# OPTIMISATION AND INTEGRATION OF RENEWABLE ENERGY GENERATION AND MANAGEMENT OPTIONS

**PhD Thesis**

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**OPTIMISATION AND INTEGRATION OF RENEWABLE ENERGY GENERATION AND MANAGEMENT OPTIONS**

**(A MEGÚJULÓ ENERGIA ELŐÁLLÍTÁS ÉS KEZELÉSI LEHETŐSÉGEINEK AZ OPTIMALIZÁLÁSA ÉS INTEGRÁLÁSA)**

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## Abstract

Inspite of several negative impacts such as air pollution, depletion of the ozone layer, excessive soil erosion and pollution caused by various substances, water pollution as well as energy dependence, limited sources of energy, centralisation of energy sources etc., the primary energy productions are still based mainly on fossil energy sources. The aim of this research was to support the integration of renewable energy sources within various types of processes according to heat demand. Whilst studies have dealt with the integration of solar energy sources in the form of electricity, fewer has been done on the topic of integrating Solar Thermal Energy. The goal of this work was to fill this gap. A multi-period model was created with an assumed steady load within time intervals of supply and demand. The following developments have to be achieved in order to allow the integration of Solar Thermal Energy:

1. Creating combined Time Slices for the integrating of Solar Thermal Energy. The integration of Solar Thermal Energy has to be performed separately within each Time Slice. The number of Time Slices on both the supply and demand sides have to be decreased as much as possible in order to reduce the complexity of integration. This has to be performed carefully as any reduction in Time Slices leads to lower accuracy of the model. A mixed-integer linear model has to be developed based on the trade-off between the number of Time Slices and inaccuracy.
2. Ensuring feasible integration of Solar Thermal Energy. After determining a proper number of Time Slices the focus is then on the feasible integration of heat. The driving force for heat exchange is the appropriate temperature difference, which depends on i) the required minimal temperature difference and ii) correlation of heat capacity flow rates of the two streams between which the heat exchange occurs. A Minimal Capture Temperature Curve (MCTC) and an algorithm for its construction has to be created in order to obtain a feasible heat exchange.
3. Estimation of storage size and required solar collector area. The storage size and solar collector area should be estimated in order to evaluate the whole design of the Solar Thermal Energy integration system. The size of the solar collector area and solar panels is determined based on the number of sunny and shady days. This ratio is then used to determine the size of solar panel surfaces by considering the solar panel surface for a single day and multiply it by this ratio in order to obtain the total for all days. The storage size depends on the quantity of heat, which is the sum of the number of shady days, a single night demand and heat losses. By determining the size of the solar panels and collector area

one can prepare a preliminary Solar Thermal Energy integration system analysis for integration of solar energy.

4. A model for the monitoring/short-term estimation of the integrated amounts of solar thermal energies. The preliminary analysis for evaluation of a Solar Thermal Energy integration system would be based on the average values of solar irradiation as well as on the more probable heat demands of the process. However, when the integration system is operating, the loads on both the supply and demand sides could differ quite significantly from those forecasted average values made at the preliminary analysis stage. Therefore, the real time performance of the system needs to be monitored and used for short-term estimation. A model was created for this purpose and once applied regarding the outlet temperatures of the collector the storage temperatures at the ends of each time interval could be determined together with the amounts of heat at both heat exchanges.

**Kivonat**

Az elsődleges energiatermelés még mindig elsősorban a fosszilis energiaforrások felhasználásával zajlik, a sok negatív hatás ellenére – beleértve a légszennyezést, az ózonréteg elvékonyodását, a túlzott talajeróziót és annak szennyezését a különböző szennyezőanyagokkal, a vízszennyezést, valamint az energiafüggőséget, a korlátozott energiaforrásokat, az energiaforrások központosítását stb. A tanulmány célja a megújuló energiaforrások integrálásának a támogatása – különböző hőigényes folyamatokba. Számos tanulmány készült a napenergia integrálására villamos energia formájában, viszont a termikus napenergia használata nagyüzemi méretekben nem része a szokásos gyakorlatnak, ezért ez a tanulmány erre a területre összpontosít. Egy olyan multi-periódus modell lett kifejlesztve, amely állandó terhelést tételez fel a periódusokban a kínálat és a kereslet oldalán is. Az alábbi fejlesztésekre volt szükség a termikus napenergia integrálására:

1. Az ún. combined Time Slices (egyesített időszeletek) a termikus napenergia integrálására. A termikus napenergia integrálása az egyes időszeletekben külön-külön van kivitelezve. Az időszeletek száma a kínálat és a kereslet oldalán is csökkentve volt az integrálási feladat bonyolultsága csökkentése érdekében. Ezt fokozott figyelemmel kell kivitelezni, hiszen az időszeletek csökkentése a modell pontatlanságának a növeléséhez vezet. Egy vegyes egész lineáris modell lett kifejlesztve az időszeletek száma és a pontatlanság „trade-off"-ja alapján.

2. A termikus napenergia integrálásának a megvalósíthatósága. A megfelelő számú időszeletek meghatározása után a hangsúly a megvalósítható hő-integráláson van. A hőcsere mozgatóereje a megfelelő hőmérséklet-különbség, amely a 1) minimális hőmérséklettől és 2) a hőt cserélendő folyamok hő-áram kapacitásának az összefüggésétől függ. Az ún. „Minimal Capture Temperature Curve" (minimális előállítási hőmérsékleti görbe) és ennek szerkesztésének az algoritmusa került kifejlesztésre.

3. A tároló méretének és a napkollektorok területének becslése. A tároló mérete és a napkollektorok területének a becslése a termikus napenergia integrálási rendszerének az elemzésére lett kifejlesztve. Az elemzés keretét a napos és az azt követő árnyas napok száma adja meg. A napkollektorok területét az összes nap (napos és árnyas) és a csak napos napok hányadosa alapján határozzuk meg. Ez a hányados tényezőként szolgál a napkollektorok területének a növelésére, méghozzá az egy napos napra meghatározott terület növelésére úgy, hogy az eleget tegyen az összes nap hőigényének. A tároló méretének a becslésére az árnyas napok hőigénye és egy éjszakai hőigény, valamint a hőveszteségek összege az alap. A kifejlesztett módszerek által a termikus napenergia integrálási rendszerének elsődleges elemzése végezhető el.

4. Az integrált termikus napenergia mennyiségének a folyamatos megfigyelésére, ill. rövid távú előrejelzésére kifejlesztett modell. A termikus napenergia integrálási rendszerének elsődleges elemzése az átlagos napsugárzási értéken, valamint a legvalószínűbb folyamat hőigényein alapul. Amikor azonban az integrálási rendszer működésben van, a terhelés mindkét (keresleti és kínálati) oldalán jelentősen eltérhet az elsődleges elemzés alatt előrelátott átlagos értékektől. Ezért a rendszer valós idejű teljesítményét folyamatosan kell követni, és az itt szerzett adatokat felhasználva rövid távú előrejelzést is ki lehet vitelezni. Ennek érdekében egy modellt hoztunk létre, amely által a napkollektorok kimeneti hőmérsékletét, a tároló hőmérsékletét az időszakok végén és a hőcsere mennyiségét mindkét hőcserére meg lehet határozni.

**Zusammenfassung**

Trotz der vielen negativen Einflüsse wie z.B. die Luftverschmutzung, der Abbau der Ozonschicht, übermäßige Bodenerosion und durch unterschiedliche Substanzen verursachte Bodenverschmutzung, Wasserverschmutzung, wie auch Energieabhängigkeit, begrenzte Energieträger, Zentralisierung von Energieträgern usw., basiert die primäre Energieerzeugung immer noch an fossilen Energiestoffen. Das Ziel dieser Forschung ist es die Integration von erneuerbarer Energie in unterschiedlichen Prozessen mit Wärmebedarf zu unterstützen. Im Mittelpunkt steht der Gebrauch von Solar Thermal Energie, deren Integration (vor allem im Bezug auf die Solarenergieträger wie z.B. der Strom) das Thema zahlreicher Studien war. Viel weniger dagegen wurde über die Integration von Solar Thermal Energie geschrieben. Das Ziel dieser Studie ist es diese Lücke zu fällen. Zu diesem Zweck wurde ein Mehrperiodenmodel mit angenommen konstanten Angeboten und Nachfragen erstellt. Die Integration von Solar- und Thermalenergie verlangte folgendes:

1. Die Erschaffung von kombinierten Zeitscheiben für die Integration von Solar Thermal Energie. Die Integration von Solar Thermal Energie tretet binnen jeder Zeitscheibe getrennt auf. Die Menge von Zeitscheiben wurde bei Angebot und Nachfrage möglichst reduziert, um so die Komplexität der Integration zu verringern. Das sollte allerdings nur mit großer Vorsicht ausgeübt werden, denn die Verringerung von Zeitscheiben kann zu einer niedrigeren Modelgenauigkeit führen. Demzufolge wurde ein gemischtes ganzzahliges lineares Model entwickelt, das an einem „Trade-off“ zwischen der Zeitscheibenmenge und Ungenauigkeit basiert.

2. Versicherung einer durchführbaren Integration der Solar Thermal Energie. Nach Festlegung der richtigen Menge von Zeitscheiben wird der Focus auf die durchführbare Wärmeintegration übertragen. Die treibende Wärmekraft tauscht den passenden Temperaturunterschied aus; dieser hängt von i) dem benötigten minimalen Temperaturunterschied und ii) der Korrelation der Wärmekapazität-Durchflussmenge der zwei Strömungen, zwischen denen der Wärmeaustausch stattfindet, ab. Um einen durchführbaren Wärmeaustausch zu verschaffen, wurden die minimale festgenommene Temperaturkurve (MCTC) und ihr Algorithmus entwickelt.

3. Einschätzung der Größe des Lagerungs- und Sonnenkollektorgebiets. Für die Einschätzung des gesamten Integrationssystems für Solar Thermal Energie soll man die Größe der Lagerungs- und Sonnenkollektorflächen festlegen. Die Größe der Sonnenkollektoren und

Solarpanelle legt man anhand der Sonnen- und Schattentage fest. Diese Maßzahl wird dann für die Festlegung der Solarpanelfläche verwendet. Dabei wird die Grüße der Solarpanelle, deren Energie für einen Tag ausreicht, mit dieser Maßzahl multipliziert um die Gesamtanzahl aller Tage festzulegen. Die Größe des Lagerungsgebiets hängt aber von der Wärmemenge ab; diese wird als Summe der Schattentage, des Energiebedarfs für eine Nacht und der Wärmeverluste festgelegt. Durch die Festlegung der Größe der Sonnenkollektor- und Solarpanelflächen kann man eine Analyse des Integrationssytems der Solar- und Thermalenergie für die Integrierung von Solarenergie vorzeitig vorbereiten.

4. Das Model für die kurzfristige Einschätzung der integrierten Menge von Solar Thermal Energie. Die Voranalyse für die Einschätzung des Integrationssystems der Solar Thermal Energie basiert auf dem Durchschnittswert der Sonneneinstrahlung und des wahrscheinlichsten Wärmebedarfs beim Prozess. Während das Integrationssystem läuft, können die Belastungen bei Angebot und Nachfrage wesentlich von dem angesagten und in der Anfangsphase vorhergesehenen Durchschnittswert abweichen. Die tatsächliche Leistungsfrist des Systems sollte überwacht und für kurzfristige Einschätzungen verwendet werden. Für diesen Zweck wurde ein besonderes Model erschaffen, das bei Anwendung die Austrittstemperatur der Stromabnehmer, die Aufbewahrungstemperatur auf beiden Enden jeder Zeitscheibe und die Wärmemenge bei beiden Wärmeaustauschen festlegen kann.

# 1 Introduction

Nowadays, primary energy production is mainly based on fossil energy sources as the oil share of global energy consumption in 2011 was 33.1 %, the share of coal 30.3 % and that of natural gas 23.7 %, which altogether represents 87.1 % (BP, 2012). The utilisation of fossil fuels have many negative impacts which are manifold: (i) on the environment: air pollution, depletion of the ozone layer, excessive soil erosion and its pollution by various substances, water pollution etc., and (ii) also on the economy: energy dependence, limited sources of energy, centralisation of energy sources. For example in 2011 the Middle East held 48.1 % of the proven global reserves of oil (BP, 2012). For natural gas the Middle East held 38.4 % while Europe and Eurasia 37.8 % of the proven reserves. Most of the proven reserves of coal were held by Europe and Eurasia (35.4 %). Additionally, the energy demand was increasing, in the year 2011 2.5 % was the energy growth regarding world primary energy consumption (BP, 2012). Therefore, the consequences of utilising fossil fuel might have led to a socio-economic crisis of because of an unreliable supply of energy, with high environmental impact, which would consequently have also seriously affected human beings. Certain urgent actions to reduce fossil fuel consumption had already been performed in the past. Firstly, and the most valuable approach, had been increasing the efficiency of energy consumption, as it also reduces the impact. However, despite the enormous development of methodologies for reducing energy consumption, the population on the earth is constantly growing therefore the energy demand is still also growing. It can be observed from the following data that the primary energy consumption has grown in OECD countries by 0.8 %, whilst in the non-OECD countries by 5.3 % (BP, 2012). Additionally, the people from developing countries are also increasing their consumption per capita. All these observations have led to the conclusion that other sources of energy are needed in order to cover the energy consumption within an environmentally friendlier way. Alternative options, which are becoming reality, are the renewable sources of energy. However, their share in global energy consumption is still quite low, 1.6 % in 2011 (BP, 2012). The two targets set by Directive 2009/28/EC for achievement by 2020 in the EU are the following: 20% share of energy from renewable sources, and a 10% share of energy from renewable sources for transport regarding Community energy consumption (EC, 2009). IEA is predicting a share of renewables in the world energy mix of almost one-third by the year 2035 for electricity production (IEA, 2012). According to the definition of the Texas Renewable Energy Industries Association –TREIA renewable energy is "Any energy resource that is naturally regenerated over a short time-scale and derived directly from the sun (such as thermal, photochemical, and photoelectric), indirectly from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). Renewable energy does not include energy resources derived from fossil fuels, waste products from fossil sources, or waste products from inorganic sources." (TREIA, 2013). A simpler definition of renewable sources is that they are energy sources that can be easily and quickly replenished, therefore they have unlimited supply.

Their main advantages are:

- Sustainability, as long as the sun is available,
- Usually decreased environmental impact when utilising them,
- Local availability, thus resulting in energy independence, and
- Low costs or even free regarding the sources.

There are many different sources with their own specific properties. The more common sources are biomass, solar, wind, and geothermal. These energy sources are highlighted briefly in the following section 2. Literature review.

## 1.1 Problem statement

The wind and solar sources of energy are types of renewable sources, which are available almost everywhere all around the world. However, when integrating them they have an important property of a significantly varying supply that needs to be taken into account.

Therefore, a methodology is needed that accounts for these variations. In order to overcome them either energy storage or connection within a larger scale grid needs to be established. In this presented thesis the focus is on the solar source of energy. It is a source of energy the utilisation of which is growing more rapidly than any other renewable energy source (IEA, 2012). There are two common ways of obtaining energy from the solar source namely:

(i) Power using photovoltaic (PV) cells

(ii) Heat using thermal collectors

On the smaller scale (in residential areas) heat is usually produced while on a larger scale (in industry) PV is the common solution. Significant differences can be observed, when comparing the efficiencies of the diverse systems. The efficiencies of PV panels are usually within the range of 12 – 18 %, whilst thermal collectors' efficiencies are within the range of 45 – 60 %. As the efficiency of the heat collection system is triple that of PV panels, utilisation of thermal collectors within large-scale industrial plants would be a more efficient solution. However, the complexity of the problem is higher when producing thermal energy.

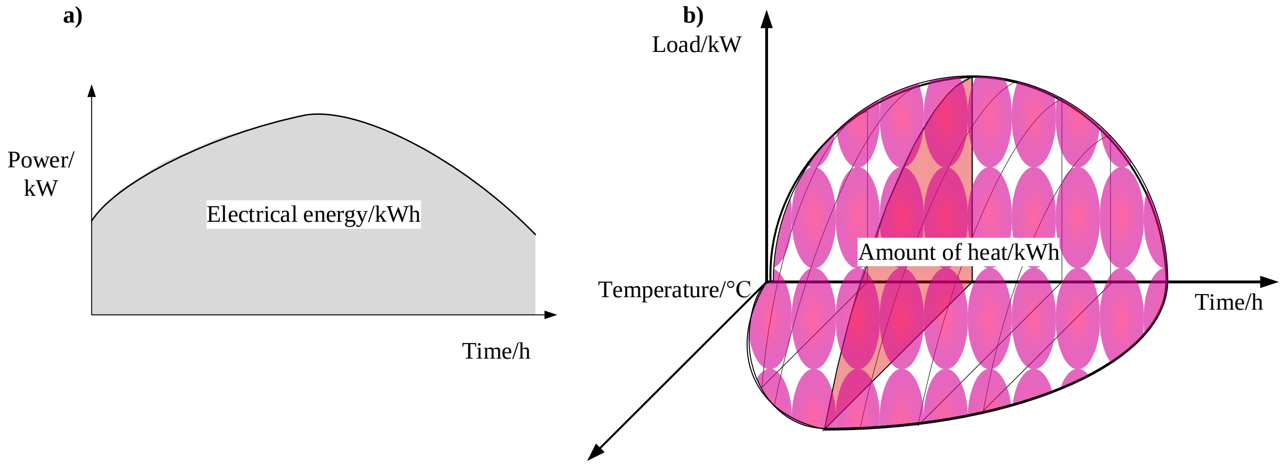


*Figure 1: Dimensionality of the integration of a) the power from solar source and b) the Solar Thermal Energy*

The power supply from PV panels can be described as having two variables: power and time (Figure 1a). For comparison, when supplying heat the problem can be presented as having three variables: time, temperature, and load (Figure 1b). Despite the complexity of the problem, installing solar thermal collectors might also be a better option for the larger-scale however, a proper design is inevitable for obtaining reliable and economically-viable utility supplies

## 1.2 Research objective

The objective of this research was to develop a methodology that would provide for the integration of Solar Thermal Energy within processes regarding heat demand. An important view of this integration was to consider the available energy and the heat requirements simultaneously. The integration of renewables into a process system or another energy use needs a specific approach due to variations in energy supply availability from renewable sources, as well as fluctuations in the users' energy demands. Two approaches were possible for this purpose:

i. A dynamic model formulation, followed by dynamic optimisation.
ii. A multi-period model involving a series of steady states associated with time intervals within the modelling horizon.

The advantage of dynamic models is that they describe the systems' behaviour very precisely. They are usually employed for solving servo- and regulatory tasks during process control. There are dynamic models that describe those plants using Solar Thermal Energy as a utility (Chaabene and Annabi, 1998). However, dynamics models are often too complex for solving larger scale problems so this work applied a multi period steady-state model. A high number of periods are applied during this approach therefore its horizon is short enough for a steady state to be assumed with insignificant error. This approach was thus applied when obtaining the design for the presented Solar Thermal Energy system. There were two main aims set by this thesis. The first one was to determine a thermodynamically feasible design with minimum utility requirement, besides Solar Thermal Energy. This aim was important during decision-making about the system before it was constructed. The second aim was to develop a method for the monitoring and short-term estimation of integrated amount of solar thermal energy based on a weather forecast, which is usually quite reliable for a couple of days in advance. This aim when achieved could support decision-making during the operation of the system.

## 1.3 Methodology and research strategy

An analogy from batch process integration was used for the integration of solar irradiation. The Heat Integration of batch processes is a well described field of research that uses steady-state. During batch processes, energy demands vary over time. In order to account for these variations Batch Process Integration was initiated by Kemp and Deakin (1989), who developed two models:

(i) Time Average Model, where the heat loads are averaged through the time horizon, and
(ii) Time Slice Model, where the Time Slices can be obtained by combining the starting and ending time points when the involved process streams are present.

Within these Time Slices the Heat Integration can be performed in the same manner as for the continuous processes. The analogy is done by applying the Time Slice Model (TSM). However, in the case of solar irradiation there is no time starting and ending time of the stream, instead the profile is increasing or decreasing continuously.

A somewhat different approach was developed. Firstly, Time Slices (TiSl) had to be obtained for the supply having an assumed constant load. A mixed-integer linear programming (MILP) model was developed for this purpose. It had a multi-objective optimisation, with two objectives - to minimise:

(i) The number of TiSl.
(ii) The inaccuracy.

It could be created either by two-stage optimisation or by combining within one-stage optimisation as well. When the TiSl for the supply side is obtained the TiSl from the demand side has to be determined. This is done similarly to Batch Process Integration by applying the starting and ending times of the streams present. When the Time Slices from the supply and demand sides are set, they have to be combined. After obtaining Combined Time Sliced (cTiSl) an inevitable part of methodology is to obtain feasible integration of solar thermal energy within each TiSl separately. Two major properties have to be evaluated for this purpose:

(i) The temperature difference.

(ii) The heat capacity flow-rate.

The following step was to estimate the required minimal storage size and the minimum solar collector area requirement. A more complete design can be obtain by making these estimations.

On average irradiation curves are applied when creating a design for the integration system of Solar Thermal Energy. However, in reality greater deviation from average values is possible. Therefore, a methodology for analysing the integrated amount of solar thermal energy based on real-time forecast should be performed, in order to forecast the external utility consumption for a couple of days in advance. The evaluation of the integrated amount of solar thermal heat and the performance of the integrated system could be monitored in this way. A basic model for short-term evaluation was developed based on the heat balances of the integration system.

## 1.4 Outline of the Thesis

This thesis has been constructed in such a way as to present each important step of the methodology separately. In Section 2 – Literature reviews the more common renewable energy sources and their properties with special emphasis on solar thermal energy. The following Sections 3-5 are dedicated to the presentation of our own developed methodology for integrating solar thermal energy before operating the system. Section 6 contains a case study putting the previously developed methodology into practise. Figure 2 presents each important step of the methodology within each section for integrating solar thermal energy together where each step is described individually. The first important step of the methodology is the cTiSl, described in Section 3, obtained from the supply and demand side within which the steady state might be assumed. After obtaining cTiSl the integration of Solar Thermal Energy is performed for which the ground is set in Section 4. For this purpose the temperature and heat capacity flow-rates should be evaluated in order to ensure feasible heat exchange. After obtaining the feasible heat exchange and therefore successful integration of solar thermal energy, the third important design aspect of the system is its storage size and the solar collector area requirement. This issue is discussed in Section 5. As the investment and maintenance of the storage are directly proportional to the storage size, it should be as minimal as possible, however still allowing the required capacity. After all the theoretical ground has been presented in detail, a case study is performed, in order to present the methodology application of the developed methodology. This case study is based on a real case taken from the literature and is presented in Section 6. Section 7 includes the model developed for evaluating the system's performance during the operation. It contains monitoring the outlet temperature of the collector, the storage temperature at the end of the time interval and the actually integrated amount of solar thermal energy. The subsequent section 8 contains the nomenclature of symbols used in the thesis. The summary is included in Section 9. The last section contains the reference list.

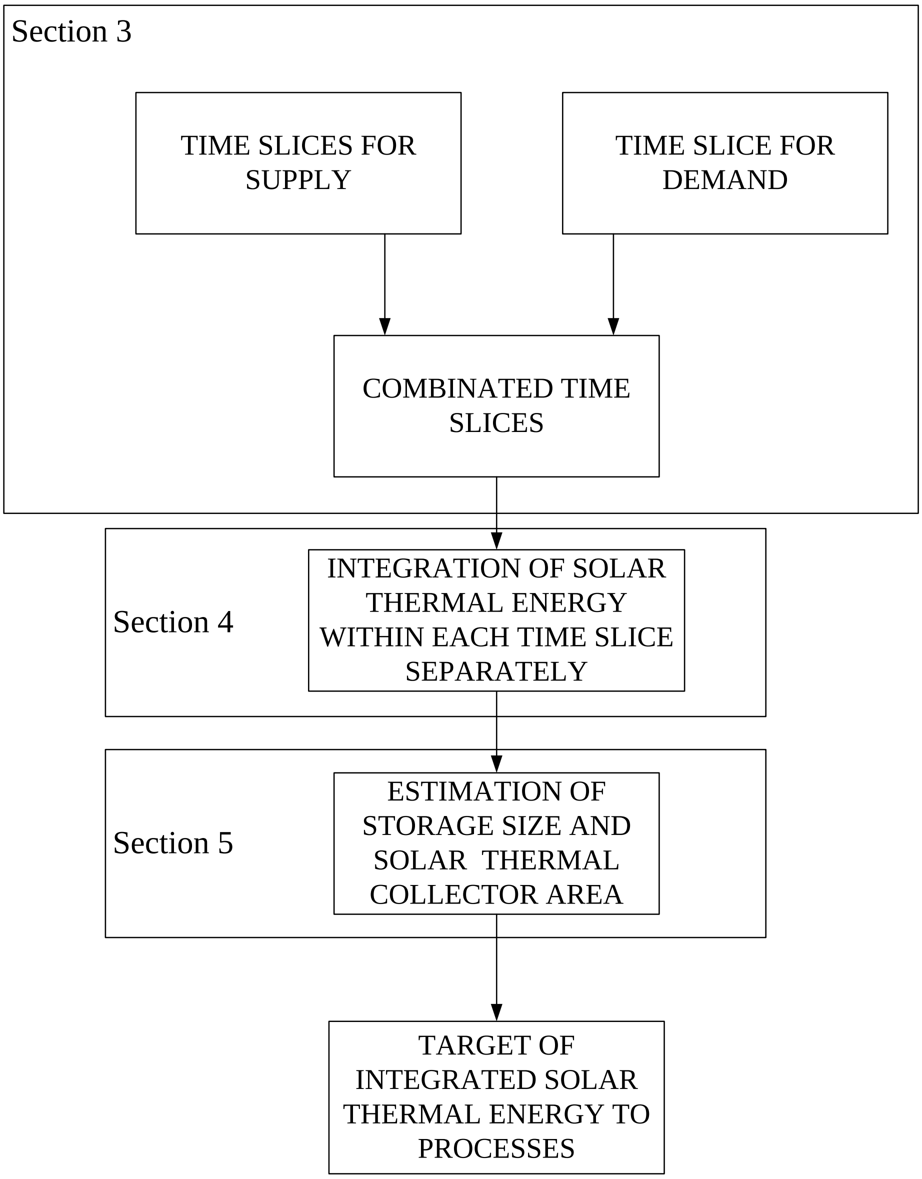


*Figure 2: Steps of solar thermal energy integration to processes with heat demand and its presentation in the Thesis*

# 2 Literature review

This section presents the more common renewable energy sources - biomass, wind, geothermal and solar sources of energy. Additionally, a non-renewable energy source ‘waste’ is presented as a source of energy as waste production is also increasing and has significant impact on the environment. Waste-to-energy technologies have a double positive effect: (i) reducing the amount of waste for landfilling and (ii) producing energy.

The advantages of utilising renewable sources of energy are numerous: they are sustainable, considered to be virtually inexhaustible, usually have low environmental impact, and support energy independence due to local availability, etc. However, all renewable energy sources have their own disadvantages. The common property of biomass and waste is their low energy density therefore; transportation has to be conducted carefully. The technologies for organic waste treatment and biomass are presented within the same section as the basic methodologies of those processes that are similar for both energy sources. The following source of energy discussed is the geothermal source of energy. The main weakness of this energy source is the local availability of it and its remote source points from the actual energy utilisation point. After presenting those sources that have mainly constant availability, the overview focuses on the wind and solar sources of energy that have varying availabilities. The fluctuating properties of the wind and solar sources of energy require special attention when designing a system for integrating energy from those sources to a utility system. An overview of the main advantages and disadvantages of renewable energy is presented in Table 1.

