transfer fluid across the integrated system with a specific heat capacity of $1.16 \text{ kWh}/(\text{t}^\circ\text{C})$ and a density of $1 \text{ t}/\text{m}^3$. The heated water flows across the collectors to the storage tank where it exchanges heat. It is further channelled to provide hot water and space heat for the buildings.

In the proposed design, hot water consumption of the three buildings in the network is linked to fresh water supply in the first storage tank (Tank 1) for replenishment. Then, depending on the temperature level of harvested solar thermal, hot water can be supplied directly to the buildings from Tank 1 through a bypass or through the second storage tank (Tank 2) for additional heating in situations

where the required temperature level is not reached. Furthermore, additional heating source is provided as a backup for Tank 2 while Tank 1 keeps functioning as a preheating source. It should be noted that Tank 1 is heated only when temperature in the tank is lower than temperature of the circulating water and thus in order to efficiently utilise solar thermal energy, Tank 2 is suggested and is further heated by backup utility to the required temperature.

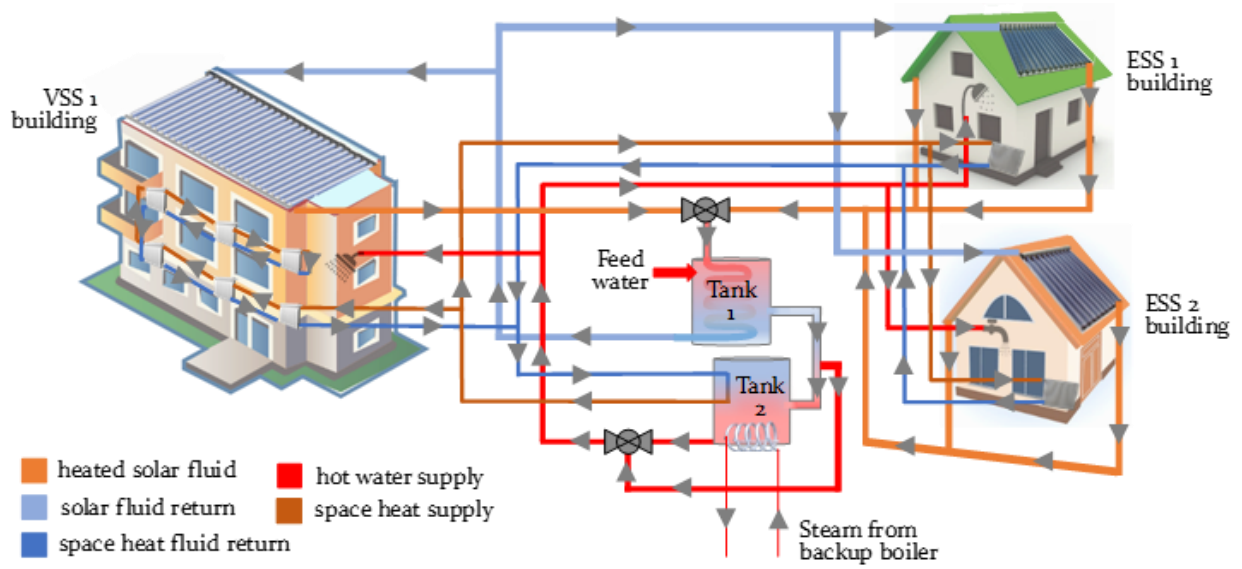


Figure 5.1: Representation of solar thermal integration for heat utilisation in buildings

5.2.2 Model approach

The developed model seeks to minimize total heat supplied to the multi-building heat demand network from backup boiler. The objective function for the developed model is shown in Eq (5.1).

$$\min \left(\sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in HP} \bigwedge_{(mp, dp) \in DPM} \dot{Q}_{backup}^{VSS1}_{mp, dp, hp} + \dot{Q}_{backup}^{ESS1}_{mp, dp, hp} + \dot{Q}_{backup}^{ESS2}_{mp, dp, hp} \right) \quad (5.1)$$

where $\dot{Q}_{backup}^{VSS1}_{mp, dp, hp}$, $\dot{Q}_{backup}^{ESS1}_{mp, dp, hp}$ and $\dot{Q}_{backup}^{ESS2}_{mp, dp, hp}$ are the yearly total sum of additional heat from backup utility required for space heating and hot water supply in each of the three buildings. Sets mp , dp and hp represent the monthly, daily and hourly time periods. Monthly and daily time periods are connected through set DPM (by logical condition), which stands for the set of pairs of days and months where January has 31 days, February has 29 days and so on [11].

Connections and interactions were established among the various model building blocks which are: solar collectors, heat storage tanks, backup boiler, mixers and splitters as well as the heat network for space heating and hot water supply to the buildings. The integrated system is modelled as a closed-loop superstructure and consists of material and energy balances for the streams flowing across the entire loop.

It is worth stating that variables such as temperatures, flowrates and energy contents of the streams flowing across each unit are dependent on the hourly changing solar irradiation and ambient temperatures while the efficiencies of solar collectors are also considered to be variables which are subject to changes on an hourly basis. Furthermore, the areas of solar thermal collectors and the volume of the fluid in both heat storage tanks are optimization variables with the most realistic sizes selected remaining constant throughout the year or in any considered time frame. Since the model involves binary variables, as well as equations that are nonlinear, it is represented as an MINLP formulation, similar to what was presented for the industrial sector scenario by Abikoye et al. [10]. The binary variables ensure that the tank fluid is heated only when the tank temperature is below a stipulated value. In like manner, the temperature of the heat transfer fluid must be lower than the temperature of the return flow to solar collector minus minimum temperature difference (ΔT_{\min}).

To reduce the complexity of the model, especially with respect to the nonlinearities, the 24 h duration of a day (hourly time periods) are discretized into smaller number of periods using a clustering rule from previous formulations, and similarly the daily time periods which consist of 29, 30 or 31 days in a month and monthly time periods are discretized to a lower number of periods in a year. The model, which is formulated as a multi-period MINLP problem, has its equations independent of the problem data. Hence, the model can be applied to establish the annual/multiannual potential contribution of solar thermal for any case study in any location.

5.3 Case Study

The integrated solar thermal utilization technique presented in this paper is implemented using heat consumption data obtained from the assessment of the district heating system in Slovenia [12]. Three types of reference residential buildings were selected from the report to test the efficacy of the developed model. The buildings are described as: VSS1 (multi-dwelling building), ESS1 (single-family building) and ESS2 (single-family building), see also Figure 5.1. The data for the case study is shown in Table 5.1.

The maximum area available for solar collectors (upper bounds) is dependent on available building. Energy consumption (in kWh/y) is calculated based on available floor area, e.g. for VSS1, space heating amounts to 255,360 kWh/y while hot water use accounts for 44,688 kWh/y, and so on. To represent the various energy consumption data on hourly basis, 24 h/d are divided into 4 periods (P1-P4): 6 am – 8 am (P1), 9 am – 6 pm (P2), 7 pm – 10 pm (P3), 11 pm – 5 am (P4). Daily time periods (29 – 31 days in a month) are regarded as one period in each month, and the energy consumption is assumed to be the same for each of the days in a month. The energy consumption for space heating and hot water use are allocated on an hourly basis as shown in Table 5.2.

Table 5.1: Baseline scenario for energy consumption in VSS1, ESS1 and ESS2 buildings [12]

Building type	Available roof area (m ²)	Available floor area (m ²)	Energy consumption kWh/(m ² y)	
			Space heating	Hot water use
VSS1	470	1596	160	28
ESS1	107	147	230	27
ESS2	107	234	190	27

Table 5.2: Allocation of energy consumption on an hourly basis for the three buildings (in %)

Building type	VSS1		ESS1		ESS2	
	Space heating ¹⁾	Hot water use ²⁾	Space heating ³⁾	Hot water use ⁴⁾	Space heating ⁵⁾	Hot water use ⁶⁾
January	25	11.25	20	11.25	31	9.25
February	20	9.17	15	8.75	20	9.08
March	10	9.58	10	9.58	10	7.92
April	5	8.75	7	8.75	2	8.58
May	/	8.08	/	8	/	8.08
June	/	7.92	/	7.67	/	7.92
July	/	3.33	/	5.17	/	6.75
August	/	3.75	/	3.42	/	7.08
September	/	8.75	/	8.75	/	9.17
October	5	9.58	7	8.58	2	8.92
November	15	9.58	21	9.67	10	8.33
December	20	10.25	20	10.42	25	8.92

¹⁾ 30 % in P1, 30 % in P2, 40 % in P3 and 0 in P4, ²⁾ 30 % in P1, 25 % in P2, 35 % in P3 and 10 % in P4,

³⁾ 10 % in P1, 30 % in P2, 50 % in P3 and 10 % in P4, ⁴⁾ 10 % in P1, 35 % in P2, 40 % in P3 and 15 % in P4,

⁵⁾ 35 % in P1, 40 % in P2, 25 % in P3 and 0 in P4, ⁶⁾ 35 % in P1, 45 % in P2, 20 % in P3 and 0 in P4

Hourly solar irradiation and ambient temperature data were considered for the selected location near Maribor, Slovenia (coordinates: Latitude 46.552 N, Longitude 15.676 E, 267 m above the sea level) and were obtained from EC JRC PVGIS project database [13]. With availability of information on hourly changes in meteorological conditions, and that of the hourly changes in total heat demand by each of the building (see Tables 5.1 and 5.2), the design and optimisation task is then to minimise heat supply from the backup utility.

Similarly, as the data for heat demand in each of the building, the model is discretised into the same four periods of a day (P1-P4) while the 29 – 31 days of the month were discretized into one period. Two scenarios were further considered due to their peculiarities: i) scenario for winter months which includes the months November – February, and ii) scenario for summer months which is made up of the months June – September. Thus, 4 hourly, 1 daily and 4 monthly periods were considered in each of the scenarios. Since the models are highly nonlinear, upper bounds were set on the flowrates (100 t/h), heat load (1,000 kW), volume of fluid in the storage tanks (300 m³), areas of solar collectors for each building (see available roof area in Table 5.1) and temperature across the loops (99 °C). The inlet temperature of feed water to Tank 1 is assumed to be 20 °C, ΔT_{\min} is 10 °C, the minimum temperature for hot water use is 55 °C, while temperature for space heating in radiator system is 70 °C. The outlet temperature of radiators is assumed to be 20 °C lower (e.g. 70/50 °C). For simplicity, the temperature of backup utility to Tank 2 is fixed at 120 °C, while the temperature of fluid returning to the backup boiler is set as a variable. For energy balance calculations, a reference temperature of 20 °C is selected.

The developed models are solved using SBB solver in GAMS environment (GAMS Development Corporation) [14]. They consist of approximately 3,300 single equations, 3,100 single variables, and 16 binary variables. The models were solved on a personal computer with Intel® Core™ i7-8700K CPU @ 3.70 GHz processor, 64 GB of RAM and solution to the problems was obtained in few seconds with 5 % optimality gap.

5.3.1 Results of the first scenario (winter months)

The average values obtained for variables, such as flowrates, temperatures and changes in heat load for the first scenario considering four winter months are shown in Table 5.3. The feasible and most realistic areas of solar collectors selected by the model are 256.79 m² for VSS1, 107 m² for ESS1 and 107 m² for ESS2, while the upper bound volume of 300 m³ is the optimal values chosen for the two storage tanks. The solution indicates using solar thermal for hot water only, while in the case of space heating, the backup utility is required. Overall, 177.28 kWh/d on average is provided by solar energy,

while 2,217.67 kWh/d is required to be provided by the backup utility. This is because the temperature achieved through solar heating of Tank 1 in the winter months considered is too low (55.67 – 56.41 °C) to be used for space heating where a minimum temperature of 70 °C is required.

Table 5.3: Average values of variables for the scenario considering four winter months

	Flowrate (t/d)	Temperature (°C)	Change in heat load (kWh/d)
Collector, VSS1	28.17	66.93 / 83.68	96.70
Collector, ESS1	11.74	66.93 / 83.68	40.29
Collector, ESS2	11.74	66.93 / 83.68	40.29
Feed water	4.311	20.60	3.02
Tank 1	55.96	55.67 – 56.41*	/
Tank 2	99.13	92.57 – 99.00*	/
Space heat, VSS1	72.81	81.87 / 61.87	1,689.29
Space heat, ESS1	9.14	80.19 / 60.19	211.87
Space heat, ESS2	13.64	81.87 / 61.87	316.28
Hot water, VSS1	3.55	56.10	148.57
Hot water, ESS1	0.31	56.10	13.13
Hot water, ESS2	0.44	56.10	18.60
Backup boiler	3.54	109 / 120	2,217.67

* temperature in the storage tank

The energy required for hot water use is provided from two sources, which are the feed water (3.02 kWh/d on average) and solar collectors (177.28 kWh/d on average) in period P2. The quantities of energy provided by solar thermal are: November (129.23 kWh/d), December (257.35 kWh/d), January (210.21 kWh/d) and February (112.32 kWh/d). In winter months therefore 7.40 % of the required energy is provided by solar thermal.

5.3.2 Results of the second scenario (summer months)

The average values obtained for flowrates, temperatures and heat loads for the second scenario, which considers four summer months are shown in Table 5.4. The most realistic areas of solar collectors considering four summer months in the three building types are 3.69 m² for VSS1, 2.42 m² for ESS1 and 27.43 m² for ESS2, while the volume of fluid in Tank 1 is 300 m³. It should be noted that the areas selected for solar collectors in the second scenario are smaller due to comparatively higher solar irradiation and less demand for heat in the summer months. The model suggests no use of backup utility and all the requirements for hot water use are satisfied by solar thermal (111.56 kWh/d on average) and feed water (0.27 kWh/d on average). The energy supplied by the solar collectors is

provided in periods P1 and P2. The quantity of energy supplied by the collectors in each of the summer months for P1 and P2 are: 18.22 and 83.29 kWh/d in June, 23.72 and 102.05 kWh/d in July, 17.76 and 98.35 kWh/d in August, 17.29 and 85.54 kWh/d in September. In this second scenario, the total energy required for hot water use across the summer months is satisfied by solar thermal.

Table 5.4: Average values of variables for the scenario considering four summer months

	Flowrate (t/d)	Temperature (°C)	Change in heat load (kWh/d)
Collector, VSS1	0.24	65.51 / 95.58	12.29
Collector, ESS1	5.99	65.51 / 95.58	8.04
Collector, ESS2	0.19	65.51 / 95.58	91.23
Feed water	2.74	20.08	0.27
Tank 1	9.16	55 – 65.50*	/
Hot water, VSS1	2.15	55.17	87.47
Hot water, ESS1	0.20	55.17	8.20
Hot water, ESS2	0.40	55.17	16.14

* temperature in the storage tank

5.4 Conclusion

In this paper, a new simultaneous multi-period MINLP approach for the design and optimization of solar heat network in a cluster of buildings has been presented. The proposed method considers hourly-based values of meteorological parameters such as solar irradiation and ambient temperature and also enables optimization of the dynamic behaviour of the solar heat supply and utilization based on hourly, daily and monthly time periods. The method is demonstrated on a case study in Slovenia involving a cluster of three different types of buildings where provision of hot water and space heat by solar thermal are demonstrated for winter and summer months. However, the method could be applied to a different case study in any geographical location because the equations surrounding the model building blocks are developed independent of the data.

The results obtained show that the maximum attainable heat from solar is 7.4 % of the total heat required, and collector sizes of 256.79 m² for VSS1 and 107 m² for both ESS1 and ESS2 are selected. Though solar heat utilization for hot water is completely satisfied in this period, space heating is constrained because the maximum temperature level (55.67 – 56.41 °C) of solar fluid in this period of the year is lower than the minimum temperature required by radiators for space heating. Hence solar energy is used only as a pre-heating source of heat in the winter months. On the contrary, in summer

months all the demand for domestic heating is satisfied by solar thermal with the collector areas of 3.69 m² for VSS1, 2.42 m² for ESS1 and 27.43 m² for ESS2. It should be noted that the selected collector areas in the two scenarios are far less than the available space on the rooftops for the three building types considered.

Nevertheless, the potentials and the total operating time of solar thermal collectors can be further extended by combining other clean energy/energy efficiency technologies with the integrated solar thermal network. The possibility of incorporating heat pump (with or without the combination of heat and power cogeneration unit) and studying the effects of heat losses on the total attainable solar thermal for utilization in buildings during long-term storage will be investigated in future works.

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Part II: Domestic Integration of Solar Thermal Incorporating Single Heat Storage Tank and Backup Burner

Preamble

Depending on the design preference, a satisfactory domestic solar heat integration can also be achieved with single heat storage tank with or without the incorporation of a backup heat supply system. Many school of thought argued that such design is more compact, economical and efficient. Extensive research work have also shown that the thermal performance and general reliability of the system can be enhanced by simple design architecture that are relatively and optimally sized according to the profile of heat demand and the maximum attainable solar heat per time. Furthermore, perfect mixing and evenly distributed heat transfer can be achieved within the storage tank if the freshwater inlet to the tank is strategically positioned in a manner that maximizes flow-contact and exchange of heat between water and the circulating hot solar fluid flowing through the heating coil of the tank. The second part of this chapter presents a domestic solar thermal design with single heat storage tank and backup burner for providing hot water and space heating needs in residential apartments. The reported work under this section is a direct reproduction of the paper invited for special issue in Renewable and Sustainable Energy Reviews Journal.

Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating

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Highlights

- Solar systems can provide significant energy savings for domestic heating
- Multi-period MINLP formulation for domestic solar thermal integration is presented
- Solar thermal utilization for water and space heating in three building designs is investigated
- Benefits of periodic heat storage across the year was implemented especially for low/non heating periods
- Design and operating parameters of the heat network are optimized simultaneously

Abstract

This study presents a generic multi-period design and optimization method for solar thermal utilization in buildings. First, the current trend of energy consumption in buildings is outlined with an overview of some previous solar thermal utilization techniques in residential and commercial buildings. Thereafter, a new design strategy is presented for integrating solar thermal with the heat network of a cluster of buildings that are characterized by varying individual heat requirement profiles from one building to another. The integration scheme, which is based on the multi-period Mixed Integer Non-Linear Programming formulation, accounts for all essential attributes of the design and operation variables. The model considers hourly changes in meteorological parameters such as solar irradiation and ambient temperature, as well as the thermal output of the integrated system. It also accounts for simultaneous optimization of the dynamic features of solar heat supply, storage and utilization, according to hourly, daily and monthly discrete time periods. The presented case study refers to a cluster of three types of residential buildings located in Maribor, Slovenia. The illustrated case study demonstrates the potential of solar thermal in providing hot water and space heating in an integrated multi-building heat supply network. The results show the maximally attainable solar thermal contribution to the buildings' heat energy demand based on the size of collector and accompanying technologies (such as storage tanks) in relation to the heat load and solar thermal potential. The design further demonstrates the annual CO₂ emission reduction potential that could be derived from the proposed design based on the two scenarios presented.

Keywords: Building sector; Energy consumption in buildings; Solar thermal integration; Space heating and hot water use; Multi-period MINLP formulation; Optimization; Attainable heat output

Nomenclature

Abbreviations and Units

CO ₂ e	CO ₂ equivalent
DWH	Domestic water heating
EC	European Commission
EJ	Exajoules
GAMS	General Algebraic Modelling System
GHG	Greenhouse gas
GWth	Gigawatt thermal
IEA	International Energy Agency
IT	Information technology
JRC	Joint Research Center
kWh	Kilowatt hour
MINLP	Mixed Integer Non-Linear Programming
PWh	Petawatt hours
PVGIS	Photovoltaic Geographical Information System
SBB	Simple Branch and Bound
SH	Space heating
SHC	Solar heating and cooling

5.7 Introduction

Energy use in buildings (residential and commercial) accounts for about 40% of global energy consumption [1], making the sector one of the largest single contributors to CO₂ emissions and climate change [2], with about 33% direct and indirect contribution to global energy-related greenhouse gas emissions [3]. The annual global energy demand from the building sector continues to grow [4], with a projected increase of about 65% between 2018 and 2050 [5]. The trend is likely to be sustained, considering the exponential growth in global population and industrialization [6], as well as its implications for resource utilization, especially energy [7]. Thus, the major challenge remains how to provide alternative, sustainable sources of energy to meet current energy demand and satisfy future demand projections [8]. Energy is indeed at the crux of today's modern world, underpinning socio-economic growth and providing support for technological advancement [9]. However, with the current pressing concern about global climate change and the fear that most conventional energy resources are finite [10], the concept of integrating renewable and sustainable energy designs in buildings is essential for emission reduction and climate change mitigation.

Solar thermal is a renewable and sustainable source of heat with great potential to satisfy most domestic energy needs and offset the deficit in regional/district energy supply to buildings [11]. The theoretical potential of solar energy resources transcends the net global energy demand, and just within a period of 90 minutes, the Earth receives a significant amount of solar radiation that is enough to satisfy the annual global energy needs [12]. The natural regenerating feature of solar energy and its availability at diverse ambient temperature levels without any mechanical work input also make it a unique sustainable source of heat for domestic heating [13]. Besides, solar thermal requires relatively less complex technology with minimal contribution to climate change [14]. Although the share of solar energy in the global energy supply mix is still very low [15], the technical feasibility [16], economic benefits [17], and potential energy contributions [18] of many available domestic solar thermal technologies have been proven, with outstanding features as an important source of energy for a sustainable future [19], even in the cold regions of the world [20].

Several design methods for using solar thermal in residential and commercial buildings have been reported [21]. These range from individual efforts aimed at policy redirection for energy savings and emission reduction [22], to designs for single family houses [20], community and district heat networks [23], as well as large scale solar projects such as IEA SHC [24], EU-UrbanSol+ [25] and Pitagoras [26]. Other available designs include the combination of solar with other technologies such as heat pumps [27] and various combi-systems [28] for efficiency enhancement. Basically, domestic hot water and

space heating temperatures, which fall between 50°C – 120°C, can be satisfied by simple solar thermal collector designs such as the evacuated tube and flat plate collectors [29]. However, as highlighted by Shafieian et al. [30], the major challenge confronting the growth of solar thermal utilization in buildings is the influence of fluctuating weather conditions on the solar heat network, and lack of suitable storage facilities/materials of high energy density. Incorporating appropriate heat storage techniques could circumvent some of these problems by bridging the gap between energy supply and demand [31]. Depending on the design preference and strength of solar resource at reference location, the storage technique could be periodic/seasonal [32] or general storage design selection based on need assessment, energy demand level and environmental considerations [33]. Regardless of design approach, an important aspect which is often neglected is that the heat storage should be designed to optimally match the fluctuations in attainable solar heat and the profile of energy demand with minimal use of a backup utility [34]. Moreover, since the potential of solar resources varies from region to region, it is pertinent that the design framework for solar thermal utilization should also be generic, so that it can be adapted to similar case studies in other locations [13]. Though, it is worth noting that obtaining a design with these features is not trivial, considering the computational complexities resulting from the technical difficulties and thermodynamic constraints involved. Nonetheless, the optimum performance of any solar thermal design could only be guaranteed when the integration scheme is formulated with utmost consideration given to the aforementioned features, as well as the changing meteorological conditions, together with the actual daily and seasonal variabilities in the profile of heat demand.

Furthermore, as water heating forms a major part of energy use in buildings [35], the design framework for solar thermal utilization should also reflect the actual (or realistic) water-draw profile of the building. The above are in addition to other essential attributes, such as the incorporation of features to satisfy the heat demand for space heating, so as to accomplish a comprehensive and all-inclusive sustainable energy design for the buildings. Unlike what is commonly found in most previous domestic solar thermal utilization methods, our study provides additional contributions to existing knowledge, given that all the aforementioned features (which are considered to be essential for a robust domestic solar thermal design), are rigorously accounted for in a comprehensive design and optimization framework. Integrating these details in a flexible structure that is applicable to other case studies and locations in any part of the world is yet another unique contribution of this study.

This Chapter presents an integrated, inter-building solar heat network design incorporated with strategies for periodic storage of harvested solar thermal and opportunity for backup utility system to satisfy heat demand for water and space heating needs of the participating buildings. The concept

evolved out of the need to promote renewable and sustainable energy designs for buildings. The developed model accounts for intermittent changes in meteorological conditions, as well as other variabilities on both the supply and demand side of the integration, together with the influence of these changes on the operating features and thermal output of the integrated system.

The remaining part of the Chapter is arranged in the following order: A summary of the state of energy consumption in residential and commercial buildings is provided in Section 5.8, with special focus on heat demand. Section 5.9 presents an overview of the application of domestic solar thermal in various parts of the world, highlighting potential areas for improvement. In Section 5.10, the design architecture for the integrated design proposed in this Chapter and the problem statement formulated for the study are presented. Section 5.11 gives information on the applied methodology and a summary of the developed model. The case study used to illustrate the proposed integration model, the results obtained and discussion surrounding the results are described in Section 5.12, while the concluding part of study and directions for future research are presented in Section 5.13. Details on the formulation of the proposed model are available in the supplementary material supplied at the end of the Chapter (i.e. Appendix 5A).

5.8 Outlook on Energy Consumption in Buildings

Residential and commercial buildings contribute heavily to global energy consumption and energy-related emissions [36]. Though the actual recorded figure for this share of energy consumption varies in many reports, owing to different quantification metrics and accounting criteria [37]. A recent statistical review [15] estimates the current global primary energy consumption to be about 13,864.9 Mtoe/y, while residential and commercial buildings jointly account for between 32% [1] and 40% [38] of final energy consumption.

Majority of the global population spend the most useful part of life inside a building. These include dwelling apartments (detached or cluster buildings), commercial buildings (shopping malls, hotels and resorts), as well as private and public office spaces such as academic and vocational rooms. Thermal comfort in these buildings (especially in the temperate climatic regions of the world) is largely accomplished through heaters and radiators, which are mostly run by energy from non-renewable sources [37]. Thus, in addition to behavioural changes and lifestyle modification towards rational energy use, opportunity exists for renewable and sustainable energy technologies in the building sector. To further highlight the opportunities and benefits to be derived from incorporating such

technologies, a more precise allocation of final energy consumed in buildings according to end-use is illustrated in Figure 5.2, where it is shown that between 63% and 81% of the total energy demand in buildings (depending on the specific climatic zone) is used for heating (i.e. water heating, space heating and cooking) [38].

