Decision support methodology for sustainable smart energy systems integration

Thesis for the Degree of Doctor of Philosophy

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Short abstract:
The global demand for energy is continuously increasing, and the carbon dioxide production related to the energy sector represents a large share of the overall anthropogenic greenhouse gas (GHG) emissions, since most of the energy needs are still provided by fossil fuels. To achieve the energy efficiency targets set by EU for the 2030 an energy transition towards more sustainable energy sources is required. The challenge will be the integration of different energy sectors in a smart energy system (SMES). Adopting a circular economy perspective it will be possible to turn the view on waste starting considering them as an energy source allowing more interactions between different stakeholders while exploiting technologies for the reduction of the environmental impact. This change in perspective needs also a change in the paradigm while taking decision on the implementation of this kind of interventions. The aim of this thesis is to fill the gaps in the development of decision support tools aiding the stakeholders in those interventions where SMES are implemented with developing and sustainable solutions.
Keywords: SMES, circular economy, waste, optimization

List of Figures

2.1 Scheme of the developed decision support system 21
2.2 Flowchart of the energy system model [1] 33
2.3 Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorization strategies of lettuce waste [2] 49
2.4 Wastewater treatment plant process flow [3] 54
2.5 Flowchart of the electric balance equation 63
2.6 Flowchart of thermal balance equation 64
2.7 Flowchart of the CH_4 balance equation 65
2.8 SMES process flow scheme 69

3.1 Udine case study: DHN layout and main city areas characterization [1] 76
3.2 DHN energy system simulation. Hourly profile (left side) and duration curves (right side) for scenario 1 to 5 [1] 80
3.3 Pareto front for scenario 4. TES capacity versus total recovered energy (left side) and bubble diagram, represeting the relation between the economic decision variables and their influence on the project's economics (right side) [1] 82
3.4 Screenshot of the online toolbox interface [4] 84
3.5 Comparison between different waste heat recovery options [4] . 85
3.6 Main effect charts of carbonization, composting, anaerobic digestion and valorization on: a) $CO_{2,red}$ and b) PB [2] 87
3.7 Mean 24h behaviour of the influent flow-rate in the analyzed WWTP [3] 90
3.8 Influence of the main input parameters on the NPV of the proposed compressed air storage system (Scenario 1) [3] 92
3.9 Influence of air storage tnak pressure and volume on NPV for different wastewater flowrates [3] 93
3.10 Influence of the main input parameters on the NPV of the proposed compressed air storage system (Scenario 2) [3] 94
3.11 Influence of the treated wastewater flowrate on NPV and PES (Scenario 2) [3] 94
3.12 Optimization variable effect on CO2 96
3.13 Environmental and economic performances 96
3.14 Thermal energy yearly behaviour (POF) 98
3.15 Thermal energy yearly behaviour (POF+OFMSW) 98
3.16 Electric energy yearly behaviour (POF + OFMSW) 99

3.17 Electric energy yearly behaviour (POF+OFMSW) 100
3.18 PES behaviour over cogenerator size P_{CHP} 100
3.19 Optimization variable effect on CF HUB 101
3.20 Optimization variable effect on CF UM 101
3.21 Optimization variable effect on CO2 102
3.22 Optimization variable effect on PES 102
3.23 PES behaviour over cogenerator size P_{CHP} 104
3.24 Pareto fronts of HUB, food market and DHN economic performances 104

List of Tables

2.1 Fuel specific consumptions 61

3.1 Analyzed scenarios 77
3.2 Variation range of the decision variables 78
3.3 MCDM applied only to Pareto front solutions 81
3.4 Range and step of variation of the considered decision variables 83
3.5 Range and step of variation of the considered decision variables 85
3.6 MCDM applied to valorization plant solutions 88
3.7 Selected input parameters in the multi-objective optimization model 91
3.8 Selected output functions in the multi-objective optimization model 91

Contents

List of Figures iii

List of Tables v

1 Introduction 1
- 1.1 Waste recovery and circular economy . . . 2
  - 1.1.1 Heat waste . . . 3
  - 1.1.2 Food waste . . . 3
  - 1.1.3 Urban waste and wastewater . . . 4
- 1.2 Smart energy systems . . . 6
- 1.3 Decision support systems . . . 11
  - 1.3.1 Multi-Criteria Decision Making . . . 13
    - 1.3.1.1 Multi-Objective Decision Making . . . 13
    - 1.3.1.2 Multi-Attribute decision Making . . . 15
- 1.4 Research gaps and objective of the thesis . . . 16

2 Developed decision support methodology 19
- 2.1 Investigative phase . . . 20
  - 2.1.1 District heating and cooling . . . 20
  - 2.1.2 Anaerobic digestion . . . 23
  - 2.1.3 Electric/absorption chillers . . . 24
  - 2.1.4 CHP . . . 25
  - 2.1.5 Methane upgrading . . . 26
- 2.2 Design phase . . . 27
  - 2.2.1 I step: waste heat fed DHN implementation . . . 28
    - 2.2.1.1 DH system modelling . . . 30
    - 2.2.1.2 DH system operation . . . 31
    - 2.2.1.3 Heat demand characterization . . . 33
    - 2.2.1.4 Environmental impact evaluation . . . 35
    - 2.2.1.5 System cost evaluation . . . 35
  - 2.2.2 II step: multiple waste heat recovery technologies . . . 39
    - 2.2.2.1 Recovery system modelling . . . 39
    - 2.2.2.2 Technology design . . . 40
    - 2.2.2.3 Availability and demand characterization . . . 40
    - 2.2.2.4 ORC . . . 41
    - 2.2.2.5 Absorption chiller . . . 42
    - 2.2.2.6 Heat exchanger . . . 43
    - 2.2.2.7 Heat pump . . . 44
    - 2.2.2.8 District heating . . . 45
    - 2.2.2.9 Environmental impact evaluation . . . 45

2.2.2.10 Cost evaluation 45
2.2.3 III step: valorisation of food waste 47
2.2.3.1 Waste treatment plant model 47
2.2.3.2 Energy demand 50
2.2.3.3 Environmental impact evaluation 51
2.2.3.4 Economic analysis 51
2.2.4 IV step: wastewater treatment 53
2.2.4.1 System configuration 54
2.2.4.2 Biological treatment unit 55
2.2.4.3 Compressed air storage 55
2.2.4.4 Anaerobic digestion unit 56
2.2.4.5 Environmental impact evaluation 57
2.2.4.6 Economic analysis 57
2.2.5 V step: waste collection modelling 59
2.2.5.1 Collection routes modelling 59
2.2.5.2 Waste treatment plant 62
2.2.5.3 Environmental impact evaluation 65
2.2.5.4 Cost evaluation 66
2.2.6 Smart multi energy system model 68
2.2.6.1 Waste treatment plant 69
2.2.6.2 Wastewater treatment plant 69
2.2.6.3 Food market 70
2.2.6.4 District heating network 70
2.2.7 Environmental analysis 70
2.2.8 Economical analysis 71
2.2.9 Multi-objective optimization 72
2.3 Decision phase 73

3 Results 75
3.1 I step: waste heat fed DHN implementation 75
3.1.1 Case study 75
3.1.2 Results 78
3.1.2.1 MCDM analysis 79
3.1.2.2 Pareto fronts 82
3.2 II step: multiple waste heat recovery technologies 83
3.3 III step: valorisation of food waste 84
3.3.1 Case study 84
3.3.2 Results 86
3.3.3 MCDM analysis 88
3.4 IV step: wastewater treatment 89
3.4.1 Case study: 89
3.4.1.1 Optimization model implementation 90

3.4.2 Result 91
3.4.2.1 Scenario 1: Compressed air storage without anaerobic digestion 92
3.4.2.2 Scenario 2: Compressed air storege with anaerobic digestion 93
3.5 V step: waste collection modelling 94
3.5.1 Validation of the route modelization 95
3.5.2 Results 95
3.6 Smart multi energy system 97
3.6.1 Scenario 1: NET + CAFC 97
3.6.2 Scenario 2: NET + CAFC + UDINE MERCATI 99
3.6.3 Scenario 3: NET + CAFC + UDINE MERCATI + DH 103

4 Conclusions **107**

Bibliography **109**

1

Introduction

The global demand for energy is continuously increasing, and the carbon dioxide production related to the energy sector represents a large share of the overall anthropogenic greenhouse gas (GHG) emissions, since most of the energy needs are still provided by fossil fuels [5]. In this context, with the aims of reduce resources consumption, fight the climate change, increase the energy security and its availability at competitive prices, European Union has adopted the 2020 climate and energy package. It sets three key goals in terms of: 1) GHG emission reduction, 2) increase of the renewable energy sources (RES) share in the energy mix, and 3) improvement of the energy efficiency [6]. Due to the commitment of the EU and its Member States to the Paris Agreement the 20% cut in emission target for 2020 has been met and new objectives have been imposed aiming at an emission reduction by at least 40% between 1990 and 2030 [7]. Targets have also been set on energy efficiency and renewable energy. Energy Efficiency and Renewable Energy Directives set a 32.5% energy efficiency target and a 32% renewable energy target for 2030, improving the goals of an energy consumption decrease of at least 27% and an increase of the RES share to 27%, compared to the levels of the 1990 reference scenario previously set[8]. The latter in particular raises the level of ambition for the heating/cooling sectors [9].

To achieve these ambitious objectives, a transition from the current approach towards a future sustainable energy system is needed. The future challenge will be the integration of the various energy sectors (electricity, heating, cooling, transport, etc.), into the so called Smart Energy System (SES), i.e. an energy system in which different energy sources, vectors and needs are combined and coordinated through a number of smart grid infrastructures in order to achieve an optimal solution for each individual sector as well as for the overall energy system [10].

1.1 Waste recovery and circular economy

The circular economy is not a concept of novelty originating from recent developments but derives from other notions established in the past decades, such as the "spaceman" economy which suggested a cyclical system capable of continuous reproduction of material, "cradle to cradle" which depicts a closed system of resource flows ” [11] and "industrial ecology" which depicts the implementation of eco-industrial park where matter are exchanged by the actors within the park and where energy is the only external input [12]. A good definition of circular economy can be "*an industrial economy that is restorative or regenerative by intention and design*", so taking into account both the environmental and economical advantages [13].
The European Commission estimated that virtuous waste management and policy design like waste prevention and reuse and eco-desing can bring up to 600 billions euro of net saving in the EU region, reducing at the same time greenhouse gas emissions. Other socio-economical effects of the implementation of circular economy can be increase of investment and generation of new job places, estimated to be 12 billions euros and 50000 respectively in the UK , and 7.3 billions euro and 54000 respectively in Netherlands.
Different application of circular economy can be found in the literature. Su et al implemented circular economy on a systemic economy-wide on three levels in China: the macro-scale (city, province and state), the meso (symbiosis association) and the micro (objects) scales [14]. Another common example of application at regional and local level are the so called eco-industrial park, based on the idea of industrial symbiosis comprehending sharing of resources and recycling waste across industries [15].
Another CE implementation approach is based on focusing on a group of sectors, products, materials or substances. This includes legislative proposals for waste management sector regarding reduction of landfilling, increased preparation for reuse and recycling of key waste streams such as municipal waste and packaging waste, following the Action Plan proposed by the European Commission to promote circular economy [16]. Turning waste into energy can be one key to a circular economy perspective, and moreover this is also in line with the EU commitments for the 2030 goals [17]. Tcvetkov reviewed the changing role of CO_2 in the global economy, considering the role of sequestration technologies in changing the view of CO_2 from not just a waste but a resource so moving from a linear to a circular economy perspective [18].