*Table 1: Advantages and Disadvantages of renewable energy sources*

| Energy source | Advantages | Disadvantages |
|---|---|---|
| **biomass** | • Unless direct combustion, there is minimal environmental impact<br>• Fuels produced by biomass are efficient, viable, and relatively clean-burning<br>• Widely available in some regions<br>• Agriculture wastes – added- value to agricultural crops. | • Low density of energy- high transportation cost- high emission into the environment<br>• Competition between areas for food and energy production<br>• Contribute to global warming and particulate pollution if directly burned |

| | | |
|---|---|---|
| | | • On a smaller scale - likely a net loss of energy |
| **Waste** | • Double benefit: reducing the landfilled waste and simultaneous production of energy<br>• Concentrates hazardous substances to ash for burial<br>• Proper control can reduce air pollution<br>• Potential to recover and sell metals and other raw materials | • High Capital cost: it costs more than short-distance transport to be landfilled<br>• Some air pollution and $CO_2$ emissions<br>• Output approach, which encourages waste production<br>• Can compete with recycling for burnable materials such as newspapers<br>• The public acceptance is poor |
| **Geothermal source** | • Energy costs may be lower when compared to many other energy sources.<br>• Low environmental impact when using geothermal.<br>• Geothermal heat pump systems can reduce energy use by storing heat from the summer/sun and making use of it during the nights and the winter. Low maintenance systems. | • Localised Depletion: should never be transported over longer distances.<br>• The heat source is mostly close to volcanic activity of some sort<br>• High Cost<br>- Drilling and exploration<br>- Corrosion and fouling maintenance can outweigh benefit |
| **wind** | • Less space required compared to an average power station.<br>• Wind turbines can be a range of different sizes<br>• When combined with solar electricity provides a steady, reliable supply of electricity. | • Unreliability factor; in many area winds' strengths are too low<br>• Wind turbines generally produce less electricity than the average fossil-fuelled power station<br>• Wind turbine construction can be very expensive<br>• The noise pollution from commercial wind turbines<br>• Protests and/or petitions usually confront any proposed wind farm development |
| **Solar** | • Good for remote applicants e.g. | • Currently, electricity from PV |

| | | |
|---|---|---|
| | rural hospital equipment in developing countries<br>• On the spot source of energy, no transportation costs<br>• The sources are free<br>• Can provide energy independence | systems is more expensive than electricity produced from fossil fuel<br>• Expensive equipment<br>• Requires engineering expertise to design and install<br>• Large areas needed to produce sufficient amounts of energy<br>• Sunlight is never constant, thus varying availability of supply: additional sources of energy and/or storage are required |

## 2.1 Waste and Biomass

Wastes are very heterogeneous materials therefore different classifications of wastes have been performed in several different ways. Some ways of classification are directly included within legislation (such as distinguishing between hazardous and other waste), other classifications correspond to the intentions the waste is to be used. As an example of purpose classification one can list the classification of municipal waste according to Speight (2008) or industrial waste classification according to Lee and Byeon (2009) created when conducting a study for South Korea. Amongst the basic possibilities of waste classification can be included the classification according to (Tabasová et al., 2012):

- State of matter
- Hazard
- Resource category
- Thermal decomposition

Utilisation of waste is divided into several groups based on whether the waste is only incinerated or a fuel, for later utilisation or is produced. The production of fuel from waste can take place either by thermal decomposition (gasification, pyrolysis, and hydrolysis) or by biological processes (anaerobic digestion, fermentation), as presented in Figure 3.

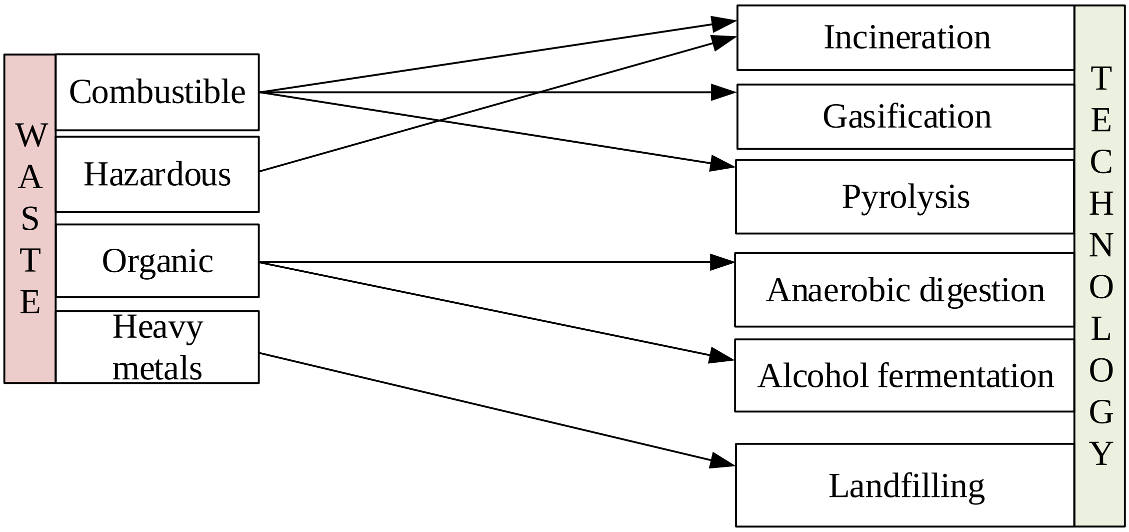


*Figure 3: Types of waste and available technologies for treatment*

### *2.1.1 Thermo – chemical technologies*

The benefits of applying thermo-chemical treatment of the waste are the lower volume and the utilisation of chemically bonded energy within the waste. Chemically bonded energy can be converted into heat and/or electric power and for producing alternative fuels. Another reason for applying incineration is the destruction of hazardous matters that can represent significant environmental and public health risks. It is necessary to take into account that thermal processing (treatment) of waste can also bring negative impacts in the form of possibly generating emissions of contaminants in flue gas; the presence of hazardous substances in the ash, pollution of water used in particular technological points of the incineration equipment etc.

The legal requirements on equipment for the thermal processing of waste are constantly being tightening up. It is for this reason that development of technologies used within units for the thermal processing of waste has gone through rapid development over last few years. The incineration process involves the burning of combustible materials in the presence of an oxidizer. This process converts the waste to flue gas, heat, metal, and ash. Flue gas is a mixture of N, $O_2$, water vapour and $CO_2$. Within its contents are sulphur oxides, nitrogen oxides and mineral acids (hydrochloric acid). This gas could be usable directly as a heat source or within a steam turbine for producing electricity or a combination of both. The incineration of waste is one of the more widespread technologies for the thermal processing of waste. Its benefit is that it can be applied to various types of waste (C-Tech Innovation, 2003). The process of incineration needs a surplus of oxygen (complete oxidation). When applying this process it is possible to reduce its initial volume by 90 % and its weight by 75 % when incinerating solid municipal waste.

The main stages of the incineration process (C-Tech Innovation, 2003):

1. Drying and degassing
2. Pyrolysis and gasification
3. Oxidation

Currently there are two of the more common types of incineration design, namely the incineration of municipal solid waste or hazardous and industrial wastes, however there are also plenty of specialised units. They are e.g. incineration plants for industrial sediments, those for pulp and paper production (Oral et al, 2005). Incineration of cleaning plants' sediments takes place in multiple hearth combustion chambers with fluidised beds. Coal firing is also used within grated combustion systems that burn coal during industrial processes. Sewage sludge often contains high content of water and requires drying or the addition of additional fuel to ensure stable and effective combustion (Oral et al, 2005).

Gasification is often defined as the partial oxidation of waste in the presence of an oxidant amount lower than the required stoichiometric combustion. In contrast pyrolysis is carried out in the absence of oxidant. It is a process of decomposition of the waste. The product of both gasification and pyrolysis is the syngas. This is mainly a mixture of $H_2$ and CO, but it contains other gases too. There are different types of gasification. Plasma arc gasification is a well-known type. Plasma is a gas of which at least some percentage of its atoms or molecules has been partially or totally ionised. This is achieved by an electric arc created by high voltage between two spaced apart electrodes. An inert gas passes through the arc to the waste.

Another type of gasification is supercritical water gasification (SCWG). During this process biomass is converted to hydrogen-rich gaseous products. A lesser known technology is also the "fast" pyrolysis of waste cooking oil (WCO), waste lubricant oil (WLO) and waste plastics (WP), off which a large amount is generated. Singhabhandhu and Tezuka (2010) investigated the pyrolysis of the mentioned wastes and their mixtures by comparing their cost–benefits, scales and sensitivities. They concluded that an integrated co-processing of WCO, WLO and WP to produce pyrolytic oil would be a profitable alternative in comparison with the usual practices of waste management. During a sensitivity analyses they also discovered no effect on the benefit-cost ratio at increased electricity costs. The ratio was no worse, not even in the case of a 100 % increase in transport costs.

The operational concepts of equipment for the thermal processing of waste are generally the same. Incineration plants consist of the thermal part, heat recovery block, and a system for the cleaning of generated flue gas. The process usually contains storage, equipment for the manipulation and preparation of waste, and equipment for processing solid and liquid products during incineration, (Stehlík, 2009). The aim of the designers of current technologies is to substitute a major part of the energy imported into technology with produced heat and electricity. Energies from outer networks are only used for starting and shutting down the incineration plant, or in emergencies. Cogeneration systems are especially suitable for this approach, when technology itself covers its own consumption of power along with steam production.

The performances of incineration plants in the EU must follow the best available technologies (BAT) according to the referential documents of the BAT methodology released by the EC. BAT for waste incineration (EC, 2006) deals directly with the incineration of waste. During the first stage of incineration (thermal block) the thermal decomposition of flammable parts of waste occurs, releasing almost all the heat contained within the combustible part of the waste. It takes place in combustion chambers with moving grates, rotary kilns, and additionally incineration within a fluidised bed may be used. Some preliminary modification or waste separation is necessary in order to meet the particle size requirement for the MSW incineration.

Incinerations of the MSW on the grate and the modelling of this process were investigated by Asthana et al. (2010). The thermal decomposition process and oxidation of combustible substances is finished in the burning-out part – secondary combustion chamber (SCC) that constitutes the second combustion stage. A proper construction of the device ensures necessary time for the flue gas to remain within the areas of high temperatures for the decomposition of even the more stable compounds within the flue gas. The walls of the secondary combustion chamber often have a built-in tubular heat exchange system from the evaporating part of the boiler, which connects the thermal block with the released heat utilisation system (Jegla et al., 2010). Recirculation of a share of flue gas from the end of the flue gas pathway back into the thermal block is often technologically favourable but there are also opinions against this solution (Liuzzo et al., 2007).The flue gas is then led into the released heat utilisation block and into the flue gas cleaning system.

In order to minimise the environmental impact, it is crucial to overview the emissions and effluents that can appear in each of the technologies. This section provides an overview of the emissions and effluents of the thermo chemical WTE technologies (Figure 4); including the latest development/research regarding cleaning.

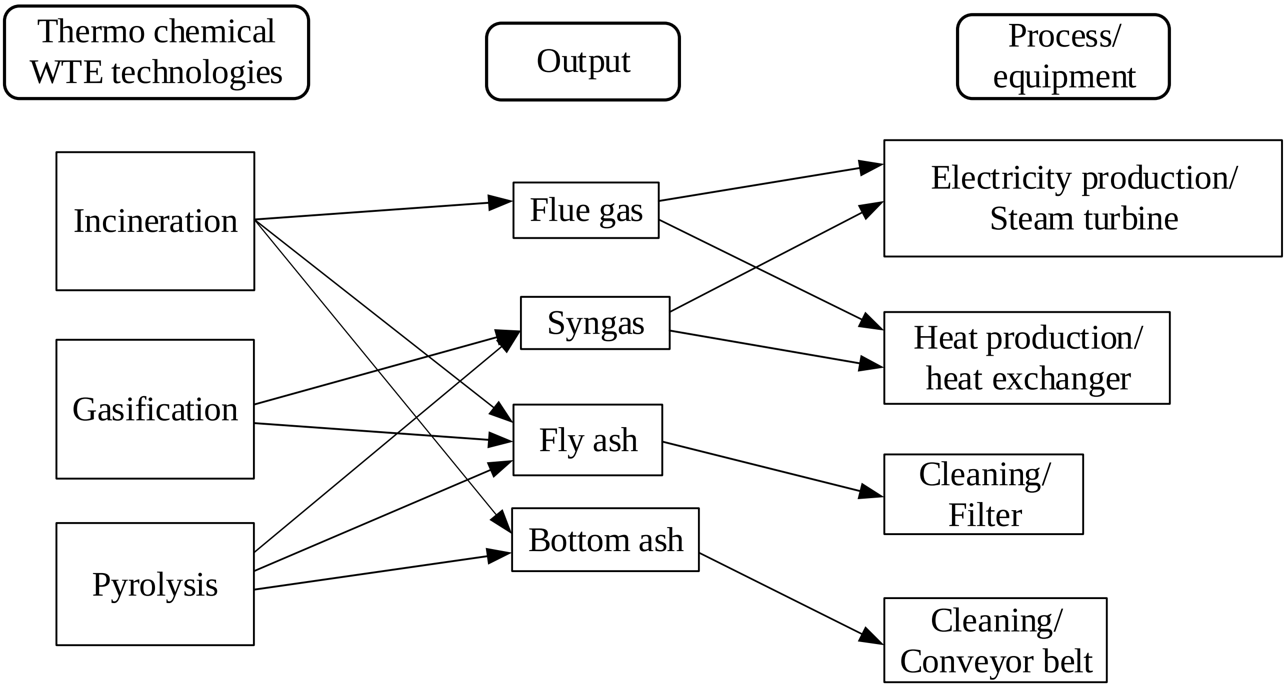


*Figure 4: Outputs and their treatment/ utilisation of thermo – chemical WTE processes*

*2.1.1.1 Off–gas treatment*

The major components of flue gas are nitrogen, oxygen, water vapour, and carbon dioxide. There are also small amounts of sulphur oxides, nitrogen oxides, and mineral acids (hydrochloric acid, when the PVC is combusted). If the combustion is incomplete the flue gases might contain significant amounts of carbon monoxide and unburned or partly burned organic materials; also polychlorinated dibenzo p –dioxin and dibenzo furan compounds of polyclinic organic matter, etc. can appear in the flue gases. The flue gas has to be cooled-down in general to 230 – 370 °C, if the flue gas is discharged to mechanical equipment. There are at four methods for cooling it down (Niessen, 2010):

(i) By water evaporation, introducing water into the hot gas stream and evaporation occurs.

(ii) By air dilution, where the hot flue gas is diluted by air.

(iii) By heat withdrawal, which uses a convection boiler where heat is removed by steam generation and

(iv) Steam plumes by adding water during wet scrubbing. As a result the flue gas leaving the stack could contain significant amounts of water vapour, which will condense under certain atmospheric conditions resulting in a steam plume.

*2.1.1.2 Fly ash treatment*

Fly ash is the fine ash that becomes airborne within the primary chamber and either settles in the ducts and devices of the incinerator or ultimately becomes an inlet loading of particulate matter. Fly ash includes those rejected constituents that have been volatilised at the high temperature zones of the furnace and condensed as particulate. It may contain heavy metals and high molecular weight hydrocarbons (Niessen, 2010).

In the paper of Huang et al. (2011), for each tonne of MSW incinerated within a mass burn unit, 15 – 40 kg of hazardous waste is created which requires further treatment and landfilling as hazardous waste. This waste is usually part of the flying ash. The more significant amounts of heavy metals present in fly ash are Pb and Zn, when the raw material is MSW. Other very toxic organic compounds can be found in residue traces, namely polycyclic aromatic hydrocarbons (PAH), chlorobenzenes (CB), polychlorinated biphenyls (PCB) and polychlorinated dibenzo-p-dioxins (PCDD) and furans (PCDF) (Huang, et al., 2011).

Mechanical cleaning of the flue gas with the aim of collecting the remaining particulates is performed in an Electro-Static Precipitator (ESP). Part of flue gas (off-gas in terms of incineration terminology) leaving this unit is recycled back to the combustion chamber and the remaining part enters the block of off-gas cleaning comprising a dioxin filter (DEDIOX®) and a wet scrubber. This is an important feature of up–to–date incinerators as recycling contributes to decreasing the exhaust emissions' amount. Based on the lower off–gas flow-rate, the size of the unit forming the final part of the off-gas cleaning system is lower as well.

There are at least four technologies applied for acid gas removal: Dry neutralisation with $Ca(OH)_2$ or with $NaHCO_3$, semi-dry neutralisation with milk of lime, and wet scrubbings. All these listed technologies are dry treatments and are unable to ensure pollutant concentrations smaller than the regulatory limits (European directive 2000/76/CE: 10 mg/Nm$^3$ HCl, 50 mg/ Nm$^3$ $SO_2$). Wet scrubbers are more powerful but they produce wastewater. Wet scrubbing plants are applied in downstream operations of dry neutralisation with $Ca(OH)_2$ in order to strongly reduce both the amount of acid gases and the wastewater production. The flue gas cleaning system can affect the plant's electrical efficiency because of the heat losses related to the liquid water within flue gas. The injection of liquid water is always present during semi-dry neutralisation. According to calculations this is one of the more disadvantageous technologies because drying leads to about 50 °C reduction in flue gas temperature (Grieco and Poggio, 2009).

In order to meet the regulatory requirements, the flue gas cleaning system needs to have been designed according to the specific environmental aspects of the plant. Dry ash for handling usually arrives along enclosed screw conveyors. These conveyors are low cost and efficient for handling the fine dust collected within the electrostatic precipitators (ESP) and bag housings (Niessen, 2010). The latest are a device for air pollution control that removes particulates from the air or gas released combustion for electricity generation.

#### *2.1.1.3 Bottom ash treatment*

Bottom ash is the non-combustible part of the waste that is a residue from incinerated waste. There are two systems for treating bottom ash. One is the wet system where the ash is immersed within water through the discharging end of the grate. The water quenches any burning materials and minimises the dusting. Water recovery is usually carried out by compression and passes up the discharge ramp. The final ash solid contains about 80 – 85 %. The second system is the dry system for bottom ash treatment. Quina et al. (2008) conducted an overview regarding municipal solid waste. A report was made concerning 11 municipal solid waste incinerators in England, where it could be seen that the bottom ash was around 25-30 % by weight of the waste put into incinerators. The production of bottom ash was approximately 300 kg of waste per tonne of MSW. In regard to animal waste treatment at temperatures of 400 – 900 °C, the ash yield was 25.3 – 20.7 % for the swine manure, 43.6 – 30.2 % for the layer manure, 34.3 – 32.1 % for the cattle manure, and 8.4 – 7.5 % for the cornstalk (Huang et al., 2011).

Münster and Mainborn (2011) performed an optimisation of investment and production within the energy system. Their conclusion was that the best economic performance is achieved when incineration is applied of mixed waste, anaerobic digestion of organic waste, and gasification of part of the refuse derived at fuel.

### ***2.1.2 Biological processes***

During bio–chemical processes certain types of microorganisms convert the organic matter into fuel and residue. The better known bio–chemical processes are:

(i) Anaerobic digestion and

(ii) Alcoholic fermentation and

(iii) Microbial fuel cells.

In the process of anaerobic digestion a set of micro-organisms convert the organic waste or biomass to biogas and solid residue. The main components of biogas are $CH_4$ and $CO_2$ but it also contains traces of hydrogen, ammonia, and carbon oxide. The solid residue can be used as fertiliser but other treatment, even WTE technologies, are also known.

Biogas is a mixture of methane (50 – 75 % vol), $CO_2$ (25 – 50 % vol) and other gases such as $N_2$, $O_2$, $H_2$, $NH_3$, $H_2S$ (<1 % vol ) (Goswami, 2008). The raw biogas requires cleaning. The more basic cleaning includes cooling and drying after production. Usually, it has to be cleaned in regard to the content of hydrogen sulphide ($H_2S$). The $H_2S$ content in biogas, at levels higher than 300 – 500 ppm, damages the energy conversion equipment. Today biological cleaning reduces the content of hydrogen sulphide to a level below 100 ppm (Holm-Nielsen et al., 2009).

Biogas can be utilised either raw or upgraded. There are several utilisation options:

(i) Production of heat and/or steam (the lowest value chain utilisation).

(ii) Electricity production with combined heat and power production (CHP).

(iii) Industrial energy source for heat, steam and/or electricity and cooling.

(iv) Upgraded and utilisation as vehicle fuel.

(v) Production of chemicals and/or proteins.

(vi) Upgrading and injection into the natural gas grids

(vii) Fuel for fuel cells.

A remarkable example of upgrading biogas and using it for vehicle fuel is in Sweden, where the market for such biogas utilisation has grown rapidly over the last decade. There were 15,000 vehicles driven in 2009 on upgraded biogas in Sweden, and the forecast is of 70,000 vehicles, running on biogas supplied from 500 filling stations, by the years 2010 – 2012. As biogas cannot always be used near production facilities and within farming areas, injecting upgraded biogas into the natural gas grids widens up the opportunities for transporting and utilising biogas within the larger energy consumption areas, where the population concentration is situated.

Biodegradable wastes contain carbohydrates that could be converted into sugar. Fermentation is an anaerobic procedure, where the microorganisms, mainly yeast, convert the sugar into alcohol called bioethanol which is used as fuel. Bioethanol can be used as vehicle fuel as a 5 % blend with petrol, which does not requires engine modification. With engine modification a bioethanol can be used at higher levels, for instance 85 % of bioethanol (Demirbas, 2007).

The biodiesel is based on vegetable oil and animal fat and is an alkyl (methyl, ethyl, propyl) ester. It can be used itself as a fuel, or in a mixture with petroleum–based diesel in different ratios. There are some concerns that raw materials for biodiesel production may compete with food production, for this reason the best option is to use the waste raw materials as food residues for biodiesel production (Demirbas, 2011).

The biodegradable waste contains carbohydrates that can be converted into sugar. Fermentation is an anaerobic procedure where the microorganisms, mainly yeast, convert the sugar into alcohol called bioethanol and used as a fuel.

In microbial fuel cells microorganisms convert acetic acid to $CO_2$, protons and electrons on the anodes of the cell. Acetic acid is a product of waste fermentation. Protons and electrons form hydrogen on the cathode side of the fuel that is then used as cleaner fuel for vehicles. The anode and cathode are kept separate using an ion-exchange membrane.

An overview is presented in Figure 5 of the main bio-chemical WTE technologies, their outputs and their utilisation in the processes.

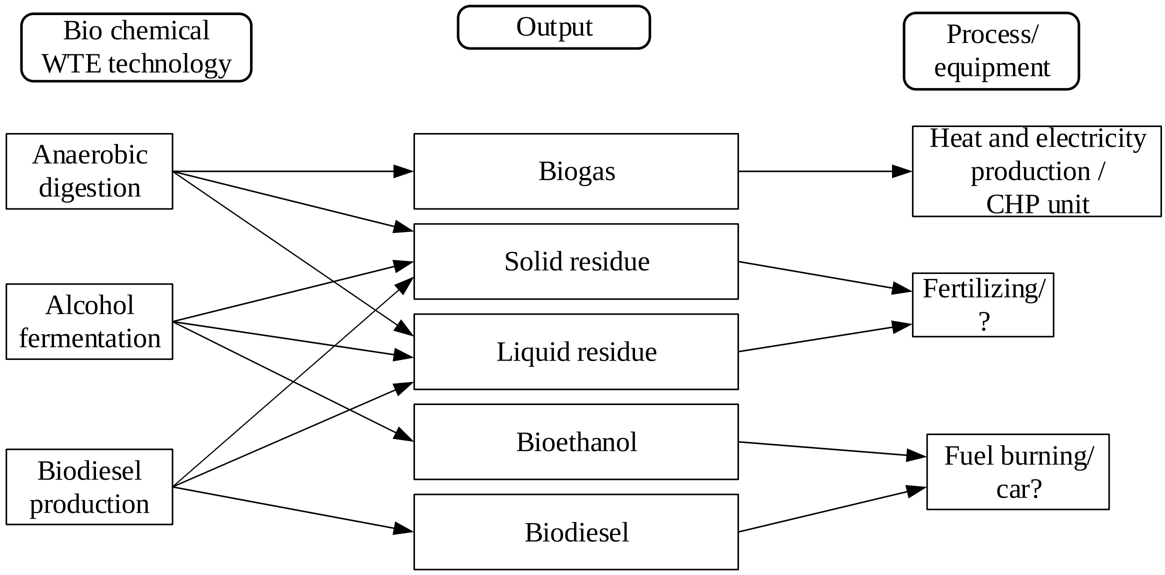


*Figure 5: Outputs and its treatment/ utilisation of bio–chemical WTE processes*

## 2.2 Geothermal Energy

A geothermal energy is the heat contained in the Earth's interior. Commonly, there are two types of well, the high-temperature (above 150 °C) and low- temperature (below 150 °C) (Barbier, 2002). The geothermal utilisation can be divided into two categories: (i) electric energy production and (ii) direct uses. Conventionally, the high temperature well is used for electric energy production, while from the low temperature well the heat is used directly. However, also an in-between solution can be obtained by applying organic Rankine cycle (this is a case, when the outlet temperature of the geothermal fluid is usually above 85 °C. An example of utilisation of Rankine cycle, combined with the gathering heat tracing (GHT) station and the oil recovery system when oil well are used as geothermal wells and geothermal power plants is presented by Li et al (2012). Applying this combined system 8,163 t of oil is saved and about 34,600 t/y of oil is recovered per year in a case study presented. Therefore, even when covering only part of the fuel needs a significant improvement by integration renewable energy sources might be obtained.

When developing generation of electricity from geothermal source, 50 % of total cost is related to identification and characterisation of reservoirs and mainly, to the drilling of production and reinjection wells, 40 % goes to power plants and pipelines and 10% to other activities (Barbier, 2002).

## 2.3 Wind

Although the simple wind devices are from ancient time the actual initial steps was made in 200 BC with the vertical axis windmills at the Persian-Afghan border. The following horizontal-axis windmills were based in Netherland and in the Mediterranean region much in later in 1300 – 1875 AD. After this improvement the development of the technology utilising wind source was performed in many different region in Europe as well as in USA (Kaldellis and Zafirakis, 2011). However, the first large scale wind energy penetration was in California of total 1.7 GW built during 1981 and 1990. Recently, the capacity of the wind power is growing rapidly e.g. in six years it quadrupled from 40 GW in 2003 to 160 GW in 2009 (Kaldellis and Zafirakis, 2011).

In the review of Australian wind industry the economic benefits of installing wind farm is presented (Gl Garrad Hassan pacific Pty Ltd, 2011). On local level the benefits are increased employment opportunities and additionally, the farmers that own land of where the wind farm is constructed can benefit substantially from the drought and flood-proof income stream offered by wind energy. The economic effect of constructing wind farm has impact not only direct employment but also the flow-on effect to the wider economy construction project and local retail and services related to the increase economic activity in the locality of the wind farm. Wider benefits are decreased greenhouse gas emissions. It also improves the security and diversity of energy system (Joselin Herbert et al., 2007).

## 2.4 Solar Energy

Compared to the annual worldwide energy consumption, $5.15 \cdot 10^{11}$ GJ (BP, 2012), a vast amount of solar energy reaches the surface of the planet, $2.7 \cdot 10^{15}$ GJ (Smil, 2006). Despite the enormous difference in magnitude, and a wide range of promising energy sectors (Schnitzer et al., 2007), only 0.13 % of the energy demands are covered from solar energy, which indicates the complexity of the integration of this type of renewable resource. An accelerating development of techniques, methodologies and equipment for exploiting solar energy has taken place, recently. An overview of a current state on solar collectors and thermal energy storage in solar thermal applications can be found in Tian et.al (2013). The new development helps to improve the existing technology. An example of this is a water desalination process with integrated solar energy (Gude et al, 2011). Müller et al (2014) presented an example of solar thermal heat utilisation in the case of liquid food industry. Their focus was on the development and optimisation of low-temperature heating systems, improving efficiency, waste heat recovery and the feasibility of a solar-thermal process heating system. Frein et al. (2014) presented a dynamic model for integration of solar thermal energy into the dyeing process of Benetton industrial facility in Tunisia. A good example of a process, where solar thermal and also electricity produced from solar source can be applied, is production of malt and beer at low temperature as presented by Mauthner et al. (2014).

A lot of attention towards the use of energy from solar source has focused on photovoltaic panels for producing electricity. There is also a significant potential for utilising solar irradiation as heat. Generally, thermal solar capture frequently offers a higher efficiency compared to photovoltaic panels.