Two distinct categorizations (i.e. residential and commercial) are mostly used to correctly track and account for the share of energy use in the building sector [38]. Accordingly, a further breakdown analysis on the cumulative share of annual global energy consumption of the building sector based on this distribution shows that 45% and 85% of the total energy demand in residential and commercial buildings is used for various heating purposes (Figure 5.3). Within the European countries for instance, over 50% of household electrical utility goes for heating [39], which is largely inefficient, with additionally burden on the primary energy sources [40]. The recourse is that most domestic heat demand could be satisfied by solar thermal if well harnessed. The above illustrations indicate that heat energy constitutes a major part of the energy demand in buildings; hence, it is a promising area of opportunity for emission reduction through the integration of renewable and sustainable energy technologies into the energy supply-mix of the buildings.

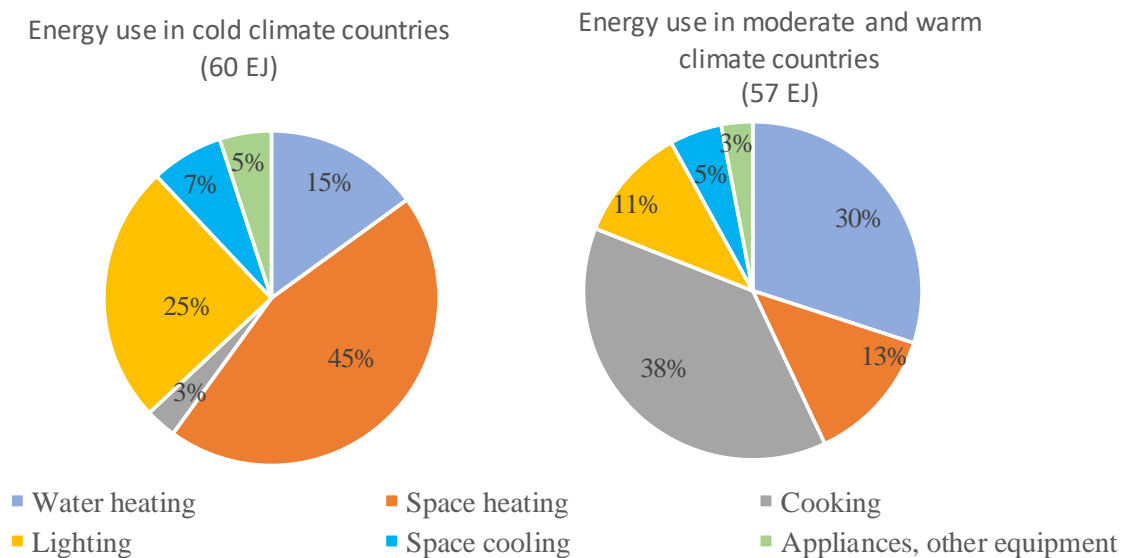


Figure 5.2: Share of end-use energy consumption of buildings in cold and temperate climates (adapted from [38])

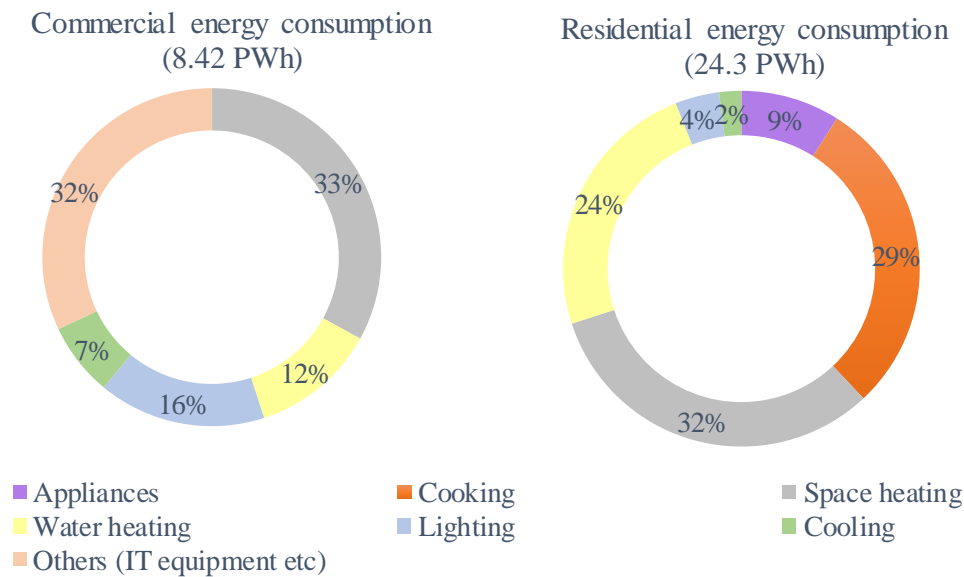


Figure 5.3: Global total energy consumption in buildings (adapted from [37])

5.9 Overview of Domestic Solar Thermal Utilization and Methodologies

Energy is fundamental and the most essential part of daily life [9]. With the abundance and socio-economic significance of global solar resources, the use of solar thermal as an alternative source of energy has become an indispensable part of modern building design [41], especially for space and water heating in domestic apartments, even in extremely cold regions [42]. Generally, domestic solar water heating designs can be classified according to the collector technology (i.e. compound parabolic-, flat plate- and evacuated tube collectors) [43], or according to the manner by which water is heated (i.e. direct heating and indirect heating through heat exchanger) [44], and according to the method of water circulation through the system (e.g. natural convection or forced circulation through various types of pumps) [45]. A number of designs have also been classified as simplified designs because they are considered to have been developed to reduce costs and design/operation complexities [46]. Regardless of the design pattern, the goal remains the same: to convert incident solar radiation to heat energy for various domestic heat needs. Jaisankar et al. [47] and Buker et al. [48] present comprehensive reviews of the most recent domestic applications of solar thermal in buildings. Their review [47] includes a detailed survey of available solar water heaters and in [48], several design techniques and collector technologies that can improve thermal efficiency in existing solar water heating systems as well as essential factors to be considered for optimal performance in grassroots designs are presented.

As various renewable energy sources continue to emerge, cost (affordability), supply security (for both present and future demand) and potential contribution to climate change are critical decision-making criteria taken into consideration for increasing the share and relevance of any energy source in the energy mix [49]. Solar heating systems in buildings are generally known to have long term techno-economic benefits [50] and a lower environmental footprint [51]. For instance, as at the end of 2017 in Kenya, it was reported that there are about 77,000 units (457,076 m² of collector area) of solar water heaters in domestic and commercial institutions, offsetting approximately 40,000 t CO₂e/y [52]. Ferrer [53] also examined the payback period for solar water heaters in low density buildings in South Africa. The impact of fluctuations in selected parameters, including the efficiency and cost of solar water heaters was used by the author to establish a unique base case scenario for estimating the economic return and energy payback of the designs investigated.

Ultimately, the performance of solar heating systems is influenced by the type of collector and prevailing environmental data such as ambient temperature, solar irradiance and size of demand. Bouhal et al. [45], examined the effects of varying heat load profile and collector technology on the overall performance of domestic solar water heaters for various climatic conditions in Morocco. It was found that the most energy savings of 43 kWh/y were realized in the case of flat plate collectors, as against 13 kWh/y and 29 kWh/y for evacuated tube and compound parabolic collectors. In Turkey, Benli [54], compared the thermal output of galvanized sheet and vacuum tube collectors under Turkish meteorological conditions. The study showed that the performance of the galvanized sheet absorber outweighs that of the vacuum tube with respect to meeting the energy requirement for water-heating across the entire country.

In South Korea, Yoo [55] investigated the performance of a solar water heating system for a multi-family apartment complex comprising 14 units and 1,179 households. It was reported that the accumulated heat gain, which the author claimed was about 52% of the design baseline, amounts to a reduction of about 71,907 L/y in oil consumption and a reduction of approximately 50.8 t CO₂e in emissions. A similar study on integration of solar water heaters with a building energy system was conducted in the Changjiang River region of China [56]. The potential contribution of solar water heating in residential and commercial buildings across the area was analysed with respect to energy savings. Thereafter, recommendations were made for energy reviews and policy redirection for the implementation of a city/regional-level solar water heating programs to achieve energy savings and emission reduction in buildings.

Beyond the tropical areas, solar thermal resource has also found use in the temperate and other parts of the world extending to the polar region and Antarctica [57]. Ampatzi et al. [58] investigated 48 modelled cases of 12 common residential housing designs in North European countries. The study considered various ranges of thermal energy demand and rooftop capacity with respect to the space available for solar collector installation. Other studies conducted to establish the possibility of obtaining improved solar water heating in extremely cold regions with temperatures below freezing point include that of Mori et al. [59] and Liu et al. [60], while the potential and viability of domestic solar thermal utilization have also been demonstrated in countries like Taiwan [61], Australia [62], Barbados [63], Mexico [64], the USA [65] and Canada [35].

Solar thermal is widely known for its intermittence feature which often impose low energy output and energy supply gap limitations on the system [66]. In this regard, solar water heating designs specifically formulated to include thermal storage technologies as a remedy have been presented by Antoniadis et al. [67]. Kabeel et al. [68] experimentally examined some materials of high thermal conductivity storage for effective thermal storage. Alva et al. [69] identified several solar thermal storage materials and techniques to circumvent the intermittence of solar energy supply. In their study [69], the properties of these materials and analysis of their application to solar thermal systems were summarized. Rodríguez-Hidalgo et al. [70] present studies with simplified methods for dimensioning storage components in solar thermal applications, while investigations on highly efficient storage media [71], improved nano fluids [72] and solid-liquid phase change materials [73] in relation to their storage and heat capacity enhancement in solar systems have also been conducted by several authors. An additional feature explored by other researchers is the inclusion of opportunity for space heating in tandem with the solar water heating network as demonstrated in the studies of Glembin et al. [74] on direct solar integration, and integration possibilities through heat enhancement as presented by Fan et al. [75].

Owing to several inherent challenges with solar energy resource (mostly caused by its supply variability), the propensity to achieve satisfactory system performance under several design constraints is at the crux of many research contributions from several authors. To this end, a number of methods seeking the best design and operating parameters under several conditions have been developed. Golić et al. [76] presented a generalised, multi-criteria integrative design approach for solar water heating by simplifying the procedure for dimensioning solar collector and heat storage tanks for residential buildings. A multi-objective optimization framework for a residential solar thermal combisystem was presented by Rey et al. [77]. Kumar et al. [78] developed a theoretical model for the design and operation of heat pipe-based solar water heating systems. While investigating the

heat transfer processes and performance of the system, the author found that the effects and influence of variabilities in solar radiation and ambient temperature on the collector performance were more significant than the influence of other design variables. Shukla et al. [79] proposed a technique to achieve optimal design of solar collector, storage tank and heat exchangers under low ambient conditions. A numerical model for estimating the thermal performance of heat storage tanks in relation to solar collectors was developed by Bazri et al. [80], while Deetjen et al. [81] proposed an optimal energy dispatch and equipment sizing technique for residential rooftop solar integration.

Despite the numerous contributions on the integration of solar thermal with building energy systems, its impact in global share of energy consumption by residential and commercial buildings is still yet to be visible [15]. This is an indication that further improvements are still needed on the established methods of solar thermal utilization with the goal of increasing the quantity of attainable solar heat that could be realized in practical applications. Such methodology improvements would be needed on both the demand and supply sides of the integration considering the discontinuous nature of solar thermal supply and the multi-period variability in the profile of heat demand, as well as the implications of these uncertainties on the heat supply network of buildings.

Apart from the underlying profile of energy supply and demand, optimal performance of a domestic solar heating system also depends on the criteria and scope of the domestic hot water draw and space heat consumption considered in the design framework [82]. Accounting for this in most studies on domestic solar thermal utilization has been based on a series of assumptions [83]. While analysing this area of research, Edwards et al. [84], found that in the few cases where practical data on the hot water draw profile and general heat consumption are used by the author, they are usually devoid of the recent household hot water consumption pattern, or even the contemporary technical standards for estimating such values. The above submission is also supported in a recent study on the review of the profile of domestic hot water consumption in buildings [85], where a similar understanding was conveyed. Meanwhile, it should be noted that factors such as seasonality and the specific period/time of day, together with ambient conditions, are essential features that significantly influence the pattern of heat demand and are also crucial prerequisites for any reasonable estimation of attainable solar heat that is harvestable per period. In essence, consideration of fluctuating energy use patterns, together with the transient features of meteorological conditions such as the changing solar irradiation and ambient temperature, are crucial for establishing a viable and more robust solar thermal integration model. From these viewpoints, a study in this direction is essential for optimal performance of domestic solar thermal utilization designs.

To the best of the authors' knowledge, a generic design and optimization framework incorporating all the above-mentioned features with strategies for periodic storage of harvested solar heat in a multi-building heat demand network is still lacking. This is especially so in the case where the multi-building heat demand network is additionally characterized by varied individual profiles of heat demand from one building to another. Therefore, a comprehensive design and optimization method for integrating solar thermal with a multi-building heat supply network is presented in this Chapter. The design incorporates strategies for periodic storage of harvested solar heat and opportunities for a backup utility system to satisfy the hot water and space heating needs of the participating buildings. The method adopted is based on a multi-period mixed-integer non-linear programming (MINLP) model formulation. The mathematical model captures the thermodynamic and operating features of the entire system according to the dynamic behaviour of the design variables, while the multi-period optimization structure of the model reflects the intermittent variabilities in design parameters (such as fluctuating solar irradiation and ambient temperature), together with the influence of such variabilities on thermal output from the system. These features are accounted for in the model on hourly, daily and monthly time periods.

5.10 Domestic Solar Heat Network Architecture and Description of the Integrated System

Figure 5.4 outlines the integrated design framework presented in this Chapter. Three types of buildings are considered to test the developed integrated solar thermal design and optimization model. The types of buildings are multi-dwelling building (VSS1) and two different types of single-family building (ESS1 and ESS2) [86]. Based on the proposed design strategy, the collectors are installed on the rooftops of a set of buildings and are capable of providing some or all the energy required for domestic water (DW) and space heating (SH) for the participating buildings. The integrated design consists of solar collectors, heat storage tank, space heating radiators, a backup utility from burner, hot water supply to the buildings as well as the mixing and splitting points. Two closed loops and one open loop are considered. The closed loops are i) solar collectors – heat storage tank – solar collectors and ii) space heating radiators – heat storage tank – space heating radiators, while the open loop involves feed water – domestic hot water use. Optimization of the integrated system is performed with the goal of minimizing the total heat supplied to the network from the backup utility.

Each of the collectors on VSS1, ESS1 and ESS2 absorbs incident flux from the sun through its surface and raises the temperature of the circulating fluid, which serves as the heat transfer fluid of the solar loop, according to the strength and intensity of solar irradiation and ambient temperature. The heated solar fluid then flows from the collectors to the heat storage tank, where it exchanges some of its heat with the fluid in the tank (water is assumed in this study) before flowing back to the solar collectors. As the need may arise, the resulting hot fluid in the storage tank is subsequently available as hot water and as a heat source for the space heating needs of any of the buildings. Depending on the temperature level attained by the fluid in the tank through heat exchange with the solar thermal fluid, the hot water and space heat demand of the buildings could be fully satisfied by solar energy. Otherwise, additional heating will be provided through a backup burner to further raise the temperature level of the solar pre-heated fluid in both the hot water supply and space heating loops. The model is formulated as a multi-period MINLP problem. Hence, the dynamic features of both heat supply (based on changes in weather conditions) as well as the changes in demand across the year are accounted for in the study.

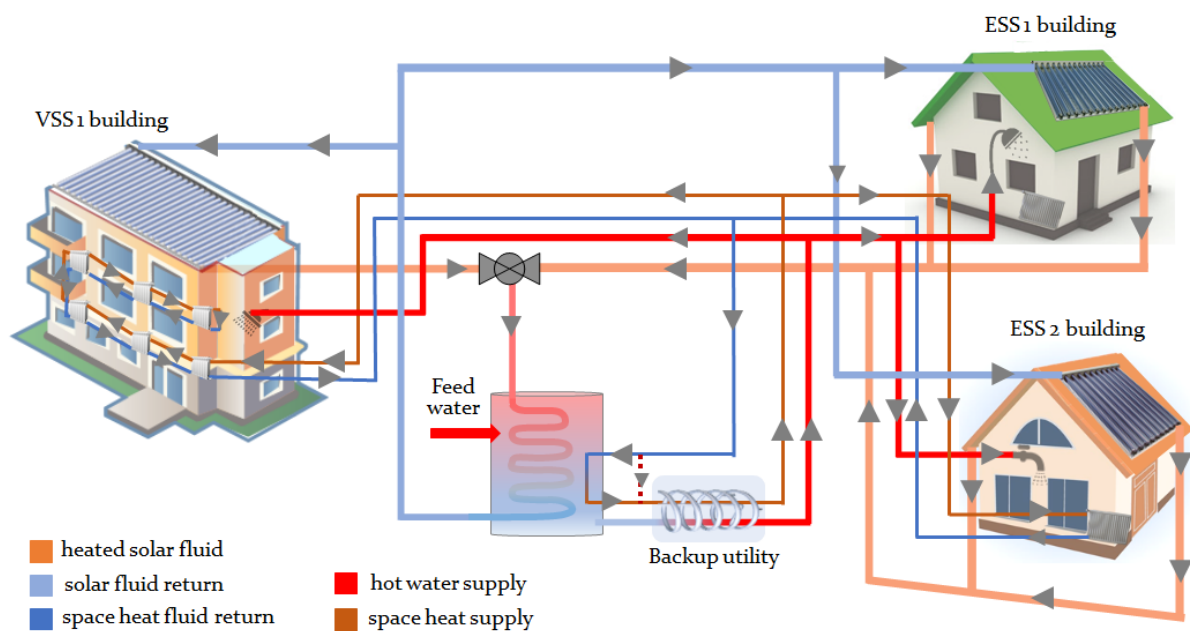


Figure 5.4: Integration of solar thermal for domestic hot water and space heating

In order to account for these features, most previous studies used simplified linear relationships between the periodic profile of streams such as temperature, flowrate and energy flow across the system (e.g., [87], [88] and [89]). However, it should be noted that the relationships among these parameters are highly nonlinear as both flowrate and temperature are periodically changing. This is accounted for in this study without any form of linearization. Besides, the proposed models in this

study include two binary decisions (which are also subject to change on an hourly basis), with respect to the thermal energy of the working fluids across the collectors - heat storage tank loop and radiators - storage tank loop. The first binary variable ensures that the water in the storage tank is heated by solar fluid only when the temperature of the fluid in the tank is lower than the temperature of the solar capture fluid circulating between the tank and the solar collector minus a minimum temperature difference (ΔT_{\min}). On the other hand, the second binary variable is set to 1 only when the temperature of the fluid in the tank is greater than the temperature of the fluid returning to the tank from the radiators plus ΔT_{\min} . In this case, the working fluid in the space heating radiators – heat storage tank – space heating radiators loop is (pre)heated by solar. Otherwise, if the temperature of the fluid in heat storage tank becomes lower during some time periods, the binary variable is set to 0, and only the backup utility is used for space heating. A detailed description of these heat transfer constraints in the integrated system and the governing equations (Eq. (14) - Eq. (17)) are provided in Section 5.5.3 of the Supplementary material. Additionally, hot water consumption by the three building types across the network is linked to fresh water supply to the tank, such that the equivalent of the quantity of hot water pushed out of the tank is continuously replenished from the fresh water source.

Thus, the problem addressed in this Chapter is stated as follows:

Given a cluster of buildings with differing roof areas, type of insulation, year of construction, and varied orientations for solar collector installation. Given also that the annual profile of heat demand for hot water and space heating for the buildings is known but varies from building to building across specific time of the day and periods of the year. The goal is to synthesize an optimally integrated heat supply network that involves solar thermal collectors, heat storage, space heating radiators, hot water consumption and a backup utility system.

To accomplish the above stated goal, the following design objectives are addressed:

- What percentage of the annual heat demand of the buildings can be provided by solar thermal, and what are the potential savings in terms of reduction in external utility?
- What are the optimal collector areas and the matching centrally located storage tank size that will be suitable for the integrated solar thermal network considering the maximum realizable solar heat from the building rooftops?

The following assumptions are considered in the model:

- Heat losses across the multi-building solar heat network are neglected;

- Variabilities in meteorological features for solar thermal utilization (i.e. changes in solar irradiation and ambient temperature) are averaged and discretized on an hourly basis;
- The minimum temperature difference (ΔT_{\min}) for the heat storage tank across the year is the same and fixed;
- Lower and upper bounds on temperatures for space heating radiators are the same for all radiators in all building types;
- The heat storage fluid in the tank is assumed to be continuously perfectly mixed.
- Specific heat capacity and density of heat transfer fluids are assumed constant to reduce the computational complexity.

5.11 Methodology and Model Development

Figure 5.5 shows the sketch of the overall framework and a summary of the applied methodology. The flowsheet for the integrated design is implemented in General Algebraic Modelling System (GAMS) environment [90], and the multi-period MINLP models are solved using SBB solver also in GAMS.

The key variables in the model are the area of solar collector (m^2) on the rooftop of each building and the volume of the fluid in the storage tank (m^3), which should be constant throughout the year. Other key variables include attainable solar heat (kWh/period), flowrates (t/period) and temperatures ($^{\circ}\text{C}$) of each stream in the integrated network, which could be changing on hourly basis. Since most backup utility systems are fossil-based, the technique adopted entails development of a procedure for obtaining maximum attainable solar thermal integration in the heat network. Achieving this will directly result in minimization of additional heat supply from other sources, which may likely be from non-renewable sources.

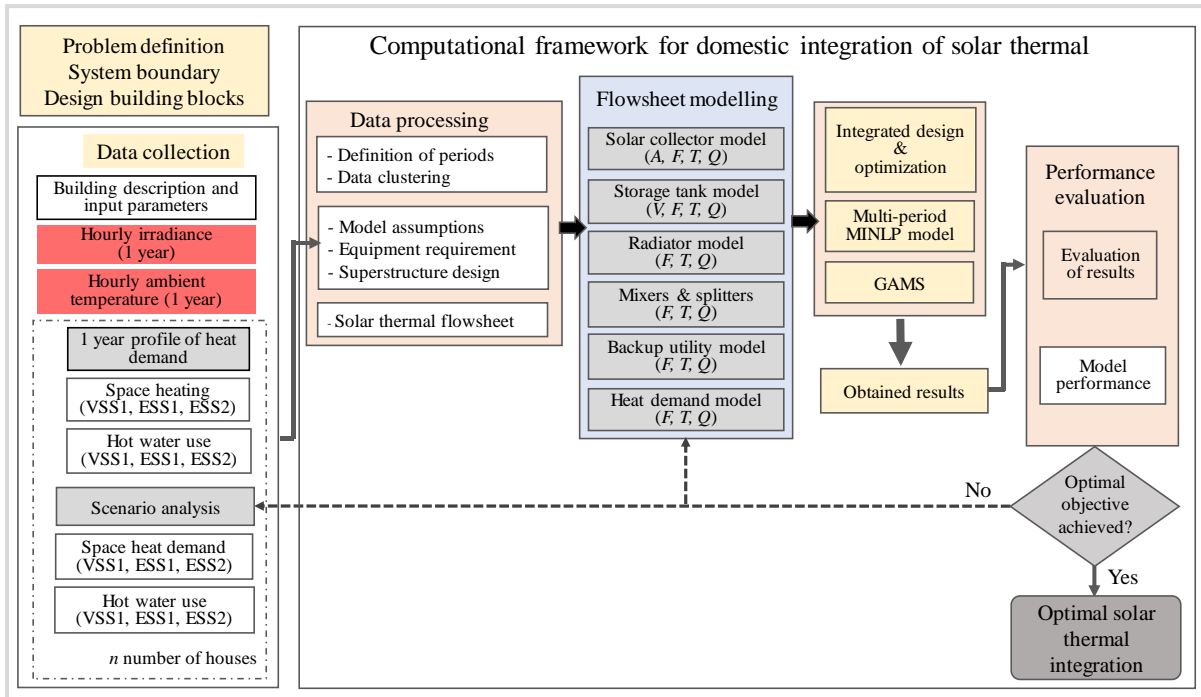


Figure 5.5: Summary of applied methodology

The data gathered include hourly solar irradiation and ambient temperature of the selected location for an entire year and the profile of heat demand for space heat and hot water use in the building types considered. Other important information includes assumptions regarding solar collectors (efficiency factor and experimental constants), selected heat transfer fluid(s), including their properties (specific heat capacity, density and boiling point) for each of the loops, minimum temperature differences and temperatures of feed water, hot water supply, and supply and return temperatures in the space heating system.

The model is formulated in a generic manner such that the model equations are developed and written independent of the data. Thus, the model can be applied to any integrated solar thermal network for hot water and space heating provision in any location with known geographical coordinates and meteorological information. It is formulated as a flowsheet superstructure where the values of variables (flow rates (F), temperature (T) and heat duty (\dot{Q})) at the outlet of each unit (u) are the same as the values at the inlet of the subsequent unit in the flowsheet ($u+1$) in each time period. The entire time period of the year is modelled as hourly (hp), daily (dp) and monthly (mp) time periods in the model.

Equations connecting the values of variables in the flowsheet as well as the detailed description of mathematical formulations for all the units in the integrated system and the objective function of the model are provided in the Supplementary material. These units include a solar collector, heat storage tank, space heating radiator and hot water supply, mixers and splitters and a backup utility (see also

Figure 5.4). The complete balanced equations for flows, temperatures and heat duty of streams across all these units are also included in the Supplementary material.

Since the model is highly nonlinear and requires significant computational time, the data and the constraints developed for the design are clustered into a set of hourly, daily and monthly time periods similar to that presented by Abikoye et al. [13]. This is to reduce the complexity and size of the problem.

5.12 Case Study

The geographical data and domestic heat demand of the city of Maribor in Slovenia (coordinates 46.552 N: 15.676 E Latitude and Longitude, 267 m above sea level, see Figure 5.6) were used to illustrate the application and capability of the developed model.



Figure 5.6: Location used as case study

The model reduction technique adopted, which helps to reduce the computational intensity of the model, entails discretizing hours, days and months into smaller numbers of periods. The 24 hours of the day are divided into 4 periods (i.e. P1 - P4) such that P1: 6 am – 8 am, P2: 9 am – 6 pm, P3: 7 pm – 10 pm and P4: 11 pm – 5 am. Each day in a month (29 – 31 days) is regarded as one period, while all the 12 months of the year are considered in the developed model as presented before in a similar study [91].