1.1.1 Heat waste

European governance is integrating energy efficiency and the recovery of waste heat into its energy policies, since industrial energy consumption constitutes about 62% of the total [19] and a huge potential for industrial waste heat recovery has been detected in Europe [20] within the identification of local heat demand and supply areas. Concerning the integration of industrial waste heat, much research has been done during the last decades, leading, among others, to the concepts of Total Site Heat Integration (TSHI) and of Locally Integrated Energy Sectors (LIES) [21]. Nardin has conducted a detailed study of the possible technologies for waste heat recovery from EAF proces, highlighting their advantages and limitations. The authors have classified these technologies in three main groups, depending on the heat recovery approach adopted: direct, indirect or innovative heat recovery [22].
The integration of the huge potential for industrial waste heat recovery detected in Europe [23] into Smart Energy System represents a main opportunity to accomplish the EU climate and energy goals. The integration of industrial waste heat has been given great attention by research during the last decades, leading, among others, to the concept of Total Site Heat Integration (TSHI), introduced with the aim to improve thermal energy saving through the integration of industrial processes. Further developments lead to the Locally Integrated Energy Sectors (LIES) conceptualisation, to include renewable energy sources as well as other sources and consumers [21]. Huge efforts have been given in developing evaluation methodologies in this field, such as e.g. Pinch Analysis, Total Site (TS) analysis and Process Integration methodologies [24].

1.1.2 Food waste

According to the estimation of the United Nations Food and Agriculture Organization (FAO), every year, one-third of the food produced in the world (about 1.3 billion metric tons) is wasted [25]. The waste generated by the fruit and vegetable sector (fruit and vegetable waste, FVW) is estimated to represent up to 60% of the food waste generated annually in the world [26]. In this regard, roughly one-third of all fruits and vegetables produced worldwide are wasted before reaching the consumer [27], and this estimation was reported to be even higher in Italy (about 87%) [28]. FVW represents a significant economic issue for companies and poses environmental problems, due to its high moisture and biodegradability. Moreover, it involves a loss of valuable biomass and nutrients. For these reasons, in the last decade, large effort has been dedicated to the development of policies for FVW management [29]. In particular, fruit and vegetable waste (FVW) valorisation into value-added derivatives has been extensively and increasingly studied in the last years. Despite this intense research activity, the current destination of FVW is mainly represented by landfilling, composting, anaerobic digestion and carbonisation [30]. However, when FVW is used this way, as a feedstock to produce energy and fertilizers, its interesting functional molecules are underutilised or lost [31]. The latter are instead maximally exploited when FVW serves as a source of bioactive compounds, functional food ingredients and biocompatible materials [32]. It must be noted that the valorisation of FVW is at an early stage of development and that essential elements must be still clarified to assess its viability [30, 33]. Firstly, data on the exact amount of waste produced from food processing is nowadays very limited. In fact, no official data are issued annually by the EU, given the commercial sensitivity of this nformation for the producers. Moreover, published data are often largely variable, due to methodological variations and to the intrinsic compositional variability of fruit and vegetables [31]. Moreover, the demand of resources (e.g. energy, water, workforce, investment for equipment) of valorisation strategies as compared to that of traditional waste management options should be evaluated. In fact, the implementation of innovative valorisation strategies is viable only if bringing environmental (e.g. reduction of carbon emission and of waste amount) and economic advantages (e.g. reduction of waste management costs and increase of revenues from sale of FVW valorisation products) as compared to traditional management strategies. It is noteworthy that most of literature studies dealing with FVW valorisation generally do not discuss these crucial environmental and economic aspects, limiting the investigation to the optimization of the process used to turn the waste material into a value-added derivative [34]. However, many of these studies exploit innovative technologies such as ultrasounds, microwaves, high pressure and supercritical fluid processing, which are well-known to require huge investment and maintenance costs, as well as specialized know-how and plants [34, 35, 36, 37]. Also, even when using technologies characterised by a high industrial maturity level (e.g. air-drying) [38, 39] an accurate cost-benefit analysis should be performed to evaluate the environmental and economic sustainability of the proposed FVW valorisation strategies [35, 36].

1.1.3 Urban waste and wastewater

In the last decades European society got wealthier changing its buying patterns, as more products are bought more often following the trends and technology

innovations leading to an higher consumption and waste production [40]. For instance, the average amount of municipal solid waste (MSW) generated in the European Union has been accounted as 477 kg per inhabitants per year in 2015 [41, 42]. Moreover, studies highlighted the strong correlations between a region wealth and its energy consumption [43]. In particular, the primary energy consumption in the EU region in 2015 was about 1530 Mtoe. Seen the growing energy consumption and knowing the average heating value of MSW (approximately 10 MJ/kg [44]) the exploitation of waste as an energy source seem a viable solution to face the problem. The European Commission highlighted that due to the common trend in the EU region a signifcant amount of potential secondary raw material obtainable from waste is getting lost, since just the 45% of the MSW being recycled, with the remaining share sent to landfilling (31%) or to incineration (26%) [45].
Different technologies are adopted nowadays for the management of MSW. Different authors reported the environmental benefits of applying anaerobic digestion (AD) for MSW management implementing it in the Peloponnese region [46] and in Tehran [47]. Perti et al. investigated the environmental impacts of upgrading system for biogas coming from AD of organic fraction of MSW. Results showed that water scrubbing leads to the lowest emission while membranes upgrading leads to the highest [48]. Di Maria recommends upgrading of biogas into biomethane instead of conventional exploitation in cogenerators due to higher environmental benefits. Moreover the need of reducing indirect emission coming from the upgrading process is highlighted [49]. Uusitalo analyzed the environmental impact of biomethane deriving from different feedstock. Results depicted how biogas from biowaste feedstock leads to lower emission and that emissions from digestate use should never be excluded [50].
The energy-water nexus has been given increasing interest worldwide in recent years, due to climate change, augmented global energy demand and significant water scarcity [51].Furthermore the energy utilization and optimization in the wastewater treatment plant (WWTP) sector has become a growing concern, considering both the economic and environmental aspects [52]. Nowadays while designing WWTPs energy efficiency is not considered a main target, and, as a consequence, information regarding WWTPS' energy consumption and recovery in the literature is still unsatisfactory [52]. Wastewater treatment is an energy-intensive sector and its energy demand is continuously augmenting due to the stringent requirements on treated water effluent quality, requiring advanced technologies for pollutant removal [53]. Indeed energy consumption in wastewater is the third largest electricity consumer in the United states, accounting for about 3.4% of the total electricity consumption [54].
Depending on the influents composing the wastewater this can be characterized by higher internal energy (in terms of chemical oxygen demand COD) leading

to more energy consuming treatment process in the plant [52]. Energy recovery from wastewater treatment can help to reduce the overall economic costs and the related environmental impact [53]. Indeed, wastewater can contain up to 12 times the energy that is needed for its treatment, and following sustainability and circular economy principles, nutrients and valuable compounds can be recovered changing the perspective on wastewater starting seeing it as a resource and no longer as a waste [55]. In addition energy surplus from the treatment plant can be integrated into energy distribution systems, . Techniques to reach this and improve energy balance have been proven to be anaerobic digestion (AD) [2, 56] sludge incineration, photovoltaic generation and thermal energy recovery [52].

1.2 Smart energy systems

In the literature a smart energy systems has been defined as "an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system" [57]. The same authors added more details in the definition saying that it is fed by 100% renewable energies, consumes a sustainable level of bio-energy, utilizes the synergies of a system to maximize efficiency and reduces costs making it more affordable [58].
A typical smart energy system is constituted by four different elements: energy generation systems, energy end users, energy distribution and storage systems, and smart energy management systems. Energy is fed into SMES by energy generation systems transforming primary energy sources into other forms like electricity and heat (cold), preferibly utilizing renewable energy sources technologies like photovoltaic solar, hydro and wind turbine and co or trigeneration units (CCHP). However due to unpredictability of renewable energy sources often the integration of fossil fuel is requested to assure resilience and normal operation of the system. Many different studies investigating energy generation in SMES can be found in literature. Good environmental and economic advantages can be obtained in distributed energy generation system by the implementation thermal energy storage to a CHP system and solar plant [59]. Multi-objective optimization of trigeneration system, considering boilers, CHP engine, absorption and compression chillers to satisfy cooling, heating and electricity needs, have been carried on. The optimization identified a configuration characterized by energy supply stability and increased energy and economic benefits [60]. Other studies showed the benefits on energy generation stability

deriving from the combination of photovoltaic system and diesel fed power plants. The results showed a good economic feasability allowing also a very reliable and efficient distribution output thanks also to the implementation of battery storage to ensure continuous power supply [61].
The second important element are the energy end user constitued mainly by industrial, residential, accounting for the major part, and transportation sectors. Residential sector requests heat, cold and electric energy allowing good performances after the implementation into SMES due to flexibility deriving from the mutual conversion and connections between the different energy sources. In literature several studies investigated the implementation of buildings into SMES. Chow et al. investigated the effect of the building type on the performances of a district cooling network, considering office, residential, shop, hotel and railway station buildings [62]. The effects of flexible energy buildings have been investigated through theoretical methods, focusing on the variation in energy consumption patterns between different types of buildings and the coordination of load shifting to improve renewable energy use [63]. Other authors tried the solve the problem of distribution grid congestion due to simultaneous consumption increase in multiple buildings applying benchmark pricing methods. The results outlined that building can provide flexible demand due to their thermal inertia [64].
Energy distribution and storage systems have an important role in connecting energy generation systems and end users, transferring the energy produced by first to the second, and maintaining the energy balance between the supply side and the demand side by storing excess energy when generation exceeds demand and release stored energy otherwise. Energy distribution systems include distribution electric networks and district heating/cooling networks. Studies showed that through coordinated optimization of transmission and transformation network the overvoltage problem can be eliminated [65]. Others modeled distribution electric systems as spatial networks, analyzing the topological and spatial characteristics of different European distribution electric networks and the relationship between geographical constraints and performance optimization are analyzed. The results showed that distribution electric networks are affected by spatial constraints, which distinctly affect the total performance [66]. Regarding energy storages, that can be electricity or heat storage, studies optimized the distributed power storage system in distribution electric network. A method that consider the economy and security performance is proposed for optimizing the capacity and location of a distributed power storage system [67]. Compressed air energy storage utilization in renewable power generation has been investigated showing that allows to increment the renewable energy exploitation rate [68].
The smart energy management system ensure optimal control and management of smart energy systems integrating and providing communication between the

energy generation systems, end users, distribution and storage systems to create responsive and flexible energy systems. Several studies have investigated the optimization of management and control of district heating and cooling system achieving energy balance between user needs and system energy generation [69], and the potential load response capability of residential buildings [70].
For identifying the optimal configuration when designing a SMES the appropriate optimization technique should be adopted, so the optimization routine should be carefully designed. Both single and multi-objective can be utilized. Typical objective functions considered are energy consumption, environmental impact, economic performance. Single-objective optimization considers just one of these functions while multi-objective optimization consider two or more functions. When compared to single-objective optimization, multi-objective optimization allow to obtain a comprehensive solution for the wide system through trade offs of the single objective functions. Energy consumption is one of the main considered objectives, cause improving the energy efficiency and increasing the utilization of renewable energy are goals of the implemetation of SMES. Since SMES allow the exploitation of multiple renewable energy sources the environmental impact is another important objective. Various pollutants, including greenhouse gas emissions, soil acidification, ozone depletion and water eutrophication occur due to the consumption of fossil energies, which utilization will be reduced through the implementation on SMES. Among the various pollutants, carbon dioaxide emissions is the most common selected as representative of the ennvironmental impact. And of course, SMES implementation should lead to economical advantages as well so initial investment, annual operating cost, net present value cost, and life cycle cost are usually adopted for the economic performances objective. In order to indentify the optimal solutions during a multi-objective optimization, the Pareto method is one of the most commonly adopted. This method has been applied to optimize the energy cost and connection to the grid of an independent photovoltaic and energy storage plant. The results showed that the system can cover 97% of the users energy need satisfying both the objectives [71].
Virtual Power Plants ($VPPs$) integrate different plants into a single control system, combining energy production, storage and demand in an efficient manner. VPPs make it possible to join and manage different electricity production units in the same area, combined with storage systems. Photovoltaic plants, wind farms, biogas plants, hydroelectric plants, cogeneration plants, micro-grids, batteries, cooling / heating systems, and electric vehicles can converge into a VPP. The Remote Control System (RCS) is the heart of a VPP. It coordinates power flows coming from generators, controllable loads and storages. Communication is bidirectional: the VPP can not only receive information about the current status of each unit, but can also send signals to control objects. Forecasting energy production is not easy because of the fluctuating nature of renewable

energy sources. Due to such errors, electricity grids with a high penetration of renewable energy sources can easily experience bottlenecks and balancing problems, which can be solved by using Energy Storage Systems (ESS).