There are several models estimating the solar irradiation (e.g. GeoModel Solar, 2013); however, only few models estimating the available solar thermal heat and available electricity (Erdil et al., 2008). Moreover, these models only evaluate a part of the whole capture system, for example, only thermal energy storage (Mawire et al., 2008). On the other hand, Ludig et al., (2011) modelled a power system model, where they investigated 14 different technologies for producing electricity. They evaluated optimal technology-mix from the viewpoint of cost. An interesting part of this work was how they dealt with the variations of renewable energy sources e.g. wind, hydro, solar. They created equal-length Time Slices and averaged the load of supply within the Time Slice.

The integration of solar thermal energy has a great potential in reducing other utilities, originating from fossil fuels, and their impact on environment, represented by footprints (De Benedetto and Klemeš, 2009). A usual problem with solar thermal energy capture is the relatively low temperature of the captured heat. However, there are still many processes with lower temperature heat requirements, especially in food industry as well as residential, service and business units. For instance, in food and drink industry there are many processes, which require heat below 80 °C – dairy plants usually need following hot streams:

- Bottle washing 60 °C
- Pasteurisation 70 °C
- Yogurt maturation 40 - 45 °C
- CIP (Cleaning-in-Place) 70 - 80 °C (Kane CRES, 2009).

One of the major difficulties for solar integration is the fluctuation and the disparateness of demands and the solar irradiation, i.e., the available solar energy (Atkins, et al., 2010). As a result, the estimation of solar irradiation has gained the focus of many researchers. Angelis-Dimakis et al. (2011) provided a detailed review of tools about the availability of different renewable energy resources. Based on these data, tools can be developed to exploit solar energy, that should be integrated as efficiently as possible (Pereira, 2009). Connolly et al. (2010) have provided a review of 37 tools comparing their availability, scenario time-frame, the considered energy sectors, and many other parameters. A combination of mathematical models and pinch analysis for integration of solar thermal energy in a tuna fish canning factory is presented by Quijera et al. (2014). Rodríguez-Hidalgo et al. (2014) developed an optimisation model for storage tank size and proved that it has a relevant impact on the solar plant performance.

Some process demands can be re-scheduled, this flexibility on the demand site has been considered by the former approaches (Varbanov and Klemeš, 2011), however, the methodology for optimal scheduling with the aim of minimising the fossil fuel consumption by rescheduling of the demand obtaining a better integration of energy from renewable energy sources has not yet been developed. Atkins et al. (2010) recently dealt with solar systems, which supplied portion of heat demand for a milk powder plant. It was designed for short-term variation. The focus was on the supply profile. They provided detailed evaluations of the performance of solar collectors and a precise supply profile. However, the relation between supply and demand still needs further investigation.

When analysing different forecast related to energy (e.g. IEA, 2012; BP, 2012) it can be concluded that all of them are forecasting the growth of world energy demand. The need of integrating renewable energy sources has become one of the promising solutions to cover at least part of the energy demand. According the targets set European Commission by 2050 the share of renewable energy sources should achieve 20 % of total (Directive 2009/28/EC). Nowadays, the energy management and integration of renewable sources are in the focus of number of researches for couple of reasons. The energy demand growing, limited amount of fossil fuel and the harmful emission when utilising fossil fuels are only few of them. The current work focuses on integration of solar thermal energy to processes with heat demand in an efficient way. The main drawback of the solar source of energy is the varying availability. Therefore, in this work the integration considering variation in solar thermal energy supply was developed.

# 3 Creating Combined Time Slices

A concept of Combined Time Slices (cTiSl) was developed in order to be able to perform the integration of solar thermal energy. These are periods in time, which are combined of TiSl from the supply and the demand side with assumed constant or linear load. The TiSl for the demand side are obtained similarly as for the batch processes by the starting and ending times of certain process or as a starting and ending of a significant change in load within certain process. The TiSl for solar thermal energy supply are obtained as result of a trade-off between the inaccuracy and number of TiSls, when assuming periods in time with constant load of supply. The inaccuracy of the approximation decreases with any increase in the number of TiSls. On the other hand, the aim is to minimise the number of TiSl, in order to simplify the computations in the following steps of the integration procedure.

## 3.1 Time Slice for supply

### ***3.1.1 Approximation of irradiation profile***

The solar irradiation ($G$) measurements or the temporal variation of the captured heat flow could be used in order to identify the TiSl for solar energy availability.

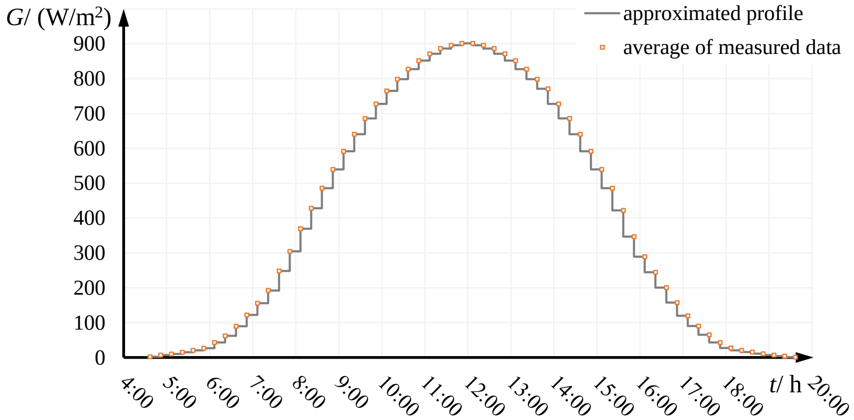


*Figure 6: Discretisation of the measured profile/ input data for optimising the number of Time Slices (Nemet, et al., 2012a)*

The procedure is based on optimising the load-levels and selecting items from a discrete superset of candidate time boundaries. These represent the measured Solar Irradiation – $G$ data by constructing a high-precision piecewise-constant profile (GeoModel Solar, 2013) (Figure 6).

Acceptability of the resulting TiSl and their properties varies from one system to another. It can be expressed as an acceptable inaccuracy-level of the energy systems' designers. A large number of time-intervals are used, therefore, the inaccuracy of this transformation is minimised and can be neglected. However, when applying this high-number of time intervals a computationally very intensive integration would be required, since the integration of solar thermal energy has to be performed within each time interval separately additionally to the heat recovery. Therefore, the piecewise–constant load profile, which would be obtained, has to contain a significantly smaller number of TiSl. This can be achieved by a suitable approximation of the irradiation profile. The irradiation is approximated separately within each time interval by the minimisation of any inaccuracy represented by those areas occurring between the approximated and real input-supply profiles (Figure 7).

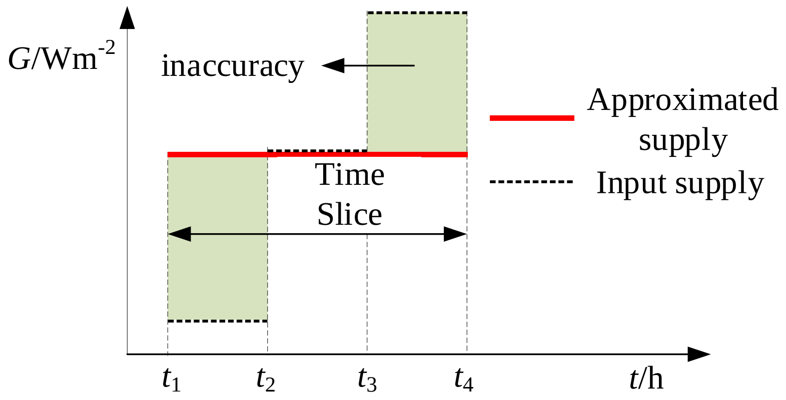


*Figure 7: Determining the inaccuracy between the input and approximated supply (Nemet, et al., 2012a)*

The boundaries of the time-intervals are the candidate boundaries for the final TiSls. If there is a difference between two consecutively approximated supply levels, the time-boundary is also a TiSl boundary. However, when two time-intervals are joined together to TiSl, the approximated supply-levels should be equal within both time intervals and the time-interval period boundary candidate is deselected as a TiSl boundary (Figure 8)

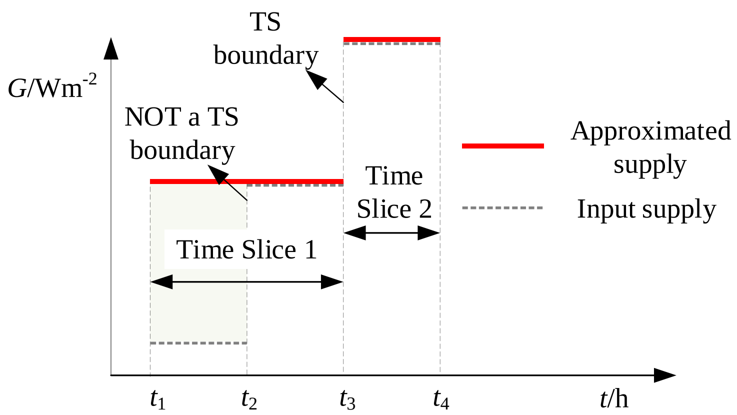


*Figure 8: Acceptance/ rejection of the candidate time interval boundary as a Time Slice boundary (Nemet, et al., 2012a)*

### *3.1.2 MILP model formulation*

A two-stage mixed-integer linear programming (MILP) model has been developed for minimising the number of TiSls at acceptable inaccuracy. At the first stage, the number of TiSls is minimised, depending on the tolerance of inaccuracy specified by the models' user. At the second stage, the inaccuracy is minimised at a fixed minimum number of TiSls, determined at the first optimisation stage.

Initially there is $N_I$ number of time intervals and, hence, $N_I + 1$ boundaries of time-intervals indexed by the following index and set:

- Index $i$ for the time-boundaries of the time-intervals, $i \in I$

The difference between the real input-supply and approximated-supply is calculated in each time interval separately:

$$SD_i = RS_i - AS_i \qquad \forall i \in I \qquad (1)$$

Since the difference $SD_i$ can have a positive or negative value, it can be represented as the difference between the positive variables $PD_i$ and $ND_i$:

$$SD_i = PD_i - ND_i \qquad \forall i \in I \qquad (2)$$

Note that when the $SD_i$ has a positive value $ND_i$ is zero, as a result of minimising the inaccuracy. When $SD_i$ has a negative value, then $PD_i$ is zero. For minimal inaccuracy the difference between the real and approximated supply should be the lowest possible.

$$ED_i = PD_i + ND_i \qquad \forall i \in I \qquad (3)$$

In Eq. 3 the positive value is obtained for the difference between real and approximated load of supply. Further equations are related to the acceptance or rejection of time interval boundary as a TiSl boundary. The decision is made by the binary variable $y_i$.

When there is a positive (Eq. 4) or negative difference (Eq. 5) between the two consecutively-approximated supply loads, there is a TiSl boundary and the value of $y_i$ is 1. If there is no difference between these supplies, there is no TiSl boundary and the value of $y_i$ is 0.

$$AS_{i+1} \leq AS_i + LV \cdot y_i \qquad \forall i \in I,\ i \neq N_I + 1 \qquad (4)$$

$$AS_{i+1} \geq AS_i - LV \cdot y_i \qquad \forall i \in I,\ i \neq N_I + 1 \qquad (5)$$

To present the selected TiSl boundaries the binary variable is multiplied with the observed time interval boundary:

$$TS_i = y_i \cdot t_{i+1} \qquad \forall i \in I,\ i \neq N_I + 1 \qquad (6)$$

The number of TiSl is obtained from Eq. 7. One is add to the sum of selected TiSl boundaries as the TiSl boundaries at the beginning and at the end of the observed time horizon were excluded within the model:

$$NTS = \sum_{i \in I, i \neq N_I + 1} y_i + 1 \tag{7}$$

The inaccuracy in each time interval is determined by multiplying the positive difference between the real and approximated supply with time horizon of the time interval.

$$IN_i = ED_i \cdot (t_i - t_{i-1}) \qquad \forall i \in I,\ i \neq N_I + 1 \tag{8}$$

The overall inaccuracy is a result of summation of inaccuracies over the time intervals:

$$INA = \sum_{i \in I, i \neq N_I + 1} IN_i \tag{9}$$

This overall inaccuracy is constrained and should be less than or equal to the $\varepsilon$ fraction of the initial amount of solar irradiation presented as an area ($A_0$) below the measured profile of Figure 6:

$$INA \leq \varepsilon \cdot A_0 \tag{10}$$

$$A_0 = \sum_{i \in I, i \neq N_I + 1} ((t_{i+1} - t_i) \cdot RS_i) \tag{11}$$

### 3.1.3 ***Optimisation procedure***

Optimisation is performed over two stages. In the first stage of optimisation, Eqs. 1-11 are used with the objective of minimising the number of TiSls as follows:

$$\min z_{\mathrm{I}} = NTS \tag{12}$$

This step requires specifying the acceptable tolerance $\varepsilon$. The result from optimisation is the minimal number of TiSls, min $NTS_I$ required to meet any constraint about the inaccuracy limit (Eq. 10). However, after the first stage, the inaccuracy is not optimal. In order to obtain a further reduction of inaccuracy, in the second stage of optimisation the same model using Eqs. 1 – 11 is used together with an additional equation (Eq. 13), which fixes the number of TiSls, and the objective is to minimise inaccuracy as expressed in Eq. 14:

$$NTS = \min NTS_I \tag{13}$$

$$\min z_{\mathrm{II}} = INA \tag{14}$$

Optimisation could also be performed over one stage as sometimes it is faster. In this case, the objective function would be a weighted sum of *NTS* and *INA* with a high enough weight *w* (e.g. 10,000) for *NTS*, in order that the minimised *NTS* has priority over the minimum of *INA*.

$$z = w \cdot NTS + INA \tag{15}$$

### 3.1.4 ***Selection of tolerance***

Selecting the number of TiSls depends on the accuracy required. Figure 9 presents the obtained results at different tolerances selected and optimised. As can be seen from Figure 9, by increasing the tolerance the number of TiSls decreases but, however, the inaccuracy becomes too high. On the other hand, if the tolerance is too small, the number of TiSls might become too high and consequently the further steps of integration would be too complex. However, no significant improvement can be

achieved.

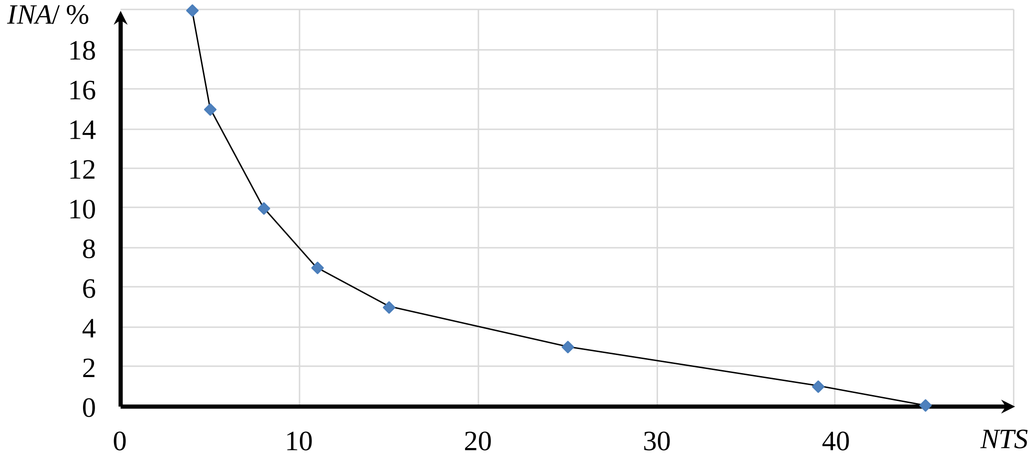


*Figure 9: Selecting an acceptable inaccuracy (Nemet, et al., 2012a)*

## 3.2 Time Slices for demand

In addition to varying availability of supply also the demand can vary. It could be a result of batch processes or different operating mode of the processes. Furthermore, if during the integration also the residential area is considered the heat consumption varies significantly.

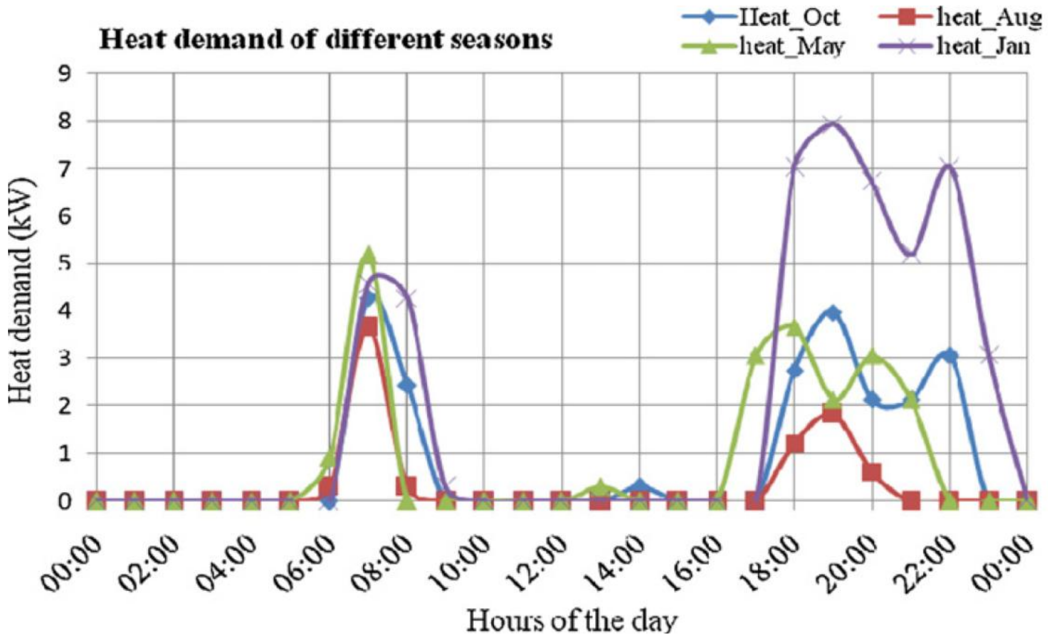

*Figure 10: Heat demand of a representative day from each season. (Shaneb et al., 2011)*

In the case of the varying demand curve as can be seen in Figure 10 the MILP model described in section 3.1.2 for obtaining the TiSl for solar thermal irradiation might be applied for this problem too. Since the model is simple enough applying it to supply and demand side would not increase the complexity of the problem considerably.

## 3.3 Combining Time Slices

When obtaining TiSls for both demand and supply side, a combination of these two types of TiSls should be performed. The combination procedure is presented in Figure 11. The TiSl boundaries for solar thermal energy and for those for varying process demands are joined together to the cTiSl boundaries. Observing this step of procedure it becomes evident how the increased number of TiSls contributes to the complexity of solving the problem. Each additional TiSl increase the complexity of the integration with an important weight.

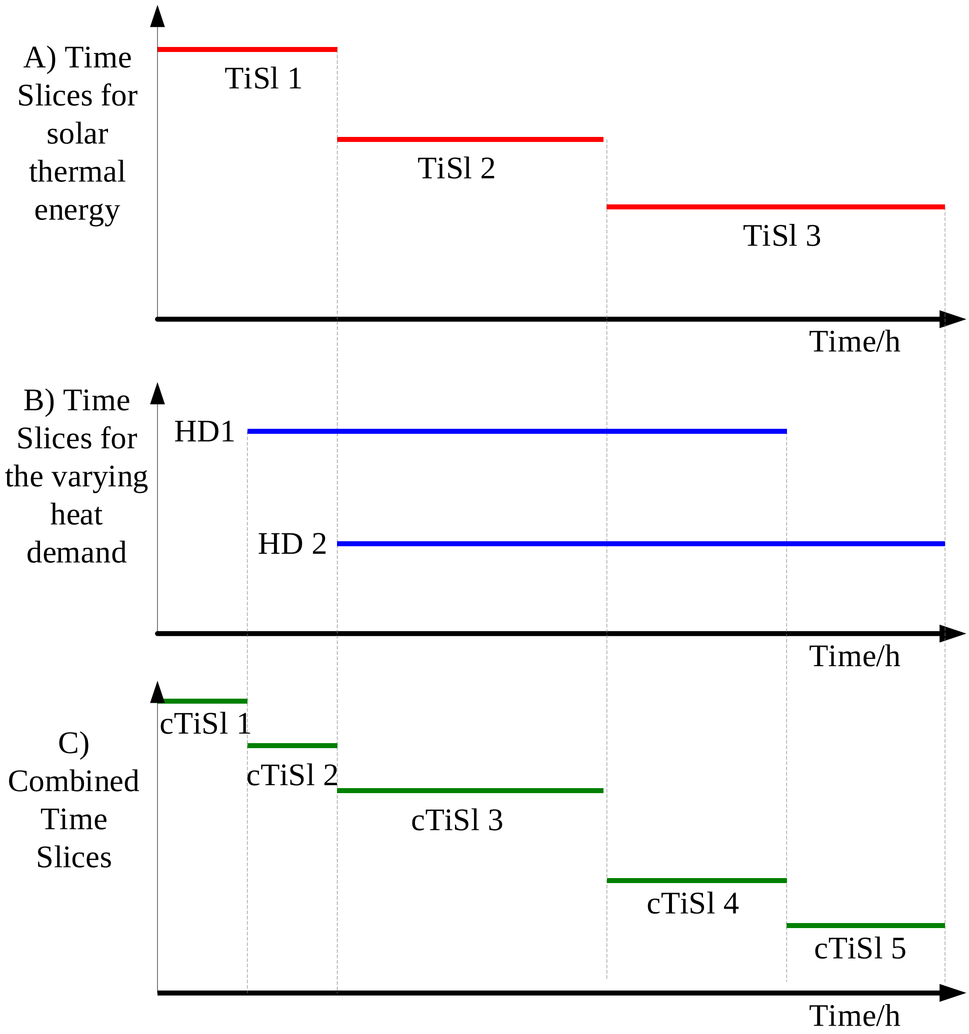


*Figure 11: Gantt chart for those TSs for supplying A) Solar thermal energy, B) Heat demand and*

*C) Combined for both (Nemet, et al., 2012a).*

## 3.4 Summary

This section evaluates one of the three variables needed for solar thermal energy integration, which is time. The result of approach applied are Time Slices, where the load can be assumed as constant, with as low inaccuracy as possible/ acceptable for the users. For this purposes a MILP model for obtaining Time Slice was presented. The model should be used for the solar irradiation profile, however if necessary also for the demand e.g. in the case of integration to residential area. In next step, the combination of the Time Slices from the demand and the supply side is performed.

# 4 Ensuring feasible integration of solar thermal energy

The evaluation of the feasible integration of solar thermal energy was performed by applying a well-developed area of Heat Integration.

## 4.1 Heat Integration

Heat Integration was pioneered from the 1970s (Linnhoff et al., 1982, last edition 1994). From that time it has been considerably extended by number of researchers worldwide, for overviews see (Smith, 2005). In current work only a part of it is be considered, mainly the graphical representation of the methodology. The integration can be performed on two levels:

(i) Process level, where the heat exchange occurs between the hot and cold streams directly and

(ii) Total Site level, when there is an indirect heat exchange between hot and cold streams via intermediate utility, which is part of the central utility system.

For the process level integration, besides others, the Composite Curves and Grand Composite Curve is applied. For the evaluation on Total Site level, the Total Site Profile has been developed.

### *4.1.1 Composite Curves (CC)*

The Composite Curves (Linnhoff et al., 1982, last edition 1994) are plot of temperature and enthalpy of all hot streams (Hot Composite Curve) and all cold streams (Cold Composite Curve) composed together. For more details see elsewhere (Klemeš et al., 2010). An example plot is shown in Figure 12. The above curve (Figure 12) represents aggregated hot streams of problem and is referred to as the Hot Composite Curve - HCC. The Cold Composite Curve - CCC (the lower one in Figure 12) represents the cold streams.

The projection of shadowed area on the $\Delta H$ axis is the amount of heat, which can be recuperated by a heat transfer from hot to cold streams – representing heat recovery. The point, at which the two Composite Curves are the closest in terms of temperature approach, equal to $\Delta T_{min}$, is referred to as the Pinch Point. The part of CCC not overlapping with the hot one presents the minimum hot utility demand $\Delta H_{HU}$ and the part of the HCC not overlapping with CCC represents the minimum cooling utility demand $\Delta H_{CU}$.0

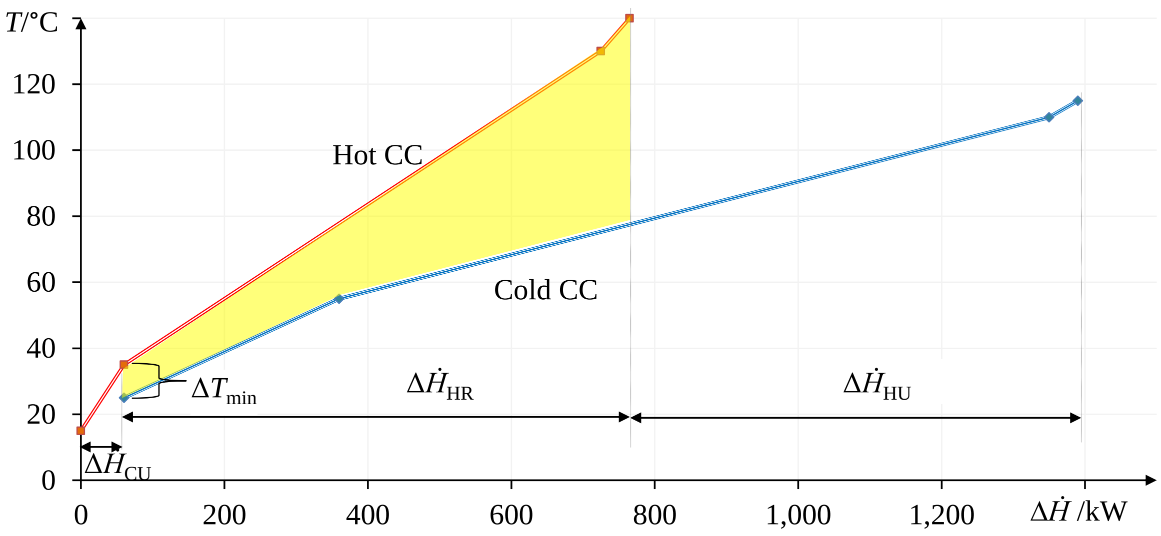


*Figure 12: Composite Curves (for details see Klemeš et al, 2010)*

Extended CCs are the Balanced Composite Curves - BCC (Linnhoff et al, 1982, overviewed elsewhere e.g. Kemp, 2007), which presents a combined view where all heat sources and sinks, including utilities, are in balance and are showing all heat recovery and utility Pinches.

### ***4.1.2 Grand Composite Curve (GCC)***

The Grand Composite Curve - GCC (Townsend and Linnhoff, 1983) represents the maximum heat recovery and the minimum utility needs for a Heat Integration problem of a single process. Unlike the CCs, these properties are shown in the GCC in terms of both heat duty and temperature.

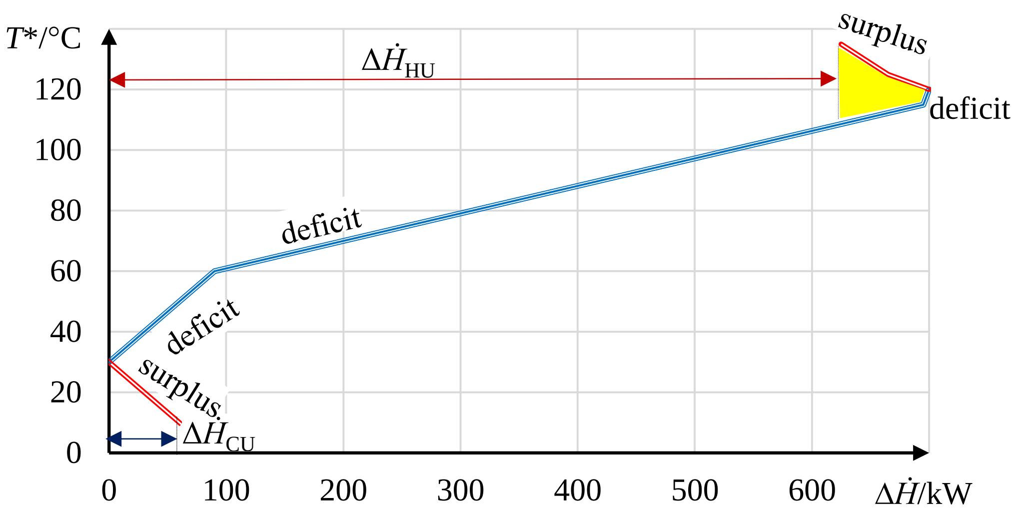


*Figure 13: Grand Composite Curve (Townsend and Linnhoff, 1983)*

The GCC is constructed using the Problem Heat Cascade of the Problem Table Algorithm (Klemeš et a., 2010, Chapter 4). The heat flows are plotted in the *T*-Δ*H* space, where the heat flow at each temperature boundary corresponds to the X coordinate and the temperature to the Y coordinate. The

GCC has several fundamental properties that facilitate an understanding of the underlying heat recovery problem. The parts with positive slope (i.e., running uphill from left to right) indicate that cold streams dominate. Similarly, the parts with negative slope indicate hot stream excess. The shaded areas, which signify opportunities for process-to-process heat recovery, are referred to as heat recovery pockets. Above the Pinch the streams require hot utility and below the Pinch – cold utility. Figure 13 shows an example of the GCC.