Hourly meteorological data for the selected location were retrieved from the EC JRC PVGIS project database [92] for 8,760 hours for the most recent year available in the database (2016) at the time

this study was conducted. Discretized irradiation data as used in the model are presented in Figure 5.7, while discretized data on ambient temperatures are shown in Figure 5.8.

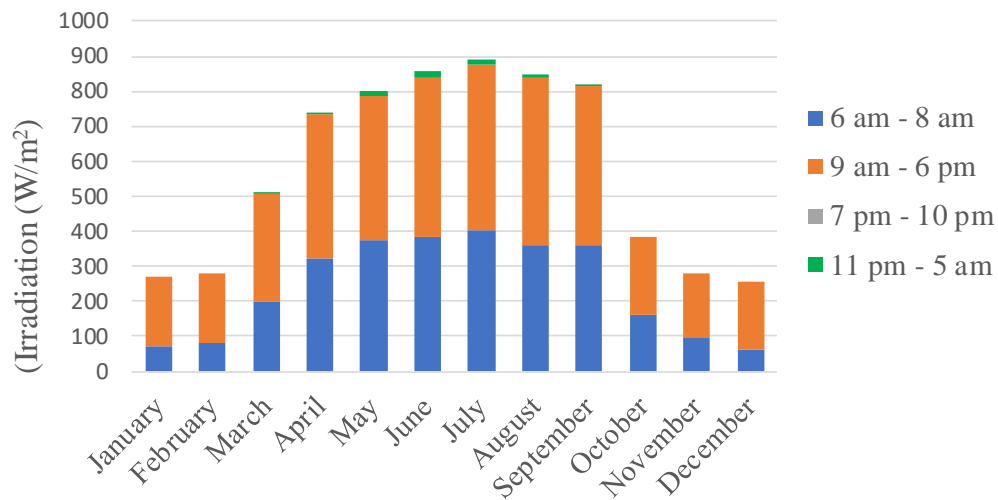


Figure 5.7: Discretized irradiation data as used in the model

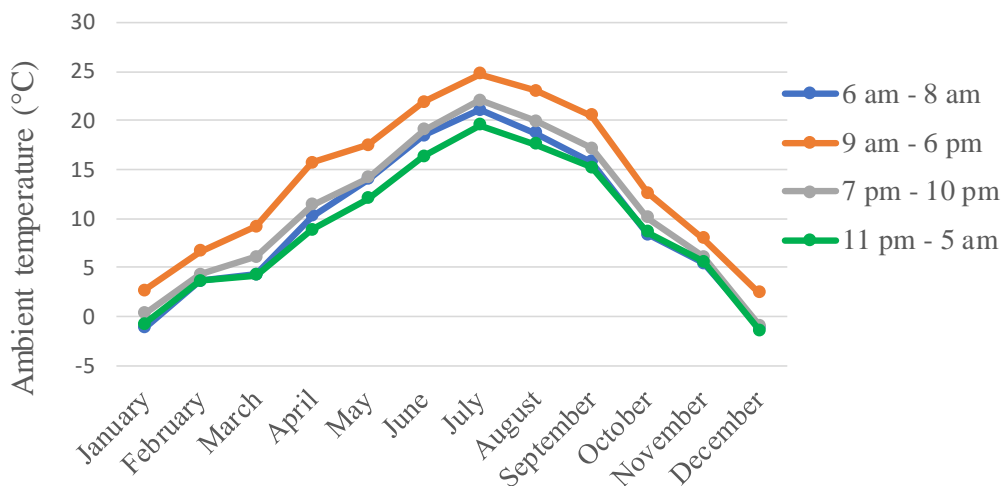


Figure 5.8: Discretized data for ambient temperature for the reference location

The developed model is implemented using heat consumption data obtained from the assessment of the district heating system in Slovenia [86]. Three types of reference residential buildings were selected from the report for solar thermal integration. The building types are described as follows: VSS1 (multi-dwelling building), ESS1 (single-family building) and ESS2 (single-family building), see also Section 5.10. Table 5.5 presents the data used for the selected buildings. The available roof area is chosen as the maximum area available for solar collector installation (upper bounds). Energy consumption data (in kWh/y) for each building is estimated according to available floor area as

obtained from the design data of the buildings, e.g. for VSS1, space heating amounts to 255,360 kWh/y, while hot water use is 44,688 kWh/y, etc., as described in [91].

Table 5.5: Baseline scenario for energy consumption in VSS1, ESS1 and ESS2 buildings (MOI, 2017 [86])

Building type	Available roof area (m ²)	Available floor area (m ²)	Energy consumption kWh/(m ² y)	
			Space heating	Hot water use
VSS1	470	1596	160	28
ESS1	107	147	230	27
ESS2	107	234	190	27

The data on energy consumption for space heating and hot water use in each building are further allocated on an hourly basis, as shown in Table 5.S1 in the Supplementary material. The energy demand data for space heating in each of the buildings for each period considered is shown in Table 5.S2, while the energy demand for hot water use is shown in Table 5.S3 in the Supplementary material.

Due to the non-linearity of the model, upper bounds were set on the flowrate (100 t/h), heat load (1,000 kW), volume of fluid in the storage tanks (between 50 and 10,000 m³), area of solar collectors for each building (available roof area in Table 5.2) and temperature across the loops (99°C). Water is considered as the heat transfer fluid, with a specific heat capacity of 1.16 kWh/(t·°C) and a density of 1 t/m³. Inlet temperature of the feed water to the storage tank is assumed to be 20°C, ΔT_{\min} is 10°C, minimum temperature for hot water use is 55°C, while the lower bounds of the supply and return temperature to the radiators are set at 65°C and 40°C according to [93]. The return temperature of the heat transfer fluid in the radiators is assumed to be at least 20°C lower than the supply temperature to the radiators, as presented in Eq. (19) in the Supplementary material.

The models for the case study consist of 9,837 single equations, 9,029 single variables and 96 binary variables. The models were solved on a personal computer with Intel® Core™ i7-8550U CPU @ 1.80 GHz X64-based processor, 8 GB of RAM. The solutions to the problems in some cases were obtained within few seconds, while it took a few hours in other cases, with a 5% optimality gap.

Based on the trend of changes in the hourly meteorological conditions, heat demand and system efficiency, the solution obtained from the models identifies periodic changes in integration features such as fluid flowrate, energy flow, temperature and efficiency of the solar collector. On the other hand, the volume of the heat storage tank and the area of the solar collectors on each of the rooftops are considered as optimization variables, which however should remain unchanged all through the year.

Series of scenarios for the integrated design are presented and solved to establish the influence of different upper bound values of the volume of fluid in the storage tank (V_{fluid}^{UP}) on the total solar collector area ($A_{collector}$) and the total attainable heat load derivable from solar thermal (\dot{Q}^{solar}). Examples of such results are shown in Figures 5.9 and 5.10, which illustrates the average monthly temperature of the fluid in the tank throughout the year for scenarios where V_{fluid}^{UP} are set as 50 m³ and 1,000 m³. In the first scenario presented in Figure 5.9, the lowest temperature of hot water in the tank is 50°C in P1 (6 am – 8 am) for the month February, while the highest temperature is 82°C in P2 (9 am – 6 pm) for September. Since perfect mixing of tank contents and negligible heat loss are assumed for the storage tank, the temperature of the water exiting the tank, as well as that delivered to the taps in the buildings, is equal to the temperature of water in the tank at each period.

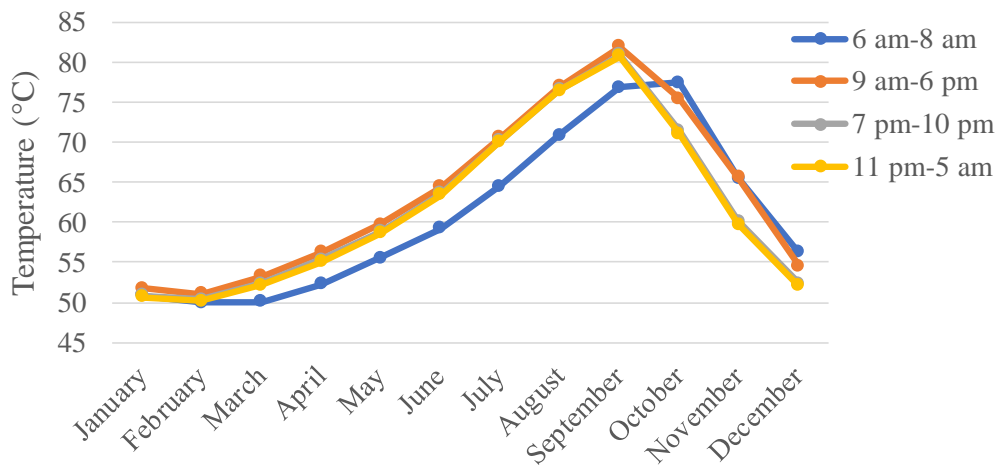


Figure 5.9: Temperature of fluid in the storage tank when V_{fluid}^{UP} is 50 m³

In Figure 5.10, where V_{fluid}^{UP} is 1,000 m³, a pattern similar to the one shown in Figure 5.9 can be observed. However, the lowest temperature of hot water in the tank is 70°C in P1 in March, while the highest temperature of water is 78°C, which occurs within P2 in September. As illustrated in these two scenarios and in other collector sizes considered, there is a continuous increase in the temperature of water in the tank from April to September, after which it starts decreasing up until February, when the lowest temperature is usually recorded. It could also be seen that, for a smaller storage tank, the range of difference in temperature of the fluid in the tank across the year is greater than that for the bigger storage tank sizes (between 50 and 83°C was obtained for $V_{fluid}^{UP} = 50$ m³, while it is between 70 and 77.5°C for $V_{fluid}^{UP} = 1,000$ m³).

It should be noted however that due to the adopted model reduction technique, where the 29 – 31 days of each of the months are discretized into one period as described in [13], the results obtained for the average monthly dispositions of temperature of the fluid in the tank, as well as the corresponding solar heat delivered to the tank in each of the months for all the scenarios considered, are the values for the discretized monthly period. The obtained model results are thus inferred/taken to be a representation of the average values of temperature of fluid in the tank for all the discretized months of the year.

Other notable results from the models include the quantity of solar heat delivered to the tank from solar collectors in every time period across the year. The results for this heat duty are shown in Figures 5.11 and 5.13, while Figures 5.12 and 5.14 show the fraction of heat supplied to the buildings in each period for domestic hot water supply and space heating. Figs. 5.11 and 5.12 show the results for the scenario where V_{fluid}^{UP} is 50 m³, while Figs. 5.13 and 5.14 are for V_{fluid}^{UP} of 1,000 m³.

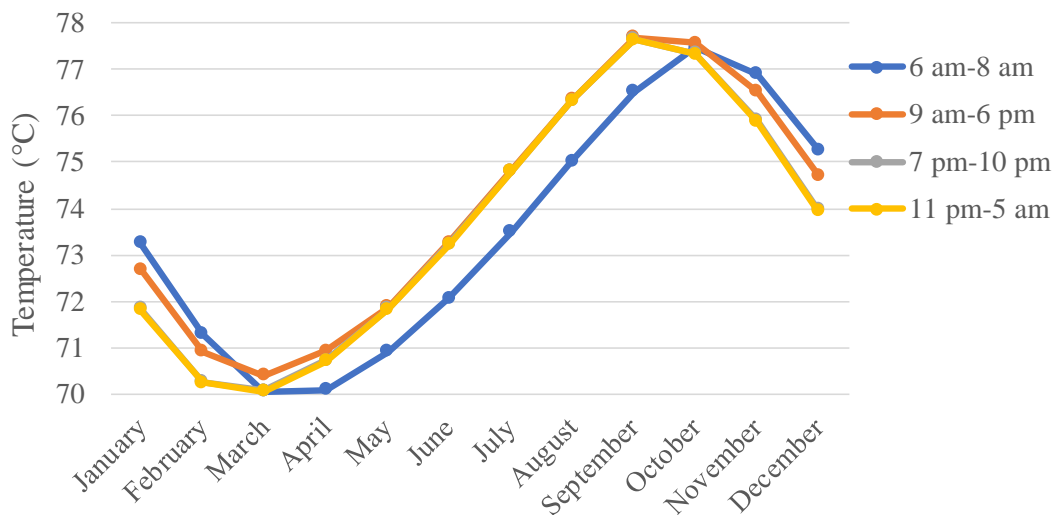


Figure 5.10: Temperature of the fluid in the storage tank when V_{fluid}^{UP} is 1,000 m³

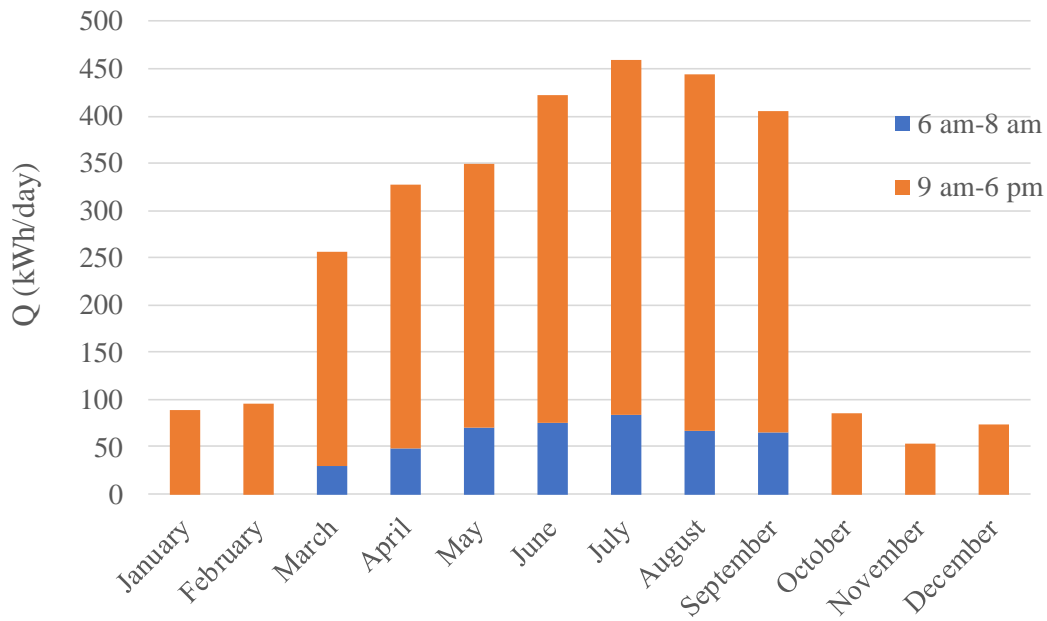


Figure 5.11: Heat transfer of solar thermal energy to the storage tank when V_{fluid}^{UP} is 50 m^3

From Figures 5.11 and 5.13, it can be observed that the active solar periods are P1 (6 am – 8 am) and P2 (9 am – 6 pm), when sufficient solar energy is captured and delivered to the tank for immediate utilization or storage for use in other periods when need may arise. Available opportunity for solar thermal utilization follows the same pattern as solar irradiation and ambient temperature shown in Figure 5.7 and Figure 5.8. Only lower quantities of heat are obtainable from solar in winter months for the two cases shown in Figures 5.11 and 5.13. In these figures, the average attainable solar heat in the winter months ranges between 54 and 95.7 kWh/day and 103.4 and 195.2 kWh/day for scenarios where V_{fluid}^{UP} is 50 m^3 and $1,000 \text{ m}^3$. This is unlike the other months, where the heat obtainable fluctuates between 255.6 and 459 kWh/day when V_{fluid}^{UP} is 50 m^3 and 315.6 and 1,908.5 kWh/day when V_{fluid}^{UP} is $1,000 \text{ m}^3$. The highest attainable solar heat is achieved between June and September, with July showing the best prospect for the highest solar thermal delivery of 459 kWh for $V_{fluid}^{UP} = 50 \text{ m}^3$ and 1,908.5 kWh when $V_{fluid}^{UP} = 1,000 \text{ m}^3$.

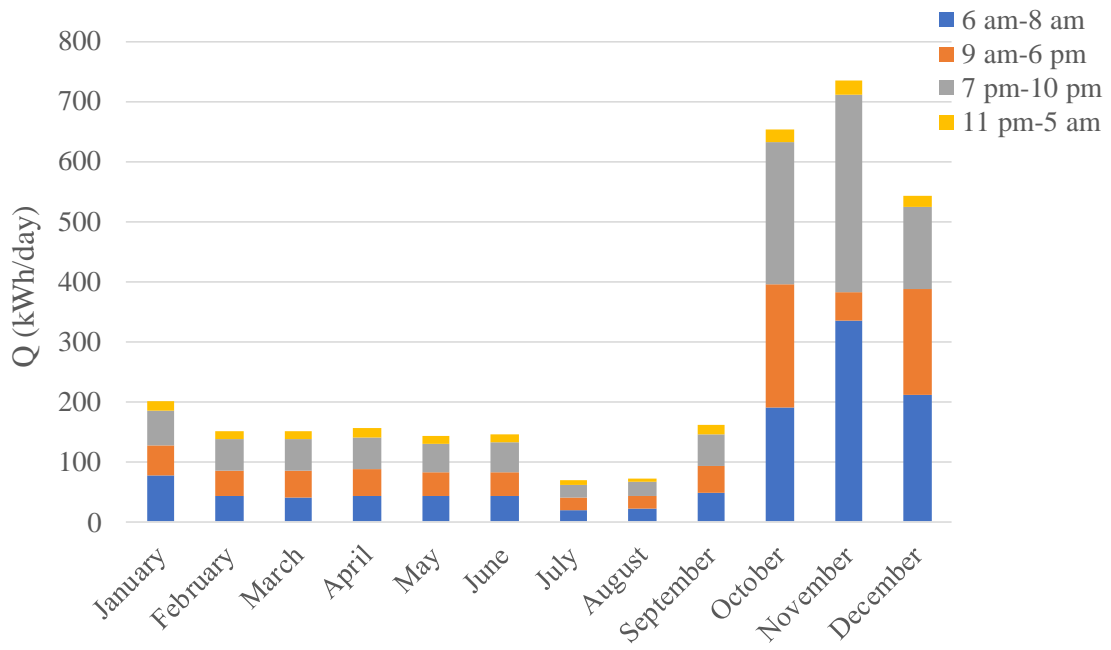


Figure 5.12: Solar thermal utilization when V_{fluid}^{UP} is 50 m³

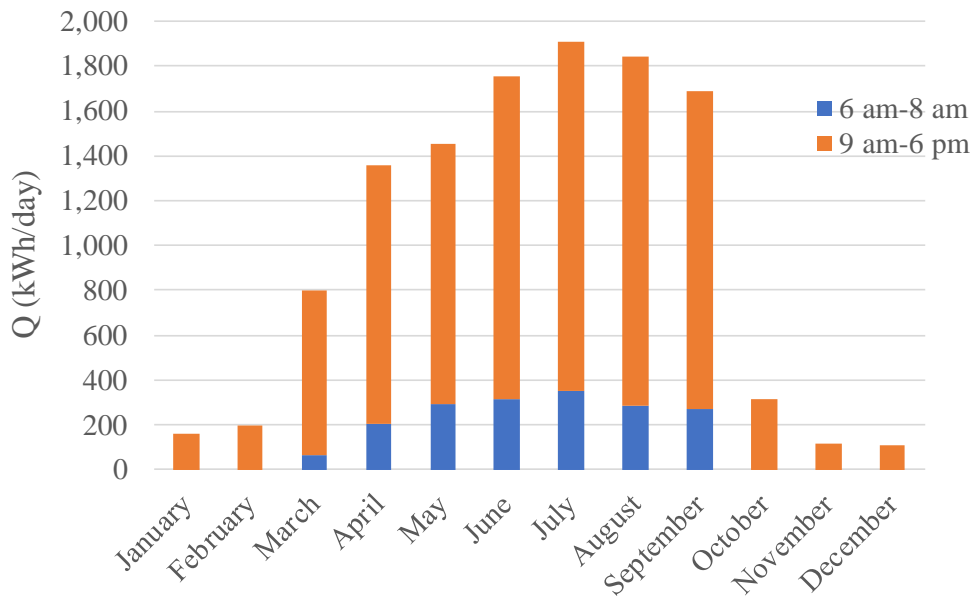


Figure 5.13: Heat transfer of solar thermal energy to the storage tank when V_{fluid}^{UP} is 1,000 m³

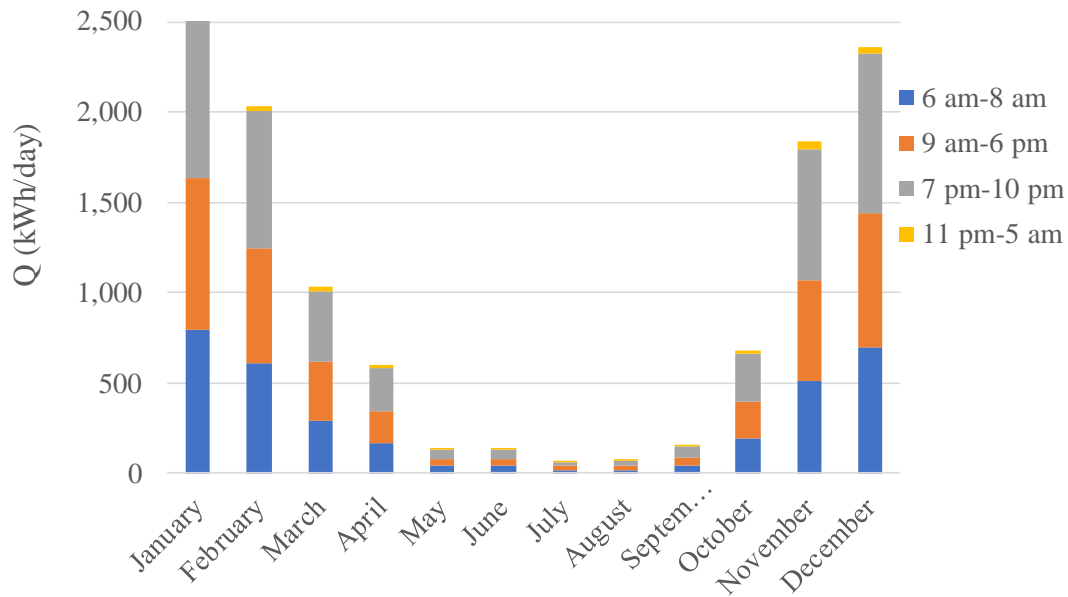


Figure 5.14: Solar thermal utilization when V_{fluid}^{UP} is 1,000 m³

Figures 5.12 and 5.14 show the monthly average quantity of solar heat released from the tank to satisfy hot water and space heating demand in the buildings when V_{fluid}^{UP} is 50 and 1,000 m³. When the volume of the tank is low, the available heat suffices mainly for the summer months when only hot water is required and for a few winter months, while for the remaining winter months, the backup utility is generally required. Only about 25% of energy demand is satisfied by the solar, where up to about 720 kWh/day is obtainable, while the remaining heat load should be provided by the backup utility. In contrast, when volume of the tank is higher, (almost) all the demand could be satisfied by solar, and up to 2,500 kWh/day is obtainable. The reason for such differences lies mainly in the amount of accumulated energy in the active solar periods/months (which is lower in the case of smaller storage volume) that is pushed to the network within the early hours of the less active solar periods (the hours immediately after sunset)/months (the early months after summer).

Figures 5.15 and 5.16 show stream data for period 2 in the months of January (Figure 5.15) and July (Figure 5.16) for the scenario when V_{fluid}^{UP} is 1,000 m³. It should be noted that these conditions are accounted for in the model on hourly, daily and monthly periods throughout the year. However, the outputs from the model are defined by the discretised number of periods as described in Section 5.12 (period 1 – period 4). In Figures 5.15 and 5.16, F , T , \dot{Q} represent the flowrate, temperature, and heat duty of the solar capture and heat transfer fluids flowing from the tank to the space heating radiator loop and domestic hot water (DHW) loop. \dot{Q}_{coil} is the quantity of the heat (in kWh/period) delivered

to water in the tank in M1, D1, P2 (the defined periods in the month of January). \dot{Q}_{solar} represents the total amount of heat delivered to the network from the storage tank, while \dot{Q}_{backup} is the amount of heat drawn from the burner to satisfy the demand in the building. Similar results are presented in Figure 5.16 but for M7, D1, P2 (being the defined period in the month of July).