The concept of VPPs was born towards the end of the 1990s, mainly with the energy market deregulation, but they have recently become more common due to the increasing number of renewable energy plants (RES) and greater efficiency of both production technologies and Remote Control Systems (RSC). VPPs can be connected with the energy market as a single large system, supporting the grid both in terms of energy supply and balancing and regulation services (thus ensuring greater grid security). A single control system provides a set of advantages:

- Optimisation of individual consumers' needs within the same VPP. Energy can be shared to manage demand efficiently: if one system is consuming more than it is producing, it can use energy from other systems connected to the VPP. In other words, it provides more flexibility in consumption;
- Optimal management of production, distribution and storage on the basis of virtual electricity conditions related to weather, price changes and energy demand. In other words, it provides:
  - Efficient peak management in a short timeframe;
  - Energy production at lower costs;
  - Reduction of emissions.

A single control system makes it possible to think of new service solutions and new business opportunities among the actors involved. To analyse the possible services applicable to the islands, the deliverable, after a brief analysis of the context, analyses the actors involved in the electricity market and the services provided classified in two systems. Finally, after reporting the data available from the islands, the deliverable presents an evaluation method for proposing services to the islands.

The concept of distributed generation (DG) has been depicted as the power paradigm for the new millennium [72]. Mancarella proposed the multi-energy system concept [73], which has evolved until the recent smart energy system (SES) concept has been settled by Lund et al. [57]. SES is an energy system in which different energy sources, vectors and needs are combined and coordinated through a number of smart grid infrastructures in order to achieve an optimal solution for each sector and for the overall energy system. SES seems to play a crucial role in facilitating cost-effective integration of renewable energy sources and in fostering end-user's participation to support power system operation and development. As reported by Connolly et al. [74], with an increasing share of renewable energies SES or smart multi-energy systems (SMES) become more decentralised and the number of actors increases significantly. Compared to traditional systems, the decentralisation of energy sources (i.e., multiple renewable energy sources (RES) located in different positions) increases variability and uncertainty and requires close control of the system flexibility.

Variability is due to changes in the energy system operating conditions across time, which can concern expected energy demand, renewable energy production and net scheduled exchange (NSE). As such changes are not exactly known, possible interruptions, contingencies and dispatchable sources that do not follow their set points cannot be neglected. All that leads to system uncertainty. Flexibility is defined in several ways in literature, but many authors agree that it can usually be measured indirectly through signs of system inflexibility, including difficulties in balancing supply and demand, resulting in load shedding; significant reductions in renewable energy; very high negative or positive market prices (i.e., penalties); and extreme volatility of market prices across time. As reported by Aggarwal et al. [75], many different resources are available to deliver grid flexibility. Flexibility can come from physical assets such as batteries and fast-ramping gas plants, but can also be the result of improved operations, such as shorter dispatch intervals, new ancillary services and improved weather forecasting. Wang [76] summarises the different literature approaches to enhance flexibility as follows:

- Improved operations: achieved through advanced models and algorithms to improve unit commitment and economic dispatch processes. Examples include the application a mixed-integer linear programming formulation for the start-up and shut-down ramping in thermal units [77] or genetic algorithms for cogeneration systems [78], the configuration of combined cycle units [79], the improvement of wind, sun and load forecasting [80], and the improvement of other forms of renewable energy such as waste heat recovery.

- Demand Response: incorporating dispatchable demand response resources (DRRs) into the energy market can increase grid flexibility. The emerging demand response techniques include smart thermostats, building automation systems, plug-in EVs, and others.

- Improved Grid Infrastructure: transmission congestion is a major bottleneck for delivering flexible power in the grid. Increased transmission capacity can facilitate electricity delivery within or among balancing areas, thus helping balance supply and demand. On the distribution side, the implementation of a large volume of sensors and smart meters, communication devices, and advanced information technologies can also help balance out supply and demand [81].

- Fast Start Resources: in real-time operations, fast start resources such as co-generative engines and combined-cycle units have short start up time and rapid ramp rates, and can therefore provide the necessary system flexibility [82].

- Energy Storage System (ESS): abundant Energy Storage Systems including grid-scale batteries, pumped hydro, compressed air, fly wheel and others can provide flexibility on the grid [83].

Energy demand can be met in a sustainable way by a combination of SMES and battery-based Energy Storage Systems (ESS). If operated in a coordinated way, ESS in local energy communities have a large potential for increasing efficiency and self-sufficiency. Schlund et al. [84] reported that if every user focuses only on self-consumption, the batteries run inefficiently and the grid is stressed unnecessarily. On the contrary, if the batteries within the considered area are connected to form a virtual energy storage community, the overall efficiency improves, the grid workload decreases and self-sufficiency is higher. He also underlined that benefits can be achieved even at small community sizes.

1.3 Decision support systems

A Decision Support System (DSS) is defined as a software-based tool assisting the decision making process by means of interacting with both internal/external user and databases, while implementing standardized or specific algorithms for problem solving [85]. DSSs belong to the broader category of Knowledge Management, where the knowledge process follow, depending on the value given to the whole process, a set of six "knowledge stages": data gathering, information selection,information analysis , insight, judgment and decision.
The decision making process follows an "horizontal path", as described by the Simon model (1960), reported in [85], from the first stages of problem classification and definition , called the *intelligence or investigative phase*, the *design phase* of alternatives generation and evaluation, ended by the alternative negotiation, selection and action determination, called the *choice or decision phase*. The author underlined the relationships and interdependencies between such stages, making the whole decision-making process a cyclical approach.

Power [86] identified 5 main types of DSSs, depending on the main drivers guiding the decisional process, that is:

- Model-driven DSSs: such DSSs require limited amount of data because of the intrinsic composition of the system, used to evaluate quantitative data in a tailor-made structure suited to adapt to other external requirements. Firstly developed for financial planning, such category of DSS were later used for multi-criteria decision making and spatial-driven decisions such as logistics or distribution modeling;

- Data-Driven DSSs: the database structure behind the DSS is emphasized and the operations of data-warehousing and manipulation are the most relevant for such DSSs. Online – in the meaning of interactive (such as the OLAP) and offline – application can be found, while web-based data-driven DSSs currently represent the natural evolutions of such models;

- Communication-Driven DSSs, are used for exploiting the network and communicating capabilities of the system, which includes the use of groupware, conferencing or other computer-based newsletter. Such category is directly related to the Group DSSs, developed in order to promote participatory approach to the decision process, and their relation with model-driven DSSs have been studied, aiming to include the shared approach of the former, with the structured modeling of the latter;

- Document-driven DSSs, also called "text-oriented DSS", they are used for document retrieval, especially in large group/organization, in order to support the decision making process. Web-based system increased the possibility of such DSSs, allowing to rapidly access documents distributed in worldwide databases;

- Knowledge-driven DSSs: these are specific, tailor-made, systems used in particular domain and developed for a particular person or group of people. The author also acknowledges the relationship with Artificial Intelligence systems, in which the DSS follows a series of rules in order to evaluate and eventually take decisions on the problem to be analyzed.

Eventually, Arnott reported a framework for DSS classification and sub-classification, identifying Personal Decision Support Systems, Group Support Systems, Executive Information Systems, Intelligent Decision Support Systems and Knowledge-Management-based DSS [87]. Each of such DSSs presents sub-branches depending on their specific features and temporal evolution.

1.3.1 Multi-Criteria Decision Making

A Multi-Criteria Decisione Making is defined as the choice between different alternatives based on two or more criteria. A criteria is defined as an index for the evaluation of the different alternatives performances. While, on general terms, DSSs require a range a functionalities for assisting the decision making process, Multi-Criteria Decision Making "deals with a general class of problems that involve multiple attribute, objective and goals" [88]). Olson, retrieved in [85] underlined the complementarities of MCDM and DSSs, especially model-driven DSSs, given their different approach in terms of "philosophies, objectives, support mechanisms and relative support roles" [89]. Multi-criteria, multi-attribute and multi-objective decision making, while similar in their main concepts of integrating, optimizing and finalizing the decision making process, present some major differences which will be now assessed.
While similar in their final purpose, which is assisting decision making process, Multi-Attribute and Multi-Objective analysis differs strongly because of their basilar concepts beneath. As reported by Pohekar, while Multi-Criteria Decision Making represents the major class of Model-Driven Decision Making Support System, Multi-Attribute and Multi-Objective represents its subclass [90]. In particular the alternatives considered during a Multi-Criteria analysis, otherwise called criteria, can be discrete and finite, or continous function and infinite. So we are talking about Multi-Attribute analysis when considering discrete and finite alternatives, and about Multi-Objective analysis when considring with continous alternatives.

1.3.1.1 Multi-Objective Decision Making

The identification of the best solution, or set of solutions, for a specific problem has been traditionally considered in decision making problems. Weise has classified optimization techniques according to their method of operation (deterministic and probabilistic algorithms), and to their properties (optimization speed, number of objectives) [91]. Deterministic algorithms are used when "a clear distinction between the characteristics of the possible solutions and their utility for a given problem exists" [91]. Probabilistic algorithms are used when "the relation between a solution candidate and its fitness are not obvious or too complicated". A typical deterministic algorithms is the "branch and bound", while Monte Carlo techniques are considered the pioneer in probabilistic algorithms. Other criteria for algorithms classification are optimization speed and objective number. Regarding the former, in offline optimization time does not represent a constraint, while optimization can take long time to be executed and get to the optimal result; in online optimization continuous optimization is required instead, thus needing for rapid algorithms, even at the expense of the accuracy of the solution required. Considering the number of objectives, single-objective and multi-objective algorithms can be identified. Given the multidisciplinary approach, described previously in this section, required when referring to the industrial sustainability issues, multi-objective methodologies will now be assessed in details.

Multi-Objective Optimization Techniques

Optimization with multiple objectives conflicting with each other has no single best solution (like most of the single-objective functions), but a set of solutions, named the "Pareto-set", from the name of Villfred Pareto (1848-1923), which firstly studied them, applying to social science, economy and game theory. Multi-objectives optimization techniques therefore identify a set of non-dominated solutions which represent the optimums for a given problem. The concept of domination can be translated by the expression that: an alternative a is non-dominated by b if a is better than b for at least one objective, while not being worse than b for all of them.Given a range of feasible solutions the Pareto front is defined as the set of solutions which cannot be improved in one of the objective (*f1* or *f2*) without worsening the performance of the second. Identifying the Pareto front means also satisfying the following requisites for the solutions identified, as reported by Alarcon [92]:

- Spread: To find a set of solutions that "capture the whole spectrum" of the true Pareto front.
- Accuracy: To find a set of solutions as close to the real Pareto front as possible;
- Diversity: To find a set of solutions as diverse as possible;

Among the multi-objective optimization techniques, a particular choice has been made, selecting evolutionary algorithms for the objective of this work. The main reason for selecting such methods has been the particular "black-box" approach, as reported by Weise of those methods, which make them suitable for a variety of problems as those referred to the main theme of this work, that is the sustainability of the industrial sector [91].