### *4.1.3 Total Site Profiles (TSP)*

The tools, presented in previous chapters 4.1.1 and 4.1.2, are applied for an analysis of a single process. For wider scope of integration the concept of Total Site has been introduced (Dhole and Linnhoff, 1993). On a Total Site there are usually various units served by a central utility system (Figure 14). Initially, the concept of Total Site was formulated for industrial processes (Klemeš et al., 1997). Perry et al. (2008) extended the formulation to also include processes from other sectors – residential, business and service, agriculture

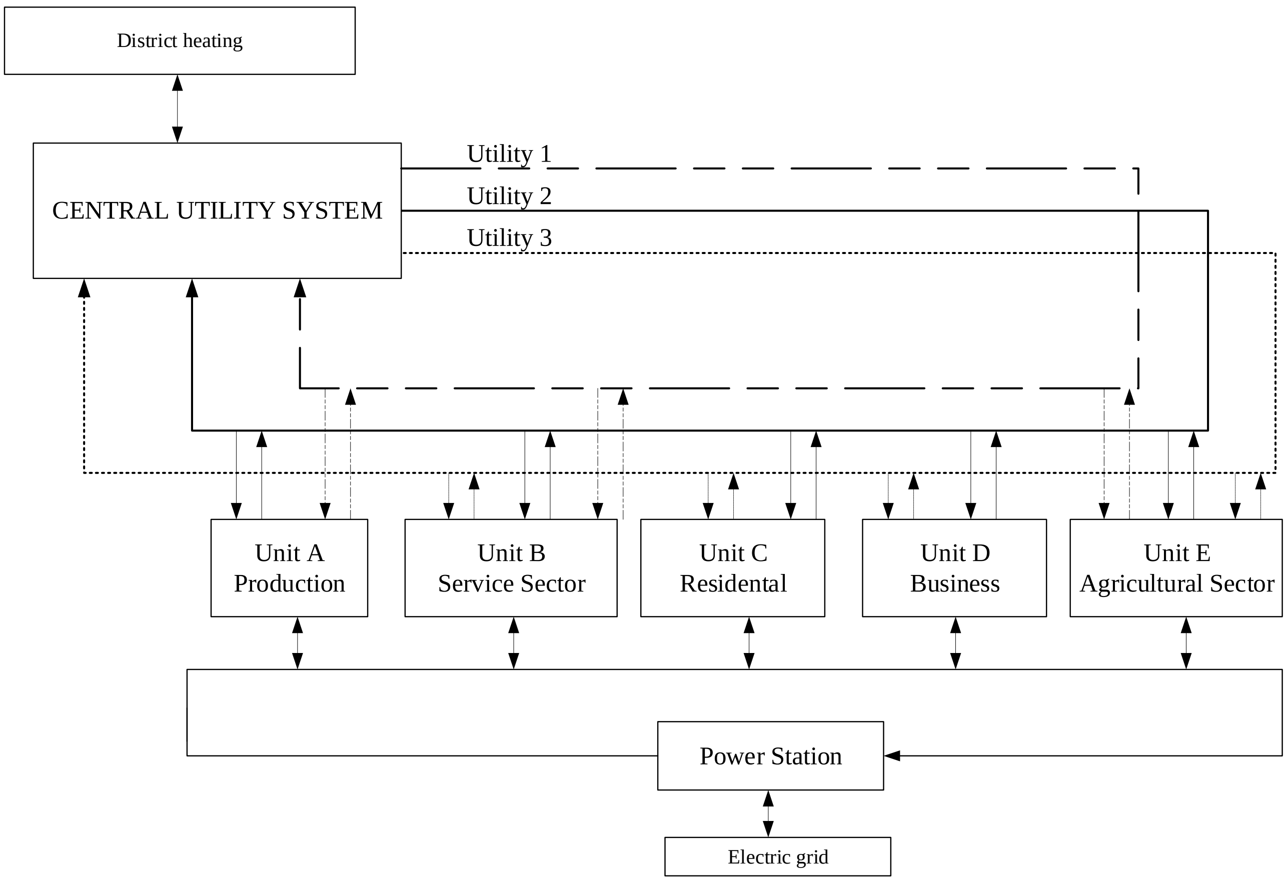


*Figure 14: Total Site (after Perry et al, 2008)*

To integrate the utilities on a Total Site, the Total Site Profiles (TSPs) (Figure 15) are constructed. These are the Sink and the Source profiles. The Sink profile represents the net heating requirements remaining after intra-process heat recovery, while the Source profile represents the net cold utility needs. TSPs are constructed from segments in GCC, which require heating or cooling. The advantage of TSP is that they allow targeting of site heat recovery through an intermediate utility. Traditional TSPs (Klemeš et al, 1997) represent the cooling and heating demands at a temperature scale shifted by a whole $\Delta T_{min}$ from the process stream temperatures. First shifting by $\Delta T_{min}/2$ is performed during the construction of the GCC. During the construction of the TSPs, a further shift by $\Delta T_{min}/2$ is performed. Both shifts are needed to guarantee minimal temperature difference required for feasible heat exchange between the process heat sources and intermediate utility, as well as between the intermediate utility and the process heat sinks. The hot streams and segments are shifted down and the cold ones – up.

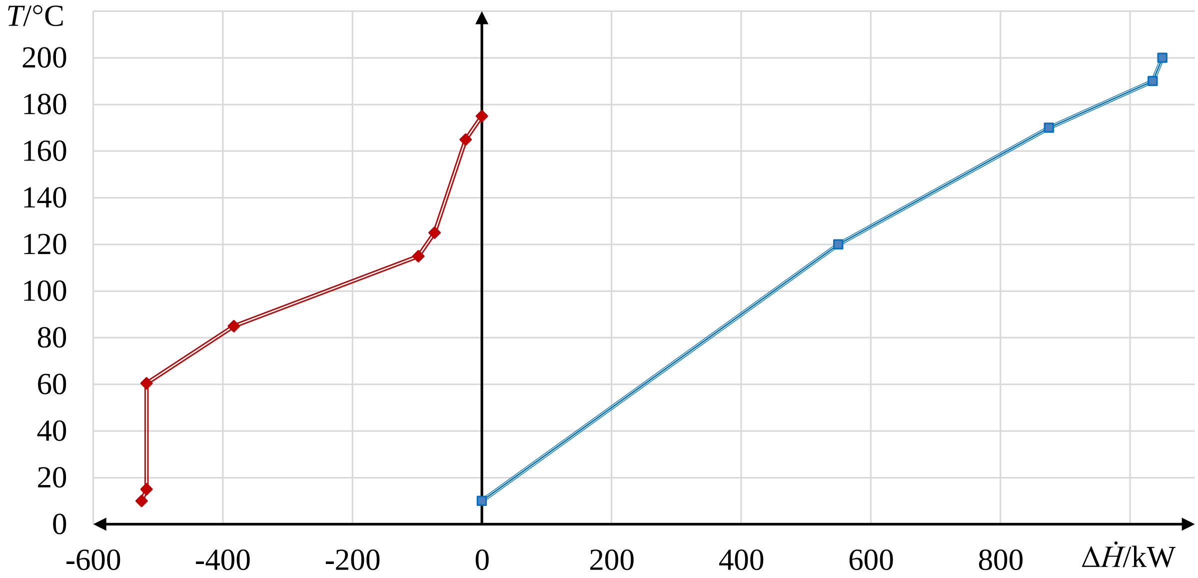


*Figure 15: Total Site Profile consists from Sink and Source Profile (TSP) (after Fodor et al, 2010)*

Fodor et al. (2010) developed a new approach, which accounts for different $\Delta T_{min}$ specifications. In that approach, $\Delta T_{min}$ values are separately specified for heat exchange between utilities and processes, as well as for the heat recovery in each process. As a result, the TSPs built by the new procedure are located at the scale of the process stream temperatures. Since the utilities are also at their own temperatures, when they are placed together with the profiles, the utility composites and TSPs feature a gap equal to the $\Delta T_{min}$ values specified for the corresponding utilities. Figure 16 presents an example for such modified profiles. In the figure it can be seen that the amount of heat recovered is 312 kW, at temperature of intermediate utility 82.5 °C.

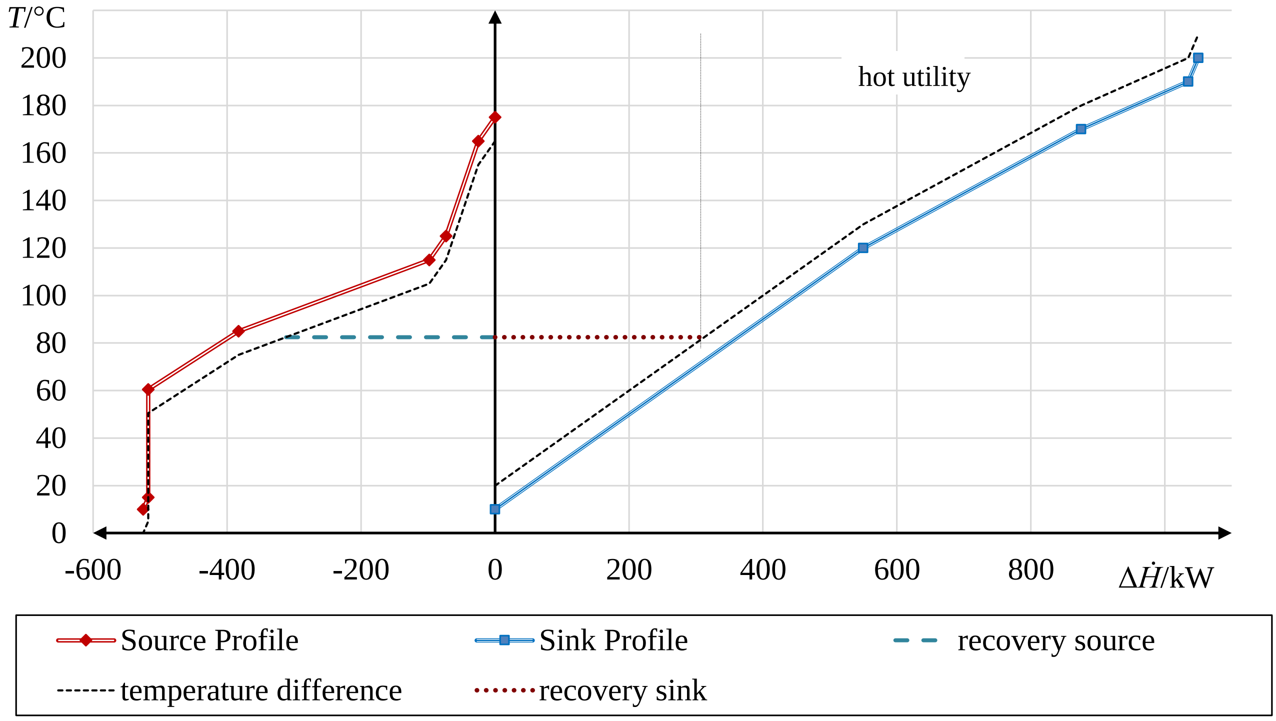


*Figure 16: Heat recovery with temperature difference required and utility requirement in TSP*

## 4.2 Minimal Capture Temperature Curve

The targeting of the maximum solar utility is based on a simplified model, which consists of a solar capture system and storage in a sequence. Storage is used to overcome the variable availability of the solar thermal energy. The storage can be different type: thermal energy storage or chemical energy storage with reversible chemical reaction etc. They are two ways to transfer heat from collectors to the heat demand (Figure 17):

- Direct heat transfer, where the heat is transferred from collectors directly to the heat demand.
- Indirect heat transfer, where the heat is first transferred from collectors to storage and after from storage to the heat demand.

For a direct heat transfer or both direct heat transfer and through storage a similar approach can be used as well. The capture itself is not enough for the integration of the solar thermal energy. The integration is achieved by feasible heat transfer from the capture system to the heat demand. The Minimal Capture Temperature Curve (MCTC) is introduced to identify the minimal temperature, at which the solar utility should be provided to the processes to ensure feasible heat transfer in dependence of the amount of heat demand. The utility requirement in Heat Integration tools are presented by the excess of the Cold Composite Curve, deficit in GCC on a process level.

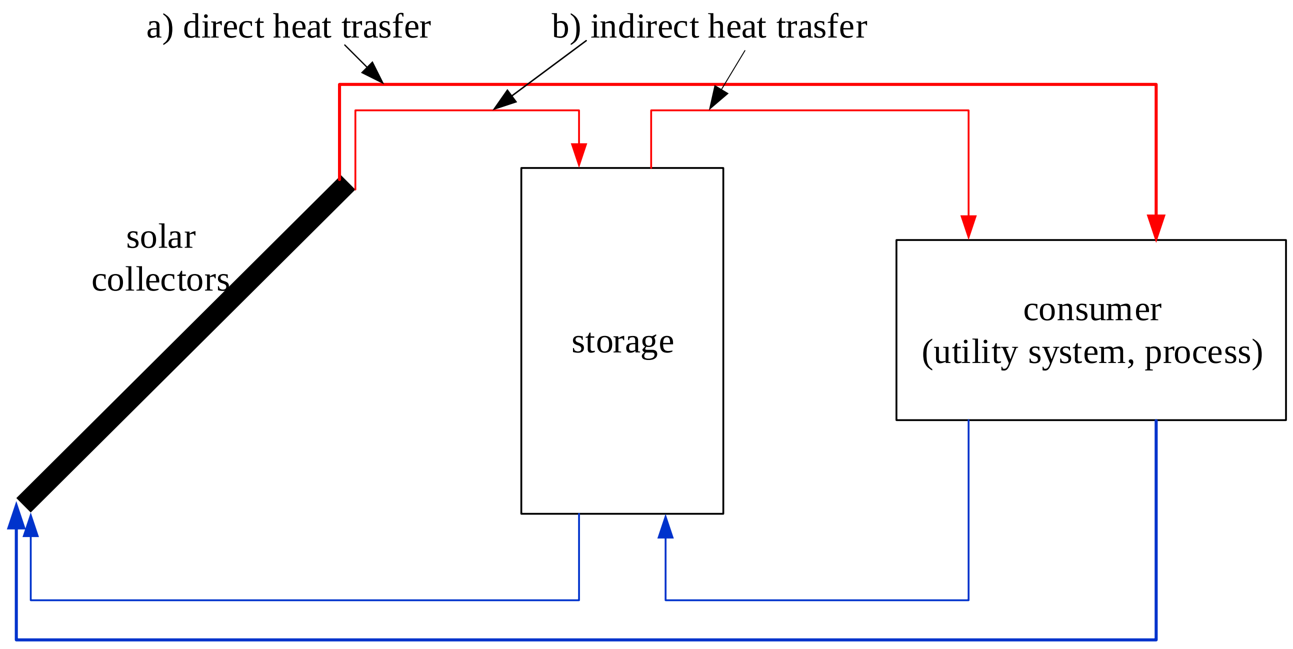


*Figure 17: Solar Thermal Capture system (Nemet et al., 2012b)*

Two different properties are included in the evaluation to ensure feasibility of delivering the solar heat to the process demands:

- Temperature difference
- Heat capacity flow-rate ( $\dot{C}P$ )

The MCTC construction when using storage follows the algorithm shown in Figure 18A. The construction starts with the collection of data for heating requirement, temperature of the demands, and *CP* of the utility streams of the capture and the supply loops from Figure 17. The curve, which represents the heat demand, is shifted up by $\Delta T_{P\text{min}}$. After that, an adjustment of the $\dot{C}P$ for the stream from the supply loop (Figure 17) is made. With it the curve for storage is constructed. This curve is shifted up in the next step by $\Delta T_{\text{Cmin}}$. The stream for the capture loop is adjusted by required $\dot{C}P$ . As a result, the MCTC curve is constructed in two stages, at each stage first ensuring feasible temperatures for heat transfer and then also accounting for the feasibility in terms of $\dot{C}P$ and finalising the MCTC curve. The algorithm for constructing the MCTC in the case of direct heat transfer is used (Figure 18B) is similar to the case when using storage. In this case the collection of the data should be performed as well. Next step is to shift the heating demand curve, which is a result of the data collected by $\Delta T_{DT\text{min}}$. $\Delta T_{DT\text{min}}$ is a temperature difference between the outlet and the inlet temperature of the stream, from which the heat is transferred to demand ($\Delta T_{DT\text{min}} = T_{D1} - T_{D2}$). The last step is to adjust the curve by the $\dot{C}P$ of the supply stream of the direct solar thermal energy.

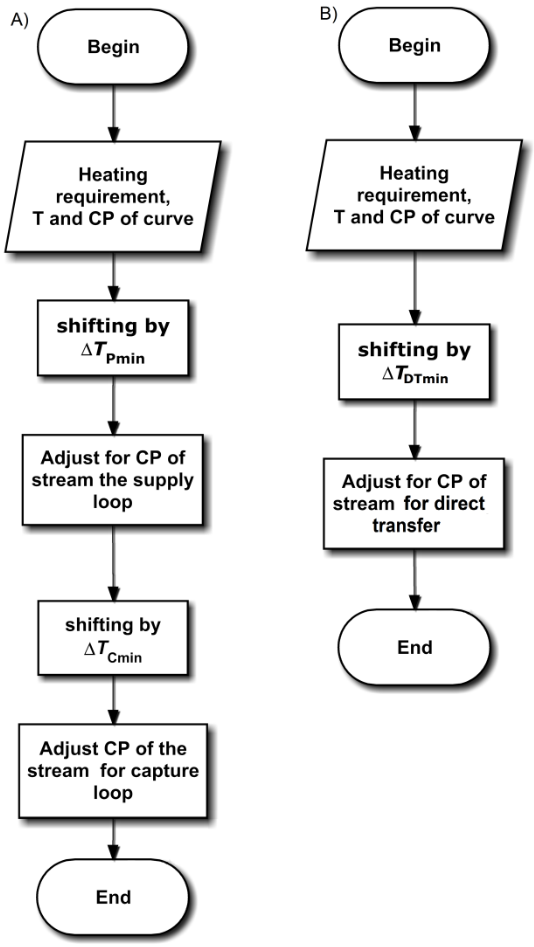


*Figure 18: Algorithm for constructing the MCTC when A) using storage and B) the heat is transferred directly (Nemet et al., 2012b)*

### 4.2.1 Temperature difference feasibility: MCTC$_T$ construction

According to the assumed model (Figure 19), two heat transfer steps are needed to deliver the solar utility to the heat demands when using storage:

- Heat transfer from the collector to the storage unit, giving rise to the minimum temperature difference between the capture and storage temperatures ($\Delta T_{C\text{min}} = T_{C1} - T_{C2}$, Figure 17).
- Heat transfer from the storage to the process demand, defining a second constraint: $\Delta T_{P\text{min}}$ ($\Delta T_{P\text{min}} = T_{P1} - T_{P2}$, Figure 17).

The temperature differences required for feasible heat exchange should be specified in advance. They are results of trade-off between the heat exchanger area and investment cost. Different type of storages can be used. In this work two types of storage are considered (Huggins, 2010):

(i) Thermal energy storage (latent and sensible) and

(ii) Chemical energy storage with reversible chemical reaction.

Minimal Capture Temperature Curve for temperature (MCTC$_T$) is used to satisfy the temperature difference requirement for the part of the curve, which requires heating. Only that part of cold composite curve is considered in the analysis, which required external heating and could not be covered by heat recovery. The thermal energy storage can be further classified in sensible or latent. If the sensible thermal storage is used, the $MCTC_T$ is constructed by shifting up the part of curve, which requires heating, by $\Delta T_{Pmin}$; see Figure 19a.

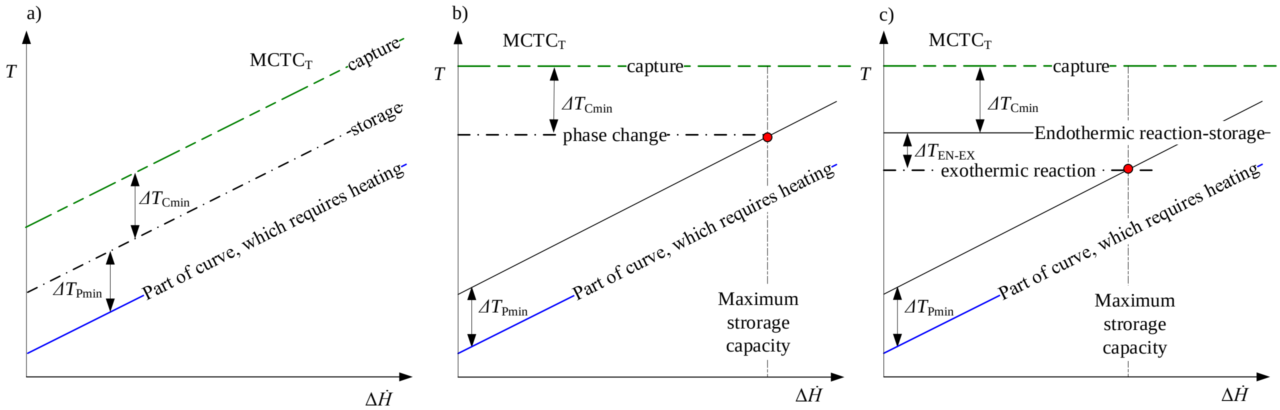


*Figure 19: Construction of MCTCT when storage mechanism is: a) sensible thermal, b) latent thermal and c) chemical (after Nemet et al., 2012b)*

In latent thermal energy storage the energy consuming process of phase change is utilised. As a result smaller volume of storage is required. This phase change of the medium in the storage determines the temperature of storage. In the case of chemical energy storage the phenomena of energy requirement of reversible chemical process is applied, therefore the temperature of the storage is determined by exothermic reaction. The part of curve, which requires heating, is shifted up by $\Delta T_{Pmin}$ for feasible heat exchange between the process demand and exothermic reaction. The storage temperature is already determined by the temperature of the endothermic reaction. In order to account for temperature difference between the exothermic and endothermic reaction - $\Delta T_{EN-EX}$, an additional curve shifting is required (Figure 19c, “endothermic reaction - storage”).
The curve which presents the temperature of endothermic reaction is shifted up by $\Delta T_{Cmin}$. By this shifting a feasible heat exchange between captured solar thermal energy and endothermic reaction is ensured. The crossing point of the exothermic reaction and the curve, which ensures feasible heat transfer to the process, determines the maximal amount of solar thermal energy, which might be reasonable to store (Figure 19b). Further increase of the amount of stored heat is not useful, as for any additional load, discharged from the storage; the temperature of the stored heat would be lower than the required.

### 4.2.2 ***Feasibility of the Heat Exchange - Heat Capacity Flow-rate***

Another factor which should be taken into account is the Heat Capacity Flow-rate - *CP*. It is the product of specific heat capacity and the mass flow-rate of a stream. The mass flow-rate depends on the many factor e.g. viscosity, piping system and pumping system. The limitation on the *CP* value should be taken into account, when constructing MCTC. In the T-H plots, *CP* values are inverse proportional to the curve slopes. The required *CP* of MCTC is marked as $CP_{\mathrm{MCTC}}$. It is the *CP* of stream between the capture and storage. The $CP_{\mathrm{HR}}$ is the *CP* of curve, which requires heating. Three different scenarios can occur:

i. $CP_{\mathrm{MCTC}} > CP_{\mathrm{HR}}$ (16)

ii. $\mathrm{CP}_{\mathrm{MCTC}} = \mathrm{CP}_{\mathrm{HR}}$ (17)

or

iii. $\mathrm{CP}_{\mathrm{MCTC}} < \mathrm{CP}_{\mathrm{HR}}$ (18)

When $CP_{\mathrm{MCTCT}} = CP_{\mathrm{HR}}$, the $\mathrm{MCTC_T}$ is directly taken as the final MCTC. In the case when $CP_{\mathrm{MCTC}} > CP_{\mathrm{HR}}$ the MCTC ending point is the same as for $\mathrm{MCTC_T}$ (Figure 20a). By required *CP* the slope of the MCTC is already determined. In the other case, when $CP_{\mathrm{MCTC}} < CP_{\mathrm{HR}}$, the starting point is the same for MCTC and $\mathrm{MCTC_T}$ (Figure 20b).

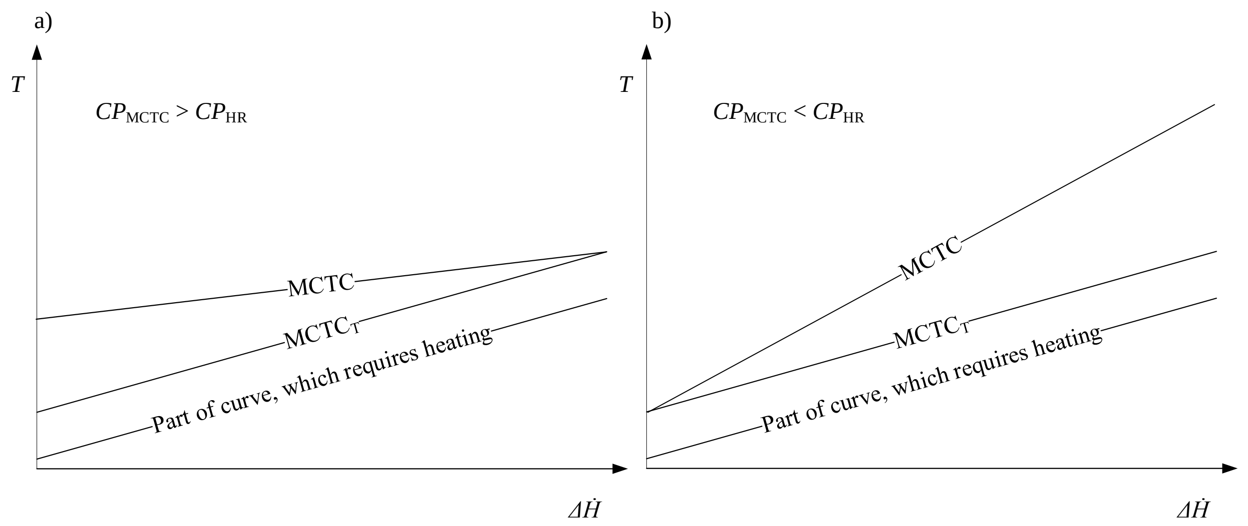


*Figure 20: Constructing MCTC when a) CPMCTC > CPRH and b) CPMCTC < CPRH (Nemet et al., 2012b)*

## 4.3 Summary

In this section an essential elements of feasible integration of solar thermal energy has been presented. Two curves $\mathrm{MCTC_T}$ and MCTC were developed in order to evaluate temperature difference and heat capacity flow-rate required. Additionally, an algorithm applying those developed curves has been introduced to set a temperature and amount of heat, which can be

4. Ensuring feasible integration of solar thermal energy

integrated.

# 5 Estimation of solar collector area and storage size requirement

The integration system has two essential parts namely, the collector system and the storage. The aim of the first one is to produce as much as possible heat amount, while the second serves for storing heat for later usage, when there is no available energy from solar source. The size of the both should be planned carefully in order to allow the highest possible integration and still the size of both should be reasonable. The performance of the integration system is affected by the days of sunny periods and days of shady period. During the days of sunny periods the collectors area should be large enough in order to gain the required amount of heat for both: i) direct during the sunny days and indirect, during shady days and night. The storage size should by high enough in order to cover the heat demand during shady day periods and for the nights, when no direct heat integration is possible due to lack of solar irradiation. Therefore, for design purposes the periods of sunny days followed by shady days has important role.