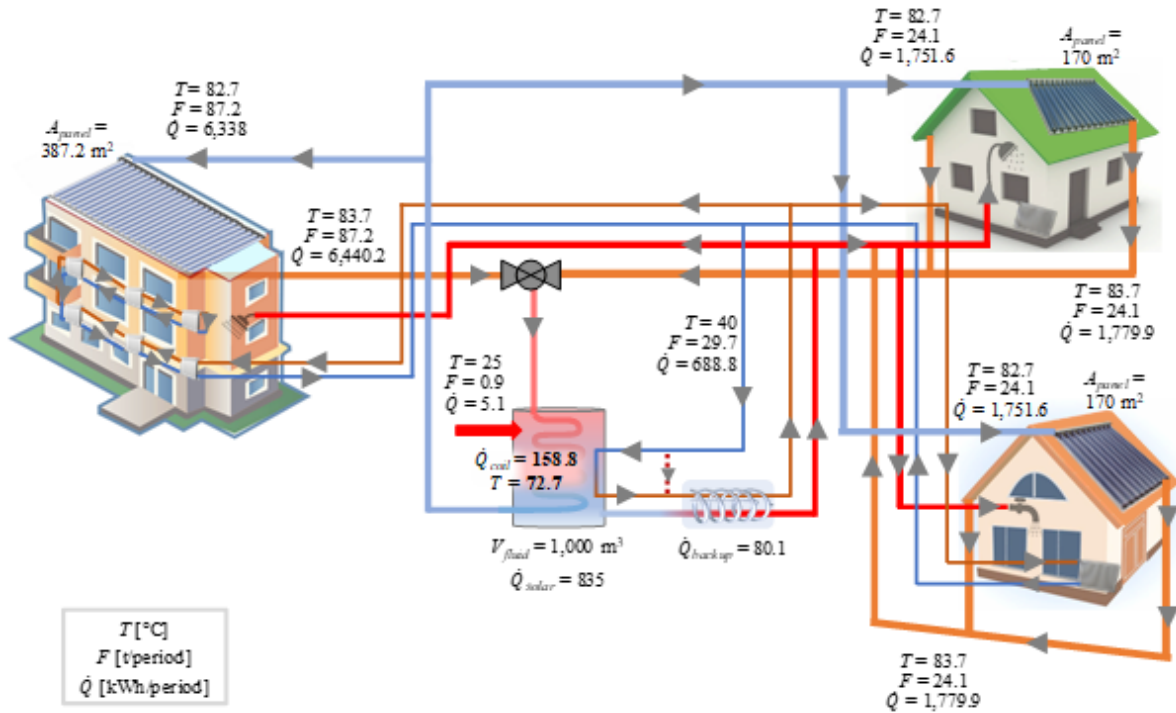


Figure 5.15: Details for the period M1, D1, P2 (January, 9 am – 6 pm) when V_{fluid}^{UP} is 1,000 m³

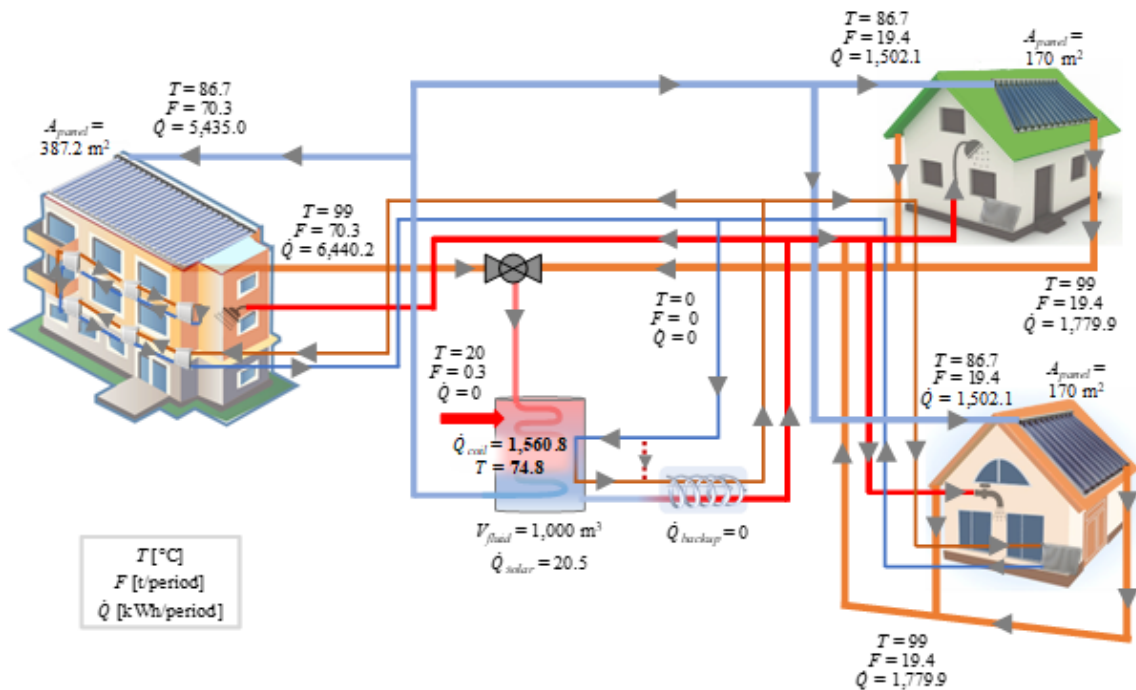


Figure 5.16: Details for the period M7, D1, P2 (July, 9 am – 6 pm) when V_{fluid}^{UP} is 1,000 m³

Figure 5.16 demonstrates a situation where there is no flow between the tank and the space heating radiator loop, owing to a lack of heat demand for space heating. Such a situation demonstrates the case for the binary variation and constraint described by Eq. (16) and Eq. (17) in the Supplementary material. Accordingly, $F = 0$ and $\dot{Q} = 0$ between the tank and radiators while the total heat delivered to the water heating network is completely satisfied by solar (i.e. $\dot{Q}_{solar} = 20.5$ kWh/period). Hence heat drawn from the burner in this period (\dot{Q}_{backup}) equals 0. Additionally, it can be seen from Figures 5.15 and 5.16 that in the summer months much higher amounts of heat are delivered from solar to heat storage tank and the temperature in storage tank is higher than in winter months (see also Figures 5.9 and 5.10).

Towards a realization of 100 % solar contribution with respect to the total heat demand for the case study considered, Table 5.3 shows the response of the key variables of the integrated system to changes in the volume fluid in tank from 50 to 10,000 m³. These variables include percentage contribution of solar thermal to the total heat demand, quantity of heat required from the backup utility to satisfy total heat demand and sizes of solar collectors needed to realize the share of heat supply from solar.

For the scenarios where V_{fluid}^{UP} is 50 and 1,000 m³ (Figures 5.12 and 5.14 respectively), percentage solar contribution is approximately 25 % and 92.3 %. Judging by the highest potential contribution of solar thermal for the presented scenarios when V_{fluid}^{UP} is 50 and 1,000 m³, and considering CO₂ emissions of diesel oil for operating a conventional burner for heat generation of 0.275 kg CO₂e/kWh [94], there exist opportunities for CO₂ emission reduction. The annual CO₂ emission reduction potential derived from the design involving the two presented scenarios of $V_{fluid}^{UP} = 50$ and 1,000 m³ are 875.3 kg CO₂e and 3,241.2 kg CO₂e.

Table 5.6: Solar potential for varying volumes of fluid in the tank and respective collector sizes

Volume of fluid (m ³)	Solar contribution (%)	Quantity of backup heat (kWh/y)	Area of collector (m ²)
50	25	291,440.9	149
100	30.4	270,645.5	194.6
300	62.8	144,256	398.8
500	80.8	74,707.3	519.2
1,000	92.3	30,055.9	601.2
3,000	98.4	6,033	629.3
5,000	99.4	2,446.8	637.1
7,500	99.7	696.3	645.6
10,000	100	0	642.5

5.13 Conclusions

Utilizing solar thermal for water and space heating has the potential to lead to emission reduction and sustainability in buildings. In this study, a comprehensive methodology for integrating solar thermal with the heat demand network of a cluster of buildings has been presented. The method, which is based on multi-period Mixed Integer Non-Linear Programming (MINLP) model, accounts for the multi-period changes in the attributes of solar thermal supply as well as the multi-period variability in the profile of heat demand from buildings across the year. The presented method can be applied to any case study in any location, since the model is formulated independent of the data.

To demonstrate the robustness of the method, a case study of integrating solar heat with a multi-building heat demand network characterized by a varied individual profile of heat demand from one building to another was considered. The method was implemented using practical meteorological and energy consumption data over a one-year period as input parameters for the integrated design framework. The dynamic changes in the key integration features such as fluid flowrate, temperature, and heat duties in the integrated system on an hourly, daily and monthly basis, as well as the response(s) of some defined optimization variables (such as collector area and volume of the fluid in the tank) were investigated. Analysis of the design and integration method for the selected case study

was presented using different scenarios to investigate the system requirements for providing a wide range for the percentage of solar contribution to the multi-building heat demand network. Various scenarios were analysed depending on the volume of fluid in the tank, while two scenarios with volumes of 50 and 1,000 m³ were presented in more detail.

The results show that when V_{fluid}^{UP} is 50 m³, there is a maximum potential for a 25% solar fraction contribution with a collector area of 18.8 m². The maximum amount of the solar fraction contribution of 459 kWh/month was obtained in July. When V_{fluid}^{UP} is 1,000 m³, about 92% of the energy required could be satisfied by solar with a collector area of 601.2 m². In this scenario, the maximum amount of the solar fraction contribution is 1,908.5 kWh/month also in July. Overall, the results show that a contribution of up to 100% of solar thermal to the building heat energy demand could be realised in domestic apartments when the solar collector and heat storage tank are considerably sized relative to the load of the building and solar thermal potential. Since implementation of the design will offset a substantial amount of conventional fossil fuel consumption (and by extension greenhouse gas emissions), it thus represents a path towards achieving sustainability and emission reduction with regards to energy consumption in buildings.

Future work will involve investigating the influence of other kinds of heat transfer fluids in enhancing the thermal performance of the system, while also accounting for heat losses in the overall integrated heat supply network. Further, the design will be expanded by increasing the number of participating buildings, and finally heat pump design features will be incorporated into the generic solar thermal integration framework to increase the thermal output and to explore the possibility of heat recovery from waste waters from the buildings.

5.14 Acknowledgements

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Appendix 5A: Supplementary Material

Integrated Design of Solar Thermal Utilization for Domestic Water and Space Heating

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This supplementary material consists of:

- Part A – Nomenclature
- Part B – Mathematical model
- Part C – Data for the case study
- Part D – References

Part A – Nomenclature

Abbreviations and Units

CO ₂ e	CO ₂ equivalent
DWH	Domestic water heating
EC	European Commission
EJ	Exajoules
GAMS	General Algebraic Modelling System
GHG	Greenhouse gas
GWth	Gigawatt thermal
IEA	International Energy Agency
IT	Information technology
JRC	Joint Research Center
kWh	Kilowatt hour
MINLP	Mixed Integer Non-Linear Programming
PWh	Petawatt hours
PVGIS	Photovoltaic Geographical Information System
SBB	Simple Branch and Bound
SH	Space heating
SHC	Solar heating and cooling

Sets

<i>DPO</i>	Set of maximal number of days in a month (31 days) with elements $dpo \in DPO$
<i>DPM</i>	Set of pairs of days and months which regularizes the number of days in a month since the months contain different number of days, $(dp, mp) \in DPM$
<i>DPOD</i>	Set of pairs of original daily period dpo and merged daily period dp $(dpo, dp) \in DPOD$
<i>HPO</i>	Set of all hours in a day (24 hours) with elements $hpo \in HPO$
<i>HPOH</i>	Set of pairs of original hourly periods hpo and merged hourly periods hp $(hpo, hp) \in HPOH$

IO	Set of inlet and outlet streams with elements $io \in IO$
MPO	Set of all months in the year with elements $mpo \in MPO$
$MPOM$	Set of pairs of original monthly periods mpo and merged monthly periods mp (mpo, mp) $\in MPOM$
U	Set of process units with elements $u \in U$
Subsets	
$BURNER(U)$	Set of external utilities required to raise the temperature of a fluid to the target or required temperature
$COLLECTOR(U)$	Set of solar collectors
$DP(DPO)$	Set of discretised or merged daily time periods with elements $dp \in DP$
$HP(HPO)$	Set of discretised or merged hourly time periods with elements $hp \in HP$
$IN(IO)$	Set of inlets to each unit with elements $in \in IN$
$MIXER(U)$	Set of mixers
$MP(MPO)$	Set of discretised or merged monthly time periods with elements $mp \in MP$
$OUT(IO)$	Set of outlets from each unit with elements $out \in OUT$
$RADIATOR(U)$	Set of radiators for domestic space heating
$SPLITTER(U)$	Set of splitters
$TANK(U)$	Set of heat storage tanks
Parameters	
a_1, a_2	Experimental constants for thermal loss coefficient of solar collector (kW/(m ² ·°C))
c_p^{fluid}	Specific heat capacity of heat transfer fluid (kWh/t·°C)
$I_{mp,dp,hp}, I'_{mpo,dpo,hpo}$	Average solar irradiation for each considered period and hourly solar irradiation for each hour of the year (kW/m ²)
$L_{mp,dp,hp}^{period}$	Length of period L for each monthly, daily and hourly time period
M	Coefficient used as a "big M" constraint for temperature feasibility in storage tank

$T_{mp,dp,hp}^{ambient}$, $T_{mpo,dpo,hpo}^{ambient}$

Average ambient temperature for each considered period and ambient temperature for each hour of the year (°C)

ΔT_{min}

Minimum temperature difference (°C)

Π_0

Efficiency factor for solar collector

ρ^{water}

Density of water (t/m³)

Continuous variables

$A_{collector}$

Area of solar collector (m²)

$F_{in,mp,dp,hp}^u$, $F_{out,mp,dp,hp}^u$

Fluid flowrates in and out of a unit for each time period (t/period)

F^{min}

Minimum fluid flow constraint between solar collector – thermal storage – solar collector loop and across the radiator – thermal storage – radiator loop

F^{max}

Maximum fluid flow constraint between solar collector – thermal storage – solar collector loop and across the radiator – thermal storage – radiator loop

$\dot{Q}_{mp,dp,hp}^{backup, burner}$

Quantity of heat exchanged between backup utility and either the hot water supply loop or the space heating radiator loop (kWh/period)

$\dot{Q}_{in,mp,dp,hp}^u$, $\dot{Q}_{out,mp,dp,hp}^u$

Quantity of heat flow in and out of a unit for each time period (kWh/period)

$\dot{Q}_{mp,dp,hp}^{solar, tank}$

Quantity of heat transferred from solar collector to fluid in the storage tank (kWh/period)

$T_{in,mp,dp,hp}^{collector}$, $T_{out,mp,dp,hp}^{collector}$

Inlet and outlet temperature of solar fluid from the collector for each time period (°C)

$T_{in,mp,dp,hp}^u$, $T_{out,mp,dp,hp}^u$

Stream temperature in and out of a unit in each time period (°C)

$T_{mp,dp,hp}^c$

Average temperature of the heat transfer fluid in solar collectors (°C)

V_{fluid}

Volume of fluid in storage tank

V_{fluid}^{UP}

Upper bound on the volume of fluid in storage tank

Discrete variables (0, 1)

$y_{mp,dp,hp}$

Binary variable representing existence of flow of heat transfer fluid from collector to heat storage tank

$y_{1 mp,dp,hp}$

Binary variable representing existence of flow between radiator loop and heat storage tank

Part B – Mathematical Model

5.S1 Global equations

The equations presented under this section are general equations describing variables across every units of the integrated system which is represented on the flowsheet. The developed mathematical model is formulated in a generic manner such that the model equations are developed and written independent of the data. Thus, it can be applied to any integrated solar thermal networks for hot water and space heating provision in any location with known geographical coordinates and meteorological information. It is formulated as a flowsheet superstructure where the values of variables (flow rates (F), temperature (T) and heat duty (\dot{Q})) at the outlet of each unit (u) are the same as the values at the inlet of subsequent unit in the flowsheet ($u1$) in each time period. Time periods in a year are modelled as hourly (hp), daily (dp) and monthly (mp). The respective equations connecting the values of variables in a flowsheet are presented by Eq. (1) for flowrates, Eq. (2) for temperature and Eq. (3) for heat flow:

$$F_{out,mp,dp,hp}^u = F_{in,mp,dp,hp}^{u1}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (1)$$

$$T_{out,mp,dp,hp}^u = T_{in,mp,dp,hp}^{u1}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (2)$$

$$\dot{Q}_{out,mp,dp,hp}^u = \dot{Q}_{in,mp,dp,hp}^{u1}, \quad \forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP \quad (3)$$

For calculation of energy content in each of the streams, a reference temperature (T_{ref}) of 20 °C is selected. The balances for each stream are applied as shown by Eq. (4) where c_p^{fluid} represents the specific heat capacity of heat transfer fluid.

$$\dot{Q}_{in/out,mp,dp,hp}^u = F_{in/out,mp,dp,hp}^u \cdot c_p^{fluid} \cdot (T_{in/out,mp,dp,hp}^u - T_{ref}), \quad \forall (in/out) \in IO, u \in U, mp \in MP, dp \in DP, hp \in HP \quad (4)$$

As the model is highly nonlinear and requires significant computational time, the data and the constraints developed for the design are clustered into a set of hourly, daily and monthly time periods similar to that presented by Abikoye et al. [1]. This is to reduce the complexity and size of the problem. Mathematical formulation of each of the unit in the integrated flowsheet design is presented in the following equations.

5.52 Solar collector

For the residential building rooftop solar collector installation presented in this Chapter, a simple design of a flat plate or evacuated tube collector is proposed. Mathematical descriptions of the thermodynamic features of solar collectors are given in Eq. (5) – Eq. (7).

$$F_{out,mp,dp,hp}^{collector} = F_{in,mp,dp,hp}^{collector}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (5)$$

$$\begin{aligned} \dot{Q}_{out,mp,dp,hp}^{collector} = & A_{collector} \cdot (\Pi_0 \cdot I_{mp,dp,hp} - a_1(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient}) \\ & - a_2(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient})^2), \quad \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (6)$$

$$\begin{aligned} \dot{Q}_{out,mp,dp,hp}^{collector} = & F_{out,mp,dp,hp}^{collector} \cdot c_p^{fluid} \cdot (T_{out,mp,dp,hp}^{collector} - T_{in,mp,dp,hp}^{collector}), \\ & \forall mp \in MP, dp \in DP, hp \in HP \end{aligned} \quad (7)$$

The mass balance across the collectors is described by Eq. (5). Variables $F_{in,mp,dp,hp}^{collector}$ and $F_{out,mp,dp,hp}^{collector}$ refer to the flowrates of heat transfer fluid into and out of each collector. Eq. (6) shows the mathematical relation that determines the solar heat gain by each collector, $\dot{Q}_{out,mp,dp,hp}^{collector}$. Heat gain is the same as the total heat captured by the solar fluid from the collector, which is described in Eq. (7). Thus, from the viewpoint of circulating the fluid around each of the collectors, Eq. (7) describes the balance for the heat captured by the fluid in each monthly, daily and hourly time periods. In these equations, $T_{mp,dp,hp}^c$ defines the average of the inlet and outlet temperatures of the heat transfer fluid in solar collectors ($\frac{T_{in,mp,dp,hp}^{collector} + T_{out,mp,dp,hp}^{collector}}{2}$), $A_{collector}$ represents each collector area, $I_{mp,dp,hp}$ and $T_{mp,dp,hp}^{ambient}$ stand for irradiation and ambient temperature, Π_0 represents the efficiency factor for

the solar collectors (0.764) while a_1 and a_2 are experimental constants for estimating the heat derived by solar collectors and their values are taken to be 1.53 W/(m²·K) and 0.0003 W/(m²·K) [2].

5.5.3 Heat storage tank

The potential of short and long-term heat storage has been widely investigated in renewable energy application systems, especially in relation to solar thermal technologies [3]. Incorporating thermal storage strategies with solar designs allow the storage of excess heat energy and subsequent utilization of the stored heat at a later time in the same or other periods, reaching up to several months in some modern designs [4]. Solar heat collected and stored in active solar periods could be utilized later in lean periods when solar irradiation is low. Thermal storage also helps to circumvent the mismatch between heat demand and availability of heat supply from solar. The thermal storage design implemented in this Chapter is modelled as a cylindrical heat storage tank with perfect mixing. A slightly elevated and insulated cylindrical metal vessel incorporated with the architectural design of the building is considered for the heat storage tank design. This positioned the storage unit between the heat source and the distribution networks and providing a multipurpose function in the integrated system; first as a storage facility to the heat network in active solar periods, and as a medium for providing energy for space heating and domestic hot water supply, which are independent of the solar heating loop. Figure 5.S1 provides a schematic representation of the flows, temperature and heat regimes around the heat storage tank (see also Figure 5.4 of the main Chapter).

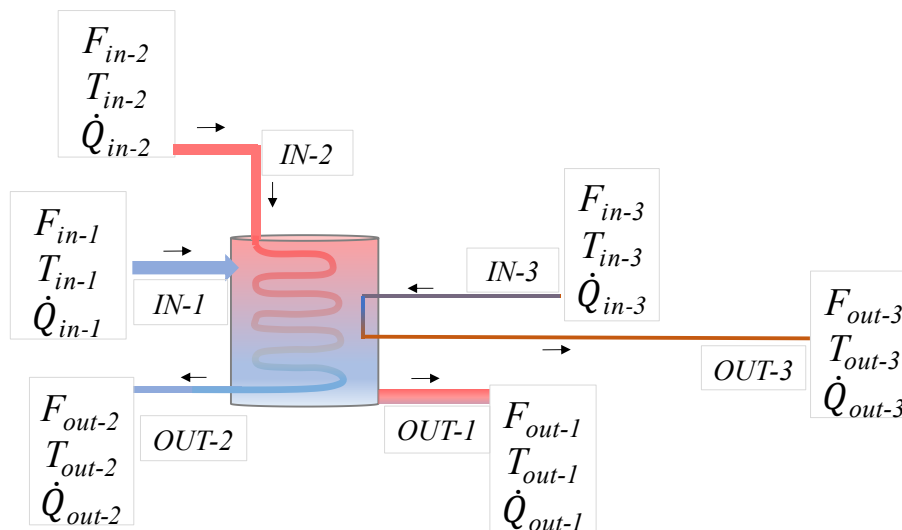


Figure 5.S1: Schematic representation of heat storage tank model

In Figure 5.S1, *IN-1* represents the inlet of fresh water to the tank in order to exchange heat with hot solar fluid flowing into the tank through the second inlet (*IN-2*). The resulting hot water is then

channelled through an outlet modelled as *OUT-1* while the fluid returning to the collectors flows out of the tank through *OUT-2*. The third inlet and outlet (*IN-3* and *OUT-3*) represent the flows of heat transfer fluid in the space heating radiator loop. As an example, $T_{out-1,mp,dp,hp}^{tank}$ describes the temperature of hot water flowing out of the tank in each time period, similarly $T_{out-2,mp,dp,hp}^{tank}$ refers to the temperature of the heat transfer fluid returning to the collectors and $T_{out-3,mp,dp,hp}^{tank}$ describes the temperature of the returning fluid to space heating radiators. The above described orientation is also used in the model to define other variables, such as the flows (F) and heat content (\dot{Q}) of the fluids flowing in and out of the tank as shown in Figure 5.S1.

Based on the features described above, Eq. (8) accounts for the flows of freshwater inlet and hot water outlet into and out of the tank. Eq. (9) accounts for the flows in and out of the tank from solar collectors, while Eq. (10) accounts for the flows of heat transfer fluid in and out of the tank around the space heating radiator loop. For streams identification in the developed model, subscripts $in - 1, -2, -3, out - 1, -2, -3$ and mp, dp, hp , are attached to the notation for each stream flow.

$$F_{out-1,mp,dp,hp}^{tank} = F_{in-1,mp,dp,hp}^{tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (8)$$

$$F_{out-2,mp,dp,hp}^{tank} = F_{in-2,mp,dp,hp}^{tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (9)$$

$$F_{out-3,mp,dp,hp}^{tank} = F_{in-3,mp,dp,hp}^{tank}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (10)$$

Eq. (11) accounts for the general energy balance across the heat storage tank. The equation demonstrates that the amount of energy accumulated in the tank in every time period is equal to the difference between the energy added to the tank and energy taken away from the tank, and this is implemented for every monthly, daily and hourly time period.

$$\begin{aligned} V^{tank} \cdot c_p^{fluid} \cdot \rho^{fluid} \cdot \Delta T_{mp,dp,hp}^{tank} \\ = \left(F_{in-1/out-1,mp,dp,hp}^{tank} \cdot c_p^{fluid} \cdot (T_{in-1,mp,dp,hp}^{tank} - T_{out-1,mp,dp,hp}^{tank}) \right) \\ + \left(\dot{Q}_{solar}^{tank} \right) \\ - \left(F_{in-3/out-3,mp,dp,hp}^{tank} \cdot c_p^{fluid} \cdot (T_{out-3,mp,dp,hp}^{tank} - T_{in-3,mp,dp,hp}^{tank}) \right) \end{aligned} \quad (11)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

In Eq (11), V^{tank} is the volume of the fluid in the tank, ρ^{fluid} represents the fluid density, while $\Delta T_{mp,dp,hp}^{tank}$ accounts for the periodic change in the temperature of the fluid in the tank across each time period. To simplify the computational complexity of the model, the density of heat transfer fluids in each flow loop is assumed to be constant over the period considered.

Eq. (12) accounts for the heat transfer from hot solar fluid to the fluid in the tank.

$$\begin{aligned} \dot{Q}_{solar,mp,dp,hp}^{tank} &= (F_{in-2,mp,dp,hp}^{tank} \cdot c_p^{fluid} \cdot T_{in-2,mp,dp,hp}^{tank}) \\ &\quad - (F_{out-2,mp,dp,hp}^{tank} \cdot c_p^{fluid} \cdot T_{out-2,mp,dp,hp}^{tank}), \end{aligned} \quad (12)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

Since the proposed integrated multi-building solar heat network is modelled as a system in continuous flow, the circular or equilibrium leads and lags techniques [5] is adopted in calculating the temperature of the fluid in the tank. The temperature of the fluid in the tank is estimated as the sum of the temperature of the fluid in previous time period and the change in temperature of the fluid in the current time period. The above description is presented mathematically by the following Eq (13):

$$\begin{aligned} T_{mp,dp,hp}^{tank} &= \bigcup_{(mp_k)_{k \in K, k=1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp--1,dp--1,hp--1}^{tank} \\ &\quad + \bigcup_{(hp_k)_{k \in K, k>1}} T_{mp,dp,hp-1}^{tank} + \bigcup_{(dp_k)_{k \in K, k>1} \wedge (hp_k)_{k \in K, k=1}} T_{mp,dp-1,hp--1}^{tank} \\ &\quad + \bigcup_{(mp_k)_{k \in K, k>1} \wedge (dp_k)_{k \in K, k=1} \wedge (hp_k)_{k \in K, k=1}} T_{mp-1,dp--1,hp--1}^{tank} \\ &\quad + \Delta T_{mp,dp,hp}^{tank}, \end{aligned} \quad (13)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

In the above Equation, $T_{mp--1,dp--1,hp--1}^{tank}$ represents the temperature in the tank at the beginning of the year (i.e. the first hour, the first day and the first month of the year, e.g. the first hour of 1 January of a particular year. This temperature is the same as the temperature at the end of the last hour of the last day in the last month of the preceding year (which in this case corresponds to the last

hour of 31 December). Similarly for the other monthly, daily and hourly time periods, $T_{mp,dp,hp-1}^{tank}$ represents the temperature in the tank for each month and day where the hour concerned does not correspond to the first hour of the day. $T_{mp,dp-1,hp--1}^{tank}$ is the temperature in the tank for every first hour of the day where the day concerned does not correspond to the first day of the month. $T_{mp-1,dp--1,hp--1}^{tank}$ refers to the temperature of the tank for each first hour in a day and each first day in the month for any month except the first month in a year (i.e. January, or as the case may be).