Evolutionary Algorithms

Evolutionary algorithms are defined as "population based metaheuristic optimization algorithms that use biology-inspired mechanisms like mutation, crossover, natural selection and survival of the fittest in order to refine a set of solution candidates iteratively" [91]. Firstly, the concept of metaheuristic is defined as a "method for solving general problems, combining objective functions in an abstract way, treating problems as a black box" [91]. The five main stages of an evolutionary algorithms involves:

1. Initial population, which allows to create the initial sample to be analyzed from the possible set of candidate solutions;
2. Evaluation, which computes the objective value from the candidate solution;
3. Fitness Assignment, which, depending on the objectives value, determines the fitness of the candidate solution relatively to a fitness criteria (weighed sum of objectives values, Pareto ranking, etc.) which evaluates the suitability of the candidates to the optimization required;
4. Selection: basing on the fitness of the candidate solution, at this stage the population (the group of candidate solutions) to be maintained is selected, while the rest is discarded.
5. Reproduction: selected candidate solutions are reproduced by different mechanisms such as partial mutation, crossovers, or complete change.

The family of Evolutionary Algorithms includes:

- Evolution Strategies
- Genetic Algorithms
- Genetic Programming
- Learning Classifier Systems

1.3.1.2 Multi-Attribute decision Making

Under the common name of Multi-Criteria Decision Making, Pohekar has reviewed the most used methodologies used in sustainable energy planning [90]. Despite the specific topic treated by the authors, this work provides a useful framework comparing the different methodologies which, given the considerations provided in the previous section, are considered as Multi-Attribute processes given that they deal with an established set of alternatives. The authors identified the following methodologies:

- Weighed Sum Method (WSM);
- Weighed Product Method (WPM);
- Analytical Hierarchy Process (AHP)

- Preference Ranking Organization Method For Enrichment Evaluation (PROMETHEE);
- Elimination And Choice Translating Reality (ELECTRE);
- Compromise Programming (CP);
- Multi-Attribute Utility Theory (MAUT)

A more general taxonomy of MADM has been given by Stewart [93], considering the following types of methodology:

- Value measuring methodologies: this category considers methodologies which associates a numerical value to each of the alternatives to be assessed, for each criteria considered. These are the most common models for alternatives' selection;
- Outranking models: in this category the so-called "French school" of outranking MCDM methodologies is described. An outranking relation, as firstly described by Roy and reviewed by Behzadian [94], is a "*binary relation S defined on the set of alternatives A, such that for any pair of alternative* $(A_i, A_k) \in AxA : A_iSA_k$ *if, given what is known about the preferences of the decision maker, the quality of the evaluations of the alternatives and the nature of the problem under consideration, there are sufficient arguments to state the alternative* A_i *is at least as good as* A_k*, while at the same time no strong reason exists to refuse this statement*". Such definition encompass many different features as the presence of preference ("there are sufficient arguments"), or indifference functions ("no strong reason exists"),
- Reference, goal and aspiration models: in this category falls a range of methodologies border line with multi-objective decision making, classified in Goal Programming, Step Methods (STEM) and TOPSIS methodologies. Such type of methodologies, while keeping dealing with a fixed range of pre-decided alternatives, aim to optimize the decision making process keeping one or more objectives to be maximized or minimized.

1.4 Research gaps and objective of the thesis

The possibility of utilize circular economy perspective as tool to reduce GHG emissions has been highlighted in the literature, identifying different kind of waste that can be subjected to recovery for this purpose and list of technology to accomplish the task. But these works focused on the development of this

kind of technology while integration of this energy sources in energy systems and their environmental and economic performances analysis is still at a base level considering just single subsystems at a time.
The aim of this thesis is the development of a decision support methodology able to assist stakeholder in those interventions in which smart energy systems are implemented with sustainable and renewable energy source in a circular economy perspective.
To this aim the thesis has been articulated as following: in chapter (2) the developed models representing the considered technologies and energy sources are explained. At first the possibility of recovery of waste heat to feed a district heating network (DHN) and other waste heat exploitation technologies have been considered. After that recovery of food waste and other forms of organic waste like wastewater through traditional technologies to exploit the waste as an energy source like anaerobic digestion, or innovative ones have been investigated. Then a logistic model for the collection of urban waste and its implementation in a waste treatment plant has been developed. Finally all these technologies are implemented together to form the smart energy system model.

2

Developed decision support methodology

The conceptual scheme of the decision support methodology developed within this thesis is represented in figure 2.1. Three typical phases of a DSS have been considered:

- Investigative phase: in which the feasable technologies are characterized and data and information are collected;
- Design phase: in which the models representing the selected technologies are developed and simulations and possible optimizations are carried on;
- Decision phase: in which the various alternatives are compared and the optimal one is chosen based on different approaches.

2.1 Investigative phase

The investigative phase consists in the acquisition of all information and data required for the characterization of the feasable technologies and energy sources. This kind of information may be the specific energy loads requested by the considered system or the amount of available energy sources or wastes that can be exploited. Of course once the fundamentals information are obtained other more detailed data can be obtained like power of the requested units and their efficiencies. More case specific data are local climate data, which can affect heat loads due to an higher or lower environment temperature or the production of electric energy through photovoltaic panels. The level of detail of the input data affect the accuracy and reliability of the choices made by the application of the DSS, and this may be case specific as well depending on the case if the case study considers a real application with the collaboration of a company (and so depends on the level of accuracy of the data given by the company) or not. The considered technologies are reported in the following sections, and will be utilized for the models developments as explained in the design phase section 2.2.

2.1.1 District heating and cooling

District heating consists in the heating (or cooling) of several buildings or districts through underground piping where heat or cold is distributed through a energy vector, usually water or low-pressure steam [95]. Several types of user can be connected through an heating network like residential, industrial or commercial, receiving heat from one or more energy sources (distributed energy production) [96, 97]. Compared to traditional energy systems, DHN showed to lead to an higher energy efficiency [98]. Indeed, energy loads required for air conditioning can be covered through heat pumps or absorption chillers to exploit the heat available in the network. District heating systems can be chategorized based on different aspects: the kind of energy vector utilized (steam, water or air), the kind of thermal energy distributed (heat energy, cold energy or both), and the kind of heat source from which the network is fed. Based on the last characterization the following heat sources can be identified: fossil fuels, nuclear, CHP, waste heat and renewable sources. Moreover, considering that DHN has also electrical loads for pumping and ancillary equipment CHP and renewable source integrations are getting more common [99]. Indeed,

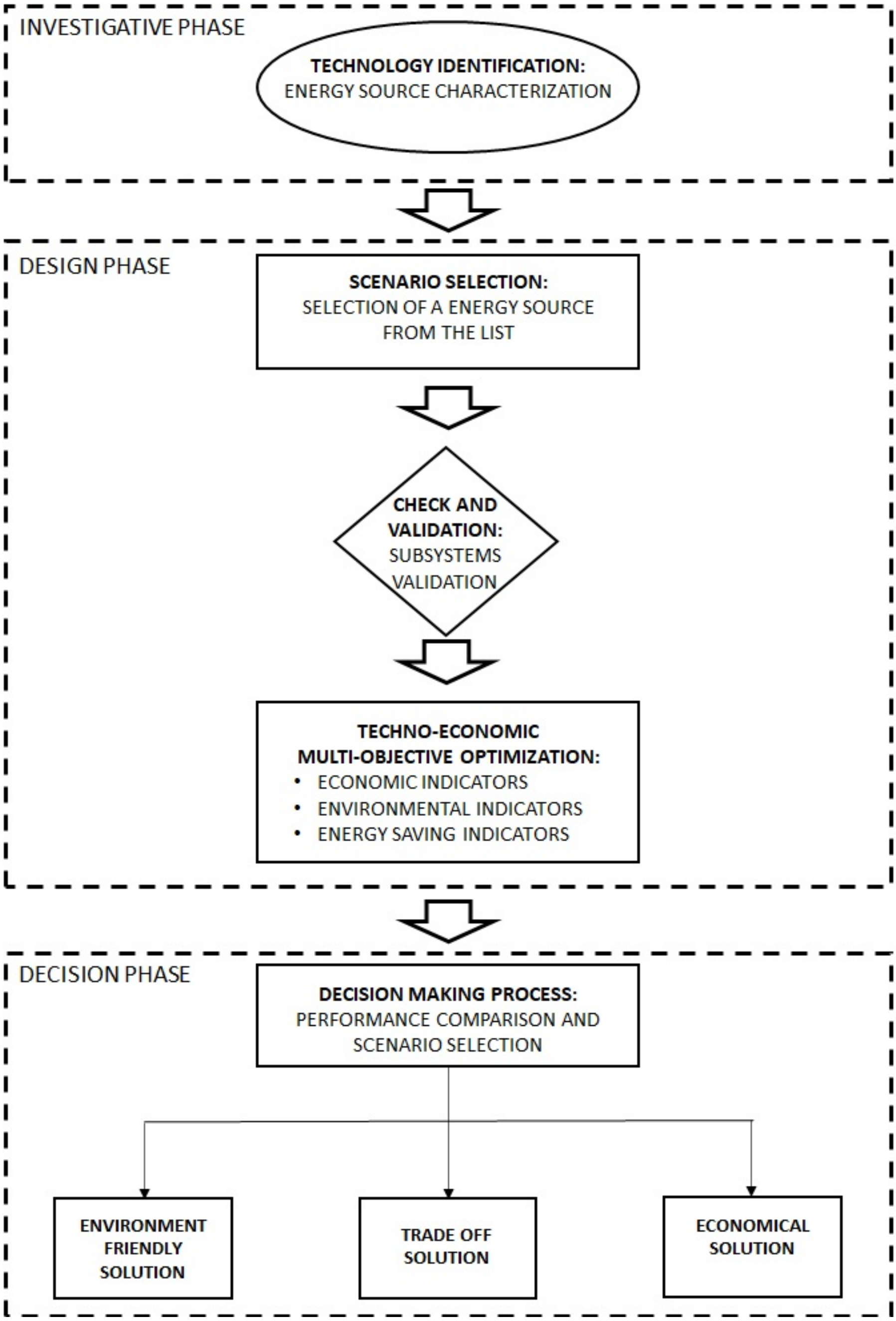


Figure 2.1: Scheme of the developed decision support system

geothermal contributes for a big share of the installed capacity of heating systems [96], and in the last decades its exploitation in district heating has increased by 10% [100]. Biomass utilization has also been investigated, showing that can be less expensive for heat production when compared to traditional fossil fuels [101], while at the sime time reducing the GHG emissions [102].
A general district energy system consists of three main subsystems: source of thermal energy (the plant that generates energy and fed it into the network), the energy distribution piping (the pipe network itself delivering heat from the generation plant to the users) and the users. Heat losses along the piping mixed with users load should be equal to energy output of the energy generation plant [103, 104]. Due to their operation principle DHNs bring environmental advantages both facilitating the implementation of sustainable energy sources and replacing less efficient energy production centrals in individual buildings with a more efficient central heating system [105]. The economic performances of DHNs may depend on the cost of the energy production (so on the energy source), the cost of the distribution network and user connection cost [96], from which derives that for high density populated users area this kind of intervention is economic beneficial [106].
Implementation of TES into DHCN has various benefits, economical, environmental and also technical [107]. In particular in combination with CHP systems allows reducing generation unit due to increased flexibility of the system [108] and allows shifts to electricity production during high price periods maximizing profits [109, 110]. When installed on the primary line of the network they allow smaller pipe size [111], and pumping cost that can account for the 1% of the total energy consumption of the network [112]. Moreover cold TES are very usefull in cooling periods cause allow to uncouple cooling demand from electricity demand, reducing the cost for covering the peaks considering also that covering peak cooling loads is very expensive due to much more important variation of the demand along the day [113]. TES utilized in DHCN can be chategorizd based on different criteria. One criteria is the physical phenomenon used for storing heat, and this way the types of TES are: sensible heat, latent heat and chemical storages. In sensible heat TES, that are the most common type, the temperature increase (or decrease) of the storage medium is used to store heat (or cold). Due to its low cost, favourable thermal properties [114], its tendency to stratification and the possibility to utilize it both as thermal vector in the network and storage medium make water based technology the most commonly used [115]. However this kind of system may need insulation layer to reduce heat losses and pressurization system to avoid evaporation. Latent heat TES have an higher energy density when compared to sensible heat TES, allowing the installation of smaller volumes while storing the same amount of energy. Thermal conductivity should be as high as possible in order to minimize the response time [116]. Moreover studies showed that latent heat TES are

characterized by reduced heat losses [117]. Chemical TES exploit chemical reactions that can be reversible (heat is stored through endothermic reactions when surplux heat is available to obtain products that can be stored to make happen the reverse reaction when needed), or absorption and adsorption. Some advantages of chemical TES are high energy density of around 400 MJ/m3 [118] and low heat losses. The characteristic of this system is highly dependent on the materials used and reactions occurring. In literature studies focusing on investigation of new materials can be found [119, 120].
Since the residential sector accounts for a large share of total energy consumption and GHG emissions [121], district heating networks (DHN) should play an important role in the implementation of future sustainable energy systems [122]. Besides representing a measure of heat supply efficiency, the integration of DHN in urban energy systems would allow the exploitation of any available source of heat, such as waste-to-energy and industrial waste heat, as well as renewables and combined heat and power [123].