## 5.1 Estimating solar collector area

The solar collector area design is estimated based on the rate between the sunny days and consecutive shady days. This ratio indicates the required speed of collecting the solar thermal energy in order to cover heat demand for this period. The speed of collecting the required solar thermal energy strongly depends on the area of the solar collector system. Therefore, the solar collector area has been determined by the following steps:

**Step 1.** *Determining the amount of heat demand within one day, which could be potentially covered by solar thermal energy*. The limiting maximal temperature of capture should be taken into account in order to determined the potential amount of heat that can be covered by solar thermal energy $\Delta\dot{H}^{\text{D-STE}}$ (Fig. 21). It is not reasonable to include in the analysis heat demands with higher temperature requirements than can be produced by the solar thermal energy integration system. The demands with higher temperature requirement will be covered by other external source of energy, therefore this amount of heat is designated as $\Delta\dot{H}^{\text{HU}}$ in Fig. 21. The potential demand, that can be covered from solar thermal energy is determined within each Time Slice separately by Eq. 19.

$$\Delta Q_{ti}^{D-STE} = \Delta\dot{H}_{ti}^{D-STE} \cdot \left(t_{\text{ti-1}} - t_{\text{ti}}\right) \tag{19}$$

where, $\Delta Q_{ti}^{D-STE}$ is the amount of heat that can be potentially covered from solar source of energy within time interval *ti*, $\Delta\dot{H}_{ti}^{D-STE}$ is the enthalpy flow of the part of the demand, for which the heat integration of STE is possible, while $t_{ti}$ is the time boundary of the time interval.

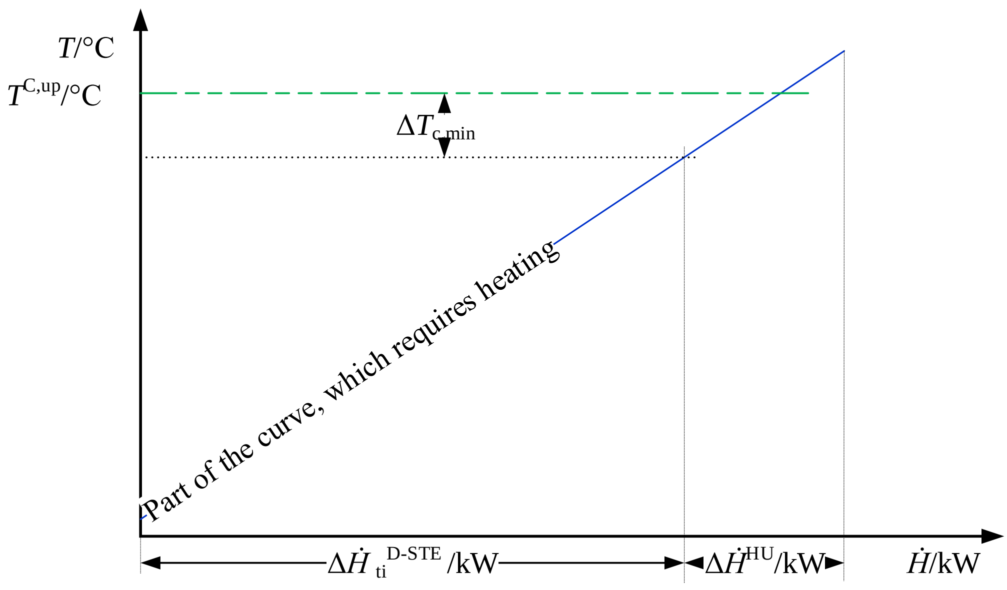


*Figure 21: Determining the demand that can be potentially covered from solar thermal*

**Step 2.** *Determining amount of heat potentially gained during sunny day per unit of area*. The calculation of the amount of heat gained is based on average values. The load of irradiation of clear sky during one typical day within each month is determined first. From all the measure values a short time interval accounting for each measured point is determined. As the irradiation is measure during all days of the year at the same time, the starting and ending time boundaries of those intervals are the same. Therefore, for each of these intervals a data for each months is available. For the averaged representative sunny day the average of the irradiation of all of the months is determined. The same procedure is applied when determining average ambient temperature within in time interval. The amount of heat gained per unit of solar thermal collector can be determined after obtaining the representative sunny day for daily irradiation on clear sky. It is determined within each time interval separately, at first, and then summed up over whole day. Within each time interval it is defined by applying Eq. 20, where $\Delta Q_{ti}$ is the amount of heat gained within time interval ti, $A$ is the area of the solar collector, $G_{ti}$ is the averaged solar irradiation of clear sky within time interval, $\eta_0$ optical efficiency, $a_1$ and $a_2$ are thermal loss coefficients for solar collector system, $T^{C,in}$ is the inlet and $T^{C,out}$ is the outlet temperature of the media flowing through collector system, $T_{ti}^{A}$ is the average ambient temperature within ti and $t_{ti-1}$ and $t_{ti}$ are the time boundaries of the time interval.

$$\frac{\Delta Q_{ti}^{STE}}{A} = \bar{G}_{ti} \cdot \left( \eta_o - \frac{a_1 \left( \frac{T^{C,out} + T^{C,in}}{2} - T_{ti}^{A} \right) + a_2 \left( \frac{T^{C,out} + T^{C,in}}{2} - T_{ti}^{A} \right)^2}{\bar{G}_{ti}} \right) \cdot \left( t_{ti\text{-}1} - t_{ti} \right) \quad (20)$$

**Step 3. Determining required amount of heat that should be collected during one sunny day in order to cover all demand set in Step 1.** This calculation is based on the number of the consecutive sunny and shady days. The ratio $n^{all/sun}$ between all days $n^{all}$ (sunny and shadow days together) and the number of sunny days $n^{sun}$ (Eq. 21) is determined in order to obtain information about number of days of heat demand for which the heat should be collected within one day. For example if the design is made typically for two sunny days followed by three shadowed day, the solar thermal energy integration system should ensure enough heat for five days demand. However, as there is only two sunny days available for gaining the solar thermal energy, the solar collector system should be able to collect heat demand for 5/2 = 2.5 days (Fig. 22).

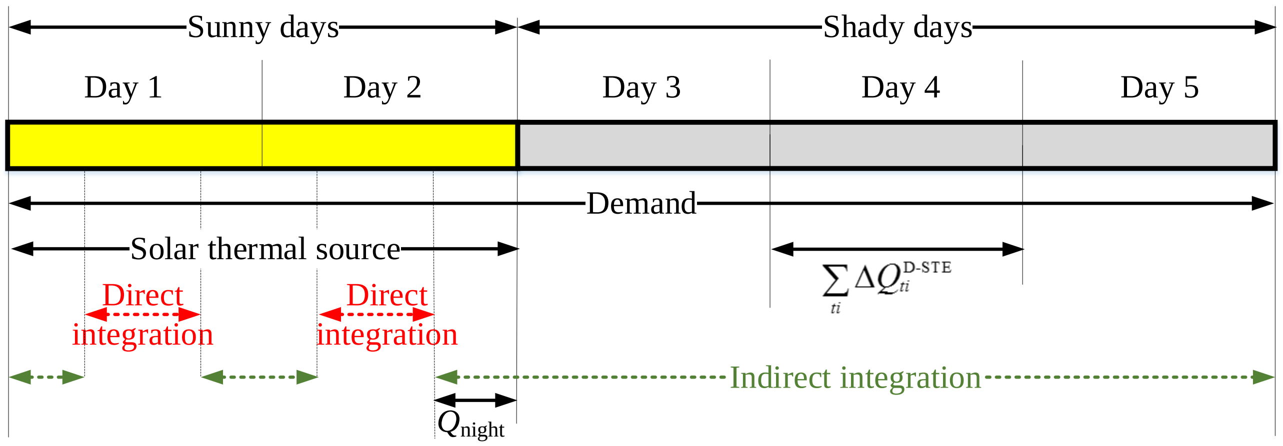


*Figure 22: Basis for determination of solar thermal collector area*

$$n^{all/sun} = \frac{n^{all}}{n^{sun}} \quad (21)$$

**Step 4. Determining solar collector area**. The solar collector area requirement can be set after the heat requirement of amount of heat collected during one sunny day is determined. The area calculation is established by the calculation of the ratio between heat that should be collected during one sunny day and the average amount of heat potentially collected during one sunny day per unit of area (Eq.22), multiplied by the ratio $n^{all/sun}$:

$$A^{SC} = \frac{\sum_{ti} \Delta Q_{ti}^{D-STE}}{\sum_{ti} \frac{\Delta Q_{ti}^{\mathrm{STE}}}{A}} \cdot n^{\mathrm{all/sun}} \tag{22}$$

## 5.2 Estimation of storage size requirement

Another essential part of the integration system is the storage. The estimation of the storage size is based on the previously developed approach of consecutive number of sunny and shady days. The storage capacity should be large enough to cover heat requirements for all of the shady days expected plus the night $Q_{night}$ of the last sunny day, which cannot be covered by direct integration of solar thermal energy. Additionally, the heat losses should also be considered for the time period of storing the heat. Therefore, the storage size is determined from Eq. 23, where $Q_{st}$ is the amount of heat, that should be stored, $t_{sh}^{D}$ is the number of consecutive shady days, $t^{sun}$ is the number of sunny days, and $Q_{loss,day}$ is the average heat loss during one day.

$$Q_{st} = t_{sh}^{D} \cdot \Delta Q_{ti}^{D-STE} + Q_{night} + \left(t_{sh}^{D} + t^{sun}\right) \cdot Q_{loss,day} \tag{23}$$

Previously, only the amount of heat demand for one day has been determined, but there is no information about the amount of heat required to cover heat demand during the last night before shady days. For this purpose, a cascade for heat demand excluding the demand covered by direct integration of solar thermal energy has to be performed (Figure 23). Therefore, the amount of heat stored during a sunny day can also be observed. Based on this observation, the maximal heat capacity of the storage during sunny day can be determined. This capacity has to be ensured, additionally to the capacity required for shady days. Therefore, the size of the storage should be increased by this required capacity.

Besides process demand, the preliminary calculation of storage vessel surface area needs to be obtained in order to determine the heat loss during a day. The storage size depends on the amount of heat stored, specific heat and temperature range of the medium in the storage. The storage size is initially determined without considering heat loss (Eq. 24).

$$V_{st} = \frac{t_{sh}^{D} \cdot \Delta Q_{ti}^{D-STE} + Q_{night}}{cp \cdot \rho \cdot \left(T^{s,up} - T^{s,lo}\right)} \tag{24}$$

The heat losses can be determined after obtaining the initial surface area of the storage. When heat losses are available the storage size estimation is performed again with the amount of heat demand increase by the amount of heat loss (Eq. 25).

$$V_{st} = \frac{t_{sh}^{D} \cdot \Delta Q_{ti}^{D-STE} + \left(t_{sh}^{D} + t^{sun}\right) \cdot Q_{loss,day} + Q_{night}}{cp \cdot \rho \cdot \left(T^{s,up} - T^{s,lo}\right)} = \frac{Q_{st}}{cp \cdot \rho \cdot \left(T^{s,up} - T^{s,lo}\right)} \tag{25}$$

## 5.3 Summary

In this section a method for an estimation of storage size and solar collector area was presented. The solar collector area is determined based on the ratio between the number of all days (sunny and shady once) and number of sunny days. This ratio then serves of as a factor for enlarging an area required for sunny day in order to obtain total for all days. The storage size estimation is based on the demand for the number of shady days summed up with one night demand and heat losses. By estimation of required solar collector area and storage size the main properties of the solar thermal integration system is obtained. Therefore, it can be concluded that a preliminary design for the integration system can be performed following methodology presented in section 3, section 4 and this section 5.

# 6 Case study

## 6.1 Targeting of solar thermal energy integration system before installation

### *6.1.1 Determining Time Slices for a solar irradiation*

The input real-supply profile is presented in Figure 6 (in Section 3.1.1). This presents the daily irradiation. The data was determined as yearly average of typical day in each month, where the data was presented always at the same hour at location Veszprém (Hungary) (GeoModel Solar, 2012). The time-period of the irradiation was from 4:37 to 19:37 as there was no irradiation before or after this period. It was a 15 h time-horizon and the measurements were taken every 15 min. This resulted in 61 measurements. The discretisation of the irradiation can be seen in Figure 6 (Section 3.1.1). The following evaluation focused on an acceptable number of TiSls. Since the ideal representation of the TiSls would be with 100 % accuracy (0 % inaccuracy) and with one TiSl the measure was selected as percent of difference from this ideal point. Therefore, for the TiSls the 0 % differrence is at one TiSl and at 100 % is at the number of time intervals, achieved by discretisation. For example, when the selected tolerance is up to 20 % of the total amount of the irradiation (6,343.76 kW), the resulting number of TiSls is 6, therefore the percentage of number of TS divided by initial number of time interval was 6/60 = 10 %. The achieved inaccuracy is 1,086.2 kW (17.12 %).

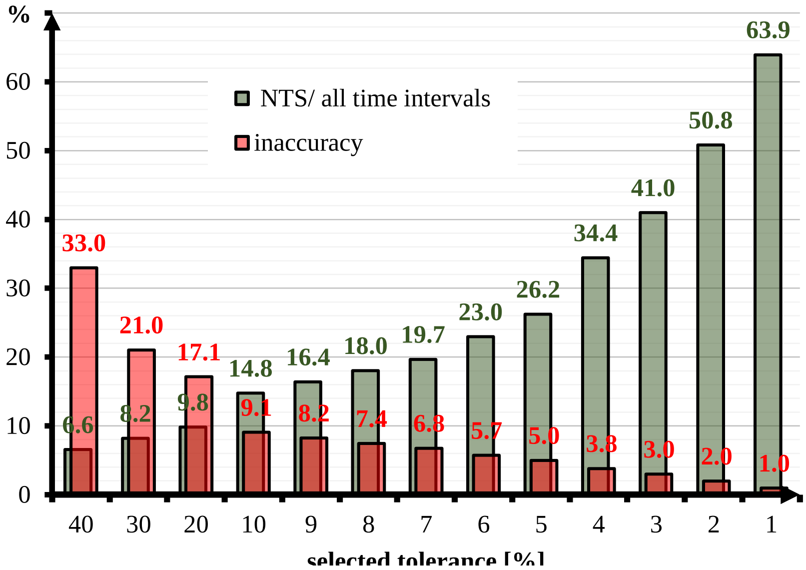


*Figure 23: Selecting an acceptable inaccuracy (Nemet, et al., 2012a)*

Figure 23 presents the inaccuracy and the number of TiSls as a result of optimisation at different selected tolerance. As can be seen in Figure 23, when number of TiSl increases after certain point the accuracy does not increase significantly. For further calculations the result at 10 % tolerance selected has been used. Number of TiSls, obtained by the proposed MILP model, was 9. It was an important achievement, as the initial number of time-intervals from the measurements was 60. The inaccuracy at this number of TiSls was 9.07 %. The assumed solar irradiation level, achieved by optimisation, can be seen in Figure 24.

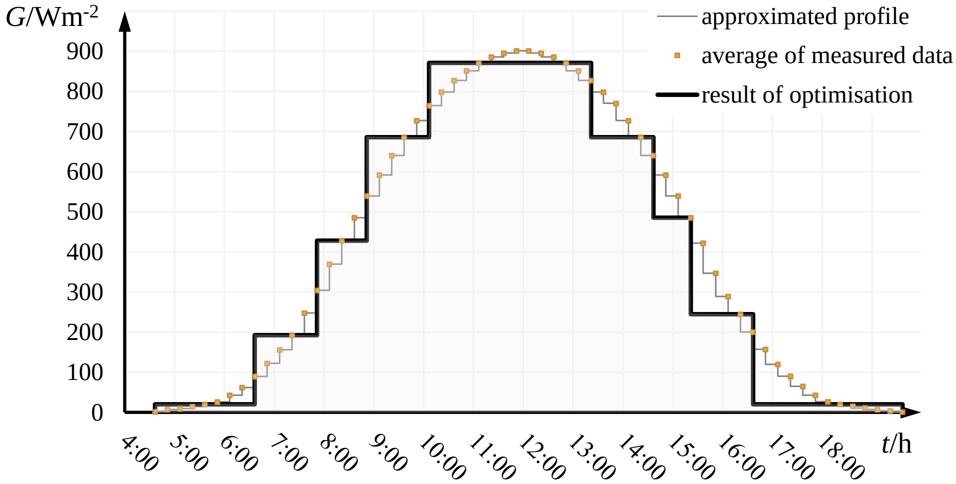


*Figure 24: Time Slice boundaries for irradiation.*

However, as it can be seen in Fig. 24 the first and the last Time Slice level of irradiation, is very low (only 20.5 W/m$^2$) and the enthaphy flow, when determining it from this equations, is negative, therefore, these two Time Slices were neglected, and only seven Time Slices were applied as presented in Fig. 25.

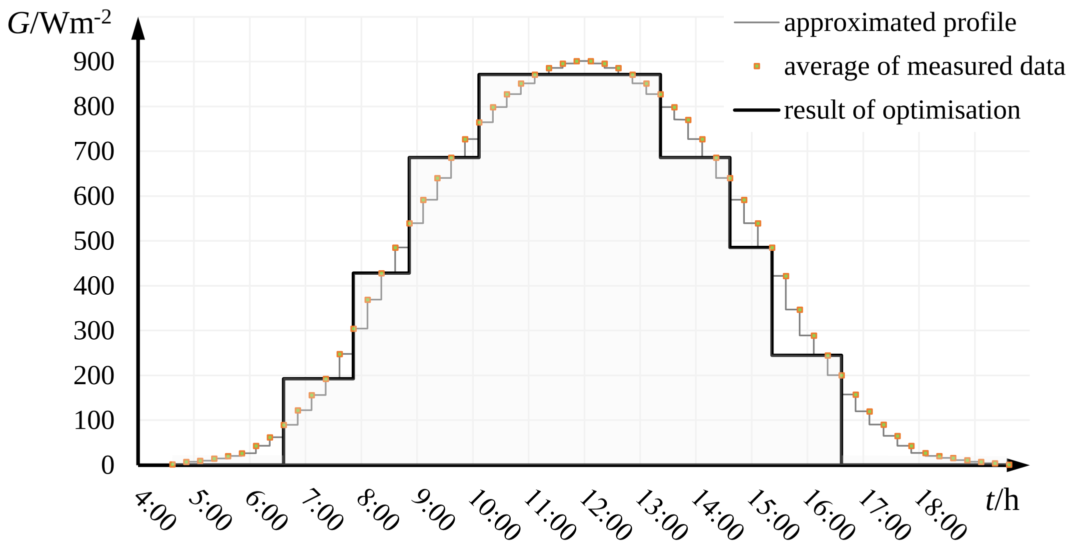


*Figure 25: Reduced Time Slice for irradiation*

### *6.1.2 Determining Time Slices for the process demand side*

Processes with heat demand were real data taken from Perry et al. (2008), which is a case study of hospital. The list of processes is presented in Table 2 including the input data required, which are the supply and target temperature, enthalpy flow $\Delta\dot{H}$, heat capacity flow rate $\dot{C}P$, and the time horizon of the process. The time interval boundaries are selected as the starting/ ending time of the processes or when a significant change occurs in the heat capacity flow rate.

*Table 2: List of streams after heat recovery as input data*

| No. | Stream | Temperature | | ΔH | Type | CP | Time interval | |
|---|---|---|---|---|---|---|---|---|
| | | supply | target | | | | start | end |
| 1 | Sanitary water 1 | 25 | 55 | 17.3 | Cold | 0.576 | 20 | 24 |
| 2 | Laundry | 55 | 85 | 18 | Cold | 0.600 | 20 | 24 |
| 3 | BFW | 33 | 60 | 12 | Cold | 0.446 | 0 | 24 |
| 4 | Sanitary water 2 | 25 | 60 | 15 | Cold | 0.429 | 6 | 17 |
| 5 | Sterilisation | 82 | 121 | 34.1 | Cold | 0.874 | 20 | 24 |
| 6 | Swimming pool water | 25 | 28 | 23.1 | Cold | 7.700 | 6 | 15 |
| 7 | Cooking | 80 | 100 | 32 | Cold | 1.600 | 6 | 20 |
| 8 | Heating | 18 | 25 | 41.1 | Cold | 5.864 | 0 | 24 |
| 9 | Bedpan washers | 21 | 121 | 5 | Cold | 0.050 | 6 | 17 |
| 10 | Space heating | 15 | 25 | 88 | Cold | 8.800 | 0 | 24 |
| 11 | Hot water base | 15 | 45 | 25 | Cold | 0.833 | 0 | 24 |
| 12 | Hot water day | 15 | 45 | 65 | Cold | 2.167 | 6 | 20 |

In Table 3 time interval boundaries are collected in ordered list following the time frame. A matrix is created including the time interval boundary list and the list of processes, signalling the presence/absence of a certain process within certain time interval.

*Table 3: Matrix of presence/absence of a certain stream within certain time intervals*

| No. | Time Slice [h]/ Stream | 0-6 | 6-15 | 15-17 | 17-20 | 20-24 |
|---|---|---|---|---|---|---|
| 1 | Sanitary water 1 | - | - | - | - | X |
| 2 | Laundry | - | - | - | - | X |
| 3 | BFW | X | X | X | X | X |
| 4 | Sanitary water 2 | - | X | X | - | - |
| 5 | Sterilisation | - | - | - | - | X |
| 6 | Swimming pool water | - | X | - | - | - |
| 7 | Cooking | - | X | X | X | - |
| 8 | Heating | X | X | X | X | X |
| 9 | Bedpan washers | - | X | X | - | - |
| 10 | Space heating | X | X | X | X | X |
| 11 | Hot water base | X | X | X | X | X |
| 12 | Hot water day | - | X | X | X | - |

The process demand is defined within each Time Slice separately (Fig. 26)

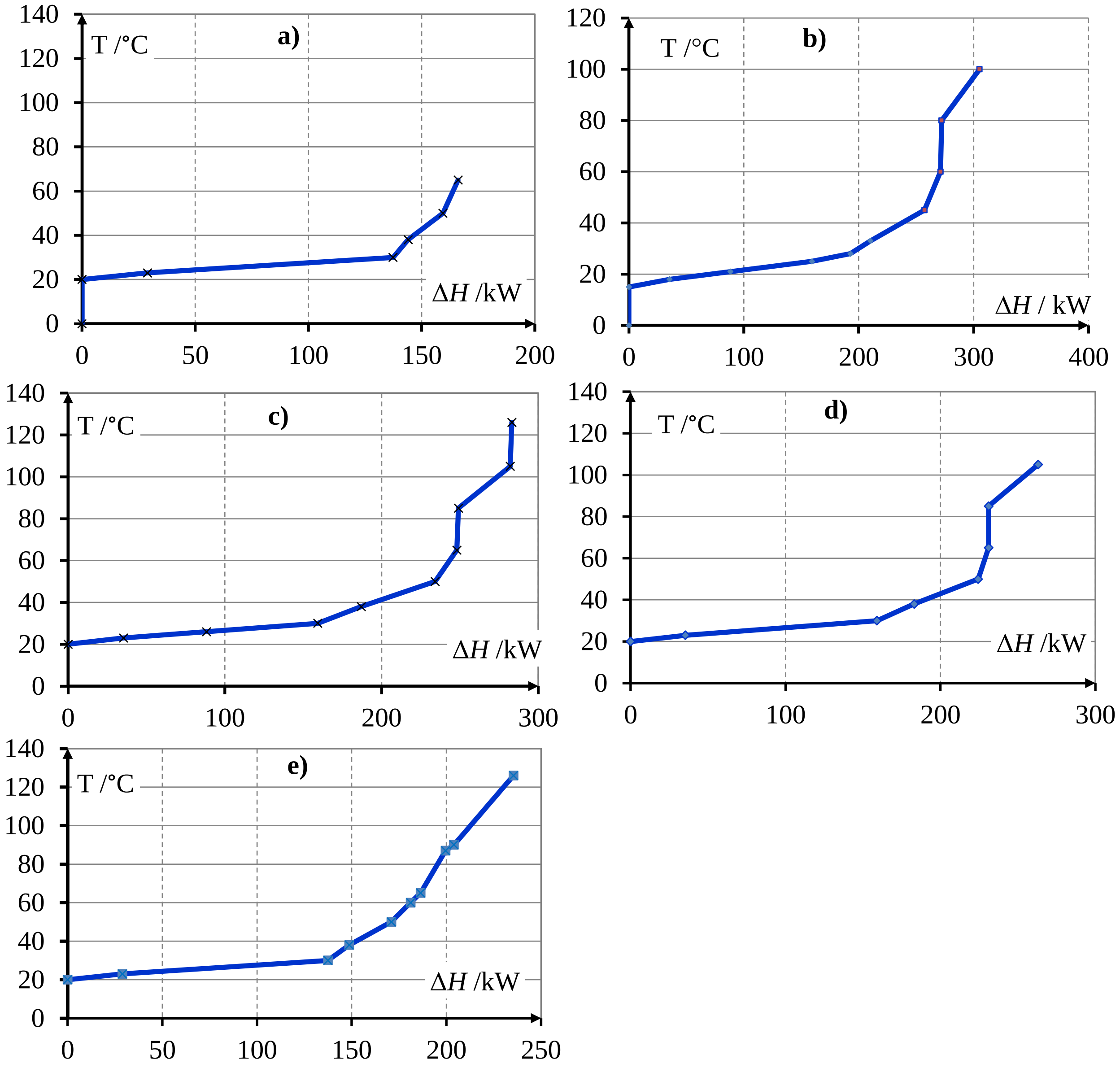


*Figure 26: GCC of the process demand for Time Slice: a) 0-6, b) 6-15, c) 15-17, d) 17-20 and e) 20-24*

### ***6.1.3 Combined Time Slices from Solar Irradiation and the demand side***

#### *6.1.3.1 Obtaining Combined Time Slice*

After obtaining seven TiSls for solar irradiation and five TiSls for processes with heat demand, combined Time Slice cTiSls should be obtained in order to perform integration of solar thermal energy. This procedure is a straightforward procedure of listing the TiSls boundary from both supply and demand side and arranging them in consecutive time order. Figure 27 presents the obtained Time Slices for solar irradiation and demand, and the resulting cTiSl for the current case study.

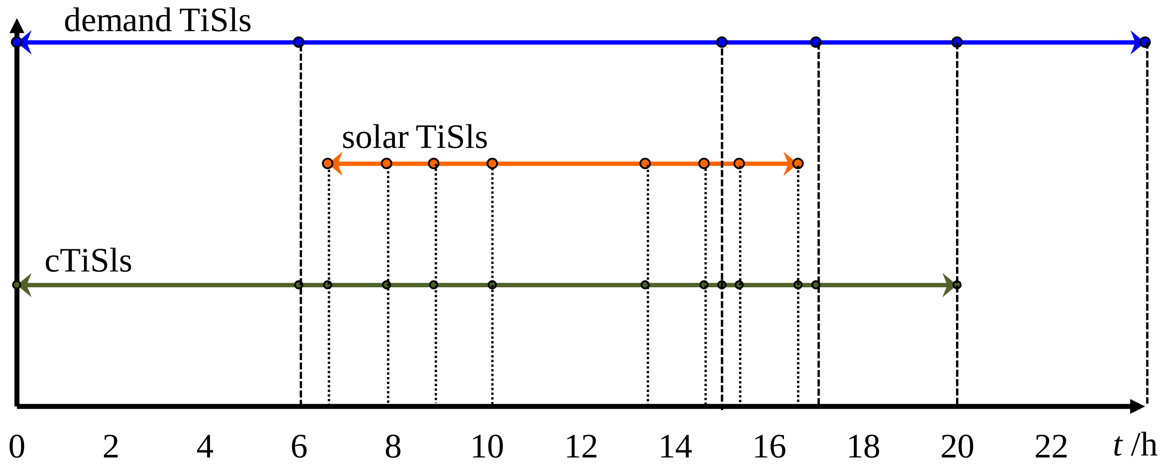


*Figure 27: Combining solar and demand Time Slices (TiSl) into Combined Time Slices (cTiSl)*

### <u>*6.1.4 Estimation of required solar collector area and storage size*</u>

#### *6.1.4.1 Estimation of solar collector area*

The estimation of solar collector is performed as described in section 5.