It is considered that the fluid in the tank is heated only when the temperature in the tank is less than the temperature of solar fluid flowing back to the collector ($T_{out-2,mp,dp,hp}^{tank}$) minus ΔT_{min} . To guarantee this, a special constraint is introduced in the model, which forces the flow to be zero (and thus there is no heat transfer) if temperature in the storage tank is too high for heat transfer. This constraint called ‘the big M constraint’ is described in Eq. (14) where M is considered as being a big enough scalar, and $y_{mp,dp,hp}$ is the binary variable which signifies the existence of fluid flow (or heat transfer) in the solar collector – heat storage loop.

$$T_{mp,dp,hp}^{tank} \leq T_{out-2,mp,dp,hp}^{tank} - \Delta T_{min} + M \cdot (1 - y_{mp,dp,hp}), \quad (14)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

If binary variable is equal to 1, then the flow should be between minimum and maximum values (F^{min}) and (F^{max}) as described by Eq. (15), otherwise it is assigned a value of zero (0) if the condition is not satisfied.

$$F^{min} \cdot y_{mp,dp,hp} \leq F_{in-1,mp,dp,hp}^{tank} \leq F^{max} \cdot y_{mp,dp,hp}, \quad (15)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

Similarly, the flows and heat transfer between storage tank and the radiator loop are accounted for as described by Eq. (16) and Eq. (17). In this case, the binary variable $y_{1mp,dp,hp}$ is implemented in the model to ensure that flows and connection (heat transfer) between the tank and radiator loop exists only if the outlet temperature of the return flow to the radiator loop is less than or equal to the temperature of the fluid in the tank ($T_{mp,dp,hp}^{tank}$) plus ΔT_{min} . Otherwise the flow from radiator loop to the tank is bypassed directly to backup utility (see also Figure 5.4 of the main Chapter).

$$T_{out-3,mp,dp,hp}^{tank} \leq T_{mp,dp,hp}^{tank} - \Delta T_{min} + M \cdot (1 - y_{1mp,dp,hp}), \quad (16)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$F^{min} \cdot y_{1mp,dp,hp} \leq F_{out-3,mp,dp,hp}^{tank} \leq F^{max} \cdot y_{1mp,dp,hp}, \quad (17)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

5.S4 Space heating and hot water use

The transfer of heat from the radiator's circulating fluid and the surrounding air is assumed to satisfy the space heating requirement of the buildings. In previous research works, different approaches have been used to model the heat transfer mechanism. Poppi et al. [6] presented a techno-economic performance of parallel configuration of solar collector supported with heat pump providing domestic space heating through the heat storage tank. Cai et al [7] and Hedegaard et al. [8] proposed statistical models for the evaluation of residential space heating demand response and thermal dynamics in buildings. Mathematical descriptions of the approach used in this study are presented in Eqs. (17) – (19). In the presented design, indoor space and immediate environment surrounding the radiators are heated by radiation and convection.

$$F_{out,mp,dp,hp}^{radiator} = F_{in,mp,dp,hp}^{radiator} \quad (18)$$

$$T_{out, mp,dp,hp}^{radiator} \leq T_{in, mp,dp,hp}^{radiator} - 20^{\circ}\text{C} \quad (19)$$

$$Q_{mp,dp,hp}^{radiator} = F_{in-1,mp,dp,hp}^{radiator} \cdot c_p^{fluid} \cdot (T_{in-1,mp,dp,hp}^{radiator} - T_{out-1,mp,dp,hp}^{radiator}), \quad (20)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

To ensure that the hot water demand requirements of the buildings are satisfied (with respect to temperature level and heat load) in every time period, and to avoid the growth of bacteria [9], a lower bound of 55 °C is set for hot water flowing out from the taps and showers in the buildings. Eq. (21) accounts for energy flows regarding hot water consumption in each of the buildings in every hourly, daily and monthly time periods.

$$Q_{in\ mp,dp,hp}^{DHW} = F_{in,mp,dp,hp}^{DHW} \cdot c_p^{fluid} \cdot (T_{in\ mp,dp,hp}^{DHW} - T_{ref}) \quad (21)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

5.5.5 Mixing and splitting points

In the proposed design, mixing and splitting points (mixers and splitters) ensure connections/interactions among the participating nodes (units) as shown in the integrated multi-building heat network design (Figure 5.4 of the main Chapter). Eq. (22) - (24) account for the flow balance, temperature balance and heat balance across the mixers for the monthly, daily and hourly time periods. Since it is assumed that c_p^{fluid} in each of the loop is constant, and heat losses are negligible, the following equations are used to model the characteristics of the mixers across the system for every monthly, daily and hourly time periods.

$$F_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} F_{in,mp,dp,hp}^{mixer}, \quad (22)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

$$F_{out-1,mp,dp,hp}^{mixer} \cdot T_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} F_{in,mp,dp,hp}^{mixer} \cdot T_{in,mp,dp,hp}^{mixer}, \quad (23)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

$$Q_{out-1,mp,dp,hp}^{mixer} = \sum_{in \in IN} Q_{in,mp,dp,hp}^{mixer}, \quad (24)$$

$$\forall mixer \in MIXER, mp \in MP, dp \in DP, hp \in HP$$

Eq. (25) to Eq. (28) on the other hand, are used in the model to account for the flow, temperature and heat balance across the splitters.

$$\sum_{out \in OUT} F_{out,mp,dp,hp}^{splitter} = F_{in-1,mp,dp,hp}^{splitter}, \quad (25)$$

$$\forall splitter \in SPLITTER, mp \in MP, dp \in DP, hp \in HP$$

$$T_{out,mp,dp,hp}^{splitter} = T_{in-1,mp,dp,hp}^{splitter}, \quad (26)$$

$$\forall splitter \in SPLITTER, out \in OUT, mp \in MP, dp \in DP, hp \in HP$$

$$Q_{out,mp,dp,hp}^{splitter} \cdot F_{in-1,mp,dp,hp}^{splitter} = Q_{in-1,mp,dp,hp}^{splitter} \cdot F_{out,mp,dp,hp}^{splitter}, \quad (27)$$

$$\forall splitter \in SPLITTER, out \in OUT, mp \in MP, dp \in DP, hp \in HP$$

$$\sum_{out \in OUT} Q_{out,mp,dp,hp}^{splitter} = Q_{in-1,mp,dp,hp}^{splitter}, \quad (28)$$

$$\forall splitter \in SPLITTER, mp \in MP, dp \in DP, hp \in HP$$

5.S6 Backup utility

Apart from incorporating thermal storage technologies, a matching backup utility system is essential for a comprehensive solar thermal integration approach. A backup burner which is connected in series to the storage tank is thus accommodated in the design. This serves as an auxiliary heating system to ensure that the final required target temperature for both domestic hot water use and space heating are satisfied. Heat energy from solar thermal could be used to completely heat up the tank to the desired temperature level or serve to preheat the stream where there is not enough solar energy available.

Eq. (29) represents the flow of the fluid for hot water use ($in - 1/out - 1$), while Eq. (30) presents the flow in the space heating radiator loop ($in - 2/out - 2$). To have a better understanding on the fraction of energy consumption that is obtained from backup burner, Eq. (31) was developed such that $Q_{mp,dp,hp}^{backup 1}$ represents the additional heat pushed to the domestic hot water supply system by the backup burner to make it up to the required temperature level as described by Eq. (32), while

$Q_{mp,dp,hp}^{backup 2}$ accounts for the additional heat supplied to the radiator loop from the burner in order to satisfy the required temperature level for space heating as shown in Eq. (33).

$$F_{out-1,mp,dp,hp}^{burner} = F_{in-1,mp,dp,hp}^{burner}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (29)$$

$$F_{out-2,mp,dp,hp}^{burner} = F_{in-2,mp,dp,hp}^{burner}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (30)$$

$$Q_{mp,dp,hp}^{backup burner} = Q_{mp,dp,hp}^{backup 1} + Q_{mp,dp,hp}^{backup 2}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (31)$$

$$Q_{mp,dp,hp}^{backup 1} = F_{in-1,mp,dp,hp}^{burner} \cdot c_p^{fluid} \cdot (T_{out-1,mp,dp,hp}^{burner} - T_{in-1,mp,dp,hp}^{burner}), \quad (32)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

$$Q_{mp,dp,hp}^{backup 2} = F_{in-2,mp,dp,hp}^{burner} \cdot c_p^{fluid} \cdot (T_{out-2,mp,dp,hp}^{burner} - T_{in-2,mp,dp,hp}^{burner}), \quad (33)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

Eq. (34) and Eq. (35) account for feasibility of temperature changes across the backup utility system in each time period.

$$T_{in-1,mp,dp,hp}^{burner} \leq T_{out-1,mp,dp,hp}^{burner}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (34)$$

$$T_{in-2,mp,dp,hp}^{burner} \leq T_{out-2,mp,dp,hp}^{burner}, \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (35)$$

5.57 Objective function

The integrated solar thermal design for multi-building heat supply network developed in this Chapter was formulated with the objective of minimizing the total heat supplied to the cluster of buildings from backup utility. To ensure that this objective is achieved with the most realistic sized heat storage

tank and solar collector areas to be located on the rooftop of each participating building in the network, small weighting factors are multiplied by the tank and collector variables in Eq (36).

$$\min \left(\sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in hP} \bigwedge_{(mp, dp) \in DPM} Q_{backup_{mp, dp, hp}}^{burner} + 0.001 \cdot A_{panel} + 0.01 \cdot V_{tank} \right) \quad (36)$$

In order to minimise the computational complexity of the model, a systematic model reduction procedure previously implemented in [1] is adopted. This entails clustering large input parameters and constraints of the model such that the problem size and computational complexity can be reduced.

Part C – Energy Consumption Data

The energy consumption data for hot water and space heating of the considered case study as obtained from [10] are shown in:

- Table 5.S1: Share of energy consumption on an hourly basis for the three buildings in different months (%)
- Table 5.S2: Energy consumption for space heating on a period basis for the three buildings (kWh/period)
- Table 5.S3: Energy consumption for hot water use on a period basis for the three buildings (kWh/period)

Table 5.S1: Share of energy consumption on an hourly basis for the three buildings in different months (%)

Building type	VSS1		ESS1		ESS2	
	Space heating ¹⁾	Hot water use ²⁾	Space heating ³⁾	Hot water use ⁴⁾	Space heating ⁵⁾	Hot water use ⁶⁾
January	25	11.25	20	11.25	31	9.25
February	20	9.17	15	8.75	20	9.08
March	10	9.58	10	9.58	10	7.92
April	5	8.75	7	8.75	2	8.58
May	/	8.08	/	8	/	8.08
June	/	7.92	/	7.67	/	7.92
July	/	3.33	/	5.17	/	6.75
August	/	3.75	/	3.42	/	7.08
September	/	8.75	/	8.75	/	9.17
October	5	9.58	7	8.58	2	8.92
November	15	9.58	21	9.67	10	8.33
December	20	10.25	20	10.42	25	8.92

¹⁾ 30 % in P1, 30 % in P2, 40 % in P3 and 0 in P4, ²⁾ 30 % in P1, 25 % in P2, 35 % in P3 and 10 % in P4,

³⁾ 10 % in P1, 30 % in P2, 50 % in P3 and 10 % in P4, ⁴⁾ 10 % in P1, 35 % in P2, 40 % in P3 and 15 % in P4,

⁵⁾ 35 % in P1, 40 % in P2, 25 % in P3 and 0 in P4, ⁶⁾ 35 % in P1, 45 % in P2, 20 % in P3 and 0 in P4

Table 5.S2: Energy consumption for space heating on a period basis for the three buildings (kWh/period)

Building type	VSS1				ESS1				ESS2			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
January	19,152.0	19,152.0	25,536.0	/	676.2	2,028.6	3,381	676.2	4,823.9	5,513.0	3,445.7	/
February	15,321.6	15,321.6	20,428.8	/	507.2	1,521.5	3,381.0	676.2	3,112.2	3,556.8	2,223.0	/
March	7,660.8	7,660.8	10,214.4	/	338.1	1,014.3	1,690.5	338.1	1,556.1	1,778.4	1,111.5	/
April	3,830.4	3,830.4	5,107.2	/	236.7	710.0	1,183.4	236.7	311.2	355.7	222.3	/
May	/	/	/	/	/	/	/	/	/	/	/	/
June	/	/	/	/	/	/	/	/	/	/	/	/
July	/	/	/	/	/	/	/	/	/	/	/	/
August	/	/	/	/	/	/	/	/	/	/	/	/
September	/	/	/	/	/	/	/	/	/	/	/	/
October	3,830.4	3,830.4	5,107.2	/	236.7	710.0	1,183.4	236.7	311.2	355.7	222.3	/
November	11,491.2	11,491.2	15,321.6	/	710.0	2,130.0	3,550.1	710.0	1,556.1	1,778.4	1,111.5	/
December	15,321.6	15,321.6	20,428.8	/	676.2	2,028.6	3,381.0	676.2	3,890.3	4446.0	2,778.8	/

Table 5.S3: Energy consumption for hot water on a period basis for the three buildings (kWh/period)

Building type	VSS1				ESS1				ESS2			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
January	1,508.2	1,256.9	1,759.6	502.7	44.7	156.3	178.6	67.0	204.5	263.0	116.9	/
February	1,229.4	1,024.5	1,434.3	409.8	34.7	121.6	138.9	52.1	200.8	258.2	114.7	/
March	1,284.3	1,070.3	1,498.4	428.1	38.0	133.1	152.1	57.0	175.1	225.2	100.1	/
April	1,173.1	977.6	1,368.6	391.0	34.7	121.6	138.9	52.1	189.7	243.9	108.4	/
May	1,083.2	902.7	1,263.8	361.1	31.8	111.1	127.0	47.6	178.7	229.7	102.1	/
June	1,061.8	884.8	1,238.8	353.9	30.4	106.5	121.8	45.7	175.1	225.2	100.1	/
July	446.4	372.0	520.8	148.8	20.5	71.8	82.1	30.8	149.3	191.9	85.3	/
August	502.7	419.0	586.5	167.6	13.6	47.5	54.3	20.4	156.6	201.3	89.5	/
September	1,173.1	977.6	1,368.6	391.0	34.7	121.6	138.9	52.1	202.8	260.7	115.9	/
October	1,284.3	1,070.3	1,498.4	428.1	34.1	119.2	136.2	51.1	197.2	253.6	112.7	/
November	1,284.3	1,070.3	1,498.4	428.1	38.4	134.3	153.5	57.6	184.2	236.8	105.3	/
December	1,374.2	1,145.1	1,603.2	458.1	41.4	144.7	165.4	62.0	197.2	253.6	112.7	/

Part D – References

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Chapter Conclusion

The building sector (residential and commercial buildings) is one of the critical sectors to consider in order to realise a low carbon future in the area of energy production and utilization. Moreso, the sector also currently embody large amount of unmet basic energy needs to which solar thermal has the potential to satisfy if appropriately harnessed. An overview of the application of solar thermal in buildings in various regions of the world has been presented with special focus on available system combinations, sizes, form of heat demand satisfied and some of the various methods used for the system design and optimization. It has been shown in this chapter that while solar thermal has found use in various regions of the world (even in cold climate), opportunities still exist for further improvements in the areas of system design, operations and management.

A comprehensive design and optimization methodology has been developed to estimate the maximum attainable solar thermal that could be integrated with the heat demand network of a cluster of different sizes of buildings where the heat network is additionally characterized by varied individual profile of heat demand from one building to another. The developed model is based on the multi-period mixed-integer non-linear mathematical programming approach. The models are generic and can be applied to any case in any location because the model equations for each design building blocks are written independent of the design data.

In the presented case studies, it has been shown that the percentage contributions of solar thermal varies according to the size of design and mode of technology integration. The result obtained from the presented case studies in part 1 of the chapter show that an average of 129.23 kWh/d, 257.35 kWh/d, 210.21 kWh/d and 112.32 kWh/d can be realized from solar thermal in the winter months of November, December, January and February respectively while the entire heat demand for water heating can be satisfied by solar thermal of the same design in the summer months. It should be noted that although the heat required for water heating in winter months is completely satisfied by solar thermal, a higher share of heating contribution from solar thermal (i.e. for space heating) is constrained due to the maximum temperature level obtained for solar fluid in this period of the year (notably between 55.67 – 56.41 °C) which is lower than the minimum temperature required in the radiator loop (70 °C) for space heating. Hence, solar is thus majorly used as a pre-heating source. It is also important to note that although the potential of solar is higher in summer months, water and space heating demands are typically less than that of the winter. In this regard, advanced methods for longer heat storage are therefore recommended for higher thermal efficiency especially for the winter months.

Part 2 of the chapter presents an improved design where it was shown that up to 100 % solar thermal contribution can be targeted for water and space heating in a multi-building heat demand network. This improved design was achieved with single heat storage tank design relatively scaled according to collector sizes. In this part of the chapter, the dynamic changes in the key integration features such as fluid flowrate, temperature, heat duties in the integrated system on hourly, daily and monthly basis, as well as the response(s) of some defined optimization variables (such as collector area, volume of the fluid in the tank) were investigated. The analysis of the presented design and integration method based on the selected case study was also presented by using different scenarios to investigate the system requirements for satisfying different solar fraction contribution to the multi-building heat demand network.

According to the results obtained, 92 % of energy requirement of the buildings could be satisfied with solar thermal when the total collector area is 601.2 m² with up to about 1000 m³ volume of fluid in the storage tank. The results show that beyond this threshold volume, the benefits of solar thermal integration continue to decrease. However, more studies are recommended in this area to further establish this trend.

Design and Optimization of Heat Pump-Enhanced Solar Thermal for Improved Thermal Performance

Background to the Chapter

Energy is indispensable in human daily life, providing the requirements for comfort and underpinning socio-economic activities¹. As the world's population increases, the escalating level of resource utilization is increasingly becoming an issue of concern, especially with respect to energy use. Largely driven by the growing energy consumption, the global CO₂ emissions have also reached an historic high level since fossil fuels remain the primary source of energy supply². Currently, energy-related emissions represent about two-thirds of the global greenhouse gas (GHG) emissions³, yet the global per capita energy supply is still said to be below the target of sustainable development goals⁴. This situation has led to increased level of awareness on the need to increase the share of renewable energy in global energy supply mix⁵. It is believed that gradual deployment of renewable energy technologies will reposition the world on the path to emission reduction⁶, and steadily reduce overdependence on conventional fossil fuels which have been widely described to be highly carbon intensive⁷. On the contrary, large scale deployment of renewable energy has been constrained over the time. This is largely caused by irregular supply pattern of most renewable energy sources as well as the fluctuations in their availability which often lead to energy supply gap and low energy output⁸.

In order to address the aforementioned problems, several technology options and performance improvement measures have been explored, part of which include the synergy between energy efficiency and renewable energy systems⁴, such as combination of solar thermal technology and heat pump systems⁹. The goal in such combination is to enhance the performance and efficiency on both the heat pump and solar thermal sides of the integration, thereby increasing thermal output of the integrated system.

Several system configurations and design methods have been proposed by many authors to achieve respective design objectives. However, the current challenge lies in the evaluation and analysis of variables in the combined system, as well as optimization of the design and operating features for further performance improvement. This, to a large extent is caused by the transient dispositions of

the system which stem from the time-dependency of solar energy, as well as the complexities imposed by the non-linear relationship among the system variables.

This chapter presents a multi-period mixed-integer nonlinear programming (MINLP) formulation to overcome the challenges in multi-period integration of solar thermal and heat pump technologies. The chapter features a full-length paper titled “Synthesis of Heat Pump Enhanced Solar Thermal Considering Multi-Period Design and Optimization Approach” to be submitted to the Journal of Cleaner Production. A second paper already accepted for publication in Computer Aided Chemical Engineering Journal on 10th January 2020 is included in the chapter as Appendix 6A. The paper is titled “Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations” and it is prepared as a summary of the work reported in Chapter 6 in conformity with the requirements of the Journal. The only changes are the referencing style in order to maintain the requirements for thesis presentation.

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Synthesis of Heat Pump Enhanced Solar Thermal Considering Multi-Period Design and Optimization Approach

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Abstract

Combination of heat pump and solar thermal systems is one of the modern sustainable energy designs demonstrating the synergy between energy efficiency and renewable energy technologies. This study presents a multi-period mathematical programming approach for the design and optimization of heat pump-enhanced solar thermal for low and medium temperature applications. Mathematical models which capture the dynamic operating properties and thermodynamic features of combined solar thermal and multi-stage vapour compression heat pump cycle have been developed. The multi-period optimization context of the model accounts for the intermittent variability of relevant meteorological conditions and their effects on heat output from the heat pump. The design and optimization of the integrated system is implemented and solved in GAMS. The results obtained show progressive increase in the amount of heat produced by the combined solar thermal- heat pump system from 237 kW to 1,615 kW at an average coefficient of performance of between 1.32 to 1.81 as the solar collector area increases from 100 m² to 6511 m², after which additional increase in collector area does not result to further increase in performance of the combined system. These results show stability and good prospect for enhanced thermal energy from solar.

Keywords: Solar thermal, Heat pump, Heat production, Multi-period design, Optimization

Nomenclature

Abbreviations and Units

COP	Coefficient of Performance
CPU	Central Processing Unit
EC JRC	Joint Research Center of European Commission
GAMS	General Algebraic Modelling System
GHG	Greenhouse gas
GWP	Global Warming Potential
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
ODP	Ozone Depletion Potential
PVGIS	Photovoltaic Geographical Information System
SBB	Simple Branch and Bound
Solar PV	Solar Photovoltaic

Sets

DPO	Set of days in a month with elements $dpo \in DPO$
DPM	Set of pairs of days and months, which regularizes the number of days in a month, since the months contain different number of days, $(dp, mp) \in DPM$
$DPOD$	Set of pairs of original daily period dpo and the merged daily period dp $(dpo, dp) \in DPOD$
HPO	Set of all hours in a day (24 hours) with elements $hpo \in HPO$
$HPOH$	Set of pairs of original hourly periods hpo and the merged hourly periods hp $(hpo, hp) \in HPOH$
IO	Set of inlet and outlet streams with elements $io \in IO$
MPO	Set of all months in the year with elements $mpo \in MPO$
$MPOM$	Set of pairs of original monthly periods mpo and merged monthly periods mp $(mpo, mp) \in MPOM$
U	Set of process units with elements $u \in U$

Subsets

$COLLECTOR(U)$	Set of solar collectors
$COMPRESSOR(U)$	Set of compressors in the heat pump circuit

$CONDENSER(U)$	Set of condensers in the heat pump circuit
$COOLER(U)$	Set of sub-coolers in the heat pump circuit
$DP(DPO)$	Set of discretised or merged daily time periods with elements $dp \in DP$
$EVAPORATOR(U)$	Set of evaporators in the heat pump circuit
$VALVE(U)$	Set of expansion valves in the heat pump circuit
$HP(HPO)$	Set of discretised or merged hourly time periods with elements $hp \in HP$
$IN(IO)$	Set of inlets to each unit with elements $in \in IN$
$MP(MPO)$	Set of discretised or merged monthly time periods with elements $mp \in MP$
$OUT(IO)$	Set of outlets from each unit with elements $out \in OUT$
Parameters	
a_1, a_2	Experimental constants for the thermal loss coefficient of solar collector ($\text{kW}/(\text{m}^2 \cdot ^\circ\text{C})$)
c_p^{fluid}	Specific heat capacity of the heat transfer fluid ($\text{kWh}/\text{t} \cdot ^\circ\text{C}$)
$I_{mp,dp,hp}, I'_{mpo,dpo,hpo}$	Average solar irradiation for each period considered and hourly solar irradiation for each hour of the year (kW/m^2)
$L^{period}_{mp,dp,hp}$	Length of period L for each monthly, daily and hourly time period
$T_{mp,dp,hp}^{ambient}, T_{mpo,dpo,hpo}^{ambient}$	Average ambient temperature for each period considered and ambient temperature for each hour of the year ($^\circ\text{C}$)
ΔT_{min}	Minimum temperature difference ($^\circ\text{C}$)
Π_0	Efficiency factor for the solar collector
ρ^{water}	Density of water (t/m^3)
Continuous variables	
$A_{collector}$	Area of solar collector (m^2)
$COP_{mp,dp,hp}$	Coefficient of performance of the system in each time period
$F_{in,mp,dp,hp}^u, F_{out,mp,dp,hp}^u$	Fluid flowrates in and out of a unit for each time period (t/period)
$h_{t,mp,dp,hp}^{out}, h_{t,mp,dp,hp}^{in}$	Mass enthalpy in and out of a unit within the heat pump circuit for each time period
$\dot{Q}_{in,mp,dp,hp}^u, \dot{Q}_{out,mp,dp,hp}^u$	Quantity of heat flow in and out of a unit for each time period (kW/period)
$\dot{Q}_{mp,dp,hp}^{gen}$	Quantity of heat recovered from the condenser and sub-cooler in each time period (kW/period)
$T_{in,mp,dp,hp}^{collector}, T_{out,mp,dp,hp}^{collector}$	Inlet and outlet temperature of solar fluid from the collector for each time period ($^\circ\text{C}$)
$T_{in,mp,dp,hp}^u, T_{out,mp,dp,hp}^u$	Stream temperature in and out of a unit in each time period ($^\circ\text{C}$)
$T_{mp,dp,hp}^c$	Average temperature of the heat transfer fluid in the solar collectors ($^\circ\text{C}$)
$\dot{W}_{comp,mp,dp,hp}$	Work done by each of the compressors for each time period (kW)

6.1 Introduction

Residential and industrial sectors contribute heavily to global energy consumption. While the industrial sector is responsible for about 40% of global energy consumption [1], residential and commercial buildings jointly account for between 32% [2] and 40% [3] of total energy consumption. The global demand for energy continues to be on the increase, and this is accompanied by increased CO₂ emissions. With projected increase of about 50 % between 2019 and 2050 [4], further increase in both energy demand and emission level is most likely [5] considering the persistent growth in global population, industrialization and economy, and its impact on energy demand [6]. Hence, the use of renewable sources of energy have received enough attention as a sustainable solution for energy security and emission reduction. In order to enhance reliability and stability of renewable energy systems in operation, a number of performance improvement measures have been explored which have led to combination of several renewable energy technologies such as combined heat pump and solar thermal systems.