2.1.2 Anaerobic digestion

The anerobic digestion process is constituted by four distinctive phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis [124]. The first phase is hydrolysis in which complex organic matter as carbohydrates, proteins and fats are broken into simpler organic molecules as sugar, aminoacids and fatty acids. Usually is the slowest or rate limiting phase due to the formation of toxic products [125], but can be accelerated feeding the process with pretreated substrates [126]. The second phase is acidogenesis, or fermatation phase in which the simpler organic molecules produced during hydrolysis break into short-chain fatty acids along with hydrogen (H_2) and carbon dioxide (CO_2). The third phase is acetogenesis in which the fatty acids coming from the acidogenesis are converted into acetic acid, H_2 and CO_2. The fourth and last phase is methanogenesis where methane is produced through two different reactions. One splits acetic acid into methane and carbon dioxide, while the other uses the intermediate products as H_2 and CO_2 for the formation of methane [127]. The last phase is highly influenced by temperature [128], and based on the operating temperature anaerobic digesters can be divided in three categories: psychrophilic regime with operating temperature around 20 °C, mesophilic regime operating at 35 °C and thermophilic regime with operating temperature around 55 °C. In the literature the mesophilic one is identified as the most common regime [129] being a more stable process [130], more cost effective and requiring less net energy for equal biogas yeald [131]. However thermophilic regime has an higher methane yeald and a shorter start up and digestion time

[132, 133].
The presence of a single substrate during anerobic digestion often leads to poorer processes performances, which results into lesser biogas yield and poor stabilised sludge [134]. Co-digestion offers better performances due to better nutrient balance [135], good buffering capacity [136] and improved process stability [137]. Depending on the substrate concentration and other process parameters, co-digestion can increase the biogas production by as much as 25-400% [138].
Pre-treatment of substrate before anaerobic digestion can lead to higher methane yield and more stabilised end products [139] due to improved decomposition rate of organic fraction, but the increment in methane production yeald depends on the type of pre-treatment adopted [140].

2.1.3 Electric/absorption chillers

In absorption chillers the working fluid is a binary solution consisting of refrigerant and absorbent. An absorption refrigeration cycles can be represented by the following processes. The refrigerant is separated out from the diluted solution by giving heat from an external source to it. Then the refrigerant vapor is condensed by giving heat to the surroundings. The liquid refrigerant, after lamination, is evaporated by receiving heat from an external source and then absorbed back into the solution by giving heat.
Performance of an absorption refrigeration systems is critically dependent on the chemical and thermodynamic properties of the working fluid [141]. In literature many different working fluids are reported. Marcriss reported that there are around 40 refrigerant fluids and 200 absorbent compounds available. However, the most common working fluids are Water/NH_3 and LiBr/water. The solution Water/NH_3 is very stable for a wide range of operating temperature and pressure. NH3 has a high latent heat of vaporization, leading to high process performances [142], and also due to its low freezing temperature (-77°C) it can be used for low temperature applications. This solution has low environmental impact and cost. Some drawbacks are its corrosive action on some metals, toxicity, and high working pressure and the need of a rectifier to avoid water accumulation in the evaporator [143, 144, 145]. In LiBr/water solutions water is used instead as refrigerant, that limits the low working temperature to that above 0°C. But has some advantages like non-volatility of the absorbent, removing the need of a rectifier and the high vaporization heat of water. The drawbacks of this system is that is corrosive and high cost, and must work under vacuum conditions [146, 147, 148].
Coefficient of performace of absorption chiller is highly dependent on the

temperature of the heat source, and can be estimated through the following [142]:

$$COP = \frac{C_{eva}}{H_{gen} \cdot W_{pump}} \tag{2.1}$$

where C_{eva} is the cooling capacity at the evaporator, H_{gen} the heat input at the generator and W_{pump} the work input for the pump.

2.1.4 CHP

Cogeneration, or combined heat and power CHP is the simultaneous production of electrical or mechanical energy and thermal energy from a single energy stream [149]. Nowadays various governments are advancing policies to extend CHP applications not only in the industrial sector but also in other sectors including the residential one [150], due also to higher energy efficiencies of over 80% compared to the average 30-35% of traditional fossil fuel fired electricity generation [151]. This increase in energy efficiency can result in lower costs and reduction in greenhouse gas emissions in comparison to the conventional methods of generating heat and electricity separately [152]. When applying CHP to a specific context, depending on the relative magnitude of electric and heat load and based on the operation strategy, so pursuing thermal or electric load, the system may operate at partial load rising the need of selling (or storing) the surplux energy or buy the integration energy to cover deficiencies [153].
More technologies like Stirling engines and fuel cells seem promising for future application due to their high efficiencies and low emissions, but currently internal combustion engines, like reciprocating engines or gas turbine, are the most common [154].
Reciprocating internal combustion engines are available over a wide range of sizes ranging from tens of kW to more than 10 MW, and can be fired on a broad variety of fuels [155], depending also on their ignition method. Apart from the fuel which they can be run by, that can be diesel or gas or gasoline, the ignition method affects also the heat recovery possibilities, limiting the temperature at 85°C for diesel engines while with spark ignition engines temperature up to 160°C are reachable [150]. In general diesel engine are more efficient when compared to spark ignition engines [156], but on average internal combustion engines efficiencies are around 25-45%. Considering also the heat recovery the overall efficiencies are in the range of 85-90% [152]. The heat can be recovered from four different sources: exhaust gas (accounting for the 30-50%), engine jacket cooling water (accounting for up 30%), and smaller amounts from lube oil cooling water and turbocharger cooling. The heat recovered from the engine

jacket is in form of hot water at a temperature of around 85-90 °C, while the heat recovered from the engine exhaust gases as hot water or low-pressure steam is around 100-120 °C [156].
Gas turbines have several advantages compared to ICE CHP systems, like compacts size, small number of moving parts and as a consequence less lower noise and an higher grade heat recoverable. However in the lower power ranges, reciprocating internal combustion engines have higher efficiency [157]. The operation process of a gas turbine based CHP system is similar to the one of gas cycle energy plants, and comprises the pressurization of intake air by the compressor that is later mixed with fuel and ignited in a combustion chamber. The resulting hot combustion gas expands moving the turbine, which drives the compressor and provides power through a connecting shaft. With a recuperator, the hot exhaust gas pre-heat the air coming from the compressor and entering the combustion chamber. Recuperator design is a complex operation cause higher recuperation effectiveness necessitates large recuperator surface area, resulting in higher pressure drop as well as higher cost so a trade off solution must be met. Efficiency increment due to recuperator implementation can lead to fuel saving of around 30-40% [157]. Gas turbine base CHP system's efficienies can be increased increasing the process temperature and pressures, leading however to higher NO_x emssions. For this reason the overall efficiencies of this system are around 80% [157].
Fuel cells represent an alternative with potential for both electric generation and CHP, with high energy performances coupled with reduced environmental impact. Their advantages are the possibility to reach high efficiencies of around 85-90% even for small power unit, with low noise level and excellent partial load operation, coupled with low emissions. In particular carbon dioxide emissions may be reduced by up to 49%, nitrogen oxide (NO_x) emissions by 91%, carbon monoxide by 68%, and volatile organic compounds by 93% [158]. The major source of emission is the fuel processing and reforming process to make the fuel exploitable [159]. On the negative side fuel cells are characterize by high cost and short lifetime.

2.1.5 Methane upgrading

The main components of the biogas produced through anaerobic digestion are methane (CH_4) and carbon dioxide (CO_2). But, depending on the substrate utilized, fermentation technology and collection method, other impurities can be present in the biogas. Besides CH_4 and CO_2, raw biogas also contains small amounts of ammonia (NH_3), hydrogen sulphide (H_2S), hydrogen (H_2), oxygen (O_2), nitrogen (N_2) and carbon monoxide (CO). Some impurities may

have negative effects both on the utilization system and human health, so in order to increase CH_4 percentage and so the calorific value of the biogas and reduce the negative effects deriving from its utilization it is important to remove impurities and upgrade the biogas to an higher fuel standard. The process of removing this impurities is called biogas cleaning and upgrading [160, 161]. The most common technologies utilized for biogas cleaning and upgrading are water scrubbing, cryogenic separation and membrane technology. In water scrubbing water is used as a solvent, taking advantage of the lower CH_4 solubility compared to CO_2. Depending on the volume of non condensable gase like N_2 and O_2 this technology can reach a gas with a CH_4 content of 80-90%. Losses of dissolution in water are contained and usually between 3 and 5 % [162, 163, 164].
Cryogenic separation is based on the different condensing temperatures of CH_4 and CO_2 so these can be separated through condensation and distillation. This technology allows to reach high purity CH_4 and CO_2 [165], but however has some negative sides: due to the high pressures requested by the process, the energy needed by this accounts for 5-10% of the methane produced, and also the biogas to be upgraded needs a pretreatment to remove water and H_2S.
In membrane separation membranes are used to separate gases constituting the biogas at molecular level. CO_2 and H_2S pass through the membrane to the permeate side, while CH_4 is retained on the inlet side. This method can reach high purities with high energy efficiencies and low cost [166]. Deng and Hägg obtained in a test CH4 purity of 98% [167], while in literature state of the art energy consumption is found to be around 0.3 kWh/m^3 [168].

2.2 Design phase

The design phase consists in the implementation of the different identified technologies to constitute the evaluated system configuration and the representation of its behaviour through a mathematical model. At first the technologies have been combined to form subsystems models of the smart energy system investigated, and each one of those has been applied to a case study and validated. The evaluated alternatives considered in the design phase are identified through a multi-objective optimization as explained in section 2.2.9.