**Step 1.** *Determining the amount of heat demand within one day, which could be potentially covered by solar thermal energy*.

In step 1 the heat demand, that can be potentially covered from solar source of energy, was determined for one day. For this purpose the solar collector system upper and lower temperature should be specified. For the case study a temperature range between 80 and 120 °C. There are two ways to integrate the solar thermal energy: i) directly or ii) indirectly. Only one heat transfer is performed, when a direct way is used, while at indirect heat integration the heat transfer is done twice. For the targeting purposes the indirect heat transfer is considered, therefore the minimal temperature difference required for feasible heat exchange is considered twice. In this case study the required minimal temperature difference is assumed at 10 °C for both heat transfers. Therefore, the maximal outlet temperature from collector is 120°C and from the storage it is 110 °C. With the stream from storage a heat demand at 100 °C can be covered. from the of the demand that can be potentially covered from solar source of energy is set at 110 °C. According to construction of GCC this temperature is represented at 95 °C as the temperature of hot streams or utility streams are shifted down and the temperature of cold stream is shifted up, in order to ensure the required temperature difference at the crossing point of the two curves (Fig. 28).

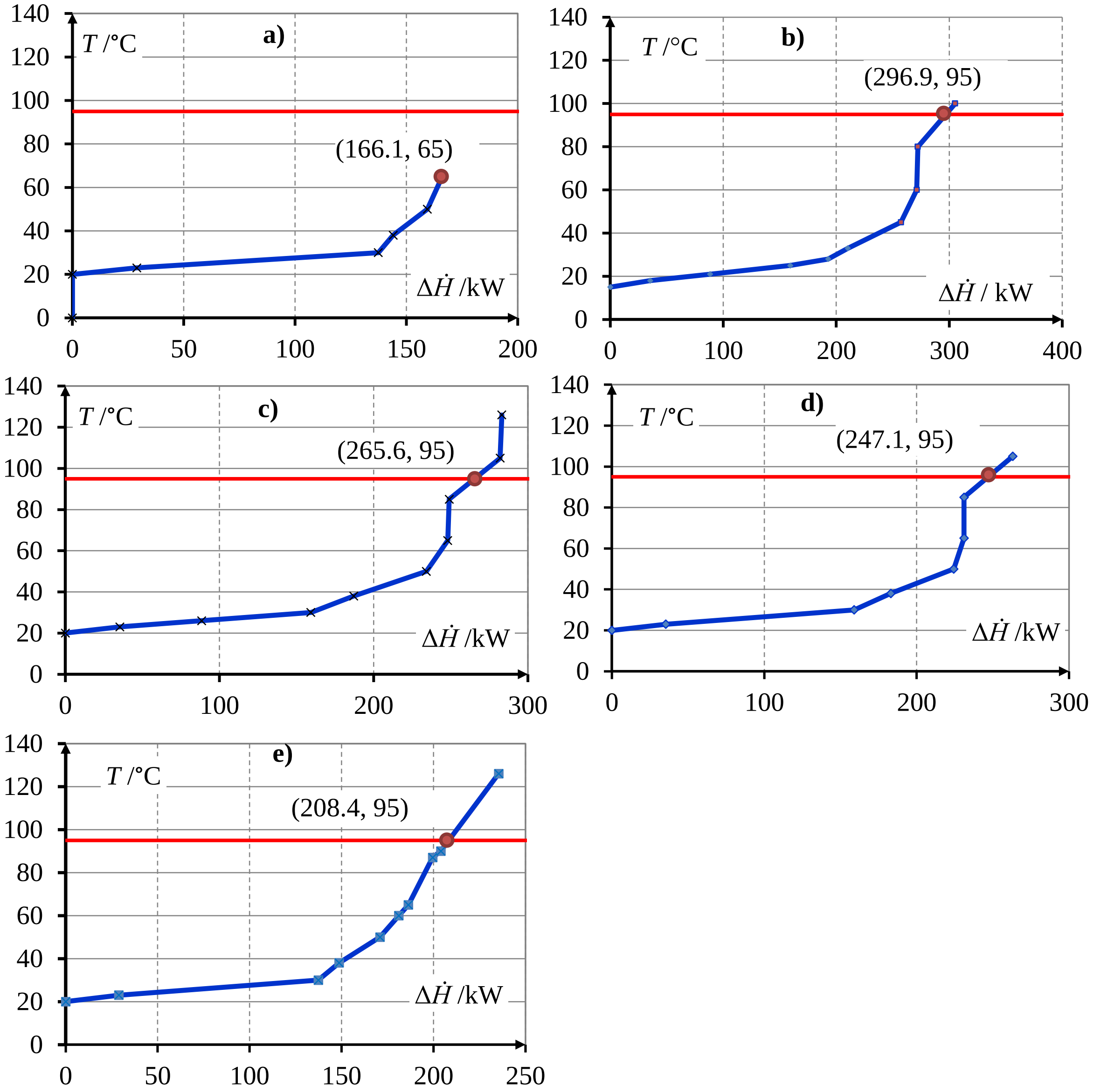


*Figure 28: Determining the potential enthalpy flow that can be covered form solar source of energy*

After obtaining the potential enthalpy flow rate within each Time Slice separately, the amount of heat that can be covered from solar source of energy can be determined as presented in Table 4. As can be seen in Table 4, the amount of heat that can be potentially covered from solar source of energy is 5,765.4 kWh, and it represents 95.4 % of all demands for a day, which is 6,040.9 kWh.

*Table 4: Determining the amount of heat demand that can be potentially covered by solar source of energy*

| TiSl/h | 0-6 | 6-15 | 15-17 | 17-20 | 20-24 |
|---|---|---|---|---|---|
| $H^{STE}$ /kW | 166.1 | 295.9 | 265.6 | 247.1 | 208.4 |
| $Q^{STE}$ /kWh | 996.5 | 2,663.1 | 531.1 | 741.2 | 833.4 |
| | | | | **Total** | **5,765.4** |

As can be seen from Table 5, the daily amount of heat gain during a typical sunny day is 3.12 kWh/m$^2$

*Table 5: Determining amount of heat potentially gained during one typical sunny day*

| Time interval/h | $\bar{G}_{ti}$ /W m$^{-2}$ | $T_{ti}^{A}$ /°C | $\frac{T^{out}+T^{in}}{2}-T_{ti}^{A}$ /°C | $\frac{\Delta\dot{H}}{A}$ /W m$^{-2}$ | $\frac{\Delta Q}{A}$ /Wh m$^{-2}$ |
|---|---|---|---|---|---|
| 07:07:00 | 156.0 | 7.2 | 92.8 | 0.0 | 0.0 |
| 07:22:00 | 192.3 | 7.5 | 92.5 | 2.1 | 0.5 |
| 07:37:00 | 248.2 | 7.9 | 92.1 | 45.1 | 11.3 |
| 07:52:00 | 304.8 | 8.2 | 91.8 | 88.7 | 22.2 |
| 08:07:00 | 369.5 | 8.7 | 91.3 | 138.6 | 34.6 |
| 08:22:00 | 428.0 | 8.9 | 91.1 | 183.4 | 45.9 |
| 08:37:00 | 485.5 | 9.3 | 90.8 | 227.7 | 56.9 |
| 08:52:00 | 539.9 | 9.6 | 90.4 | 269.5 | 67.4 |
| 09:07:00 | 591.8 | 9.9 | 90.1 | 309.5 | 77.4 |
| 09:22:00 | 640.5 | 10.2 | 89.8 | 347.0 | 86.8 |
| 09:37:00 | 685.9 | 10.6 | 89.5 | 382.0 | 95.5 |
| 09:52:00 | 727.6 | 10.9 | 89.1 | 414.2 | 103.6 |
| 10:07:00 | 765.1 | 11.2 | 88.8 | 443.2 | 110.8 |
| 10:22:00 | 798.6 | 11.5 | 88.6 | 469.1 | 117.3 |
| 10:37:00 | 827.4 | 11.7 | 88.3 | 491.4 | 122.9 |
| 10:52:00 | 851.8 | 12.0 | 88.0 | 510.4 | 127.6 |
| 11:07:00 | 871.5 | 12.3 | 87.7 | 525.8 | 131.4 |
| 11:22:00 | 886.3 | 12.5 | 87.5 | 537.5 | 134.4 |
| 11:37:00 | 895.8 | 12.8 | 87.2 | 545.1 | 136.3 |
| 11:52:00 | 901.3 | 13.0 | 87.0 | 549.5 | 137.4 |
| 12:07:00 | 895.8 | 13.2 | 86.8 | 545.8 | 136.4 |
| 12:22:00 | 886.3 | 13.4 | 86.6 | 538.9 | 134.7 |
| 12:37:00 | 871.5 | 13.6 | 86.4 | 527.8 | 132.0 |
| 12:52:00 | 851.8 | 13.7 | 86.3 | 513.1 | 128.3 |
| 13:07:00 | 827.4 | 13.9 | 86.1 | 494.9 | 123.7 |
| 13:22:00 | 798.6 | 14.0 | 86.0 | 473.2 | 118.3 |
| 13:37:00 | 770.7 | 14.1 | 85.9 | 452.1 | 113.0 |
| 13:52:00 | 727.6 | 14.2 | 85.8 | 419.5 | 104.9 |
| 14:07:00 | 685.9 | 14.3 | 85.7 | 388.0 | 97.0 |
| 14:22:00 | 640.5 | 14.4 | 85.6 | 353.6 | 88.4 |
| 14:37:00 | 591.8 | 14.4 | 85.6 | 316.6 | 79.2 |
| 14:52:00 | 539.9 | 14.5 | 85.5 | 277.3 | 69.3 |
| 15:07:00 | 485.5 | 14.5 | 85.5 | 235.9 | 59.0 |
| 15:22:00 | 422.1 | 14.4 | 85.6 | 187.7 | 46.9 |
| 15:37:00 | 347.0 | 14.4 | 85.6 | 130.6 | 32.6 |
| 15:52:00 | 289.4 | 14.3 | 85.7 | 86.7 | 21.7 |
| 16:07:00 | 244.7 | 14.2 | 85.8 | 52.5 | 13.1 |
| 16:22:00 | 200.8 | 14.1 | 85.9 | 19.0 | 4.7 |
| 16:37:00 | 157.5 | 14.0 | 86.0 | 0.0 | 0.0 |
| | | | | **TOTAL** | **3.12 kWh/m$^2$** |

**Step 2.** *Determining amount of heat potentially gained during sunny day per unit of area*. The average potential of gaining heat within one day is determined based on inlet temperature of collector at 80 °C and the outlet temperature of stream from collector is at 120 °C. Applying Eq. 20 (Section 5) the amount of heat gained in each time interval can be determined. After determining

this amount of heat within each time interval separately, it is summed up over whole day. **Step 3.** *Determining required amount of heat collected during one sunny day in order to cover all potential demand that can be covered from solar source of energy.*

The requirement of the amount of heat collected during a typical sunny day is determined on the basis of ratio between sunny and shady days. When observing data of sunny and consecutive shady days (e.g. Eumet, 2014- closest to Veszprém is Siófok station measurement or any other) it can be seen, that the most common ratio $n^{\text{all/sun}}$ is usually between 1.25 (representing four sunny days and one shady) and 3 (which represents one sunny day followed by two shady days). Therefore, different scenarios are considered in the following analysis. It should be noted, that higher is the ratio $n^{\text{all/sun}}$ larger is the solar collector area requirement. Therefore, for final decision about the solar collector size (and consequently also the storage size) a trade-off between the number of shady days covered from solar source and the required investment has to be taken into account.

**Step 4.** *Determining solar collector area.*

The final solar collector area is determined for three different ratio $n^{\text{all/sun}}$, namely for 1, 2 and 3. The first results presents area requirement if no heat is stored for shady days.

*Table 6: Required area of solar collectors for different time periods of storage*

| Ratio | 1 d | 2 d | 3 d |
|---|---|---|---|
| $A^{\text{SC}}$/ m$^2$ | 1,853.8 | 3,707.7 | 5,561.5 |

### *6.1.4.2 Estimation of storage size*

The storage size was determined for three different time periods of storing heat. The temperature range of storage operation was assumed to be between 70 and 110 °C. The heat demand, that can be covered from solar source of energy during one day was already determined in Section 6.1.4.1 - Step 1 and is 5,765.4 kWh. The amount of directly integrated solar thermal energy should be evaluated in order to enable further steps of estimation of storage size. For this purpose the previously obtained combined Time Slices has been used. The results are presented in Table 7. Within each Time Slice the total heat demand is determined at first. It has been already determined within the demand side Time Slices already. Also, the heat potentially covered from solar source of energy $\Delta\dot{H}^{\text{D-STE}}$ is included in the evaluation. Within each cTiSl the amount of directly integrated solar thermal energy is determined. This data is obtained by applying Eq. 20, however including the previously determined solar collector area. The required enthalpy flow from storage $\Delta H_{\text{STE}}$ for covering the heat demand during sunny day is determined as the difference between the required enthalpy flow and the direct enthalpy flow from solar collectors. the required amount of heat $\Delta Q_{\mathrm{STE}}$ can be obtained by multiplying the enthalpy flow and the time horizon of the interval. For the heat demand, that can not be covered from solar source of energy a constant available utility $\Delta H_{\mathrm{HU}}$ should be utilised.

*Table 7: Determining the load of solar thermal energy supply and the utility with constant load.*

| cTS | Total Heat demand | $\Delta \dot{H}^{\mathrm{D\text{-}STE}}$ | Solar thermal energy | Storage | | Constant available utility |
|---|---|---|---|---|---|---|
| Duration/h | $\Delta H_{\mathrm{UR}}$/kW | $\Delta H_{\mathrm{UR}}$/kW | $\Delta H_{\mathrm{DHT}}$/kW | $\Delta H_{\mathrm{STE}}$/kW | $\Delta Q_{\mathrm{STE}}$/kWh | $\Delta H_{\mathrm{HU}}$/kW |
| 0:00-6:00 | 166.1 | 166.1 | 0 | 166.1 | | 0 |
| 6:00-6:37 | 305.155 | 295.905 | 0 | 295.905 | | 9,25 |
| 6:37-7:52 | 305.155 | 295.905 | 9.09 | 286,815 | | 9,25 |
| 7:52-8:52 | 305.155 | 295.905 | 295.905 | 0 | | 9,25 |
| 8:52-10:07 | 305.155 | 295.905 | 295.905 | 0 | | 9,25 |
| 10.07-13:22 | 305.155 | 295.905 | 295.905 | 0 | | 9,25 |
| 13:22-14:37 | 305.155 | 295.905 | 295.905 | 0 | | 9,25 |
| 14:37-15:00 | 305.155 | 295.905 | 295.905 | 0 | | 9,25 |
| 15:00-15:22 | 283.105 | 265.555 | 265.555 | 0 | | 17,55 |
| 15:22-16:37 | 283.105 | 265.555 | 195.937 | 69,618 | 87,0225 | 17,55 |
| 16:37-17:00 | 283.105 | 247.09 | 0 | 247.09 | 94,7178 | 36,015 |
| 17:00-20:00 | 263.09 | 247.09 | 0 | 247.09 | 741,27 | 16 |
| 20:00-24:00 | 235.446 | 208.352 | 0 | 208.352 | 833,408 | 27,094 |
| | | | | Total | 1756,4483 | |

The initial volume of storage $V^{\mathrm{init}}$ is determined from Eq. 23, where the heat losses are neglected. The surface area of storage is determined with considering a cylinder shape with radius 2.5 m and the high is determined from initial volume. The heat losses for one day are determined from Eq. 26

$$Q^{\mathbf{loss\_1day}} = \sum_{ti} k \cdot A^{st} \frac{\frac{(T^{lo} + T^{up})}{2} - T_{ti}^{A}}{th^{wall}} \tag{26}$$

However, as the heat is stored within all sunny days and all shady days, therefore, the total heat loss for different scenarios is determined by multiplying the heat loss over one day with the number of all days (Eq. 27).

$$Q^{\mathrm{loss\_tot}} = Q^{\mathrm{loss\_1day}} \cdot n^{\mathrm{all}} \tag{27}$$

Finally, the storage volume $V^{\mathrm{st}}$ is determined by considering also the heat losses. A comparison between initial and final storage is made, and as can be seen the difference can be up to 5.664 (2 %).

*Table 8: Determining storage size*

| | 1 d | 2 d | 3 d |
|---|---|---|---|
| $V^{init}$/m$^3$ | 107.46 | 189.82 | 272.18 |
| $A^{st}$/m$^2$ | 125.21 | 191.10 | 256.99 |
| $Q^{loss\_1day}$/kWh | 64.384 | 98.2657 | 132.1465 |
| $Q^{loss\_tot}$/kWh | 128,768 | 294,7971 | 528,586 |
| $V^{st}$/m$^2$ | 108.374 | 192.625 | 277.844 |
| $V^{st\text{-}}\ V^{init}$/m$^2$ | 0,914 | 2,805 | 5.664 |

### ***6.1.5 Economic evaluation***

The economic evaluation of the solar integration system can be determined as the relation between investment of the solar collector area and the thermal storage on one hand and the saving of operating cost due to external utility reduction. The solar collector price is 300 €/collector with collector area 2.2 m$^2$ (Alibaba, 2014). The determined required area of solar panels is 5,561.5m$^2$; therefore, the investment for solar collectors was determined as can be seen in Eq. 32.

$$I^{C} = \frac{300}{2.2}\left[\frac{€}{\mathrm{m}^2}\right]\cdot 5,561.5\left[\mathrm{m}^2\right] = 758,386.36\left[€\right] \tag{28}$$

The other largest part of investment is the thermal storage. As the price of storage 700 L is approximately 2,800 € (ACRUX, 2014), the price for 1 L of the storage can be determined as 4 €/L. The investment for storage for the current case study was determined as can be seen in Eq. 33.

$$I^{storage} = 4\left[\frac{€}{L}\right]\cdot 279,732.5\left[L\right] = 1,118,930.0\left[€\right] \tag{33}$$

Therefore, the total investment (Eq. 34) was the sum of the investment for solar collectors and storage investment.

$$I = I^{SC} + I^{storage} = 758,386.36\left[€\right] + 1,118,930.0\left[€\right] = 1,877,316,36\left[€\right] \tag{34}$$

The investment is an expenditure, which should be made in order to gain solar thermal heat. By applying the solar thermal heat the other, usually fossil, source of heat can be reduced, exactly for the amount of heat, gained from the solar source. This reduction in other utility consumption should be high enough to cover the investment.

As it was determined, 3.12 kWh/m$^2$ of heat demand was covered from the solar source within one day. When the price of utility is 0.15 €/kWh, the savings within one year are as seen in Eq. 35 138,462.8 €/y.

$$c^{savings} = 3.12\left[\frac{kWh}{m^2}\right] \cdot 5,564.5\ m^2 \cdot 160\left[\frac{d}{y}\right] \cdot 0.13\left[\frac{€}{kWh}\right] = 361,081.34\left[\frac{€}{y}\right] \tag{35}$$

The return on investment (*ROI*) for the case study presented is the ration between investment and savings.

$$ROI = \frac{I}{c^{savings}} = \frac{1,877,316.36\left[€\right]}{361,081.34\left[\frac{€}{y}\right]} = 5.2\left[y\right] \tag{36}$$

As can be seen the *ROI* is acceptable. However, it should be noted, that this is only a preliminary analysis, therefore the real *ROI* is expected to be somewhat longer.

## 6.2 Summary

In this section 6 a case study is presented applying the developed methodology for preliminary analysis of the integration of solar thermal energy. As the case study indicated, a 3.12 kWh/m$^2$ solar thermal energy can be gained during a sunny day. For the case, when the design is made for one sunny and two shady day the area of collectors was determined as 5.564.5 m$^2$ and the storage size was estimated at 279,732.5 L. Both parts together results in investment at 1,877,316.36 €, while on the other hand savings could be 361,081.34 €/y, which result in *ROI* 5.2 y. This result is a somewhat optimistic result, however, encouraging for further analysis.

# 7 Monitoring/ Short-term estimation of integrated amount of solar thermal energy during operation

The methodology presented in Sections 3-5 serves for the evaluation of the solar integration system before its installation. However, the solar irradiation can significantly differ from the average estimation used at the design stage. Therefore, in this Section 7 the methodology is presented for monitoring and short-term estimation of integration amount of solar thermal energy. It can be applied during operation of the integration system. Therefore, in this approach there is no Time Slices used, but rather short time intervals. The monitoring is performed by simple algebraic equations, therefore, a high a number of time intervals does not create a problem. These equations are suitable for the calculation of the feasibility of energy integrations for many time intervals as well. The following hierarchy (Varbanov and Klemeš, 2011) should be obeyed in order to cover the heat demand:

- Heat recovery should be maximised.
- The use of solar thermal energy via direct heat transfer from collectors – immediately, when available.
- Usage of the energy from the storage-indirect heat transfer of solar thermal energy.
- Usage of external utility with constant availability is required.

Thus, the integration using direct transfer of solar thermal energy within time intervals is then performed, after heat recovery. If there is an unused heat from the solar source, it is transferred to storage. The solar thermal energy can be unused for different reasons. A reason can be the surplus of solar thermal energy or a higher demanded temperature than the temperature of heat available from the solar source. The stored heat will be available in other time interval. Additionally, a heat can be transferred to storage from the surplus of heat from the processes.

The inlet and outlet temperatures from collectors and from storage are varying from one time interval to another. However, this temperatures has great importance, during integration, therefore some assumptions were made in order to be able to determine those temperatures:

(i) The temperatures are varying only at the time interval boundaries, within one time interval they are assumed to be constant.

(ii) The inlet temperature of stream entering collector is equal to storage temperature at the end of previous time interval.

The outlet temperature of stream leaving the storage has constant temperature within whole time interval as it was at the end of the previous time interval.

The outlet temperature of collector and the storage temperature after heat exchanges are determined as described in following Sections 7.1 and 7.2.

## 7.1 Determining outlet temperature from solar thermal collectors

The equations for determining enthalpy are presented in Eq. 24. The enthalpy should be multiplied with the time horizon of time interval in order to determine the amount of integrated heat (Eq. 36).

$$\Delta Q_{ti} = \Delta H_{ti} \cdot \left(t_{ti} - t_{ti-1}\right) = G_{ti} \cdot A \cdot \left( \eta_0 - \frac{a_1 \left( \frac{T_{ti}^{C,out} + T_{ti}^{C,in}}{2} - T_{ti}^{A} \right) + a_2 \left( \frac{T_{ti}^{C,out} + T_{ti}^{C,in}}{2} - T_{ti}^{A} \right)^2}{G_{ti}} \right) \cdot \left(t_{ti} - t_{ti-1}\right) \quad (36)$$

In order to determine the outlet temperature of the medium leaving the collector Eq. 37 is applied:

$$\Delta Q_{ti} = \dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) \cdot \left(t_{ti} - t_{ti-1}\right) \quad (37)$$

The amount of heat captured $\Delta Q$ in the heat medium is a result of mass flow-rate $\dot{q}_m^C$, specific heat capacity of the medium *cp*, temperature difference between inlet $T_{ti}^{C,in}$ and outlet $T_{ti}^{C,out}$ temperature of medium, multiplied by the time horizon of a time interval. The amount of captured heat should be equal to the heat transferred to media, which is heated. Considering Eq. 36 and 37 the following equality can be obtained.

$$\dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) = G_{ti} \cdot A \cdot \left( \eta_0 - \frac{a_1 \left( \frac{T_{ti}^{out,C} + T_{ti}^{in,C}}{2} - T_{ti}^{A} \right) + a_2 \left( \frac{T_{ti}^{out,C} + T_{ti}^{in,C}}{2} - T_{ti}^{A} \right)^2}{G_{ti}} \right) \quad (38)$$

The aim is to determine the outlet temperature of the stream leaving collector, therefore the equations should be transform to a form, where this temperature is expose. By making a couple of transformations (Eq. 29-35) a quadratic equation is obtained.

$$\dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) = G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \left( \frac{T_{ti}^{out,C}}{2} + \frac{T_{ti}^{in,C}}{2} - T_{ti}^{A} \right) - A \cdot a_2 \cdot \left( \frac{T_{ti}^{out,C}}{2} + \frac{T_{ti}^{in,C}}{2} - T_{ti}^{A} \right)^2 \quad (39)$$

$$\begin{aligned} \dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) &= G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \frac{T_{ti}^{out,C}}{2} - A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_1 \cdot T_{ti}^{A} \\ &- A \cdot a_2 \cdot \left( \left( \frac{T_{ti}^{out,C}}{2} \right)^2 + \left( \frac{T_{ti}^{in,C}}{2} \right)^2 + \left(-T_{ti}^{A}\right)^2 + 2 \cdot \frac{T_{ti}^{out,C}}{2} \cdot \frac{T_{ti}^{in,C}}{2} - 2 \cdot \frac{T_{ti}^{in,C}}{2} \cdot T_{ti}^{A} - 2 \cdot \frac{T_{ti}^{out,C}}{2} \cdot T_{ti}^{A} \right) \end{aligned} \quad (40)$$

$$\dot{q}_{ti}^{m,C} \cdot cp^C \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) = G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \frac{T_{ti}^{out,C}}{2} - A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_1 \cdot T_{ti}^{A}$$
$$-A \cdot a_2 \cdot \left( \frac{T_{ti}^{out,C\,2}}{4} + \frac{T_{ti}^{in,C\,2}}{4} + \left(T_{ti}^{A}\right)^2 + \frac{T_{ti}^{out,C} \cdot T_{ti}^{in,C}}{2} - T_{ti}^{in,C} \cdot T_{ti}^{A} - T_{ti}^{out,C} \cdot T_{ti}^{A} \right) \quad (41)$$

$$\dot{q}_{ti}^{m,C} \cdot cp^C \cdot T_{ti}^{out,C} - \dot{q}_{ti}^{m,C} \cdot cp^C \cdot T_{ti}^{in,C} = G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \frac{T_{ti}^{out,C}}{2} - A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_1 \cdot T_{ti}^{A}$$
$$-A \cdot a_2 \cdot \frac{T_{ti}^{out,C\,2}}{4} - A \cdot a_2 \cdot \frac{T_{ti}^{in,C\,2}}{4} - A \cdot a_2 \cdot \left(T_{ti}^{A}\right)^2 - A \cdot a_2 \cdot \frac{T_{ti}^{out,C} \cdot T_{ti}^{in,C}}{2} + A \cdot a_2 \cdot T_{ti}^{in,C} \cdot T_{ti}^{A} + A \cdot a_2 \cdot T_{ti}^{out,C} \cdot T_{ti}^{A} \quad (42)$$

$$-\frac{1}{4} \cdot A \cdot a_2 \cdot \left(T_{ti}^{out,C}\right)^2 + \dot{q}_m \cdot cp \cdot T_{ti}^{out,C} - A \cdot a_1 \cdot \frac{1}{2} T_{ti}^{out,C} - A \cdot a_2 \cdot \frac{T_{ti}^{in,C}}{2} \cdot T_{ti}^{out,C} + A \cdot a_2 \cdot T_{ti}^{A} \cdot T_{ti}^{out,C}$$
$$+G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_1 \cdot T_{ti}^{A} - A \cdot a_2 \cdot \frac{\left(T_{ti}^{in,C}\right)^2}{4} - A \cdot a_2 \cdot \left(T_{ti}^{A}\right)^2 + A \cdot a_2 \cdot T_{ti}^{in,C} \cdot T_{ti}^{A} + \dot{q}_{ti}^{m,C} \cdot cp^C \cdot T_{ti}^{in,C} = 0 \quad (43)$$

$$-A \cdot a_2 \cdot \frac{1}{4}\left(T_{ti}^{out,C}\right)^2 + (-\dot{q}_{ti}^{m,C} \cdot cp^C - A \cdot a_1 \cdot \frac{1}{2} - A \cdot a_2 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_2 \cdot T_{ti}^{A}) \cdot T_{ti}^{out,C}$$
$$+G_{ti} \cdot A \cdot \eta_0 - A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_1 \cdot T_{ti}^{A} - A \cdot a_2 \cdot \left(\frac{T_{ti}^{in,C}}{4}\right)^2 - A \cdot a_2 \cdot \left(T_{ti}^{A}\right)^2 + A \cdot a_2 \cdot T_{ti}^{in,C} \cdot T_{ti}^{A} + \dot{q}_{ti}^{m,C} \cdot cp^C \cdot T_{ti}^{in,C} = 0 \quad (44)$$

$$A \cdot a_2 \cdot \frac{1}{4}\left(T_{ti}^{out,C}\right)^2 - (-\dot{q}_{ti}^{m,C} \cdot cp^C - A \cdot a_1 \cdot \frac{1}{2} - A \cdot a_2 \cdot \frac{T_{ti}^{in,C}}{2} + A \cdot a_2 \cdot T_{ti}^{A}) \cdot T_{ti}^{out,C}$$
$$-G_{ti} \cdot A \cdot \eta_0 + A \cdot a_1 \cdot \frac{T_{ti}^{in,C}}{2} - A \cdot a_1 \cdot T_{ti}^{A} + A \cdot a_2 \cdot \left(\frac{T_{ti}^{in,C}}{4}\right)^2 + A \cdot a_2 \cdot \left(T_{ti}^{A}\right)^2 - A \cdot a_2 \cdot T_{ti}^{in,C} \cdot T_{ti}^{A} - \dot{q}_{ti}^{m,C} \cdot cp^C \cdot T_{ti}^{in,C} = 0 \quad (45)$$