Combination of solar thermal and heat pump systems (in various forms) are alternative renewable and sustainable source of heat for domestic and industrial heat supply. One of the captivating features of solar thermal is its natural availability at diverse ambient temperature levels without any mechanical work input [7]. Heat pump on the other hand is an energy efficient technology that is used to upgrade a relatively low-temperature heat source and eventually deliver more heat energy to the system than the total work input [8]. These attributes provide the platform for using the combined technology to circumvent the low energy output limitation of most solar thermal designs (especially in periods with low solar irradiation and ambient temperature), while also providing a sustainable means of overcoming the start-up problem in most heat pump applications thereby enhancing the performance of heat pumping cycle. In the resulting system, the individual performance of the two integrated technologies (solar thermal and heat pump) are enhanced leading to overall increase in thermal performance of the integrated system.

Several designs involving solar energy and heat pump systems have been reported in literature [9, 10]. These could be categorized under (i) solar photovoltaic (PV) systems outputting electrical energy for the heat pump from the incident solar radiation [11], and (ii) solar thermal converting the collected solar rays to usable thermal (heat) energy for evaporator unit of the heat pump [12]. An hybrid of these technology options have also been reported [13], where both the PV and collector technologies are combined with various types of heat pumps. However, due to their ability to be used for heat production either in series or parallel [14], and considering the high costs involved with other design possibilities [15], the use of solar thermal in combination with compression heat pump systems is

more dominant when compared with the other types [16]. Such system can also be operated with refrigerants in direct expansion collectors while glazing is eliminated to reduce costs, and it can also be hybridized with air to provide alternative heat source in the complete absence of solar energy. The conventional combination of solar thermal and heat pump consists of the solar thermal collector unit separated from the heat pump circuit [17]. The two technologies are usually connected by a heat exchanger which transfers solar energy to the heat pump mainly through the use of secondary heat transfer fluid. There are other designs in which solar collector also function as the evaporator[18] . This is widely referred to as the direct expansion solar thermal-heat pump system. In this type of design, there is no need for any intermediate working media as direct expansion of the refrigerant occur in the collector/evaporator [19].

The integration of heat pumps with heat networks operating at a relatively low temperature level is usually considered to be less complex with matured technologies widely available around the world. However, the desire for improved and higher thermal output have led to several capacity enhancements in heat pump designs which still require more research efforts [20], especially when higher temperature lift is desired [21]. To this end, different performance improvement measures for heat pump systems have been sought by various authors over the years. Shelton and Grossmann [22, 23] proposed efficient mixed integer linear programming (MILP) formulations of heat pump superstructure that minimizes costs. In [23], the author presents a design feature that allows flexibility in refrigeration systems with multiple temperature grids, while the work presented by the author in [22] focused on heat networks involving heat pump systems incorporated with heat recovery loops. Kamalinejad et al. [24] presented a mixed integer non-linear programming (MINLP) approach for optimal synthesis of vapour compression systems considering economic trade-off, partition temperature and compression configuration. The research focus in these earlier studies was the representation of possible connections of heat design problems that reduces the complexity with heat pump designs and general refrigeration systems, without considering solar as potential source of energy.

For the combination of heat pump and solar thermal systems in operations, a comprehensive analysis of possible system configurations was discussed in [25]. However, more research attention are directed towards the design, modelling and experimental investigation of the system, with less attention on optimization of the system. This may not be unconnected to the complexities imposed by the time dependency features of critical integration parameters [26]. Neves et al. [27] presented an hourly based model for combining solar thermal with heat pump and its impact as substitute for electrical energy. Strategies that could be adopted to increase the performance of combined solar and

heat pump system were investigated by Vega et al. [28]. In the presented design, an existing solar water heating system was incorporated with air-to-water heat pump for high temperature water heating. A theoretical analysis investigating the essential features in solar ejector-compression heat pump was reported by Chen et al. [29], while Suleman et al. [30] presented detailed energy and exergy analyses of combined solar heat and heat pump for low temperature process heating operations.

The nature and properties of the source of heat play significant role in the design, arrangement of components and performance of heat pump systems. Due to varying weather conditions, solar energy systems feature considerable intermittency with inherent uncertainties in solar radiation and by implication, the energy supply from the system (especially in lean periods with low ambient temperature). Heat pump can complement this limitation in solar thermal designs if well harnessed, while a low temperature solar heat can also circumvent the common start-up problem encountered in some heat pump applications. For typical heat pump circuit operating in varying weather conditions, several studies have been presented describing the methods applied to achieve satisfactory system performance. The study of Zhang et al. [31] and Vieira et al. [32] deal with air source heat pump water heating systems. In [32], critical parameters essential for the improved system performance are investigated and tested while the technique that could be used to optimize variables in such system is presented in [31]. An illustration for optimal design in water – water heat pumps was described in [33] where the merit of the design over other types of design are highlighted while the procedure for multiperiod consideration of the design features in dual purpose heat pump systems operating with natural fluids was discussed in [34]. Though issues relating to variation in weather conditions are considered in the above studies, none of the studies involve the use of solar heat in the heat pump cycle.

Solar thermal designs offer clean and sustainable source of renewable heat with varieties of technological options for design preference. The synergy between solar thermal and heat pump technologies has been extensively researched in recent years and several design configurations could be found in the literature [19, 35-37]. A comprehensive energy conservation analysis and long term techno-economic benefits of the combined system is presented in [19] while strategies to enhance performance of the system with phase change material (PCM) are proposed in [35]. In [36], a direct expansion design of solar finned tube evaporator incorporated to air source heat pump system was presented where the collector performs the functions of an evaporator and simultaneous heat absorption from both ambient air and solar radiation. The study reported in [37] features an indirect expansion solar thermal collection design harnessed with a multi-functional heat pump system for enhanced coefficient of performance (COP). Carbonell et al. [8] proposed a design simulation of

combined solar thermal and heat pump system for water and space heating. Weeratunge et al. [38] presented a predictive control analysis of heat pump system incorporated with direct solar radiation heat and ground source solar heat energy to minimize electricity consumption. A similar design was presented by Li et al. [39] using TRNSYS commercial simulation tool. In the study, the effect of variable soil temperature on the performance of the simulated design was investigated.

Although the integration of solar thermal and heat pump systems have been widely studied and described by several authors over the years, an important aspect which is often neglected is simultaneous optimization of the design features under the multiperiod variability in meteorological and ambient conditions in order to ensure efficiency (stability) and optimal heat output from the system. This aspect is considered and implemented in this chapter in that instead of having a fixed evaporating temperature as obtainable in most conventional design methods, the heat source side of the integration is linked with multiperiod changes in solar radiation and ambient temperature of the reference location. Hence, the thermodynamic and operating features as well as the state variables in the integrated system are accounted for according to the different ambient conditions.

More so, it is widely known that basic vapour compression cycle for heat pump consists of an evaporator, compressor, condenser and expansion valve with refrigerant circulating through the components in closed circuit during operation. However, when a high temperature lift is desired, a multi-stage compression cycle is essentially required due to the wide difference between evaporator and condensing temperatures. When this happens, it is possible to further enhance the thermal performance of the integrated system by investigating the technical and thermodynamic feasibility of extracting more useful heat from the condenser side of the integration through successive desuperheating or subcooling. While examples of heat pump systems incorporating series connection of condenser and desuperheater exist in literature [40, 41], such application cannot be found for the combined design of heat pump and solar thermal technologies, especially for the case of dual heat recovery mode connected in series.

To the best of authors' knowledge, there is no existing study on heat pump/solar thermal heat network design where the integration features (particularly the heat source side temperatures) are based on the multi-period variability of ambient conditions, while the simultaneous optimization of variables in the system such as temperature, flowrate, pressure, enthalpies, heat duty, work done by the compressors and other relevant variables in the system are accounted for according to the multi-period variability of the input parameters. Therefore, this study presents a comprehensive synthesis method for combining solar thermal and heat pump technologies for low and medium temperature level heat generation. In the conceptual framework of the design, the recovered heat could be used

directly at any heat energy demand point or stored within a thermal storage medium to be used at a later time when it will be needed at the demand point. However, it should be noted that only the multiperiod integration between solar thermal and heat pump components of the integration is discussed in this chapter in line with the scope and objective of this thesis.

6.2 Description of Integrated Heat Pump Enhanced Solar Thermal System

This section presents detailed description of the integrated heat pump enhanced solar thermal design proposed in this chapter. In thermodynamic systems, the attributes (physical and chemical properties) of the working media are essential design consideration to achieve specific design objective. Hence, the section starts with brief description of the decision criteria for selecting the working media for the heat pump circuit while the second part provides detailed description of the integrated system.

6.2.1 Selection of refrigerant

An important decision criterion for optimal design and operation reliability in heat pumps is the selection of the working fluid. Some essential features influencing the performance of the working media in compression heat pumps include some thermodynamic features such as: suitability at high temperature (especially in high temperature lift), suitable working pressure (for evaporation and condensation), heat retention and thermal conductivity [42], as well as some environmental and safety criteria such as global warming potential (GWP), ozone depletion potential (ODP), non-toxicity, non-corrosivity and non-flammability [43]. For utility system linked with solar energy resource however, the uncertainties in the ambient conditions should also be considered especially as the ambient temperature goes to the extreme (either minimum or maximum). In this regard, comprehensive information on the behaviour of various working fluids under varying conditions is required. Detailed analysis and description of various refrigerants used in absorption and vapour compression heat pumps have been presented by Zhang et al. [17].

In this study, R-245CA was chosen as the refrigerant for the heat pump cycle and the decision criteria was primarily based on the desired target temperature level that the heat pump should deliver at the heat recovery side of the integrated system, bearing in mind the functionality of the refrigerant especially at low solar irradiation and ambient temperature. In addition to that, R-245CA has been compared with several other refrigerants with respect to environmental footprints and safety considerations [44], costs, thermal efficiency and suitability at diverse operating pressure range [45,

46], and it was found that it performs best. R-245CA is also known to be suitable for upgrading a low temperature heat source to a wide range of temperature levels (100 °C – 140 °C) at moderate operating conditions [47]. These attributes make the selected refrigerant to be well fitted for the objective pursued in this chapter.

6.2.2 Description of Heat Pump Enhanced Solar Thermal Cycle

Figure 6.1 presents the schematic diagram of the closed loop heat pump circuit alone isolated from the integrated system shown in Figure 6.2. The components of the proposed heat pump cycle include evaporator, two compressors (for double stage compression), a condenser and sub-cooler connected in series, and an expansion valve. The absorbed heat energy enters the evaporator and it is transferred to the refrigerant. After absorbing heat in the evaporator, the liquid refrigerant boils and the resulting gas flows to the compressor (point 1). In the compressor, the hot refrigerant gas compresses, leading to increase in pressure and further increase in temperature. The two-stage compression cycle is represented in the figure as point 1 – 2 (first compression cycle) and point 2 – 3 (second compression cycle). From the second compressor, the vaporised refrigerant exits at high pressure and temperature (high enough to satisfy specific heat demands beyond the initial level of the heat source). The compressed hot refrigerant gas then flows to the condenser and condenses (point 3 – 4) by giving off some of its heat energy to a secondary circulating fluid (pressurized water), and the refrigerant gas reverses back to a hot liquid. Point 4 – 5 represents additional cooling (in sub-cooler) incorporated for further heat transfer from the hot refrigerant liquid to the circulating water. Thereafter, the sub-cooled refrigerant liquid then flows through the expansion valve (point 5 – 6) which reduces its pressure and temperature. This marks the end of the cycle, and then the refrigerant returns to the evaporator (point 6 – 1) to commence another cycle.

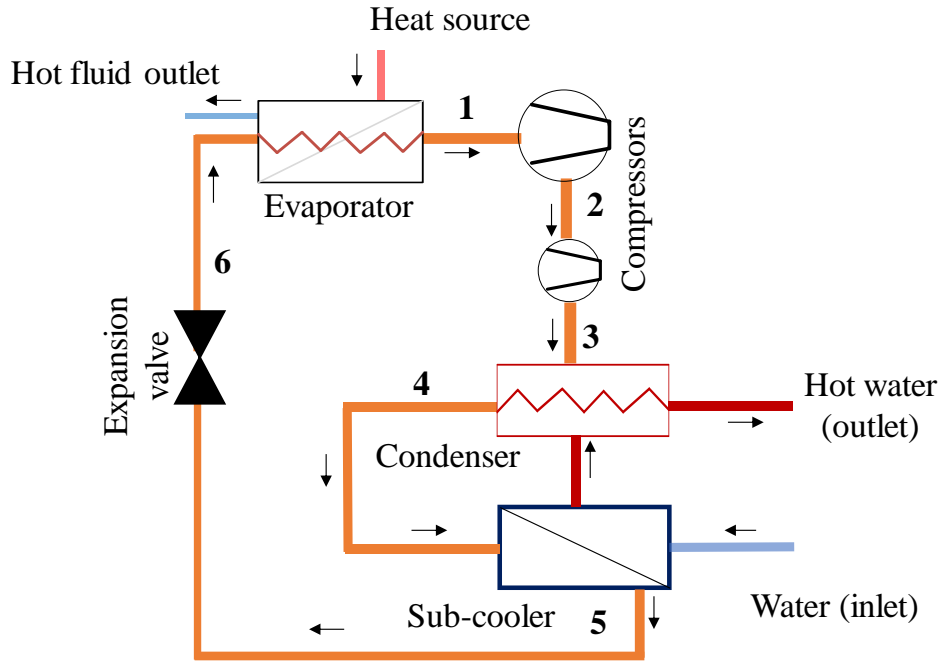


Figure 6.1: Schematic representation of multi-stage heat pump cycle

Most previous studies conducted in this line of research utilized ambient air [48], geothermal heat [49], sea water [50], wastewater [51] and waste heat [52]. However, the conceptualized superstructure adopted in this work incorporates solar thermal as the heat source for the evaporator and the proposed integration considers multiperiod variability in the temperature level of the heat source as well as its implication on the thermodynamic features and all state variables within the integrated system.

Figure 6.2 presents the superstructure for the combined solar thermal and heat pump technologies. It is developed by upgrading the closed loop heat pump circuit to heat pump enhanced solar thermal system by connecting the superstructure presented in Figure 6.1 to the data on hourly irradiation and ambient temperature of the reference location to form an integrated system. The resulting system then consists of the solar thermal collector (which supplies heat to the evaporator side of the heat pump), the heat pump cycle (as in Fig. 6.1), and the heat recovery loop where low/medium temperature heat is harvested. Accordingly, Figure 6.2 contains three separate but interconnected loops with three different working fluids: i) closed loop comprising solar collector – heat pump – solar collector; ii) closed loop comprising heat pump alone; and iii) open loop comprising heat pump – industrial process – heat pump.

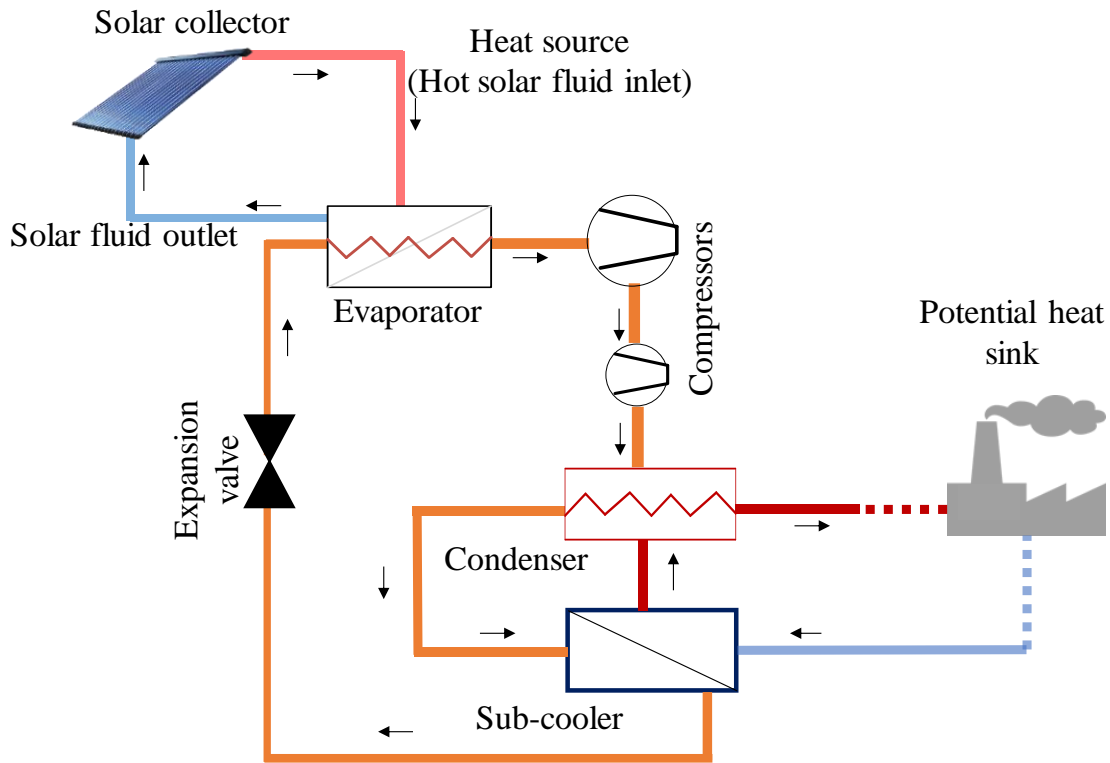


Figure 6.2: Integrated heat pump-enhanced solar thermal system

The heat transfer fluid (HTF) that runs through solar collector – evaporator – solar collector loop is assumed to be a mixture of water and ethylene glycol, R-245CA refrigerant is used as the working media in the closed loop heat pump cycle, while pressured water is considered as the circulating fluid which is used to recover heat from the hot refrigerant gas. The working principle of the integrated system is as follows:

Having increased in temperature, the solar heat capture fluid enters the evaporator and is used to vaporize the low-pressure refrigerant contained within the sealed compartment of the evaporator. The two working media are separated (and do not physically mix) in heat exchanger which enables heat transfer between the hotter solar heat capture fluid and the colder refrigerant. After absorbing solar heat, the refrigerant boils and then flows across the closed loop heat pump circuit as previously described (Figures 6.1 and 6.2). The integrated system is considered as a continuous process taking into consideration the variabilities of the meteorological conditions and their impacts on the performance of the system. The advantage of a system such as the one described above is that more heat is obtained from the system than the total work input. Depending on the demand, the heat

generated could be integrated with industrial and residential heat supply networks or used for operations utilizing heat energy in other sectors.

6.3 Methodology and Model Development

The developed model and optimization framework presented in this chapter seeks to maximize the total heat output of the integrated system shown in Fig. 6.2. Analysis of the model and computational framework are implemented in General Algebraic Modelling System (GAMS) [53] environment. The systematic methodological approach is categorized into three parts: i) problem definition and data collection, ii) equipment and system design, and iii) performance evaluation. A summary of the applied methodology and computational framework is presented in Figure 6.3.

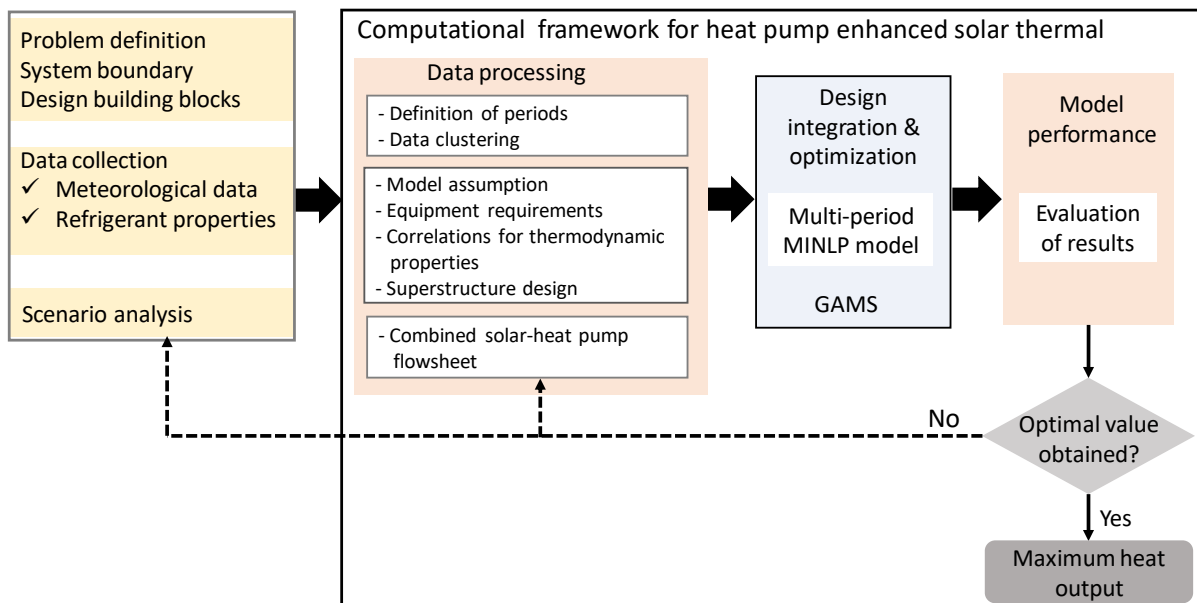


Figure 6.3: Summary of applied methodology for heat pump-enhanced solar thermal integration

6.3.1 Correlations for thermodynamic properties

The system design and analysed in this chapter consists of the heat pump circuit in tandem with the solar thermal collection system where the refrigerant undergoes transcritical cycle by changing phase and vaporising from its ambient state (liquid) to superheated vapour. In general heat pump designs, the influence of changes in temperature and pressure on the thermodynamic properties of the system is critical to the performance of the system. In order to evaluate the periodic changes on the heat pump side of the integrated system, correlations are developed for some thermodynamic properties across the two-phase region of the refrigerant (R-245CA). To achieve this, simulation of the proposed multi-stage vapour compression with successive condensation and sub-cooling was implemented in

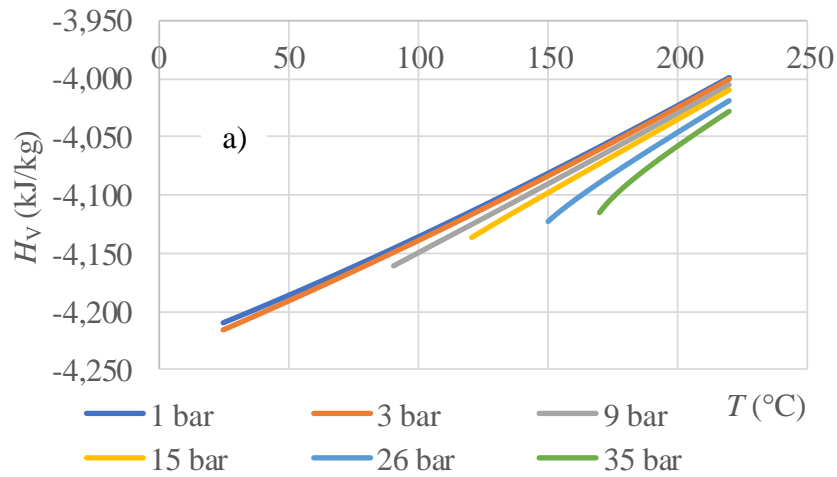


Figure 6.5a: Changes in mass enthalpy with varying temperature and pressure for vapour phase

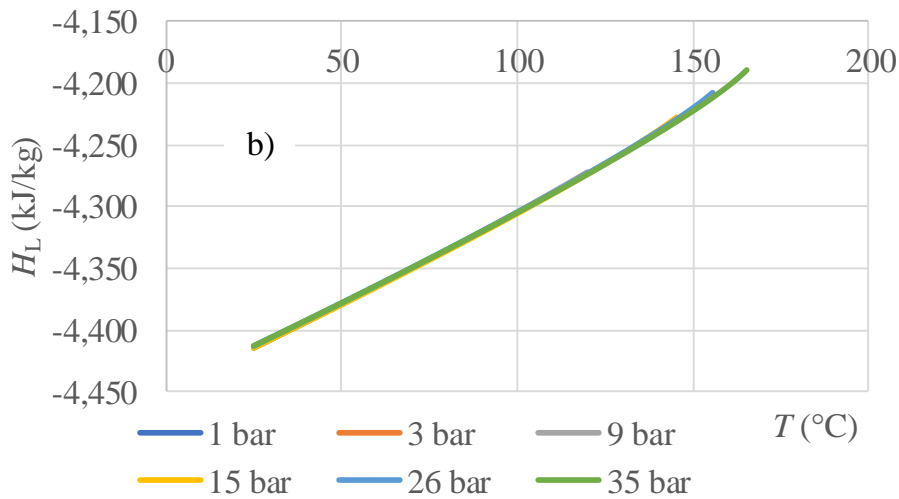


Figure 6.5b: Changes in mass enthalpy with varying temperature and pressure for liquid phase

6.3.2 Model formulations

An important aspect of the developed model is the implementation of the design and optimization of the integrated systems considering the multiperiod changes in solar irradiation and ambient temperature, as well as the influence of these variations on the integration variables. The objective of the developed framework is to maximize the total heat recovered from hot refrigerant gas at the heat recovery side of the heat pump. The main variables considered in the model include temperature, flowrate and energy flow of streams across the system. Other variables are the area of solar collector, mass enthalpies across the heat pump loop, efficiencies, mass fractions of liquid and vapor, heat capacities and c_p/c_v ratio. Similar to the models previously presented in Chapters 4 and 5 of this thesis,

the model presented in this chapter is also formulated as a flowsheet superstructure where global equations are used to connect all the model building blocks.

The general relation for the mass flowrates (F) between the units in the superstructure is shown in Eq. (6.1).

$$(F)_{out,mp,dp,hp}^u = (F)_{in,mp,dp,hp}^{u1}, \quad (6.1)$$

$$\forall (in, out) \in IO, (u, u1) \in U, mp \in MP, dp \in DP, hp \in HP$$

F (t/period) represents mass flow rate from unit u to unit $u1$ in the integrated system for each monthly (mp), daily (dp) and hourly (hp) period. This implies that the flow rate at the outlet of unit u is equal to the flowrate at the inlet of unit $u1$ in each time period. In a similar manner, the same relations are used for temperatures (T) and heat flows (Q) across the entire units, and for pressures (P), mass enthalpies (h) and liquid/vapour mass fractions (x) of streams within the heat pump circuit.