2.2.1 I step: waste heat fed DHN implementation

A DHN represents a technically complex and high investment cost infrastructure whose optimal design and operation require to make use of optimization techniques, which can be grouped into few main families. Several models aim at the optimal design and operation of DHN for efficiency improvement through the detailed representation of the network physics by equations based on the thermo-fluid dynamics. Following this approach, a detailed representation of fluid distribution and thermal gradients within the network and its components can be obtained. With the aim of improving district heating (DH) system efficiency through the optimization of the return temperature at the plant, an integer programming model considering the optimal selection of the type of heat exchangers to be installed at the users was developed [169]. DH simulation was also used to analyse the performance of different real-time control strategies from a management perspective [170]. For design purposes, integer programming models capable of solving small scale examples of energy production plant based on cogeneration and RES have been developed [171]. The design, analysis and optimization of DHN is the objective of the in-house software developed by Ancona et al. [172], which allows to obtain mass and heat flows in the pipes by solving a system of equations with the so-called Todini-Pilati iterative algorithm. Probabilistic estimation of user consumption has been used to propose a new method for optimizing the size of DH network pipes [173]. Guelpa et al. presented a thermo-fluid dynamic model for the detailed simulation of large DHN operational strategies, thus representing a versatile tool for the advanced management [174]. They also investigated the optimal operating conditions of DHN with a special focus on the role played by the pumping power required [175]. However, the computational complexity of the above models makes them not suitable for large real-world networks serving hundreds of users [176]. In this case, the accuracy of the network representation should be sacrificed to allow the numerical solution of the model, using aggregation techniques of the network elements [177]. Bordin et al. developed a mathematical model to select the optimal set of new users to be connected to an existing DHN, maximizing revenues and minimizing infrastructure and operational costs [176]. The model considers steady state conditions of the hydraulic system and takes into account the main technical requirements of the real-world application. The modelling of DHNs can be alternatively approached by empirical simulation, based on observation of temperature and pressure distributions of the real system [178]. Another modelling approach focused on optimal design and operation of DHN for the economic optimization (single-objective), is based on simple network configurations, or avoid detailed simulation tools of the

DHN thanks to simplified assumptions. In some papers, DHN is modelled as a black box, only accounting for the end users' overall heat demand [179]. The simulation model developed by Sartor et al. deals with the optimal operation of CHP plant connected to a DH network, focusing far more on the facility side than on the network [180]. A mixed-integer programming model has been developed for an industrial area where different services (heating and cooling) and renewable technologies such as a concentrated solar power unit are considered in DHN system design [181]. A mixed-integer non-linear formulation for the optimization of the design of a DHN from a structure and technologies point of view has been proposed by Mertz et al. [182]. The optimization objective is to minimize the global cost of the DHN over 30 years, accounting both for operating costs (including thermal losses and pressure drops) and investment costs. Considering the lack of knowledge of local energy companies regarding how a meshed district heating network behaves when different generation sites are involved, an optimization of the total operating costs of a multi-source network, with constraints on the pressure and temperature levels in the user areas and on the heat generation characteristics at each production site has been addressed [183]. The mixed-integer linear optimization problem formulated by Haikarainen et al. for optimizing both structure and operation of a DHN considers several decision variables such as the types of fuels, the technology and the location of the heat production sites, the capacity and the location of heat storage utilities and also the layout of the distribution pipes, pursuing either optimal economic or environmental performances [184]. A multi-objective optimization approach has also been adopted to account for different objective functions while optimizing design and operation of DHN. A multi-objective model for optimizing the design and operating strategy of DH systems that selects the resources, heat production technologies and the piping network's configuration has been developed by Fazlollahi et al. [185]. Morvaj et al. investigated the optimal design and operation of distributed energy systems as well as optimal heating network layouts for different economic and environmental objectives [186]. A mixed integer linear programming model was used for multi-objective optimization to minimize total cost and carbon emissions. Pavicevic et al. developed an optimization model capable of handling both the sizing and the operation of a district heating system based on different generation technologies while considering building refurbishment [187]. Concerning a waste heat based DHN, it should be able to exploit as much as possible of the available carbon free source [188], which depends on the overall size and features of the selected users' basin. GIS (geographic information system) planning method for assessing the costs of DH expansions has been developed by Nielsen, considering distribution costs based on the geographic properties of each area and assessing transmission costs based on an iterative process that examines expansion potentials gradually [189].

Another work has reported the importance of taking both the socio-economic and consumer-economic approaches into account when expanding existing and building new DH systems has been reported [190]. The analysis of the literature shows that in recent years many evaluation methodologies have been developed in this field, but some authors, highlight the lack of a comprehensive framework for planning and design and the need for greater attention to research directions such as the examination of sustainability factors for the integration of industrial clusters with urban clusters and RES [24]. In addition an industrial waste heat-based DHN project involves several stakeholders, each driven by different, often conflicting, objectives. Typically, the industrial facility offering the waste heat, the end users, an energy service provider, the policy makers, private investors and the citizenship might represent the main actors involved.

2.2.1.1 DH system modelling

Basically, a DHN based on industrial waste heat recovery consists of three main elements: 1) a waste heat source such as an industrial company which provides the thermal energy through a recovery process; 2) a basin of consumers to which allocate the recovered heat for space heating purposes; 3) a provider of energy services interested in the construction and management of the DH infrastructure. The industrial waste heat source represents the core of the DH smart energy system. The amount of heat available for recovery H_{avail} depends on the specific characteristics of the productive process, but it is usually quite constant over a typical day. The heat source can therefore be characterised by an available daily energy profile. Plant downtime can occur due to ordinary and extraordinary maintenance interventions, which has been taken into account in the developed model by the availability factor AF. The available heat will be transferred to the DH network through a heat exchanger, to be placed nearby the waste heat source, thus generating, together with auxiliary components and the necessary circuitry changes, an investment cost. Since the focus of the present work is not on a detailed simulation of the DH network physic behaviour (i.e. fluid mass flow and pressure distribution, thermal gradients), but rather a sustainability evaluation at the planning level, the developed DHN model is based on some fundamental hypothesis:

- constant DH supply and return temperatures;
- steady state conditions of network operation, no dynamic effect (transient conditions) are considered;

- the generation efficiency of the heat only boilers and heat exchangers are assumed to be constant. The efficiency drops of equipment at partial load operation are neglected to simplify the analysis and calculation.

The characterization of the potential sink for the recovered heat is a crucial aspect to assess the sustainability of the project for an energy service provider and will be described in more details in the following subsection 2.2.1.3. In subsection 2.2.1.2 the energy system sizing is described, while in section 2.2.1.5 system cost evaluation is addressed.

2.2.1.2 DH system operation

The project is based on the idea of supplying a portion of the DHN seasonal heat demand through a waste heat recovery source, integrating the remaining thermal power request by auxiliary boilers fed by natural gas. Thus, in its simplest configuration, the energy generation plant should combine a heat exchanger to recover the waste heat from the industrial source, a thermal energy storage (TES) system and natural gas fired heat only boilers (HOB) for integration and back-up purposes. The total installed heat generation capacity is determined by the maximum power requirements of the DHN. TES systems can contribute to maximize the operation efficiency of the energy system by improving the exploitation of the waste heat source, since energy can be stored when the request is low (for instance during the night), and then used when the request is high, without dissipating the surplus energy. Furthermore, the thermal load diagram can be flattered, and the need of peak load boilers reduced, thus leading to a decrease of fossil fuel requirements. Moreover, TES allow an easier optimization of the operation, with higher conversion efficiencies and a smoother operation of the plants, which leads to less need for maintenance [191]. In the proposed configuration the HOB is not directly connected to the TES. This is a common setup in most of the renewable powered DH systems as the HOBs are usually used only for integration purposes, covering peak loads, or as backup units. The developed model calculates the share of the overall waste heat energy available from the source that can be exploited for district heating by simple energy balances ensuring that, in each time interval and for each node, the sum of energy inputs equal the sum of the energy outputs. The space heating demand must be covered in every time interval h of the simulated period by the combination of different energy generation options, namely industrial heat recovery (H_{rec}), peak load boilers (H_{HOB}), and TES (H_{TES}), as in 2.2.

$$L_{th,h} - H_{rec,h} - H_{HOB,h} - H_{TES,h} = 0 \tag{2.2}$$

The model is driven by the total space heating demand, as described in figure 2.2. The fuel consumption of the DH system is obtained considering the constant efficiency of the boilers fuelled by natural gas η_{HOB}. Simulations have been based on a time step of 1 h, given the hourly heat demand profiles as discussed in section 2.2.1.3. The algorithm is based on energy balance equations, which is:

$$L_{th,h} \leq H_{avail}$$

and

$$L_{th,h} > H_{avail}$$

In the first case, so when the heat load requested by the user basin of the network $L_{th,h}$ is lower than the heat availability H_{avail} the following happens:

- $H_{rec,h} = L_{th,h}$
  the recovered energy is equal to the heat load of the DHN;
- $H_{waste} = H_{avail} - H_{rec}$
  since the availability is higher than the the energy requested by the network the remaining share has to be dissipated;
- $H_{int,h} = 0$
  and the amount of energy integrated through the HOB is equal to 0.

while in the second case so when the waste heat availability H_{avail} is lower than the heat load of the network $L_{th,h}$:

- $H_{rec} = H_{avail}$
  all the available energy is recovered;
- $H_{waste} = 0$
  since the heat availability is lower than the load there's no remaining share that needs to be dissipated;
- $H_{int} = L_{th,h} - H_{avail}$
  the remaining part of the load not covered by the availability is covered by the backup boilers HOB.

For the aims of the current research, the thermal energy storages are modelled with some important assumptions. The storage medium is water. Coherently with the hypothesis made for the DHN model, supply and return temperatures to the tank are fixed at the same values, i.e. the temperature gap is assumed to be constant. The equation governing the TES are the common energy balance relation with constraints on the maximum and minimum energy content of

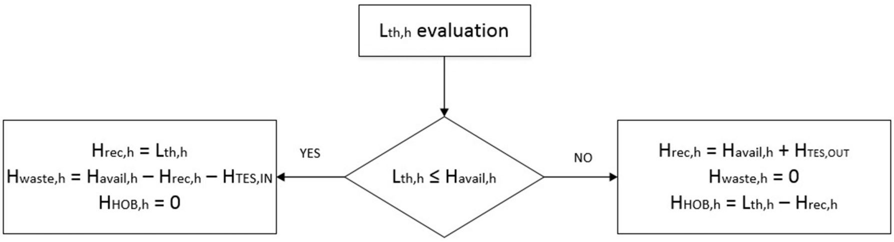


Figure 2.2: Flowchart of the energy system model [1]

the storage, which depends on the considered volume once the thermodynamic properties of the fluid are set [192]. If a surplus heat is available at any time interval h, this thermal energy is sent to the storage system until its capacity is filled, with priority over being dissipated. Furthermore when the heat availability H_{avail} is not sufficient to cover entirely the heat load $L_{th,h}$ energy stored in the TES can be used to cover the remaining part of the heat load reducing the amount of energy to be integrated through the HOB H_{int}, minimizing the greenhouse gases emissions.

2.2.1.3 Heat demand characterization

The overall heat demand of the potential DH network depends mainly on climate conditions (i.e. outdoor temperatures of the considered location), on thermophysical characteristics of buildings, as well as the intended use and the behavioural habits of their occupants. To overcome the typical lack of reliable data on thermal requirements, a simplified model for the evaluation of the hourly heating requirements of buildings when only the value of the power installed for every user is known, based on the correlation between thermal power required and external temperature [193]. This approach is suitable for a quick to perform estimation of the overall heating load of a DHN, since a precise evaluation of each building's heating load for a given hour h is out of the scope of the research. Given the nominal capacity H installed at each building thermal plant j of consumer type w, the estimation of the total heating load $L_{th,h}$ of the selected DH basin in the considered hour h of the heating season, can be obtained as in 2.3:

$$L_{th,h} = SF \cdot \sum_{w} \left(\sum_{j} H_{w,j} \right) \cdot \frac{\theta_{id,w} - \theta_{o,h}}{\theta_{id,w} - \theta_{o,d}} \tag{2.3}$$

where $\theta_{id,w}$ represents the indoor design temperature, which is fixed for each consumer type w, $\theta_{o,h}$ is the hourly average value of the outdoor temperature and $w_{o,d}$ represents the outdoor design temperature, which is site-specific, according to the national regulations. The simultaneity factor SF takes into account that the maximum thermal power demand in a district heating system is lower than the sum of the individual nominal power of its heat customers due to the contemporaneity effect. The approximating equation for the simultaneity factor regarding groups with less than 200 members reported in literature [194] was embedded in the proposed model, while for more than 200 users the simultaneity factor SF has been considered to level off at approximately 0.47 [194]. According to Ciotti [193], in order to perform the above evaluation, the following input data should therefore be acquired:

- Indoor design temperature $\theta_{id,w}$ and daily heating period for each consumer category w (e.g. residential buildings, schools, etc.) served by the district heating network;
- The heat capacity currently installed, distinguished by each consumer category w;
- The average hourly temperature distribution of a typical year, which is easily provided by the local meteorological agencies.