As can be seen in Eq. 45 the quadratic equation is quite complex, therefore some assumption has been required. The approximation was made when determining the efficiency of the solar collectors. In that equation the $a_2$ has been set as zero, as its value is usually quite low e.g. 0.0003 W/m$^2$, therefore it does not significantly contribute to the results obtained. Using this approximation the equations become less complex, and could be easily applied for determining the outlet temperature of media leaving the collector. Therefore, in the following Eq. 46-51 present the transformations of equations required to obtain the approximate equation.

$$\dot{q}_{ti}^{m,C} \cdot cp^C \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) = G_{ti} \cdot A \cdot \left( \eta_0 - \frac{a_1 \left( \frac{T_{ti}^{out,C} + T_{ti}^{in,C}}{2} - T_{ti}^{A} \right)}{G_{ti}} \right) \quad (46)$$

$$\dot{q}_{ti}^{m,C} \cdot cp^C \cdot \left(T_{ti}^{out,C} - T_{ti}^{in,C}\right) = G_{ti} \cdot A \cdot \eta_0 - a_1 \cdot A \cdot \left( \frac{T_{ti}^{out,C}}{2} + \frac{T_{ti}^{in,C}}{2} - T_{ti}^{A} \right) \quad (47)$$

$$\dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot T_{ti}^{out,C} - \dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot T_{ti}^{in,C} = G_{ti} \cdot A \cdot \eta_0 - a_1 \cdot A \cdot \frac{T_{ti}^{out,C}}{2} - a_1 \cdot A \cdot \frac{T_{ti}^{in,C}}{2} + a_1 \cdot A \cdot T_{ti}^{A} \tag{48}$$

$$\dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot T_{ti}^{out,C} + a_1 \cdot A \cdot \frac{T_{ti}^{out,C}}{2} = G_{ti} \cdot A \cdot \eta_0 - a_1 \cdot A \cdot \frac{T_{ti}^{in,C}}{2} + a_1 \cdot A \cdot T_{ti}^{A} + \dot{q}_{ti}^{m,C} \cdot cp^{CP} \cdot T_{ti}^{in,C} \tag{49}$$

$$(\dot{q}_{ti}^{m,C} \cdot cp^{C} + 0.5 \cdot a_1 \cdot A) \cdot T_{ti}^{out,C} = G_{ti} \cdot A \cdot \eta_0 - 0.5 \cdot a_1 \cdot A \cdot T_{ti}^{in,C} + a_1 \cdot A \cdot T_{ti}^{A} + \dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot T_{ti}^{in,C} \tag{50}$$

$$T_{ti}^{out,C} = \frac{G_{ti} \cdot A \cdot \eta_0 - 0.5 \cdot a_1 \cdot A \cdot T_{ti}^{in,C} + a_1 \cdot A \cdot T_{ti}^{A} + \dot{q}_{ti}^{m,C} \cdot cp^{C} \cdot T_{ti}^{in,C}}{\dot{q}_{ti}^{m,C} \cdot cp^{C} + 0.5 \cdot a_1 \cdot A} \tag{51}$$

When all the available solar thermal heat from the direct and indirect transfers is integrated, the rest of the demand should be covered by those utilities with constant availability.

## 7.2 Determining storage temperature

When determining storage temperature the heat balance for the storage has been observed. It is assumed that the outlet streams from storage occur at the beginning of time interval, while the inlet streams to storage are at the end of time interval.

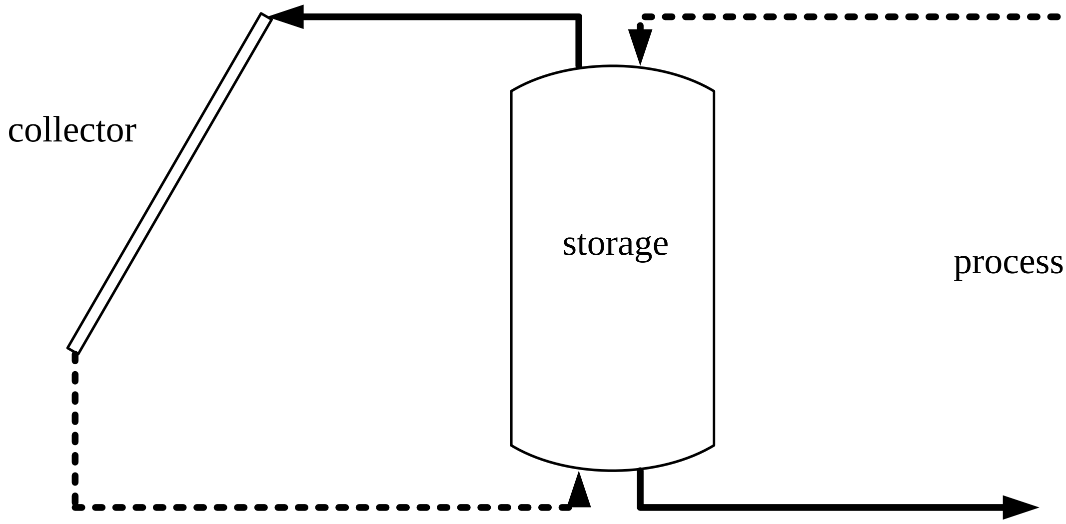


*Figure 29: Scheme of the system for indirect heat integration of solar thermal energy*

The heat balance in certain time interval is presented in Figure 24 and can be determined as follows from Eq. 52.

$$Q_{ti}^{S} - Q_{ti-1}^{S} = Q_{ti}^{C,out} + Q_{ti}^{excess} - Q_{ti}^{C,in} - Q_{ti}^{demand} \tag{52}$$

The aim is to determine the temperature of storage at the end of the Time Slice after all the heat exchanges is performed. In more detail the heat balance is showed in Eq. 53.

$$\begin{aligned} m^{S} \cdot T_{ti}^{S} \cdot cp - m^{S} \cdot T_{ti-1}^{S} \cdot cp = \dot{q}_{ti}^{m,C} \cdot cp \cdot T_{ti}^{out,C} \cdot (t_{ti} - t_{ti-1}) + \dot{q}_{ti}^{m,ex} \cdot cp \cdot T_{ti}^{ex} \cdot (t_{ti} - t_{ti-1}) \\ - \dot{q}_{ti}^{m,C} \cdot cp \cdot T_{ti}^{in,C} \cdot (t_{ti} - t_{ti-1}) - \dot{q}_{ti}^{m,dem} \cdot cp \cdot T_{ti}^{dem} \cdot (t_{ti} - t_{ti-1}) \end{aligned} \tag{53}$$

Eq. 54 is obtained by rearranging Eq. 53

$$m^S \cdot T_{ti}^S \cdot cp^S - m^S \cdot T_{ti-1}^S \cdot cp^S = (t_{ti} - t_{ti-1}) \cdot (CP_{ti}^C \cdot T_{ti}^{out,C} + CP_{ti}^{ex} \cdot T_{ti}^{ex} - CP_{ti}^C \cdot T_{ti}^{in,C} - CP_{ti}^{dem} \cdot T_{ti}^{dem}) \quad (54)$$

The storage temperature can be determined from Eq. 45.

$$T_{ti}^S = \frac{(CP^C \cdot T_{ti}^{out,C} + CP_{ti}^{ex} \cdot T_{ti}^{ex} - CP^C \cdot T_{ti}^{in,C} - CP_{ti}^{dem} \cdot T_{ti}^{dem}) \cdot (t_{ti} - t_{ti-1}) + m^S \cdot T_{ti-1}^S \cdot cp^S}{m^S \cdot cp^S} \quad (55)$$

Presented in different way, the storage temperature after all the possible heat exchange, which can performed in one Time Slice is equal to the temperature of storage at the end of previous Time Slice increased/decreased by the amount of heat balance derived by the mass of storage and specific heat capacity of the medium in the storage, Eq. 56.

$$T_{ti}^S = T_{ti-1}^S + \frac{\left(CP^C \cdot T_{ti}^{out,C} + CP_{ti}^{ex} \cdot T_{ti}^{ex} - CP^C \cdot T_{ti}^{in,C} - CP_{ti}^{dem} \cdot T_{ti}^{dem}\right) \cdot \left(t_{ti} - t_{ti-1}\right)}{m^S \cdot cp^S} \quad (56)$$

If each heat transfer medium is the same presenting the same specific heat capacity the equation becomes somewhat simpler and therefore the storage temperature can be determine as follows:

$$T_{ti}^S = T_{ti-1}^S + \frac{(\dot{q}_{ti}^{m,C} \cdot T_{ti}^{out,C} + \dot{q}_{ti}^{m,ex} \cdot T_{ti}^{ex} - \dot{q}_{ti}^{m,C} \cdot T_{ti}^{in,C} - \dot{q}_{ti}^{m,dem} \cdot T_{ti}^{dem}) \cdot (t_{ti} - t_{ti-1})}{m^S} \quad (57)$$

## 7.3 Determining the amount of heat exchanged within Time Slices

In Section 4 a graphical approach for determining the feasible amount of heat, which can be integrated has been presented. It can be a viable approach, however it is very time consuming approach to perform it and can be applied only in design stage, and therefore a development of a different approach was required. It has been assumed, that the temperature of the storage during the heat exchanges with the process streams are constant. In the case when heat surplus is stored in the thermal storage, the temperature is assumed to be constant and is equal to the storage temperature at the end of the time interval $T_{ti}^S$ (Figure 31a). However, when covering heat demand, the temperature of stream channelled from storage is equal to the temperature of storage at the beginning of the Time Slice $T_{ti-1}^S$ (Figure 31b). By making this consideration the minimal amount of heat, which can be covered or stored from/in storage can be determined. This is the minimal limit, however a higher amount of heat can be also stored, which can be significant if the *CP* of the stream connected to the storage is very low. However, since the temperature of the storage is not varying suddenly with high peaks. Assumptions made are close enough to reality, especially in the case of large thermal heat storage. Figure 31 presents the heat exchange made under assumptions described previously. In Figure 31a the heat exchange between hot stream and storage is presented. The hot stream is the red line, while the storage in case takes a function of cold stream. $T_S$ is the supply and $T_T$ is the target temperature of hot stream. The amount of heat exchanged between hot stream and storage is presented by the shadowed area. As a backup a cold utility is still needed, to cover any excess cooling requirements. Figure 31b presents the heat exchange between storage and cold stream. In this case the storage is represented with red line, as it has the heat surplus needed to cover the heat demand of cold stream. $T_T$ is target and $T_S$ is the supply temperature of cold stream. Additionally, an external source of heat might required as well, therefore, it should be included in the evaluation as well.

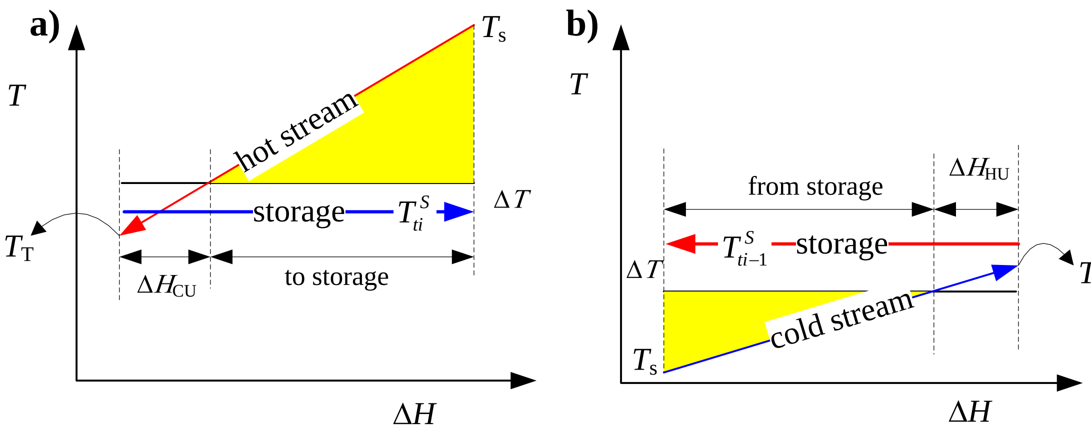


*Figure 30: Heat transfer of a) process heat surplus to storage and b) from storage to heat demand*

To determine the amount of heat transferred the proper outlet temperature of the process stream should be selected.

When the heat is transferred from the process stream to the storage, three different situations can occur (Figure 26a-c).

- (i) All the heat available from process stream can be stored for a later use (Figure 24a).
- (ii) Part of the heat can be stored, however for part of the heat has to be cooled down utilising cold utility (Figure 26b).
- (iii) No heat can be stored, because of the infeasible heat exchange, therefore for all the heat surplus has to be cooled with cold utility (e.g. cooling water) (Figure 26c).

Similarly there are three options, when covering heat requirement for a process stream (Figure 26 d-f):

- (i) All the heat requirement can be covered from the storage (Figure 26 d).
- (ii) Part of the heat can be covered from storage, however for part of the heat has to be covered from hot utility (Figure 26e).
- (iii) No heat can be covered from storage, because of the infeasible heat exchange, therefore for all the heat demand the hot utility has to be used (Figure 26f).

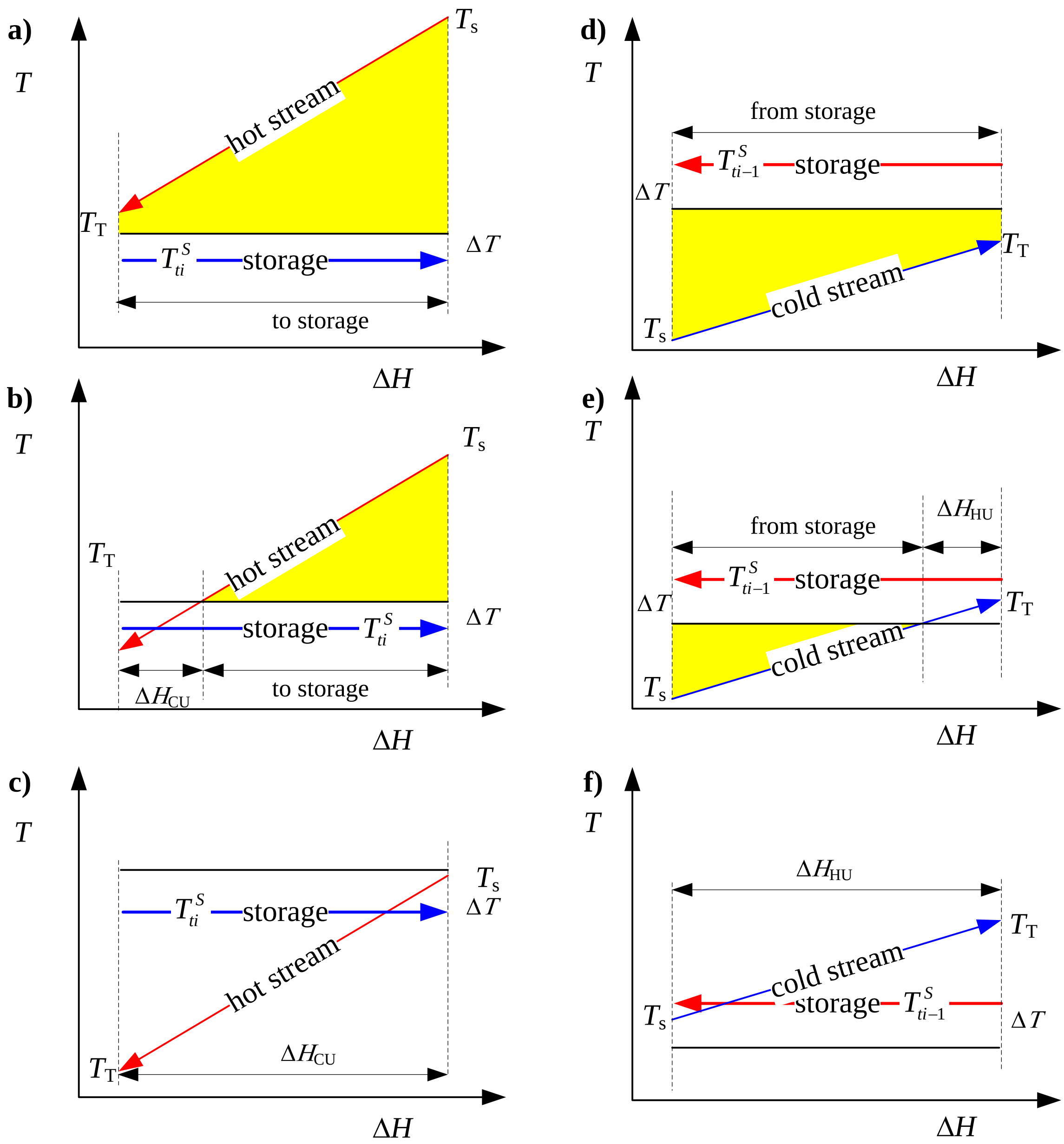


*Figure 31: Possible options of a)-c) storing heat from process or d)-f) covering process heat demand from storage*

Eq. 58 is applied based on process stream properties in order to determine the amount of the stored heat:

$$Q_{ti}^{excess} = CP \cdot \left(T_{ti}^{in} - T_{ti}^{out}\right) \cdot \left(t_{ti} - t_{ti\text{-}1}\right) \qquad (58)$$

When only part of the heat surplus can be stored the equation has to be modified, in order to calculate the amount of heat, which is feasible to transfer (Eq. 59)

$$Q_{ti}^{excess} = CP \cdot \left(T_{ti}^{in} - \max\left(T_{ti}^{S} + \Delta T_{\min}, T_{ti}^{out}\right)\right) \cdot \left(t_{ti} - t_{ti-1}\right) \qquad (59)$$

However, when no heat can be stored, the above equation would give negative value, which would mean that the heat is taken from the process, which requires heating and transferred to the storage. This is meaningless to perform, what should be taken into account also in the equation; therefore to calculate the amount of heat stored the following equation is used.

$$Q_{ti}^{excess} = \max\left(0, CP \cdot \left(T_{ti}^{in} - \max\left(T_{ti}^{S} + \Delta T_{\min}, T_{ti}^{out}\right)\right) \cdot \left(t_{\mathrm{ti}} - t_{\mathrm{ti}-1}\right)\right) \tag{60}$$

The determination of heat amount transferred from storage to process stream with heat demand the initial equation is the following.

$$Q_{ti}^{demand} = CP \cdot \left(T_{ti}^{out} - T_{ti}^{in}\right) \cdot \left(t_{\mathrm{ti}} - t_{\mathrm{ti}-1}\right) \tag{61}$$

In order to ensure feasible heat transfer, when the heat is covered only partly from the storage Eq. 61 is updated to:

$$Q_{ti}^{demand} = CP \cdot \left(\min\left(T_{ti}^{out}, T_{ti}^{S} - \Delta T_{\min}\right) - T_{ti}^{in}\right) \cdot \left(t_{\mathrm{ti}} - t_{\mathrm{ti}-1}\right) \tag{62}$$

In order to exclude infeasible heat exchanges, with negative heat transfer the equation for determining the amount of heat for process stream covered from storage is the following:

$$Q_{ti} = \max\left(0, CP \cdot \left(\min\left(T_{ti}^{out}, T_{ti}^{S} - \Delta T_{\min}\right) - T_{ti}^{in}\right) \cdot \left(t_{\mathrm{ti}} - t_{\mathrm{ti}-1}\right)\right) \tag{63}$$

As a last step, the utility requirement in each time interval should be determined as the difference between hear surplus/ requirement and the heat stored to/ covered from storage.

## 7.4 Application of the model in an Excel spreadsheet

An Excel spreadsheet has been developed in order to be able to perform the calculations described in this section. It consists of couple of subsection:

- (i) Time interval, Solar irradiation
- (ii) Solar collector
- (iii) Storage
- (iv) Process heat demand
- (v) Process heat surplus
- (vi) Utility requirement
- (vii) Storage cascading

| TIME SLICES, SOLAR IRRADIATION | | | |
| --- | --- | --- | --- |
| **Time Slice** | **Ending time [h]** | ***G* [kW/m$^2$]** | **$T_a$ [°C]** |
| 1 | 6 | 0 | 15.00 |
| | | | |
| | | | |
| | | | |
| | | | |
| 2 | 6.367 | 0 | 15.00 |

*Figure 32: Time interval enumeration and the solar irradiation, together with the ambient temperature presented in the Excel Spreadsheet*

The first column in the spreadsheet is devoted to the enumeration of the time interval. As can be seen in Figure 34, one time interval can occupy more than one row, since there can be many difference processes present in the same time interval. In the second column the ending time of the time interval are presented. This approach has been chosen in order to determine the time horizon of each time interval, which can be determined as a difference between two consecutive time interval rows. For the first Time Slice the starting time is assumed to be zero. The third column is dedicated to the measured / forecasted amount of solar irradiation. Additionally, the average ambient temperature has to be given.

Next subset of columns (Figure 35) is assigned for the solar collector system. The input data required for the modelling of the collector are:

(i) The optical efficiency of the collector ($\eta_0$)

(ii) Area of the solar collector system ($A$)

(iii) Mass flow-rate of the media through the collector ($\dot{m}$)

(iv) Solar collector thermal loss coefficient ($a_1$)

(v) Specific heat of the medium used for heat transfer from collectors to the storage ($cp$)

The inlet temperature of the solar collector system is equal to the temperature of the storage at the end of the previous time interval. The outlet temperature is determined as described in Section 7.1. The amount of heat is determined as the temperature difference between outlet and inlet temperature multiplied with the specific heat capacity of the medium for heat transfer, mass flow-rate and the time horizon of the time interval.

| SOLAR COLLECTOR | | |
|---|---|---|
| | | |
| n0= | 0.76 | % |
| A= | 1000 | $m^2$ |
| m= | 1 | kg/s |
| a1= | 0.0153 | $kW/m^2$ |
| cp= | 4.2 | kWs/(kg °C) |
| **$T_{in}$ [°C]** | **$T_{out}$ [°C]** | **$Q$ [kWh]** |
| 15.00 | 15.00 | 0.00 |
| | | |
| | | |
| | | |

*Figure 33: Input and calculated data regarding the solar collector system in the Excel spreadsheet*

The following subset of columns is dedicated to the storage (Figure 36). For describing the storage performance the mass of heat storage medium and its specific heat capacity should be specified as an input data. The storage temperature at the end of the time interval is determined as described in Section 7.2. The determination of the amount of heat stored in a certain time interval is performed similarly as for the amount of captured heat.

| STORAGE | | |
|---|---|---|
| | | |
| cp | 4.2 | kWs/(kg °C) |
| m= | 5000 | kg |
| **$T_{in}$ [°C]** | **$T_{out}$ [°C]** | **$Q$ [kWh]** |
| 20 | 20.00 | 0 |
| | | |
| | | |
| | | |

*Figure 34: Part of the Excel Spreadsheet regarding the storage*

The third subsection of columns (Figure 37) presents the heat demand for the processes, included in the evaluation. In order to obtain feasible heat transfer the temperature difference as presented in Section 7.3 should be considered. Therefore, the following input data are required for the process demand:

(i) Supply temperature

(ii) Target temperature

(iii) Heat capacity flow-rate

(iv) Temperature difference required for a feasible heat exchange.

From these data, the achieved temperature obtained by the heat available from the storage can be determined as described in Section 7.3. When it is determined, the amount of heat covered from storage can be determined as well, and furthermore, the amount of hot utility required in certain time interval can be determine as the difference between the heat demand of the stream and the demand covered from the heat available from storage. Additional flexibility of the integration can be achieved by selecting the required temperature difference between the storage and the process demand separately for each stream.

| **PROCESS HEAT DEMAND** | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| $T_{in}$ [°C] | $T_{out}$ [°C] | **CP** | $\Delta T_{min}$ | $Q$ [kWh] | **ΔT/°C** | **from Storage** |
| 33 | 60 | 0.446 | 5 | 72.252 | 0.00 | 0 |
| 18 | 25 | 5.864 | 5 | 246.288 | 0.00 | 0 |
| 15 | 25 | 8.8 | 5 | 528 | 0.00 | 0 |
| 15 | 45 | 0.83300 | 5 | 149.94 | 0.00 | 0 |
| | | | | **996.48** | **0.00** | **0** |

*Figure 35: Part of the Excel spreadsheet connected to the process heat demand*

However, the storage might be applied also for storing the heat surplus of processes. Therefore, a subset of column (Figure 30) is introduced in order to account for the heat surplus from the process.

| **PROCESS HEAT SURPLUS** | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| $T_{in}$ [°C] | $T_{out}$ [°C] | **CP** | $\Delta T_{min}$ | $Q$ [kWh] | **ΔT/°C** | **to storage** |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| 85 | 40 | 0.444 | 5 | 7.33 | 20.00 | 3.25896 |
| 80 | 40 | 1.875 | 5 | 27.53 | 15.00 | 10.32188 |

*Figure 36: Part of Excel spreadsheet dedicated to the process heat surplus*

The required data is quite similar to the one, needed for the heat demand. For the hot streams the supply and target temperature, heat capacity flow-rate and the minimal temperature difference required for a feasible heat exchange should be presented. The target temperature obtained after the heat exchange between process streams and the storage is determined as described in Section 7.2.

As mentioned before the hot and the cold utility requirement (Figure 39) are determined by the difference of the head demand/ surplus of the streams and the heat demand/ surplus covered by/ stored to storage. These columns might be extended, when multiple utilities are available. Additionally, a constraint for the distribution of heat demand/surplus between the multiple utilities available should be introduced.

| UTILITY REQUIREMENT | |
|---|---|
| **hot utility** | **cold utility** |
| 72.252 | 0 |
| 246.288 | 0 |
| 528 | 0 |
| 149.94 | 0 |
| **996.48** | |

*Figure 37: Part of the spreadsheet, which serves for determining the utility requirement*

## 7.5 Summary

As discussed already in the Section 4, the feasibility of the heat exchange is an important property in order to establish proper calculation of solar thermal energy integrated. The previously described approach for ensuring integration served for evaluation of all the heat exchanges, which occurs, when integrating solar thermal energy based on averages irradiation values. However, those average values can be significantly different from the real-time values. In the current Section 7 a numerical procedure for monitoring the current performance of the integrated amount of heat considering varying temperature during time intervals has been developed. Additionally, a short-term decision-making can be supported regarding process operation. By establishing this procedure the outlet temperature of the medium in the collector and storage temperature can be determined in every time interval separately, accounting for lower limit on of possible heat exchange in the next time interval. The advantage of the model presented is its simplicity. Therefore, it can be easily adopted to a numerous computer programmes or either by manual recalculations. An Excel Spreadsheet is presented as an example of a tool.