6.3.2.1 Solar collector

On the solar collector side of the integrated system, the temperature of the fluid exiting the collector is considered to be a function of solar irradiance, flowrate of the fluid, average temperature of the fluid and ambient temperature as presented in previous chapters. Equations for calculating the heat gain by the solar collector and heat captured by the solar fluid are described in Eq. (6.2) and Eq. (6.3). These variables are accounted for in the model on hourly, daily and monthly time periods.

$$\dot{Q}_{out,mp,dp,hp}^{collector} = A_{collector} \cdot (\Pi_0 \cdot I_{mp,dp,hp} - a_1(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient}) - a_2(T_{mp,dp,hp}^c - T_{mp,dp,hp}^{ambient})^2), \quad \forall mp \in MP, dp \in DP, hp \in HP \quad (6.2)$$

$$\dot{Q}_{out,mp,dp,hp}^{collector} = F_{out,mp,dp,hp}^{collector} \cdot c_p^{fluid} \cdot (T_{out,mp,dp,hp}^{collector} - T_{in,mp,dp,hp}^{collector}), \quad (6.3)$$

$$\forall mp \in MP, dp \in DP, hp \in HP$$

In Eq. (6.2), $A_{collector}$ represents the area of the solar collector; c_p^{fluid} is the specific heat capacity of the solar heat capture fluid, which is assumed to be constant to simplify the model; $T_{mp,dp,hp}^c$ is the average of the inlet and outlet temperatures of the solar capture fluid in the solar collector in each time period ($\frac{T_{in,mp,dp,hp}^{collector} + T_{out,mp,dp,hp}^{collector}}{2}$); $T_{mp,dp,hp}^{ambient}$ is the ambient temperature in each time period; and

$I_{mp,dp,hp}$ is the irradiation, which is also subject to change according to the monthly, daily and hourly periods; Π_o is the efficiency factor of the solar collector while a_1 and a_2 are experimental constants. The $\dot{Q}_{out,mp,dp,hp}^{collectr}$ in Eq. (6.2) accounts for the attainable quantity of solar heat from the collector which is equal to the heat captured by the fluid as presented in Eq. (6.3). More information regarding the parameters used for modelling the solar collector is available in [7] and are also described in detail in Chapter 4 of this thesis.

6.3.2.2 Heat pump circuit

On the heat pump side of the integrated system, the heat gain by the refrigerant in evaporator is considered to be equal to the heat gained by the solar capture fluid entering the evaporator from the collector.

Energy balances are calculated according to enthalpy changes of the refrigerant across the cycle. Periodic changes in heat duty and work required across the units are accounted for by the following equations:

$$\begin{aligned} \dot{Q}_{t,mp,dp,hp} &= F_{t,mp,dp,hp} \cdot (h_{t,mp,dp,hp}^{out} - h_{t,mp,dp,hp}^{in}), \\ &\forall mp \in MP, dp \in DP, hp \in HP, \\ &t \in \{\text{evaporator, condenser, sub-cooler}\} \end{aligned} \quad (6.4)$$

$$\begin{aligned} W_{t,mp,dp,hp} &= F_{t,mp,dp,hp} \cdot (h_{t,mp,dp,hp}^{out} - h_{t,mp,dp,hp}^{in}), \\ &\forall mp \in MP, dp \in DP, hp \in HP, \\ &t \in \{\text{compressor, expander}\} \end{aligned} \quad (6.5)$$

With Eq. (6.4), the heat duty (\dot{Q}) across units t such as evaporator, condenser and sub-cooler are obtained by multiplying the flowrate (F) and the difference in mass enthalpy at the entry and exit points of each unit (*i.e.* $h^{out} - h^{in}$). The periodic energy conservation within the expander ($\dot{Q}_{expander,mp,dp,hp} = 0$), while the work input of the compressors ($W_{compressor,mp,dp,hp}$) are also obtained as a product of the flowrate of refrigerant and difference in mass enthalpy in and out of the compressors.

6.3.2.3 Heat recovery section

In the presented framework, heat recovery from the heat pump takes place at the condensing and sub-cooling units through counter-current exchange of heat between the hot refrigerant gas and

pressurised water. The equation that accounts for the heat recovery around the condenser and sub-cooler in every time period is provided by Eq. (6.6):

$$F_{out-2, t, mp, dp, hp} * C_{P_{water}}_{out-2, t, mp, dp, hp} * (T_{in-2, t, mp, dp, hp} - T_{out-2, t, mp, dp, hp}),$$

$$\forall mp \in MP, dp \in DP, hp \in HP,$$

$$t \in \{ \text{condenser, sub-cooler} \}$$
(6.6)

In the above equation, $F_{out-2, t, mp, dp, hp}$ represents the fluid flowrate for the pressurised water on both condenser and sub-cooler, $C_{P_{water}}_{out-2, t, mp, dp, hp}$ is the specific heat capacity of water while $(T_{in-2, t, mp, dp, hp} - T_{out-2, t, mp, dp, hp})$ is the difference between the inlet and outlet temperature of water on each of the components for every hourly, daily and monthly time periods.

6.3.2.4 Objective function

The optimization of the integrated solar thermal and heat pump design is performed with the objective of maximizing the heat recovered from vaporized refrigerant by the circulating pressurised water at the heat recovery side of the heat pump. The objective function of the developed model is as shown in Eq. (6.7).

$$\max \left(\sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in HP} \bigwedge_{(mp, dp) \in DPM} \dot{Q}_{mp, dp, hp}^{gen} \right)$$
(6.7)

In Eq. (6.7), $\dot{Q}_{mp, dp, hp}^{gen}$ describes the total periodic heat produced by the integrated heat pump and solar thermal system which is a cumulative sum of the total heat recovered from the sub-cooler and condenser by the working media for heat recovery. Set DPM represents set of pairs of days and months with the same orientation as described in Chapters 4 and 5.

The coefficient of performance of the system ($COP_{mp, dp, hp}$) is evaluated for every monthly, daily and hourly time period considering the periodic net work performed by the compressors ($\sum W_{comp, mp, dp, hp}$) as shown in Eq. (6.8).

$$COP_{mp, dp, hp} = \frac{\dot{Q}_{mp, dp, hp}^{gen}}{\sum W_{comp, mp, dp, hp}},$$

$$\forall mp \in MP, dp \in DP, hp \in HP,$$
(6.8)

6.4 Case Study and Results

In the proposed design, solar thermal is incorporated with heat pump cycle to form an integrated heat pump-enhanced solar thermal design. The implementation of the developed framework rests on the idea that thermal output from industrial [7] and residential [55] solar heat networks presented in Chapters 4 and 5 could be further enhanced to increase the thermal performance of the integrated systems.

The integrated system considers the multi-period variabilities in solar irradiation and ambient temperature. Thus, climatic data of a reference location is needed to test the developed model. As with the case studies presented in Chapters 4 and 5, a reference location in Maribor, Slovenia (elevation of 267 m above sea level, coordinates 46.552 N: 15.676 E Latitude and Longitude) is also used in this chapter to retrieve the meteorological data used in the model. The data is obtained from EC JRC PVGIS project database [56] for the period of January to December 2016 which is the most recent year for which the complete data is available as the time this study was conducted.

The optimal performance of the system is pursued by optimizing the integration variables (i.e. flowrates, temperatures, pressures, energy flows, work required, mass enthalpies, mass fractions of liquid and vapor, efficiencies, collector area, heat capacities and cp/cv ratio) in order to satisfy the main objective of the design, which is to maximize the total heat output from the system. Since the model is highly non-linear, data and model aggregation is needed so as to reduce the problem size and computational time. Accordingly, the model reduction techniques as presented in Chapters 4 and 5 of this thesis were used to reduce the size of the problem.

The resulting multi-period MINLP models for the combined solar thermal and heat pump system were solved with 0.1 % optimality gap on Intel® Core™ i7-8550U CPU @ 1.80 GHz processor with 8 GB of RAM. The model consists of 9,971 single equations, 11,186 single variables and solutions to the model was obtained in about 60 minutes using SBB solver in GAMS [53].

The proposed design is conceptualized in a manner that allows solar collector to provide heat to the evaporator. Operational features of the collector (solar irradiation, ambient temperature and collector outlet temperature) are part of the essential features that influence the performance of the system especially the amount of heat supplied to the evaporator. Thus, harvestable solar heat across the discretized time periods was investigated to have a clear orientation of the potential solar heat pushed to the integrated system.

Figure 6.6 and Figure 6.7 present the periodic heat supply to the evaporator for cases when the solar collector size is 50 m² and 5,000 m².

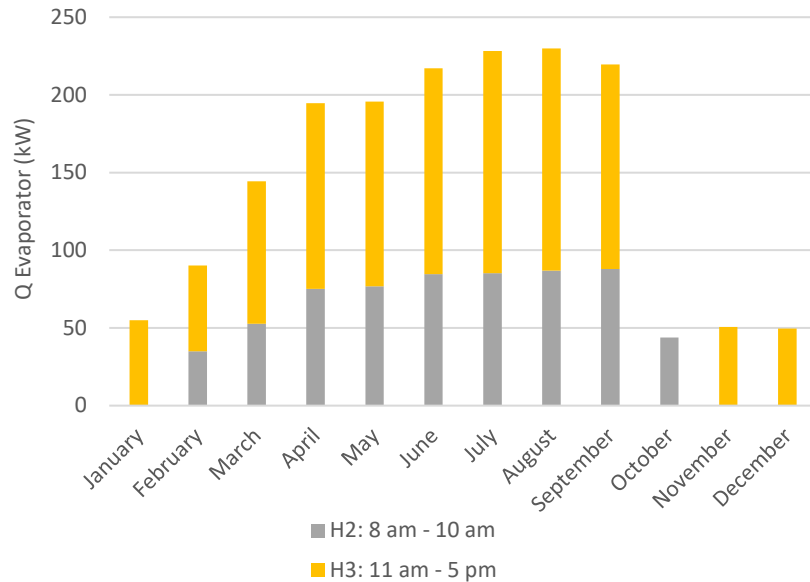


Figure 6.6: Periodic solar heat supply to the evaporator with a solar collector area of 50 m²

From Figures 6.6 and 6.7 it could be observed that the potential for solar heat supplied to evaporator shows a linear increase as the collector size increases (i.e. for 10 times larger collector area, 10 times more heat is supplied). It is also observed that the active heating periods is period H2 (8 am – 10 am) and period H3 (11 am – 5 pm) which coincide with periods with higher solar insolation (incoming solar radiation received by the Earth) [57].

A visual outlook of solar heat potential in this manner provides insights into how the heat pump side of the integration could be upgraded to a multifunctional heat pump system where other potential heat source could be incorporated with the heat pump in addition to solar thermal. In this context, the additional heat source will complement the solar heat (i.e. in period 1, H1 and 4, H4), thereby improving the performance of the system.

An important observation from Figures 6.8 and 6.9 is relative stability in the system with respect to total heat output despite the fact that March is typically a colder month in Slovenia with relatively low irradiation and ambient temperature as compared to August. Such display of stability is one of the benefits derived from the combined technologies.

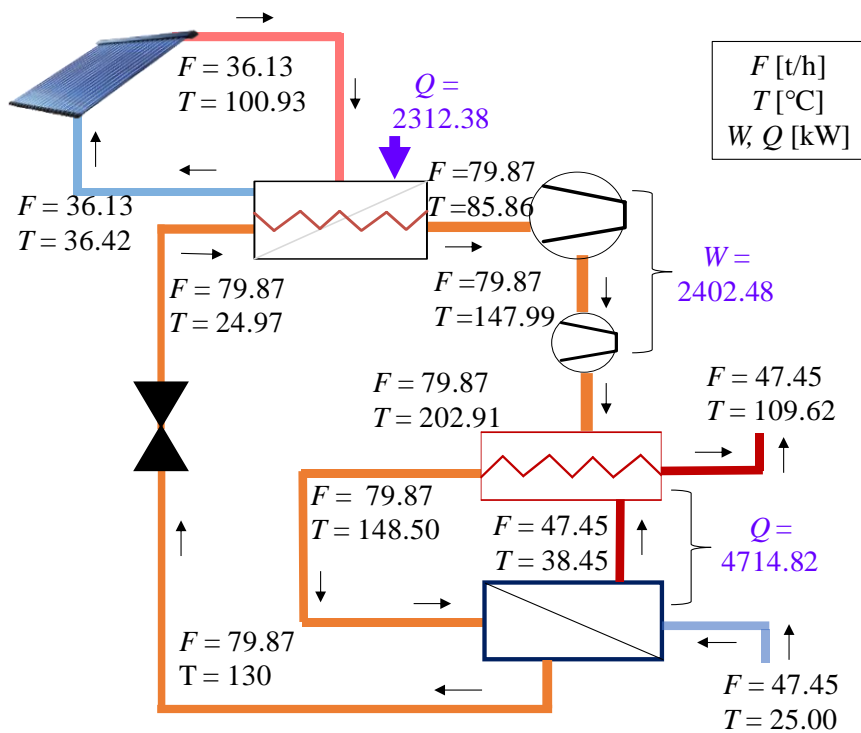


Figure 6.9: Values of variables in selected period and collector area ($A = 5,000 \text{ m}^2$, M8, 8-10am)

Figure 6.10 shows the relationship between the average heat output obtained from the integrated system (\dot{Q}^{gen}) with changes in the area of solar collector ($A_{collector}$). From Figure 6.10, a steady increase in the amount of heat recovered from the heat pump could be observed up to a point when the area of collector is $6,510.6 \text{ m}^2$. Beyond this collector area, no significant change is observed in the quantity of heat generated from the system.

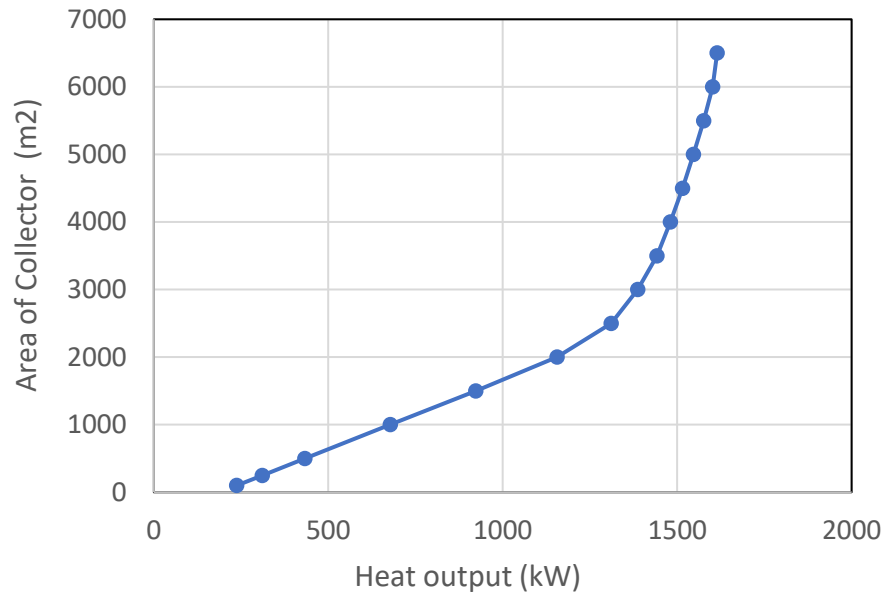


Figure 6.10: Average heat output with different sizes of solar collector

Table 6.1 presents a summary of the results which shows the average heat supply to the evaporator, average work done by the compressors, heat generated by the integrated system and corresponding coefficient of performance (COP). These system variables are investigated for different solar collector sizes.

Table 6.1: Average values of some integration variables for different collector areas

$A_{\text{collector}} \text{ (m}^2\text{)}$	$\dot{Q}_{\text{evap}} \text{ (kW)}$	$\dot{Q}_{\text{cond}} \text{ (kW)}$	$\dot{Q}_{\text{cool}} \text{ (kW)}$	$\dot{W}_{\text{comp}} \text{ (kW)}$	$\dot{Q}^{\text{gen}} \text{ (kW)}$	COP
100	11.94	-40.12	-8.85	37.04	237.20	1.32
500	59.67	-200.61	-44.26	185.20	433.10	1.32
1,000	119.35	-401.22	-88.52	370.40	677.99	1.32
2,000	236.94	-792.23	-175.18	730.46	1155.44	1.33
3,000	345.48	-995.64	-228.36	878.52	1387.08	1.39
4,000	440.49	-1090.49	-239.24	889.24	1480.20	1.50
5,000	551.56	-1177.43	-238.38	864.26	1546.33	1.68
6,000	629.90	-1263.52	-245.33	878.95	1601.92	1.78
6,510.6	672.60	-1328.97	-256.08	912.46	1614.58	1.81

As shown in the Table, there is improvement in thermal performance of the system as the area of collector increases. This increase is limited to certain collector area after which further increase in the area does not show any upward change in the amount of heat generated from the system, likewise its COP. Though it is expected that there should be further increase in the output of the system beyond

this collector area, the behaviour of the system in this manner may not be unconnected to the highly non-linear feature of the design and optimization problem which often lead to poor locally feasible solutions. Similar behaviour is observed in the required work input of the compressor when collector area is 5000 m² which falls outside the increasing trend as the collector area increases from 100 m² to 4000 m². Moreover, it should be noted that the proposed system considers a multi-stage compression cycle (which is unavoidably needed due to the large temperature differences between heat source and sink, and to realise the targeted temperature level at the heat sink side of the integrated system). A resultant effect of this complexity may not be unconnected to the values obtained for COP in all the presented cases. Further investigation on this type of results and the limitation of heat generation in the system as the size of solar collector approaches some maximum values will be more interesting, but this was not considered within the scope of this PhD research. However, such analysis is recommended for future studies.

6.5 Conclusion and Future Research Directions

The frequency in occurrence of climate change-induced environmental problems and natural disasters [58] suggest that the world is at a critical point to implement climate change mitigation strategies. Emissions associated with energy/power production from fossil fuels have been described to be one of the largest single contributors to climate change [5]. While increasing the share of renewable source of energy could reduce energy-related emissions to a large extent, only the combination of such increased utilization of renewables with other energy efficiency strategies and technologies [59] can lead to significant reduction in energy-related emissions which will achieve the global warming threshold target of less than 1.5 °C.

In this study, the potential of harnessing the synergy between renewable energy and energy efficiency technologies has been demonstrated through the multi-period integration of solar thermal and heat pump systems for enhanced thermal output. The input parameters in the proposed design framework are based on the hourly-based changes in solar irradiation and ambient temperature of the considered location. Thermodynamic characteristics of the system and the thermal output on the heat recovery side of the integrated system are also accounted for on hourly basis according to the changes in integration features.

Apart from the generic nature of the proposed framework (such that it is applicable to any geographical location), the mathematical representation of thermodynamic state features of components that make up the integrated system and its systematic development into a single design

and optimization problem is also another unique contribution of the study. This is achieved using multi-period mixed integer non-linear programming approach which allows ideal representation of relationships among parameters and variables in the model without simplifications. Considering the two case studies presented, for period 2 in the months of March and August (i.e. H2: M3 and H2: M8), the total heat output obtained from the system is 4904.89 kW and 4714.82 kW respectively.

Future work will involve investigations on how to further improve the COP of the system and subsequent integration of the design with residential and industrial heat networks. Further, the use of different heat transfer fluids in the heat pump circuit will be investigated. Finally, the model will be extended to include the features for multifunctional heat pump circuit such that the source of heat for heat pump will be from multiple sources.

6.6 Acknowledgements

The authors wish to acknowledge the supports received from the Erasmus+ programme of the European Union, Postgraduate Research Office and Faculty of Engineering and the Built Environment at the University of Cape Town, South Africa, and the Slovenian Research Agency (research core funding No. P2-0412 and P2-0032).

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Appendix 6A: Accepted Paper in Computer Aided Chemical Engineering Journal

Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations

The research paper reported under this section is the author's contribution to the 30th European Symposium on Computer Aided Process Engineering that will be held in Milano, Italy between 24th and 27th May 2020, accepted for publication in Computer Aided Chemical Engineering Journal.

Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations

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Abstract

This study presents a multi-period mathematical programming approach for the design and optimization of heat pump-enhanced solar thermal for low and medium temperature applications in industrial, residential and other sectors. Mathematical models which capture the dynamic operating properties and thermodynamic features of combined solar thermal and multi-stage vapour compression heat pump cycle have been developed. The multi-period optimization context of the model accounts for the intermittent variability of relevant meteorological conditions and their effects on heat output from the heat pump. The design and optimization of the integrated system is implemented and solved in GAMS and analysis of the system shows good prospect for enhanced thermal energy from solar. The results obtained show significant increase in the amount of heat recovered from the heat pump as solar collector area increases up to 6,511 m² with average heat duty of about 1,615 kW and coefficient of performance of 1.81 obtained for that same collector size.

Keywords: Solar thermal, Heat pump, Solar-driven heat pump synthesis, Low and medium temperature level applications, Design and optimization.

1. Introduction

Due to the urgent need to reduce energy-related emissions as well as increasing supports for stringent environmental regulations, energy system designs that showcase the synergy between energy efficiency measures and renewable energy technologies have received global interests and considerable research attention [1]. One of such technologies is integrated design of solar thermal and heat pump system which has been widely described to be a relatively preferred sustainable source of heat [2], especially for low and medium temperature operations.

One of the captivating features of solar thermal is its natural availability at diverse ambient temperature levels without any mechanical work input [3]. Heat pump on the other hand is an energy efficient technology that is used to upgrade heat from a relatively low temperature heat source and eventually deliver more heat than the total work input [4]. These attributes provide the platform for using the combined technology to circumvent the low energy output limitation of solar thermal systems (especially in periods with low solar irradiation and ambient temperature). It also provides a sustainable means to overcome the start-up problem in most heat pump applications thereby enhancing the performance of heat pumping cycle.

While numerous studies have been carried out on heat pump technologies, less information is available in literature on the synthesis of solar-driven heat pump and on the application of combined solar thermal and heat pump for low and medium temperature level applications [5]. This is especially the case for studies that include optimization of the integrated systems. Most previous research contributions combining solar thermal and heat pump designs have been largely applied to residential buildings, while few other available cases of industrial heat pump design and optimization are based on industrial waste heat recovery through thermoelectric devices and organic Rankine cycles [6].

Utilization of solar thermal in any form is a task that is highly challenging due to considerable intermittent supply and multi-period variability features of its energy output. Even with modern synthesis techniques, the general requirements for achieving realistic (optimal) design solution is still a challenge. More so, if a moderately-sized solar design with simple technology is considered, not much higher temperature level can be reached for typical industrial streams [3]. However, integrating heat pump with such simple design could enhance the thermal output of the system, but combination of the two technologies is not trivial considering the transient nature of solar resource and its influence on the heat output from the combined technology. This is in addition to the complexities at the heat pump side of the integrated network when a high temperature lift is desired. Such intricacies are generally unavoidable due to the wide difference between evaporator and condensing temperatures while trying to maximize the heat load recoverable from condensing vapour in the heat pump.

To the best of authors' knowledge, study on combined heat pump/solar thermal utility system that incorporate the aforementioned features using a simultaneous design and optimization approach is still lacking. Hence, this study presents a comprehensive synthesis method for the utilization of combined solar thermal and heat pump technologies for low and medium temperature level heat generation.

2. Methodology

2.1. System description

The integrated system presented in this paper consists of solar thermal system (which supplies heat to the evaporator side of the heat pump) and the heat pump cycle (having multi-stage vapor compression features with successive condensation and sub-cooling for maximum heat recovery) and low/medium temperature heat production for potential integration with the industrial or residential heat network.

Figure 6A1 presents the structure of the combined solar thermal and heat pump technology. The integrated design comprises three loops: i) closed loop solar collector – heat pump – solar collector; ii) closed loop of heat pump alone; and iii) open loop heat pump – industrial process – heat pump. The heat transfer fluid (HTF) that runs through solar collector – evaporator – solar collector loop (first loop) is a mixture of water and ethylene glycol. In the second loop (closed loop of heat pump cycle), R-245CA refrigerant is used as the working media, while circulating pressurized water is used to recover heat from the hot refrigerant gas which is then further used in the industrial process loop (third loop). In Figure 1 the third loop is presented with a dashed line, as it is modelled as an open loop.

Having increased in temperature, the HTF from solar collector is used to vaporize the low-pressure refrigerant within the sealed compartment of the evaporator. Thereafter, the vaporized refrigerant goes through multi-stage vapor compression which further increases the pressure and temperature of the gas. The hot refrigerant gas is then finally used to raise the temperature of the circulating HTF on the heat recovery side of the heat pump cycle (i.e. condenser and sub-cooler). The advantage derived from an efficient heat pumping system is that more heat is delivered to the system than the total work input. In the conceptual framework of the design, the recovered heat can be used directly in the plant or stored in the tank to be used at a later time within the industrial heat network as shown in the integrated system (Figure 6A2) or for other potential uses such as space and water heating as demonstrated by [7]. However, it should be noted that only the multiperiod integration between solar thermal and heat pump components of the integration is discussed in this paper.

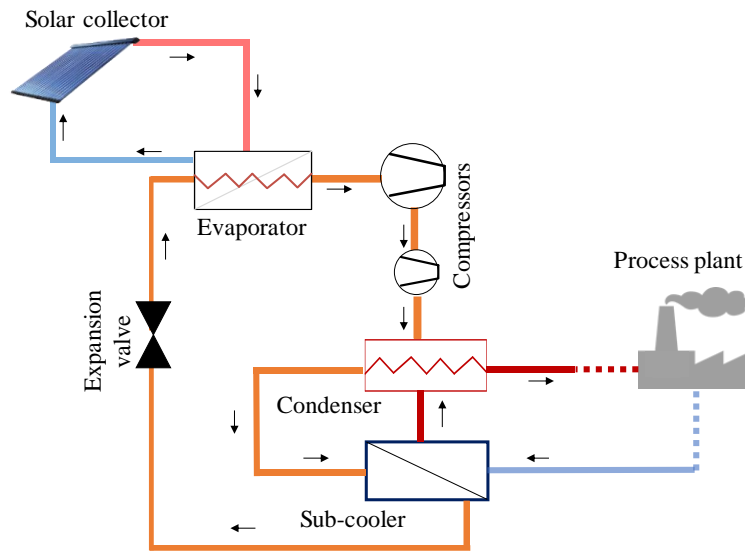


Figure 6A1: Integrated heat pump-enhanced solar thermal system

2.2 Model approach

The objective of the presented study is to maximize the total heat recovered from the vaporized refrigerant at the heat recovery side of the heat pump. The objective function is developed as shown in Eq. (1), where $\dot{Q}_{mp,dp,hp}^{gen}$ represents the total heat generated from the sub-cooler and condenser and delivered to the HTF in the process plant – heat pump – process plant loop. Sets mp , dp and hp represent monthly, daily and hourly periods, while DPM represents set of pairs of days and months as in [8].

$$\max \left(\sum_{mp \in MP} \sum_{dp \in DP} \sum_{hp \in hP} \bigwedge_{(mp,dp) \in DPM} \dot{Q}_{mp,dp,hp}^{gen} \right) \quad (1)$$

The main variables considered in the model include temperatures, flowrates and energy flows of streams across the system, mass enthalpies across the heat pump loop, the area of solar collector and efficiencies (for both solar collector and compressors). An important factor in modelling of combined solar thermal and heat pump system is the intermittent changes in ambient conditions and its effects on the heat output from the system. Hence, the mathematical model is formulated as a multi-period model. The model accounts for the dynamic behavior of the operating and thermodynamic features of the combined solar thermal-heat pump systems. The multi-periodicity framework of the model captures the time-dependency disposition of all the integration features. These characteristics are accounted for on hourly, daily and monthly time periods in the model.

Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations

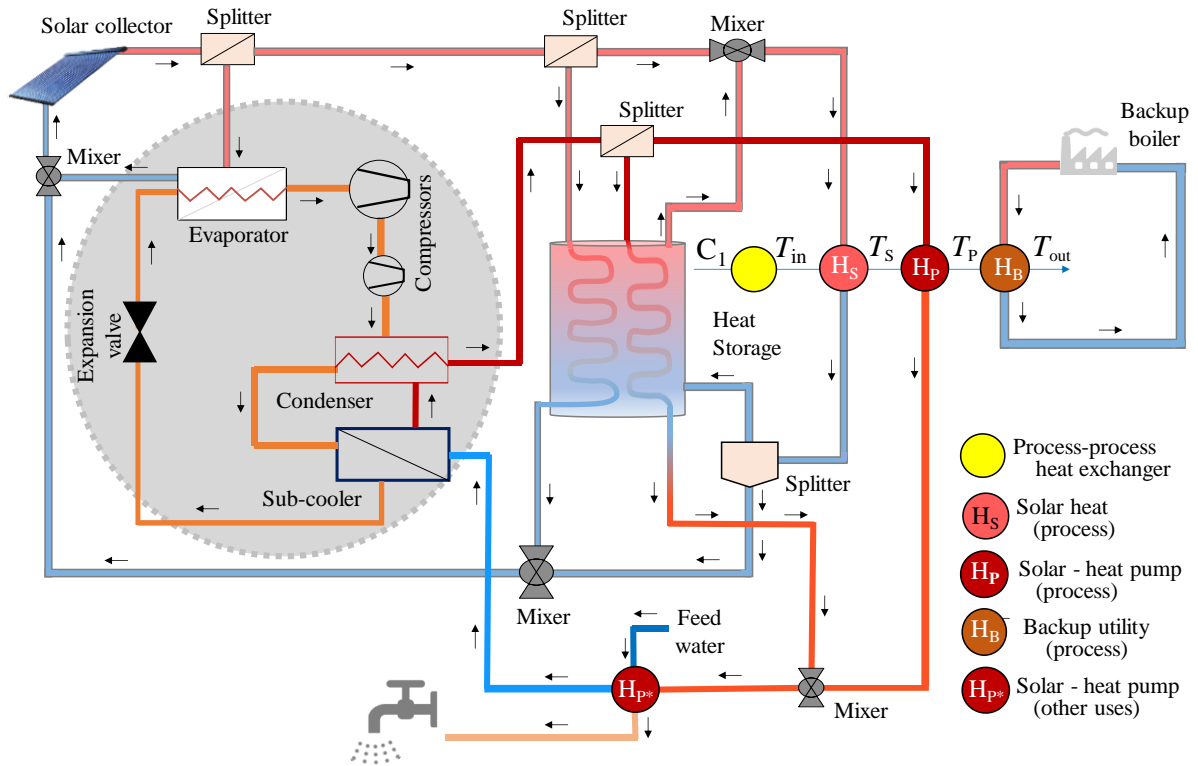


Figure 6A2: Industrial integration of combined solar thermal and heat pump system incorporated with periodic heat storage

To evaluate the periodic features on the heat pump side, correlations are developed for the changes in mass enthalpy with changes in temperature and pressure across the two-phase region of the refrigerant as shown in Figure 6A3 for R245CA. Thermodynamic data for the refrigerant are obtained from Aspen Plus V10 using REFPROP property method [9].

The periodic heat duty (\dot{Q}) and work (\dot{W}) required across units t such as evaporator (*evap*), compressors (*comp*), condenser (*cond*), sub-cooler (*cool*) and expander, are obtained by multiplying the flowrate (F) and the difference in mass enthalpy ($h^{out} - h^{in}$):

$$\dot{Q}_{t,mp,dp,hp}, \dot{W}_{t,mp,dp,hp} = F_{t,mp,dp,hp} \cdot (h_{t,mp,dp,hp}^{out} - h_{t,mp,dp,hp}^{in}),$$

$$\forall mp \in MP, dp \in DP, hp \in HP, \quad (2)$$

$$t \in \{\text{evaporator, compressor, condenser, sub-cooler, expander}\}$$

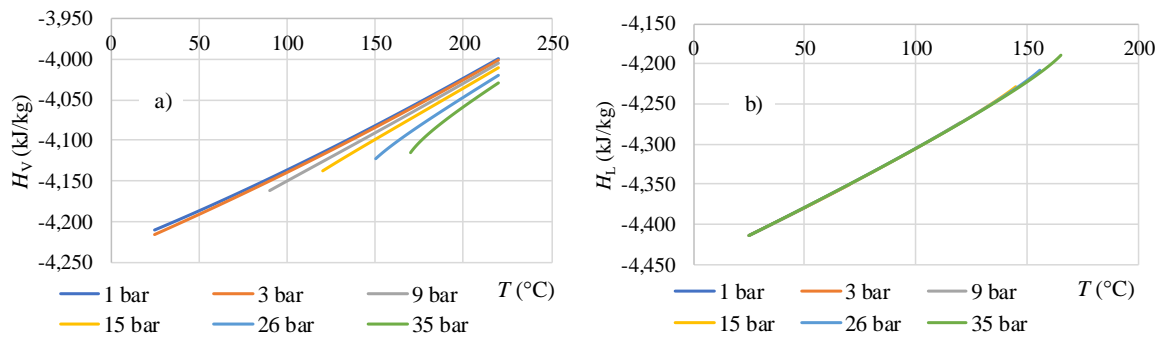


Figure 6A3: Mass enthalpy changing with temperature and pressure for a) vapor and b) liquid phase

3. Case Study and Results

The developed model is implemented based on the previous design of industrial integration of solar thermal by [3]. The integrated solar thermal design is now modified by including the heat pump enhanced solar loop. The design is then simultaneously optimized for the maximum amount of heat energy that can be obtained from heat pump. Most integration parameters (such as flowrates, temperatures, pressures, energy flows, work required, mass enthalpies, mass fractions of liquid and vapor, efficiencies, collector area, heat capacities and cp/cv ratio) are variables which are then optimized to satisfy the objective of the design.

A reference location in Maribor, Slovenia, is used as the case study. Meteorological data (hourly solar irradiation and ambient temperature) of the location for the year 2016 are obtained from EC JRC PVGIS project [10]. To reduce the complexity of the model and computational time, the discretization of hourly, daily and monthly time periods follows the same techniques as used by [3]. Readers are referred to the study for more details on solar thermal utilization in industrial process stream without heat pump. The resulting model consists of 9,971 single equations and 11,186 single variables. Solutions to the model was obtained in 60 minutes using SBB solver in GAMS [11] with 0.1 % optimality gap on a personal computer with an Intel® Core™ i7-8700K CPU @ 3.70 GHz processor with 64 GB of RAM.

Figures 6A4 and 6A5 and Table 6A1 present summary of the results obtained. An example of the variability in the properties of streams in specific time period and collector area is shown in Figure 6A4 (e.g. when $A_{\text{collector}} = 5,000 \text{ m}^2$ and period is M8, D1, H2 i.e. August 8-10 am). Figure 6A5 shows the relationship between the average \dot{Q}^{gen} obtained and solar collector sizes ($A_{\text{collector}}$). From Figure 6A5, a steady increase in the amount of heat recovered from the heat pump could be observed up to $A_{\text{collector}} \approx 6,510.6 \text{ m}^2$. A summary of the results showing this relationship is presented in Table 6A1 for different variables such as heat duty, power required, heat generated, and coefficient of performance (COP).

Synthesis of Heat Pump Enhanced Solar Thermal for Low and Medium Temperature Operations

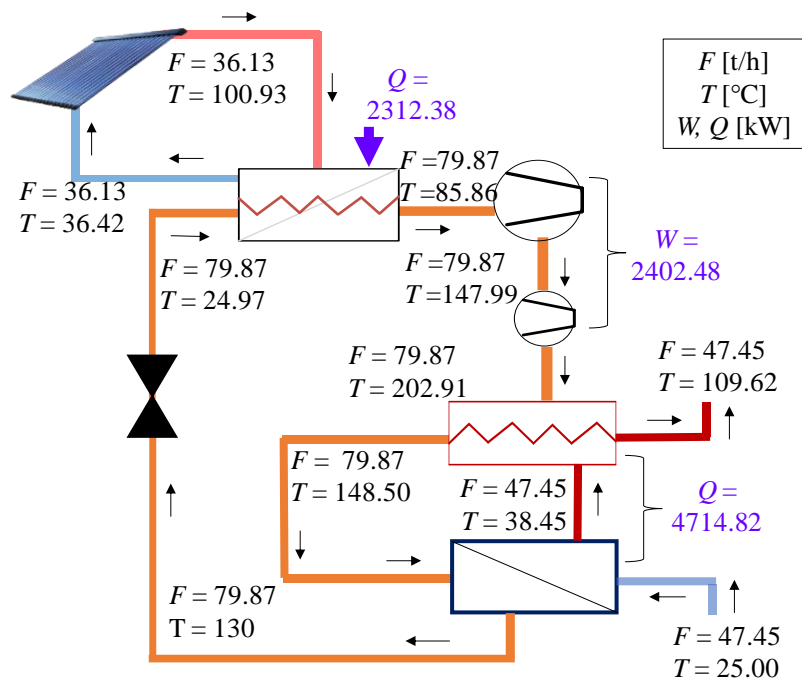


Figure 6A4: Values of variables in selected period and collector area ($A = 5,000 \text{ m}^2$, M8, 8-10 am)

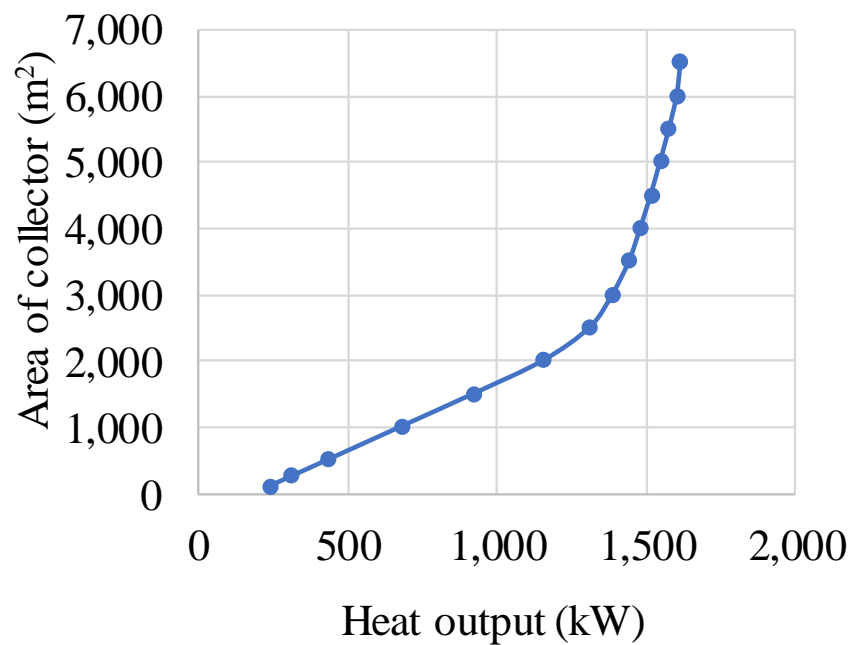


Figure 6A5: Average heat output with different sizes of solar collector

4. Conclusions and Recommendations

In this study, an integrated design and optimization framework that combined solar thermal and heat pump technologies has been proposed for enhanced thermal performance. The framework and method are based on a multi-period model formulation where the dynamic features of solar integration and heat output from the system are evaluated and accounted for on hourly, daily and monthly time periods. The obtained results show that combining heat pump with solar thermal can enhance the thermal performance and reliability of the solar system. Future work will include integration of the proposed design with industrial and residential heat network for maximum heat delivery, as well as the inclusion of economics and sustainability objectives of the integrated design in the model.

Table 6A1: Average values of some integration variables for different collector areas

$A_{\text{collector}} \text{ (m}^2\text{)}$	$\dot{Q}_{\text{evap}} \text{ (kW)}$	$\dot{Q}_{\text{cond}} \text{ (kW)}$	$\dot{Q}_{\text{cool}} \text{ (kW)}$	$\dot{W}_{\text{comp}} \text{ (kW)}$	$\dot{Q}^{\text{gen}} \text{ (kW)}$	COP
100	11.94	-40.12	-8.85	37.04	237.20	1.32
500	59.67	-200.61	-44.26	185.20	433.10	1.32
1,000	119.35	-401.22	-88.52	370.40	677.99	1.32
2,000	236.94	-792.23	-175.18	730.46	1,155.44	1.33
4,000	440.49	-1,090.49	-239.24	889.24	1,480.20	1.50
6,000	629.90	-1,263.52	-245.33	878.95	1,601.92	1.78
6,510.6	672.60	-1,328.97	-256.08	912.46	1,614.58	1.81

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Chapter Conclusions

The frequency in occurrence of several climate change-induced environmental problems and natural disasters suggest that the world is at a critical point to implement climate change mitigation strategies. Emissions associated with energy/power production from fossil fuels have been described to be one of the largest single contributors to climate change. While increasing the share of renewable source of energy could reduce energy-related emissions to a large extent, only the combination of such increased utilization of renewables with other energy efficiency strategies and technologies can lead to significant reduction in energy-related emissions which will achieve the global warming threshold target of less than 1.5 °C.

In this Chapter, the potentials of incorporating solar thermal with heat pump has been investigated. The proposed heat pump cycle is made up the features for multistage compression units and successive sub-cooling system outside the condenser. This components arrangement provides opportunities for high temperature lifting of low grade heat solar heat source (especially at lean periods with low solar irradiation) and also offers strategy for additional cooling of the circulating hot refrigerant (i.e. extracting more heat from the system), thereby enhancing the heat capacity of the integrated system.

The presented design provides the dual benefits of overcoming the low energy output in solar thermal designs and circumventing the start-up problem in most heat pump applications. These attributes satisfy the technical and operational requirements for combining renewable energy technologies in order to achieve clean energy development targets of the sustainable development goals. Though some authors would argue that solar collectors could be viewed to be more effective when the collector temperature is low. However, the design is pointless when the energy produced is lower than the required load temperature. When this occur, energy absorbed by the collector could be upgraded by the heat pump. Hence, the coupling of solar collector with heat pump system is beneficial.

Moreso, When the evaporated of heat pump circuit is linked with the multi-period solar thermal supply, the periodic thermal output from the integrated system is accounted for on hourly, daily and monthly time periods. Since several renewable sources (such as ambient air and geothermal heat) could be simultaneously incorporated with combined heat pump and solar thermal designs, the proposed design is a useful tool in planning and decision-making process for implementing such multi-functional heat pump system.

General Conclusions and Future Research Directions

This chapter presents a general overview and significance of the research reported in the context of this PhD thesis. The unique contributions of the research are presented, followed by general benefits of a study of this nature. The chapter ends with summary of the limitations in the course of executing the work and recommendations for future research outlook.

7.1 Concluding Remarks

Thermal energy constitutes the major part of energy demand in industrial and residential sectors, most of which are within the range that could be satisfied with renewable heat from solar thermal. As parts of the largest single contributors to global energy demand, integrating renewable energy technologies with industrial and residential heat networks will lead to energy security and reduction in energy-related emissions.

This thesis presents sets of generic multi-period design and optimization methodologies for integrating the techniques and technologies to utilize solar thermal and heat pump in industrial and residential sectors. The multi-period design and optimization context of the models accounts for intermittent variability of relevant meteorological and ambient conditions as well as their effects on total heat output from the integrated systems, while the mathematical models are formulated to capture the dynamic operating conditions and thermodynamic features of the systems according to the changing ambient conditions.

The main objective set for the study was oriented towards the development of a systematic approach based on multi-period MINLP formulation for: (1) direct and indirect integration of solar thermal with industrial heat network considering periodic heat storage and backup utility, (2) integration of solar thermal with domestic water and space heating network considering the incremental change in temperature of fluid in the tank (otherwise referred to as seasonal storage of harvested solar heat), and (3) multi-period integration of heat pump and solar thermal technologies considering periodic variabilities in solar thermal resource and simultaneous optimization of the integrated system.

First, an in-depth analysis of previous studies and available literature in this research domain that is useful for this PhD research was undertaken. Then, correspondence between the existing knowledge and main features of this particular study are established and presented in Chapter 2 to set the

background for the thesis. Due to the nature of the reporting style adopted for the thesis (as approved by the Doctoral Degrees Board of the University of Cape Town), insights into the developed solar thermal utilization methodologies, together with its multiperiod integration with heat pump system, are discussed in Chapter 3, while detailed application of the methods are presented in subsequent respective chapters that address each component of the objectives of study.

A comprehensive integration method for direct and indirect utilization of solar thermal with industrial heat network considering periodic heat storage and backup utility was presented and discussed in Chapter 4. The developed method for industrial utilization of solar thermal is applied to selected industrial case studies in two parts (i.e. paper 1 and paper 2). Paper 1 shows the application of the developed method for industrial utility retrofit scenario where the solar heat network design is applied to an illustrative case study of preheating industrial cold stream. In part 2 of Chapter 4, two distinct solar thermal integration alternatives are presented. The first design targets one industrial cold stream of a selected dairy plant while the second design targets multiple cold streams in the plant. The designs presented in part 1 and part 2 of the chapter are aligned towards the direct and indirect (via heat storage) utilization of solar thermal for low/medium temperature industrial operations.

Chapter 5 deals with the case of domestic integration of solar thermal where two integration possibilities of solar thermal for domestic water and space heating are shown. The integration scheme proposed in this chapter are also presented in two parts (i.e. paper 3 and paper 4) for the case of residential utilization of solar thermal for space and water heating incorporated with 2 heat storage and single heat storage tank respectively. Both design possibilities consider periodic heat storage and backup utility. While the use of a backup boiler is considered for the case of 2 heat storage tanks presented in part 1 of Chapter 5 (i.e. paper 3), a backup burner that is systematically integrated with solar thermal water and space heating networks is considered for the case involving only 1 heat storage tank (i.e. paper 4).

In Chapter 6, a generic multi-period design and optimization approach for combining solar thermal and heat pump technologies is presented. Apart from the generic nature of this proposed method, its other unique feature is the mathematical representation of the thermodynamic state features of all the components that make up the integrated system and its systematic development into a simultaneous design and optimization problem using multi-period mixed integer non-linear programming approach. The implementation of the model presented in Chapter 6 rests on the idea that the previous designs for solar thermal integration with industrial and residential heat networks presented in Chapter 4 and Chapter 5 could be expanded further to include the heat pump features. However, only the multiperiod integration between solar thermal and heat pump components of the

integration is discussed in this thesis on the premise that the resultant heat produced could be integrated with relevant heat network at any potential heat demand points.

In general, the presented methods allow simultaneous optimization of direct and indirect (through heat storage) solar heat utilization according to the formulated discrete time intervals based on hourly, daily and monthly time periods. The methods also permit the estimation of maximum harvestable solar heat potential alongside with technical and thermodynamic requirements of the heat network based on collector area, with or without the economic considerations which could also vary significantly both spatially and temporarily. This is so for the integration methods for solar thermal utilization in both residential and industrial sectors, as well as the method developed for multiperiod integration of solar thermal with heat pump technology. Thus, the developed framework is a useful tool in energy planning and decision making process.

Therefore, the key benefits and significance of this PhD research include:

1. *Generic solar thermal utilization framework considering multi-period time frame and simultaneous optimization of the design:* The integration methods presented in this thesis could be applied to any case study in any geographical location. This is because the model equations for each design building blocks are written independent of the design data while the models also account for the multi-period variabilities in the key integration parameters and variables on hourly, daily and monthly time periods for one calendar year. To the best of author's knowledge, development of such solar thermal utilization techniques for both industrial and residential sectors is unique to this thesis.
2. *Solar thermal integration considering multi-period variabilities on both energy supply and energy demand sides of the integration:* The direct and indirect solar thermal integration technique presented in Chapter 4 consider the periodic changes in the profile of heat demand and intermittent variability in attainable solar heat across the discretized time periods, along with the implications of these uncertainties on the actual heat network. Similar approach was demonstrated in Chapter 5 with an extension to the model by combining space and water heating potentials of solar thermal in a multi- building heat demand network that is also characterized by varied individual profile of heat demand from one building to another.
3. *A systematic approach for accurate modelling of solar heat storage system considering multi-period changes in attainable solar heat and variability in heat demand (i.e. via indirect solar integration):* An important aspect which is often neglected in solar thermal designs is that the

heat storage should be designed to optimally match the fluctuations in attainable solar heat and the profile of energy demand with minimal use of a backup utility. This is essential because apart from the properties of heat storage media, the storage design topology is critical to maximize the potential of solar thermal and to minimize heat loss. These heat storage features are incorporated as variables to be optimized in the proposed in Chapter 4 and Chapter 5 of this thesis.

4. *Synergising between energy efficiency and renewable energy technologies considering multi-period changes in ambient conditions and simultaneous optimization of the integrated system:* A unique feature of this design is linking of the multi-period solar heat availability with evaporator unit of the heat pump circuit. The proposed methodology for the design involves the mathematical representation of the thermodynamic state features of all the components that make up the combined technology. Contrary to most previous design methods, the proposed method allows parameters and variables in the integrated system to be optimized according to the changing ambient conditions in order to achieve the objective of the design.
5. *Regional energy self-sufficiency:* By region, what is implied is energy generation and sharing starting from a group of people in a multi-family apartment to inter-building heat, district and community networks. As shown from the case studies and papers presented in Chapter 4 and Chapter 5, it is possible for the solar thermal integration system to be designed according to available space on the roof-top for solar collector installation and also according to the level of heat demand. This could be implemented among a number of participating buildings as demonstrated in the chapter. Thus, the distributed nature of solar resource provides technological options for individual/decentralized energy planning and management which is needed to offset the deficit in regional/district energy supply, especially in developing countries.
6. *Energy security and emission reduction:* This study has implicitly shown that integration of solar thermal with residential and industrial heat/energy networks can potentially lead to energy security and reduction in energy-related CO₂ emissions in the two sectors. This by extension, could translate to energy security and emission reduction in the global energy system; a sustainable pathway to mitigating global climate change. However, further research effort to extend this study in this direction is required in order to explicitly establish these potentials.

7.2 Recommendation for Future Research Directions

As shown in the work carried out in this thesis in which the major contributions are highlighted above, the proposed methodology provides opportunities for realistic representation and synthesis of solar heat networks (in both industrial and residential sectors). The method was slightly modified in Chapter 6 to achieve the objective formulated for the chapter. While the several problems with respect to solar thermal utilization and heat pump designs were addressed in this thesis, and solutions that give the best system performance are sought in all the presented case studies, there also exists a number of conditions where poor locally feasible solutions are obtained (e.g. see Table 4.2 and Table 4.3 in Chapter 4). Therefore, for further improvement in the presented designs, and to improve the developed solutions methods for design and optimization problems such as those presented in this thesis, the following suggestions are recommended in future investigations:

- a. In the study, one of the major problems encountered with the solution methods emanated from the MINLP representation of the problem. This presents some inherent difficulties where significant computing efforts are required but only locally feasible (or suboptimal) solutions are obtained. Therefore, the use of “modern optimization techniques and computing tools” such as metaheuristic algorithms and artificial intelligence is recommended for accurate forecasting of fluctuations in solar irradiation. This is because the combination of classical and modern optimization techniques may be more efficient in solving problems of this nature. This will be a progressive path for further studies in order to ensure scientific continuum of the elements of this PhD research and also guarantee more accurate results for a study of this nature in future. Another potential solution to circumvent this type of problem is to pursue improvements in the capability of existing MINLP solvers (or development of more robust solver technology) that can handle larger multidimensional system problems comprising multiple time splits in multiperiod time frames.
- b. If the above recommendation is achieved, the developed models can be extended and combined by linking the industrial solar heat network with residential heat demand to form a single integrated system. A design superstructure reflecting this has been developed and presented briefly shown in the thesis (though discussions on this is outside the scope of this PhD research). However, a key limitation to the synthesis of the problem is complexity of the design for existing solution methods. Hence, a robust synthesis method would be required.

- c. Future work will also involve the inclusion of sustainability criteria as an objective in the model and consideration of solar thermal integration for higher temperature industrial operations and its integration with grassroots heat exchanger networks (HENS).
- d. For the residential and industrial heat designs, the possibility of extending the model to include the features for power (electricity) generation will be investigated both through the use of solar photovoltaic/thermal (PVT) collectors route and via electricity generation through concentrated solar thermal.
- e. For the residential integration of solar thermal, more participating nodes (buildings and their roof-tops will be included in the model) with emphasis on seasonal heat storage (preferably with the use of underground storage well) and potential heat losses for different solar collector types at different degree of thermal insulation and storage thickness. In line with this, the influence of different heat transfer fluids on thermal stability and heat output of the system will also be investigated.
- f. Integration of the developed heat pump-enhanced solar thermal with industrial and residential heat networks (individually and in combined mode) and investigations on how to further improve the COP of the system for enhanced thermal performance.
- g. Since the developed design already provides insight into the periods when the combined solar thermal and heat pump loop is active in the integrated system, the possibilities of extending the model to include the features for multifunctional heat pump circuit such that heat source to heat the heat pump can be from multiple sources (e.g. solar and ambient air) will also be explored to achieve 100 % all year round operational mode for the integrated system. Furthermore, interactions between the collector heat output together with coefficient of performance and other essential features of the integrated system will be investigated in detail to establish the trade-off and compromise among the attributes of the combined system.

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