The heat load pattern depends mainly on what kind of activity takes place in a building. In this study, the following consumer categories have been considered: 1) residential buildings (one- and two-dwelling buildings, multi-dwelling buildings); 2) public institutions (schools, administrative offices ...); 3) health and social services; 4) commercial buildings (supermarkets, malls); 5) manufacturing plants. This information can be easily obtained from a census on the field of the potential DH basin and/or from municipality regulatory plans. Each consumer type w has been associated with a different operation scheduling of the heating systems, similar to the ones identified by Verda [195], to describe how the indoor temperature is kept at the set point, namely:

- "Continuous operation": the building heating system operates 24 h per day, 7 days per week. This has been adopted for health and social services buildings;
- "Night set-back": the set point for the indoor temperature is lowered during the night. This has been chosen for residential buildings;
- "Time clock operation": this control strategy has been assigned to school buildings, public administration offices and commercial building consumer categories, since only daytime activities occur.

2.2.1.4 Environmental impact evaluation

The implementation of a DHN has in first place substituted the natural gas fed boilers installed by every user with a centralized heat production station, and feeding the network with waste heat allowed to substitute the natural gas for the centralized boilers with a sustainable heat source. These virtuous interventions lead to an important energy and environmental impact reduction of the heat forniture, that can be expressed and evaluated in primary energy saving PES and carbon dioxide CO_2 emission avoided determined by the primary energy consumption avoided through the exploitation of a waste heat source. Knowing the amount of waste heat recovered H_{rec} the total amount of gas combusted avoided can be computed from its lower calorific value $H_{i,CH4}$ and assuming a boiler conversion efficiency $\eta_{BB} = 90\%$:

$$CH_{4,av} = \frac{H_{rec}}{H_{i,CH4} \cdot \eta_{BB}} \tag{2.4}$$

However the boilers of the centralized heat production station are fed with natural gas bought from the national grid, so when analyzing the environmental impact the primary energy consumption and the carbon dioxide emissions deriving from the utilization of natural gas for energy integration H_{int} must be accounted:

$$CH_{4,int} = \frac{H_{int}}{H_{i,CH4} \cdot \eta_{BB}} \tag{2.5}$$

2.2.1.5 System cost evaluation

The investment cost C_{TOT} is composed by two main terms: the DHN infrastructure, i.e. pipelines connecting the main generation plant to the end users C_{pipe}, and the energy generation plant (involving HOBs C_{HOB}, TES C_{TES}, the heat exchanger for the recovery of industrial waste heat, pumps, etc.). Regarding the infrastructure, in DH models, a simplified evaluation of the capital cost of the pipeline is often used [187], considering an average investment cost per unit length. A detailed model has been developed by Nielsen [189] to assist territorial planning, but it only finds an indication of the size and length of the network, which are then not optimised in any way. Moreover, estimating the investment costs for distribution using a statistical method based on empirical data is problematic, because the correlation between heat densities and pipes is very weak due to simplifications of the geographic properties within each area. Since in a brown field context DH pipes are mostly placed close to or underneath the road network, the latter has been followed to design the DH grid reaching each neighborhood area. The relative infrastructure investment has been calculated by sizing the pipes depending on the nominal heat demand, with a constraint imposed on the maximum value of the fluid speed. As designing criteria in order to minimize pressure losses those would lead to higher pumping cost of the heating water inside the network, a constraint on the flowing velocity inside the pipes has been imposed, limiting it to 3 $\frac{m}{s}$. With reference to the expression of mass flow in a circular pipe:

$$\dot{m} = \frac{\pi \cdot D^2}{4} \cdot v \cdot \rho \tag{2.6}$$

Reorganizing and expliciting the fluid speed from the equation 2.6 and imposing the condition of maximum velocity the following can be obtained:

$$v_{max} = \frac{\dot{m}_{max} \cdot 4}{\pi \cdot \rho \cdot D^2} < 3 \tag{2.7}$$

from which the minimum commercially available pipe diameter that satisfy the condition can be identified. Once the diameter is identified also its specific cost is known.

Knowing so the amount of energy circulating the network (equal to the heat load $L_{th,h}$), and that the heat is transported within the network through hot water ($c_p = 4.186 \frac{kJ}{K \cdot kg}$) and imposing temperature difference between the input and return temperature of $\Delta T = 20°\text{C}$, the instantaneous water mass flow circulating the network can be computed with the following:

$$\dot{m} = \frac{L_{th,h} \cdot 10^6}{c_p \cdot \Delta T} \tag{2.8}$$

The maximum mass flow obtained through equation 2.8 will be utilized to design the pump size and the diameter of the pipes constituting the network. Once the distribution grid has been sized, the investment costs are estimated, based on data provided by Nielsen [189] (specific investment cost per unit length, varying with commercially available diameters), which include the costs for projecting, fieldwork, pipe work, materials, and digging. It is important to notice that context dependent variations of the investment costs related to field and pipe work can occur but are not accounted in the present version of the model. For instance, in dense cities investments can be much higher than in green field development and lower density areas, due to higher costs of digging a pipeline [196]. About heat losses from the network, a calculation based on empirical data obtained from Nielsen [189] has been embedded in the present model. In order to estimate energy generation plant investment costs, capacity dependent specific investment costs have been considered for all commercially available technologies, together with their efficiencies, capacity bounds, and the fixed operation and maintenance costs, according to reports of the Danish Energy Agency [197]. About TES, hot water tanks are the most common types for short-term heat storage and vary greatly in size, ability to store heat, maximal discharge capacity and price [187]. Storage capacity related specific investment costs C_{TES} have been considered according to [198]. A two-step function has been used, assuming each TES type suitable for different storage capacity range: steel tanks up to about 7000 m^3 (typically in the configuration of multiple steel tanks installed in parallel), and concrete hot water storages, up to about 20,000 m^3 (one single insulated concrete tank).

$$C_{TES} = \begin{cases} steel, & 8 \cdot 10^{-6} \cdot V_{TES}^3 - 0.0692 \cdot V_{TES}^2 + 293.76 \cdot V_{TES} \\ concrete, & 1 \cdot 10^{-6} \cdot V_{TES}^3 - 0.0365 \cdot V_{TES}^2 + 347.3 \cdot V_{TES} \end{cases} \tag{2.9}$$

The total investment cost C_{TOT} can be computed knowing the investment of all the equipments:

$$C_{TOT} = C_{pipe} + C_{HOB} + C_{TES} \tag{2.10}$$

The operating costs associated with the DH system concern mainly the heat energy supply costs, i.e. heat only boilers feeding fuel and recovered energy costs, and maintenance costs, neglecting for the sake of simplicity the costs of the electricity for plant auxiliary operation. Operation and maintenance (O&M) cost is mainly due to heat only boilers and DH network components. About natural gas boilers for DH, a fixed nominal capacity specific O&M cost (expressed in EUR/MW/year) and a variable O&M (expressed in EUR/MWh) specific cost based on the generated thermal energy are considered [199]. As regards DH network O&M, a fixed energy specific cost (expressed in EUR/MWh/year) has been accounted, as provided [197]. The following equation gives the annual operating costs C_{ope} (expressed in EUR/year), where $C_{O\&M}$ is the total cost of operation and maintenance (as described above), c_f the specific cost of fuel, $c_{energy,rec}$ the specific cost of the waste heat energy bought from the industrial company, and c_{waste} is the specific cost of surplus heat dissipation. All specific costs are expressed in EUR/MWh, and only volumetric fees of heat supply are considered.

$$\begin{aligned} C_{ope} = C_{O\&M} + c_f \cdot \sum_{t=1}^{N} F_{HOB,t} + c_{energy,rec} \cdot \sum_{t=1}^{N} (H_{rec,t}) \cdot \Delta t \\ + c_{waste} \cdot \sum_{t=1}^{N} (H_{waste,t}) \cdot \Delta t \end{aligned} \tag{2.11}$$

The annual operational profit R_{ope} is obtained by multiplying the overall heating energy supplied to the consumers E_{user} and the specific price of the DHN heating service to the end users p_{user}. Potential incentive mechanisms, such as carbon tax (accounted as an avoided cost) and the so-called White Certificates (TEE), that reward the primary energy savings measures, can be properly added as shown in Equation 2.12. These items are accounted respectively as specific bonus to be multiplied by the overall carbon dioxide emission savings (c_{carbon_tax}, expressed in EUR/tCO2-eq) and by primary energy consumption savings (p_{TEE}, expressed in EUR/toe).

$$R_{ope} = p_{user} \cdot E_{user} + c_{carbontax} \cdot CDE + p_{TEE} \cdot PES \tag{2.12}$$

The economical analysis is carried on as explained is section 2.2.8.

2.2.2 II step: multiple waste heat recovery technologies

In this section different recovery technologies for waste heat exploitation are compared.

2.2.2.1 Recovery system modelling

Despite what said in literature [1] on the utilization of waste heat, this chapter studies the possibilities of the recovery of industrial waste heat for internal use inside the facility itself or to be used in the area surrounding the company, so only two elements have been considered in this model: 1) the waste heat source and 2) the basin of consumers. As the model has been developed to be implemented in an online tool as an aid for industries seeking energy efficiency interventions, both energy availability of the source and energy demand of the consumer can be modified by the user in order to meet the case's specific requirements (as it will be explained in more details in the following subsection). Given the wide range of activities and processes taking place in the companies, the model takes also into account the fluid that is carrying the waste energy (exhaust gases or hot water). In order to meet the different requirements of the users, as said before six different solutions have been investigated:

- ORC cycle: when electric power is required;
- Absorption chiller: when the user has refrigeration needs;
- Heat exchanger: to satisfy heat demand through a direct utilization of the waste heat;
- Heat pump: in order to allow the utilization of low temperature waste heat;
- District heating: to cover heat demand of user basin located in a far distance from the recovery source;
- Combination ORC + district heating: to analyze the feasibility of a technology cascade system aiming to the minimization of the wasted exergy.

2.2.2.2 Technology design

Every considered technology, which model is described in details in the following subsections, is fed with the energy recovered from the waste heat source, and, since the idea on which the work is based is not to design a system in order to cover the energy demand of the user but instead the recovery and utilization of waste heat, any other integration energy source has been considered. Thermal energy storages have been inserted in the plant, as an aid to the recovery source. This contributes to the maximization of the recovered energy since the TES can provide energy in those period when the user energy demand is not directly covered by the waste heat source. TES are necessary also to cover the demand during the maintenance stops of the heating source. So the total required TES is obtained summing the capacity necessary to cope with these two source voids, and is computed from the maximum energy request due to the time mismatch between the availability of the source and the demand of the users. For the technologies analysis the model takes as input the installed nominal power of the considered technologies, defined from the user and utilized to carry on the environmental and economical analysis, and time availability of the heat source and user demand (section 2.2.2.3). The requested nominal powers are:

- the installed nominal power of the absorption chiller P_{ABS};
- the installed nominal power of the heat exchanger P_{HE}
- the installed nominal power of the heat pump P_{HP}
- the size of the designed district heating network Q_{DHN}

2.2.2.3 Availability and demand characterization

While studying a solution for heat recovery, the main aim is not the satisfaction of the user demand but the maximization of the recovery of waste energy. With this idea, the model is not based on the characterization of the user demand, but on the time scheduling of the availability of the heat source. The week has been divided in 7 days, and in every days 4 groups of 6 hours have been considered. Using a boolean variable it has been indicated if the heat source was available in the selected time slot. The same method has been applied on the characterization of the user demand. From the number of availability days in a year d_{year} and knowing the number of 6 hour slots n_{slot} available every day the number of availability hours in a year $n_{h,year}$ is computed:

$$n_{h,year} = d_{year} \cdot n_{slot} \cdot 6 \tag{2.13}$$

The characterization ends with the definition of the source and user input and output temperatures and mass flow rates. From the selected input and output temperature of the source, the specific enthalpy of the fluid can be determined. Depending of the fluid type two different equations can be used:

$$h = \frac{T}{1000}\left[692 + 0.075T + \frac{17.5 + 0.0547T}{\lambda_{a/f}} + R\right] \tag{2.14}$$

in the case of exhaust gases, where:

- T is the fluid temperature in K;
- R is the gas constant
- $\lambda_{a/f}$ is the equivalent air fuel ratio.