# 8 Nomenclature

| | |
|---|---|
| $LV$ | large value (Big M formulation) |
| $y_i$ | binary variable for selection/deselection of time interval boundary as Time Slice boundary |
| TiSl | Time Slice |
| cTiSl | combined Time Slice |
| CC | Composite Curve |
| BCC | Balanced Composite Curve |
| GCC | Grand Composite Curve |
| TSP | Total Site Profiles |
| MCTC | Minimal Capture Temperature Curve |
| $MCTC_T$ | Minimal Capture Temperature Curve considering required temperature difference |
| $CP$ | heat capacity flowrate |
| $\Delta T_{\mathrm{min}}$ | minimal temperature difference for heat exchange |
| $\Delta T_{P\mathrm{min}}$ | minimal temperature difference for heat exchange between cold process stream and a stream from storage |
| $\Delta T_{\mathrm{Cmin}}$ | minimal temperature for heat exchange between stream from collector and storage |
| $\Delta T_{DT\mathrm{min}}$ | temperature difference between the outlet and the inlet temperature of the stream, from which the heat is transferred to demand |
| $\Delta T_{DT\mathrm{min}}$ | minimal temperature difference required |
| $\Delta T_{\mathrm{EN\text{-}EX}}$ | temperature difference between the exothermic and endothermic reaction |
| $\dot{q}_m^{storage}$ | mass flow rate of the stream transporting heat from storage to process demand |
| $cp^C$ | specific heat of medium in the stream flowing through collectors |
| $Q_{ti}^S$ | amount of heat in storage at the end of the time interval *ti*, kWh |
| $Q_{ti-1}^S$ | amount of heat in storage at the beginning of the time interval *ti*, kWh |
| $Q_{ti}^{C,out}$ | amount of heat in stream transported from solar collector to storage within time interval *ti*, kWh |
| $Q_{ti}^{excess}$ | amount of heat transferred from hot processes to storage, kWh |
| $Q_{ti}^{C,in}$ | amount of heat in stream transferred to solar collector within time interval *ti*, kWh |

| | |
|---|---|
| $Q_{ti}^{demand}$ | amount of heat utilised for covering process heat demand, kWh |
| $m^{S}$ | storage mass , kg |
| $T_{ti}^{S}$ | temperature of storage at the end of the time interval ,°C |
| $cp^{S}$ | specific heat of medium in storage, |
| $T_{ti-1}^{S}$ | temperature of storage at the beginning of the time interval, °C |
| $CP_{ti}^{C}$ | heat capacity flow rate of stream from storage to collector and vice versa, kW/°C |
| $CP_{ti}^{ex}$ | heat capacity flow of stream from storage to hot process stream and vice versa, kW/°C |
| $CP_{ti}^{dem}$ | heat capacity flow of stream from storage to cold process stream and vice versa, kW/°C |
| $CP_{representative\_stream}$ | heat flow rate capacity of representative stream |
| $Cp_{storage\_medium}$ | specific heat of medium for transport from storage to process demand |
| $m^{storage}$ | estimated mass of storage |
| $t^{res}$ | residence time in pipes and heat exchangers |
| $Q_{ti}^{S}$ | amount of heat in storage within time interval *ti*, kWh |
| $Q_{out}^{C}$ | amount of heat returned from solar collector within time interval ti, kWh |
| $Q^{excess}$ | surplus of heat in process within time interval |
| $Q_{ti}^{C,in}$ | amount of heat in the inlet stream to collector, kWh |
| $Q_{ti}^{demand}$ | amount of heat transferred from storage to process demand, kWh |
| $\Delta Q_{ti}$ | amount of heat gained from solar source of energy within time interval *ti*, kWh |
| $\Delta H_{ti}$ | enthalpy of heat gained from solar source of energy, kW |
| $t_{ti}$ | boundary of time interval |
| $\Delta H$ | enthalpy, kW |
| $T$, | temperature, °C |
| $G$ | solar irradiation, W/m$^2$ |
| $G_{ti}$ | solar irradiation approximation within time interval, W/m$^2$ |
| $t$ | time, h |
| $\Delta H_{\mathrm{TiSl}}$ | enthalpy change within Time Slice *i*, kW |
| $A$ | solar collector area, m$^2$ |
| $A_{TiSl}$ | solar collector area within Time Slice |
| $\eta_{\mathrm{C}}$ | efficiency of solar collector |
| $\eta_0$ | optical efficiency of solar collector |

8.Nomenclature

| | |
|---|---|
| $T_A$ | ambient temperature |
| $\Delta H_{CU}$ | cold utility enthalpy, kW |
| $\Delta H_{HU}$ | hot utility enthalpy, kW |
| $\rho^{medium}$ | density of the medium in storage |
| $T_{in}^{C}$ | inlet temperature of stream flowing through collector |
| $V^{storage}$ | volume of storage |
| $I^{C}$ | investment of solar collectors |
| $I^{storage}$ | investment in storage |
| $I$ | investment |
| $c^{savings}$ | cost of savings due to integration of solar thermal energy in one year |
| $ROI$ | return on investment |
| $T_{out}^{C}$ | outlet temperature of stream flowing through collector |
| $T_{ti}^{C,out}$ | outlet temperature of stream flowing through collector within time interval |
| $T_{ti}^{C,in}$ | inlet temperature of stream flowing through collector within time interval |
| $T_{ti}^{A}$ | ambient temperature within time interval |
| $T_C$ | average temperature of medium in the collector, °C |
| $a_1, a_2$ | solar thermal loss coefficients, W/(°C m$^2$), W/(°C$^2$ m$^2$) |
| $SD_i$ | straightforward difference between real and approximated irradiaton in Time slice *i*, W/m$^2$ |
| $RS_i$ | real irradiation in Time Slice *i* W/m$^2$, |
| $AS_i$ | approximated irradiation in Time Slice *i,* W/m$^2$ |
| $PD_i$ | positive difference between real and approximated irradiation in Time Slice *i*, W/m$^2$ |
| $ND_i$ | negative difference between real and approximated irradiation, W/m$^2$ |
| $ED_i$ | absolute value of the difference between real and approximated supply in Time Slice *i*, |
| $TS_i$ | Time Slice boundary |
| $NTS$ | number of Time Slices |
| $IN_i$ | inaccuracy within Time Slice *i*, |
| $\dot{q}_{ti}^{m,C}$ | mass flowrate of the medium through |
| $INA$ | overall inaccuracy, Wh/m$^2$ |
| $A_0$ | amount of solar irradiation on a unit of surface, Wh/m$^2$ |

| | |
|---|---|
| $\varepsilon$ | tolerance set by user |
| $w$ | weight in the objective function for number of Time Slices |
| $T_T$ | target temperature of stream, °C |
| $T_S$ | supply temperature of stream, °C |
| $z$ | objective function |

# 9 Summary of accomplishments

## 9.1 Original Contributions

Based on the novel approaches and scientific contributions presented in previous chapters are representing some basic discoveries. These accomplishments and the main results of the work can be summarised as follows.

### *9.1.1 Creating Combined Time Slices for integration of Solar Thermal Energy*

The most challenging property of some of the renewables, including solar, is their intermittent load of supply. Different approaches are possible for dealing with this property. Usually there are two main approaches: i) either a dynamic model, which can be precise but however time and human resource consuming or ii) multi-period models with considered steady-states within periods. The latter approach was used in this work. Traditionally, a number of time intervals are high enough in order to achieve high accuracy. This is a well-developed approach, when the only supply-side is described. However, when the aim is to integrate the Solar Thermal Energy the demand-side has to be considered as well. Therefore, a higher number of time intervals increases the complexity of the problem. Thus, the integration of Solar Thermal Energy is performed at each time interval separately and furthermore the variations in load can also occur on the demand-side, so the number of time intervals should be kept as low as possible. A decreased number of time intervals leads to increased inaccuracy. It is a typical trade-off problem, for which a mixed integer linear optimisation was used. Therefore, a large number of time intervals are reduced to Time Slices with longer time horizons with assumed constant loads at acceptable tolerance. After obtaining Time Slices on both the supply and demand -sides, they are joined to one time frame only, which are the Combined Time Slices.

### *9.1.2 Ensuring feasible integration of Solar Thermal Energy*

The first step of integration was to obtain the same time frames for the supply and the demand sides. In this way any possible heat exchange matches could be identify. For a successful heat exchange also the temperature difference as a driving force of exchange also had to be guaranteed. It depends on two main factors i) the required minimal temperature difference and ii) correlation of heat capacity flow-rates of the two streams between which the heat exchange occurs. This is important during the integration of Solar Thermal Energy as two feasible heat transfers should be achieved, usually by applying indirect way of utilization through heat storage is applied. As the heat collected through solar panels is stored for latter utilization regarding heat demands it is transferred from collector to storage and when needed to processes with heat demand. In order to evaluate these entire heat transfers two graphical tools were deployed, namely the Minimal Capture Temperature Curves (MCTC) for temperature feasibility and for heat capacity flow rate. Furthermore, an algorithm was developed regarding how to use these curves for the direct and indirect Solar Thermal Energy Integration.

### 9.1.3 ***Estimation of integrated amount of Solar Thermal Energy***

Modelling the collector system solely does not contain information about the amount of integrated solar thermal energy. The storage size and solar collector area should be estimated in order to evaluate the whole design of the Solar Thermal Energy integration system. The size of the solar collector area and solar panels is determined based on the number of sunny and shady days. This ratio is then used to determine the size of solar panel surfaces by considering the solar panel surface for a single day and multiply it by this ratio in order to obtain the total for all days. The storage size depends on the quantity of heat, which is the sum of the number of shady days, a single night demand and heat losses. By determining the size of the solar panels and collector area one can prepare a preliminary Solar Thermal Energy integration system analysis for integration of solar energy.

### 9.1.4 ***Model for monitoring and short term estimation of integrated amount of solar thermal energy***

At the designing stage of the solar integration system an average solar irradiation is used, however, the daily irradiation curve can differ from averages quite significantly. For the purpose of monitoring the current state of the solar system performance a short-term monitoring is required. This short-term monitoring can support the short-term expected requirement of external utility consumption or can help the scheduling of the processes if there is a degree of freedom. For this purpose a simple algebraic approach for determining the outlet temperature of medium from solar collector, the storage temperature, the integrated amount of solar thermal energy can be estimated. Moreover, the cumulative amount of gained and integration amount of solar thermal energy can be monitored in order to follow up the external utility consumption as well as the efficiency performance of the integration system.

## 9.2 List of publications

The PhD publication is categorized according to the PhD school credit system (Accomplished over the 3 year PhD School), 3 Journal papers and 20 International conference papers:

**International Journals with impact factor:**

**Nemet A,** Klemeš JJ, Varbanov PS, Kravanja Z, 2012, Methodology for Maximising the Use of Renewables with Variable Availability, Energy, 44(1), 29-37, doi: 10.1016/j.energy.2011.12.036

**Independent citation No.:16**

**Impact factor: 3.651**

**Nemet A,** Klemeš JJ, Kravanja Z, 2012, Integration of Solar Thermal Energy into Processes with Heat Demand, Clean Technologies and Environmental Policy, 14(3), 453-463, doi: 10.1007/s10098-012-0457-6.

**Independent citation No.:6**

**Impact factor: 1.827**

Tabasová A, Kropáč J, Kermes V, **Nemet A**, Stehlík P, 2012, Waste-to-Energy Technologies: Impact on Environment, Energy, 146–155, doi: 10.1016/j.energy.2012.01.014

**Independent citation No.:15**

**Impact factor: 3.651**

**International Conference Papers / Presentation**:

C1. **Nemet A.**, Varbanov P. S., Klemeš J. J., An Algorithm for Determination of Time Slices with Constant Load for Integration of Renewable Sources of Energy, VOCAL 2010 PROGRAM and ABSTRACT, pg 46

C2. **Nemet A.**, Klemeš J. J., Determination of optimal temperature for solar capture and storage– Captured Solar Energy Curve and Minimal Capture Temperature Curve, Conference of Chemical Engineering 2011, pg 52

C3. **Nemet A.**, Klemeš J.J., Optimising the Temperature of Heat Storage to Serve Processes with Varying Supply and Demand - Captured Solar Energy Curve. Chemical Engineering Transactions, 25, 2011, 605-610, DOI:10.3303/CET1125101.

**Citation No.:3**

C4. Nemet A., Varbanov P., Klemeš J.J., Waste-to-Energy Technologies Performance Evaluation Techniques. Chemical Engineering Transactions, 25, 2011, 513-520, DOI:10.3303/CET1125086.

**Citation No.:7**

C5. **Nemet A**., Klemeš J. J., Varbanov P. S., 2011. Methodology for Maximising the Use of Renewables with Variable Availability. Computer Aided Chemical Engineering, 29(B), 2011, 1944-1948

**Citation No**.:**2**

C6. Varbanov P., **Nemet A.**, Klemeš J.; The Dynamic Total Site Heat Cascade for Integration and Management of Renewables with Variable Supply and Demand, Book of abstracts on 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES, September 25-29, 2011, Dubrovnik, Croatia, pg.74.

C7. **Nemet A.**, Varbanov P.S., Kapustenko P., Durgutović A., Klemeš J. J. 2012, Capital Cost Targeting of Total Site Heat Recovery, Chemical Engineering Transactions, DOI:10.3303/CET1226039

**Citation No.:3**

C8. **Nemet A.**, Varbanov P. S., Kapustenko P., Durgutovic A. , Klemes J. J., Capital Cost Targeting of Total Site Heat Recovery, CAPE Forum 2012, 26 – 28 March 2012, Veszprém, Hungary. INTHEAT-D6.1-02

C9. **Nemet A.**, Klemeš J.J., Varbanov P.S., Kravanja Z., (2012) Integrating renewables with varying availability to processes with heat demand, Conference of Chemical Engineering 2012, Veszprém, 24-26 April 2012, p135.

C10. Varbanov P.S., **Nemet A.**, Klemeš J.J., 2012, Heat Exchanger Area Targeting by an Extended Total Site Methodology, Conference of Chemical Engineering 2012, Veszprém, 24-26 April 2012, p133.

C11. **Nemet A.**, Klemeš J.J., Varbanov P.S., Kravanja Z., Maximising the Use of Renewables with Variable Availability, The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems – ECOS 2012, June 26th-29th, 2012

C12. **Nemet A.**, Hegyháti M., Klemeš J.J., Friedler F., Rescheduling operations demands to increase solar energy utilisation, 7th Conference on Sustainable Development of Energy, Water and Environment Systems, 1-7 July 2012, Ohrid, Republic of Macedonia SDEWES12-0380

C13. **Nemet A,** Čuček L, Varbanov P S, Klemeš J J, Kravanja Z., The Potential of Total Site Process Integration and Optimisation for Energy Saving and Pollution Reduction, Proceedings of the 7th Conference on Sustainable Development of Energy, Water and Environment Systems, 1-7 July 2012, Ohrid, Republic of Macedonia, SDEWES12-0555

C14. **Nemet A.**, Klemeš J. J., Varbanov P. S., Walmsley M. R. W., Atkins M. J., (2012), Total site methodology as a tool for planning and strategic decisions, Chemical Engineering Transactions, 29, 115- 120.

**Citation No.:4**

C15. **Nemet A.**, Boldyryev S., Varbanov P. S., Kapustenko P. O., Klemeš J. J., (2012), Capital cost targeting of total site heat recovery, Chemical Engineering Transactions, 29, 1447-1452

**Citation No.:3**

C16. **Nemet A.**, Hegyháti M., Klemeš J. J. and Friedler F., (2012), Increasing solar energy utilisation by rescheduling operations with heat and electricity demand, Chemical Engineering Transactions, 29, 1483-1488

C17. Barkaoui A.E., **Nemet A.**, Varbanov P.S., Klemeš J.J., Zarhloule, Y., Rimi A., 2013. Integration of Geothermal Energy in the Case of North Eastern Morocco, Chemical Engineering Transactions, 32, 247-252 DOI: 10.3303/CET1332042

C18. Boldyryev S., Varbanov P.S., **Nemet A.**, Kapustenko P., Klemes J.J., 2013, Targeting minimum heat transfer area for heat recovery on total site, Chemical Engineering Transactions, 35, 79-84 DOI:10.3303/CET1335013

C19. Boldyryev S, Varbanov P, **Nemet A.**, Klemeš J.J, Kapustenko P., Minimum Heat Transfer Area for Total Site Heat Recovery Proceedings of the 8th Conference on Sustainable Development of Energy, Water and Environment Systems, 22-27, September, 2013, Dubrovnik, Croatia SDEWES2013-0214,

C20. Barkaoui A.-E., Zarhloule Y., Duić N., Krajačić G., Klemeš J.J., Varbanov P., **Nemet A.** Geothermal energy in Morocco: sustainability and environment impact. Proceedings of the 8th Conference on Sustainable Development of Energy, Water and Environment Systems, 22-27, September, 2013, Dubrovnik, Croatia, SDEWES2013-0186

# 9. Summary of accomplishments

# 10 References


1. ACRUX, 2014,< www.acrux.hu/en/sun/solarcollector2.html>, accessed: 2.5.2014
2. Alibaba, <www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=solar+collector>, accessed: 4.5.2014
3. Angelis-Dimakis A., Biberacher M., Dominguez J., Fiorese G., Gadocha S., Gnansounou E., Guariso G., Kartalidis A. Panichelli L., Pinedo I., Robba M., 2011, Methods and tools to evaluate the availability of renewable energy sources, Renewable and Sustainable Energy Reviews, 15(2), 1182-1200.
4. Asthana A., Ménard Y., Sessiecq P., Patisson F., 2010. Modeling On-Grate MSW Incineration with Experimental Validation in a Batch Incinerator. Industrial and Engineering Chemistry Research, 49, 7597-7604.
5. Atkins M. J., Walmsley M. R., Morrison A. S., 2010. Integration of solar thermal for improved energy efficiency in low-temperature-pinch industrial processes. Energy, 35(5), 1867-1873.
6. Barbier E., 2002. Geothermal energy technology and current status: an overview. Renewable and Sustainable Energy Reviews, 6, 3-65.
7. BP, Statistical Review of World Energy June 2012. <www.bp.com/content/dam/bp/pdf/ statistical-Review-2012/statistical_review_of_world_energy_2012.pdf>, accessed 14.01.2014
8. EC, 2006 Integration Pollution Prevention and Control Bureau. Reference Document of the Best Available Techniques for Waste Incineration. , <eippcb.jrc.ec.europa.eu/reference/BREF/wi_bref_0806.pdf>, accessed 14.01.2014
9. EC, 2009, Official Journal of the European Union, Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
10. Chaabene, M., Annabi, M., 1998. Dynamic thermal model for predicting solar plant adequate energy management. Energy Conversion and Management, 39, 349-355.
11. C-Tech Innovation, L., 2003. Biffaward programme on sustainable resource use - Thermal methods of municipal waste treatment. <www.resol.com.br/textos/Thermowaste.pdf>, accessed 14.01.2014
12. D. Connolly, H. Lund, B.V. Mathiesen, Leahy, 2010, A review of computer tools for analysing

the integration of renewable energy into various energy systems, Applied Energy, 87(4),

13. De Benedetto L., Klemeš, J., 2009. The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. Journal of Cleaner Production, 17(10), 900-906.
14. Demirbas A., 2007. Progress and recent trends in biofuels. Progress in Energy and Combustion Science, 33(1), 1-18.
15. Demirbas A., 2011. Competitive liquid biofuels from biomass. Applied Energy, 88(1), 17-28.
16. Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions and cooling. Computers and Chemical Engineering, 17, 101-109.
17. Erdil E., Ilkan M., Egelioglu F., 2008. An experimental study on energy generation with a photovoltaic (PV) -solar thermal hybrid system. Energy, 33(8), 1241-1245.
18. Frein A., Calderoni M., Motta M., 2014, Solar thermal plant integration into an industrial process, Energy Procedia 48, 1152-1163.
19. Fodor Z., Perry S., Varbanov P.S., Klemeš J.J., 2010, Total site targeting accounting for individual process heat transfer characteristic. Chemical Engineering Transactions, 21, 49-54. doi:10.3303/CET1021009
20. GeoModel Solar, 2013, <re.jrc.ec.europa.eu/pvgis/apps4/pvest.php> accessed 10.10.2013
21. Gl Garrad Hassan pacific Pty Ltd, Barry H., Yeo S., 2011. Review of the Australian wind industry 2011. <www.cleanenergycouncil.org.au/dms/cec/reports/2011/CEC_Review-of-the-Australian-wind-industry-2011/Review%20of%20the%20Australian%20wind%20industry%202011.pdf> , accessed 8.11.2013
22. Grieco E., Poggio A., 2009. Simulation of the influence of flue gas cleaning system on the energetic efficiency of a waste-to-energy plant. Applied Energy, 86(9), 1517-1523.
23. Goswami D. Y, Kreith F., 2008, Energy conversion, CRC Press, Boca Raton, USA.
24. Gude V. G., Nirmalakhandan, N., Deng, S., 2011. Desalination using solar energy: Towards sustainability. Energy, 36 (1), 78-85.
25. Holm-Nielsen J., Al Seadi T., Oleskowicz-Popiel P., 2009. The future of anaerobic digestion and biogas utilization. Bioresource Technology, 100 (22), 5478-5484.
26. Huang Y., Dong, H., Shang, B., Xin, H., Zhu, Z., 2011. Characterization of animal manure and cornstalk ashes as affected by incineration temperature. Applied Energy, 88(3), 947-952.
27. Huggins R., 2010. Energy Storage. Springer, New York, USA.
28. Internationa Energy Agency - IEA, 2012. World Energy Outlook 2012 Executive Summary. <www.iea.org/publications/freepublications/publication/English.pdf> accessed 10.02.2014
29. Jegla Z, Bébar L, Pavlas M, Kropác J, Stehlík P., 2010. Secondary Combustion Chamber with

Inbuilt Heat Transfer Area-Thermal Model for Improved Waste-to-Energy Systems Modelling. Chemical EngineeringTransactions, pp. 859-864.

30. Joselin Herbert G., Iniyan S., Sreevalsan E., Rajapandian S., 2007. A review of wind energy technologies. Renewable and Sustainable Energy Reviews, 11(6), 1117-1145.
31. Kane CRES—Center for Renewable Energy Sources and Savings ,2009, Solar systems applications in the dairy industry. <www.cres.gr/kape/pdf/download/dairy_leaflet.pdf > accessed 10.12.2013
32. Kaldellis J. K., Zafirakis D., 2011. The wind energy (r)evolution: A short review of a long history. Renewable Energy, 36(7), 1887-1901.
33. Kemp I. C., 2007. Pinch Analysis and Process Integration A User Guide on Process Integration for the Efficient Use of Energy. 2. ed. New York: Butterworth-Heinemann.
34. Kemp I., Deakin A., 1989. The Cascade Analysis for Energy and Process Integration of Batch Processes, Part 1: Calculation of Energy Targets. Chemical Engineering Research and Design, 67, 495-509.
35. Klemeš J., Dhole V.R., Raissi K., Perry S.J., Puigjaner L., 1997, Targeting and design methodology for reduction of fuel, power and $CO_2$ on total sites. Applied Thermal Engineering, 17, 993-1003.
36. Klemeš J., Friedler F, Bulatov I, Varbanov P, 2010. Sustainability in the Process industry – Integration and Optimization.McGraw-Hill, New York, USA.
37. Lee B., Byeon S., 2009. Energy Potential from Industrial Solid Waste. Proceedings of the 4$^{th}$ IASME / WSEAS International Conference on Energy and Environment (EE'9), 88-93.
38. Li T., Zhu J., Zhang W., 2012, Cascade utilization of low temperature geothermal water in oilfield combined power generation, gathering heat tracing and oil recovery, Applied Thermal Engineering, 40, 27-35.
39. Linnhoff B., Townsend D. W., Boland D., Hewitt G.F., Thomas B.E.A., Guy A.R., Marsland R.H., 1982, last edition 1994. A user guide on process integration for the efficient use of energy. IChemE, Rugby UK.
40. Liuzzo G., Verdone N., Bravi M., 2007. The benefits of flue gas recirculation in waste incineration. Waste Management, 27(1), 106-116.
41. Ludig, S., Haller, M., Schmid, E., Bauer, N., 2011. Fluctuating renewables in a long-term climate change mitigation strategy. Energy, 36(11), 6674-6685.
42. Mauthner F, Hubmann M., Brunner C., Fink C., 2014, Manufacture of malt and beer with low temperature solar process heat, Energy Procedia 48, 1188-1193.
43. Mawire A., McPherson M., van den Heetkamp, R., 2008. Simulated energy and exergy

analyses of the charging of an oil-pebble bed thermal energy storage system for a solar cooker. Solar Energy Materials and Solar Cells, 92(12), 1668-1676.

44. Müller H., Brandmayr S., Zörner W., 2014, Development of an evaluation methodology for the potential of solar-thermal energy use in the food industry, Energy Procedia 48, 1194-1201.
45. Münster M., Meibom, P., 2011. Optimization of use of waste in the future energy system. Energy, 36(3), 1612-1622.
46. Nemet A., Klemeš J. J., Varbanov P. S., Kravanja Z., 2012a. Methodology for maximising the use of renewables with variable availability. Energy, 44(1), 29-37.
47. Nemet A., Kravanja Z., Klemeš J. J., 2012b. Integration of solar thermal energy into processes with heat demand. Clean Technologies and Environmental Policy, 14, 453-463.
48. Niessen W., 2010. Combustion and Incineration Processes. Marcel Dekker, Inc., Basel, Switzerland.
49. Oral J., Sikula J., Puchyr R., Hajny Z., Stehlík, P., Bébar, L., 2005. Processing of waste from pulp and paper plant. Journal of Cleaner Production, 13(5), 509-515.
50. Pereira T., 2009. Sustainability: An integral engineering design approach. Renewable and Sustainable Energy Reviews, 13(5), 1133-1137.
51. Perry S., Klemeš J., Bulatov I., 2008. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy, 33(10), 1489-1497.
52. Quijera J.A., María González Alriols M., Jalel Labidi, 2014, Integration of a solar thermal system in canned fish factory, Applied Thermal Engineering, DOI: 10.1016/j.applthermaleng.2014.04.012
53. Quina M. J., Bordado J. C., Quinta-Ferreira R. M., 2008. Treatment and use of air pollution control residues from MSW incineration: An overview. Waste Management, 28(11), 2097-2121.
54. Rodríguez-Hidalgo M.C., Rodríguez-Aumente P.A., Lecuona A., Legrand M., Ventas R., 2012, Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank, Applied Energy, 97, 897-906.
55. Schnitzer H., Brunner C., Gwehenberger G., 2007. Minimizing greenhouse gas emissions through the application of solar thermal energy in industrial processes. Journal of Cleaner Production, 15(13-14), pp. 1271-1286.
56. Shaneb, O., Coates, G., Taylor, P., 2011. Sizing of residential µCHP systems. Energy and Buildings, 43(8), 1991-2001.
57. Singhabhandhu A., Tezuka, T., 2010. The waste-to-energy framework for integrated multi-waste utilization: Waste cooking oil, waste lubricating oil, and waste plastics. Energy, 35(6),

2544-2551.

58. Smil V., 2006. Energy: A Beginner's Guide. Oneworld Publications, 185 Banbury Road, Oxford,UK.
59. Smith R., 2005. Chemical Process Design and Integration. John Wiley and Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.
60. Speight J., 2008. Synthetic fuels handbook: properties, process, and performance. The McGraw-Hill Companies, Inc, New York, USA.
61. Stehlík P., 2009. Contribution to advances in waste-to-energy technologies. Journal of Cleaner Production, 17(10), 919-931.
62. Tabasová A. Kropác, J., Kermes V., Nemet, A., Stehlík, P., 2012. Waste-to-energy technologies: Impact on environment. Energy, 44(1), 146-155.
63. Texas Renewable Energy Industries Association -TREIA, 2013. <www.treia.org/renewable-energy defined> accessed 14.01.2014
64. Townsend D.W., Linnhoff B., 1983, Heat and power networks in process design. Part II: Design procedure for equipment selection and process matching. AIChE J, 29(5), 748-771.
65. Tian Y., Zhao C.Y., 2013, A review of solar collectors and thermal energy storage in solar thermal Applications, Applied Energy, 104, 538–553
66. Varbanov P. S., Klemeš J. J., 2011. Integration and management of renewables into Total Sites with variable supply and demand. Computers and Chemical Engineering, 35(9), 1815-1826.