And

$$h = 4.1915T + 0.7836 \tag{2.15}$$

in the case of water, where:

- T is the water temperature in °C.

Once the input and output enthalpies are determined and knowing the yearly working hours of the source it is easy to calculate the yearly produced energy. Two different clusters have been identified based on productive cycle features:

- Continuous: the heat source is available 24 hours a day for 7 days a week. This has been adopted for steel casting facilities, glass, paper and concrete manufacture;
- Discontinuous: the heat source is available for 12 hours a day for 5 days a week (from Monday to Friday), for example textile and food industries.

2.2.2.4 ORC

From the input and output values of the enthalpy calculated above (2.14 and 2.15) and from the known value of mass flow of the heat source fluid from which the heat is being recovered, it is possible to estimate the available heat power:

$$Q_{rec} = (h_{in} - h_{out}) \cdot \dot{m} \tag{2.16}$$

By multypling it for the number of hours of operation the total heat recovered in a year can be found.
At this point a model, developed by the university of Maribor, has been implemented to determine the operation fluid which would have led to better performances of the *ORC* system. Once the fluid is determined the efficiency of the *ORC* system is known, and the eletric power produced by the system can be computed:

$$P_{ORC} = Q_{rec} \cdot \eta_{ORC} \tag{2.17}$$

and then again multiplyng it for the number of hours of operation the total electric energy recovered in a year can be found:

$$E_{prod} = \frac{P_{ORC} \cdot f_{avail} \cdot n_{h,year}}{1000} \tag{2.18}$$

where P_{ORC} represents the installed nominal power of the *ORC* system, f_{avail} is an availability factor that takes into account the stops due to predicted and straordinary maintenance, $n_{h,year}$ the number of hours of operation in a year, 1000 is the unit of measure coefficient to obtain the result expressed in kW. Knowing the total amount of produced energy along the year, assuming the amount of energy requested inside the facility itself it is possible to compute the amount of energy sold:

$$E_{sold} = E_{prod} \cdot r_{s/u} \tag{2.19}$$

where $r_{s/u}$ represents the ratio, expressed in %, between the sold and produced amount of energy.

2.2.2.5 Absorption chiller

The yearly produced cold energy is computed from the cooling power and the number hours when cold energy request from the user, with an equation similar to the one seen for the energy produced by the *ORC* (equation 2.18):

$$C_{avail} = \frac{P_{ABS} \cdot n_{h,year} \cdot f_{avail}}{1000} \tag{2.20}$$

where f_{avail} is an availability factor.
Since even insulating the components and the distribution pipes heat losses

and leakages the cold energy effectively sold is lower than the one produced. In order to take into account these losses the following equation has been utilized to calculate the amount of cold energy sold:

$$C_{sold} = C_{avail} \cdot (1 - f_{loss}) \tag{2.21}$$

where f_{loss} represents the amount of cold energy loss due to heat leakages through the insulation expressed in percentage of the total cold energy available C_{avail}.

2.2.2.6 Heat exchanger

From the value of the nominal power of the installed heat exchanger Q_{EX} and the time slots of demand identified previously (section 2.2.2.3) is possible to obtain the total yearly heat energy available from the implementation of the heat exchanger through the following:

$$H_{avail} = \frac{Q_{EX} \cdot n_{h,year} \cdot f_{avail}}{1000} \tag{2.22}$$

where f_{avail} is an availability factor as explained in 2.2.2.4, and 1000 is the unit of measure coefficient to obtain the result expressed in MWh.
Knowing the yearly available energy H_{avail} the amount of energy actually sold and recovered considering the heat losses along the distribution system can be computed:

$$H_{sold} = H_{avail} \cdot (1 - f_{loss}) \tag{2.23}$$

where f_{loss} is a factor similar to the one seen for the absorption chiller in equation 2.21 and represents the amount of heat energy loss expressed in percentage of the total heat available H_{avail}. In order to compute the primary energy saving (PES) deriving from the substitution of fossil fuels derived with recovered heat thanks to the implementation of the heat exchanger, assuming that the heat would have been otherwise produced with natural gas fired boilers, the amount of natural gas combusted avoided has to be calculated:

$$m^3_{CH4} = \frac{H_{sold} \cdot Hi_{CH4} \cdot \eta_{BB}}{1000} \tag{2.24}$$

where H_{iCH4} represents the lower calorific value of natural gas and η_{BB} represents the efficiency of the backup boilers otherwise utilized.
Once the amount of avoided combusted natural gas the PES is computed as explained in section 2.2.2.9.

2.2.2.7 Heat pump

The analysis of the heat pump is similar to the one regarding the heat exchanger seen previously (section 2.2.2.6). Substiting the heat pump nominal power P_{HP} to the heat exchanger power P_{HE} in equation 2.22 the available heat energy H_{avail} can be computed. Through equation 2.23 the yearly sold heat energy is calculated following the amount of natural gas combusted avoided is determined applying equation 2.24. Before calculating the PES deriving from the implementation of the considered technology, is necessary to take into account the amount of energy consumed by the heat pump compressor:

$$E_{compr} = \frac{P_{compr} \cdot n_{h,year} \cdot f_{avail}}{1000} \tag{2.25}$$

where P_{compr} is the compressor power, obtained through the following:

$$P_{compr} = \frac{P_{HP} \cdot \eta_m}{COP} \tag{2.26}$$

where η_m is the mechanical efficiency of the compressor and COP is the coefficient of performance of the heat pump calculated through the equation given by university of Maribor:

$$\begin{aligned}
COP = \Big(&2.595 \cdot 10^{-10} T_{sink}^4 - 8.172667 \cdot 10^{-8} T_{sink}^3 + 9.67185 \cdot 10^{-6} T_{sink}^2 \\
&- 5.111793 \cdot 10^{-4} T_{sink} + 1.02299 \cdot 10^{-2}\Big) T_{source}^3 \\
&+ \Big(-2.083375 \cdot 10^{-8} T_{sink}^4 + 6.548858 \cdot 10^{-6} T_{sink}^3 - 7.729671 \cdot 10^{-4} T_{sink}^2 \\
&+ 4.068362 \cdot 10^{-2} T_{sink} - 0.8082695 \cdot 10^{-2}\Big) T_{source}^2 \\
&+ \Big(5.747083 \cdot 10^{-7} T_{sink}^4 - 1.805458 \cdot 10^{-4} T_{sink}^3 + 2.131203 \cdot 10^{-2} T_{sink}^2 \\
&- 1.123215 \cdot T_{sink} + 22.4175\Big) T_{source} \\
&+ \Big(-5.10416710 \cdot 10^{-6} T_{sink}^4 + 1.595417 \cdot 10^{-3} T_{sink}^3 \\
&- 0.1871896 T_{sink}^2 + 9.760158 T_{sink} + 188.643\Big)
\end{aligned} \tag{2.27}$$

Environmental and economical analysis are reported in sections 2.2.2.9 and 2.2.2.10 respectively.

2.2.2.8 District heating

From the value of the nominal power of the designed district heating network DHN Q_{DH} and the time slots of demand identified previously (section 2.2.2.3) is possible to obtain the total yearly heat energy recovered and sold from the implementation of the DHN through equation 2.22. Since the district heating network is fed with waste heat and the heat delivered substitutes heat otherwise produced with natural gas fed boilers, the implementation of the DHN network leads to a reduction in fossil fuels exploitation. This reduction can be measured in cubic meters of natural gas and computed from the sold energy through the equation 2.24. Environtmental analysis and economical analysis are carried on as explained in sections 2.2.2.9 and 2.2.2.10 respectively.

2.2.2.9 Environmental impact evaluation

Depending on the analyzed technology, its exploitation could lead to a primary energy consumption or saving depending on its actual utilization. In particular the technologies those recover waste heat to cover an user load (like ORC, absorption chiller, heat exchanger or district heating) lead to a primary energy saving, while the implementation of the heat pump would lead to a primary energy consumption since its using the heat availability just as a heat source and requiring external load for its operation. So, from the recovered and sold or consumed energies calculated in the previous section (E_{sold}, C_{sold}, H_{sold}, E_{compr}) the PES, PEC and share of CO_2 produced and emitted are claculated mutatis mutandis from the equations 2.4 and 2.5.
The environmental analysis is carried on in detail in section 2.2.7.

2.2.2.10 Cost evaluation

As reported in the decision support system paragraph, multi-objective optimization takes into account also economic parameters. Each technology is composed by specific components that differ from one system to another like turbines, compressors, generators, pumps, heat exchangers, cooling towers, pipes, fans.

Cost functions are used to estimate the purchasing cost of individual component of any technology considered. The cost functions are constructed as proposed by [200] where the purchase cost of an equipment item C_y at a size or capacity X_y can be calculated based on knowledge of the cost C_{ref} at a different size or capacity X_{ref} by use of a scaling exponent a:

$$C_y = C_{ref} \cdot \left(\frac{X_y}{X_{ref}}\right)^{\alpha} \tag{2.28}$$

In addition to the cost of the specific components, general costs and revenues common to all technologies have been considered. These are the operation and maintenance costs (O&M), the engineering costs, the costs for civil buildings constructions, and once the sold energy price has been fixed also the revenues due to the sold energy can be considered. Through the calculation of cash flow and total investment the economic analysis has been carried out as explained in section 2.2.7

2.2.3 III step: valorisation of food waste

According to the most recent studies, the feasibility assessment of FVW valorisation cannot be adequately estimated without considering the vast potential of integrated technologies for FWV valorisation in achieving sustainable and carbon-efficient biorefineries [201]. In fact, the waste material can be subjected to multiple valorisation options by means of integrated biorefinery interventions aiming at reducing waste to zero. The waste proportion to be destinated to each of these options has to be selected after evaluation of a large number of technical (e.g. integrability of different processes, process scalability), economic (e.g. investment cost, market price of the valorisation output) and environmental (e.g. process requirement of solvents, water and energy) variables [30, 201, 202, 203, 204]. In view of the above, the choice of a FVW valorisation system is a multi-criteria decision making (MCDM) process and, like all multicriteria evaluation problems, it faces the challenge of how to determine the preferred outcomes given the presence of more than one assessment criterion. The models supporting MCDM are designed to provide a framework for assessing this information on preferences in combination with deterministic or empirical information, so that decisions involving the assessment of multiple criteria can be reached within a structured framework. In this regard, the multi-objective method described by Simeoni et al. [78] could represent a valuable tool to estimate the environmental and economic implications related to the integration of FVW valorisation strategies in the traditional waste management system, on an industrial scale. In this chapter the model of a decision support system (DSS), based on techno-economic and environmental analysis, that identifies the system layout and plant size to support fruit and vegetable producers in waste valorisation actions is developed. In particular, ready-to-drink juices, antioxidant extracts, functional flour and a biodegradable expanded material have been obtained by using high pressure homogenisation, ultrasounds, air-drying and supercritical-CO2-drying, respectively [205, 206, 207, 208, 209]

2.2.3.1 Waste treatment plant model

To produce value-added derivatives intended for food use, lettuce waste is required to present a high homogeneity level. In addition, waste generation sites should not be very scattered, to facilitate the collection and thus cut both collection and transportation costs [210]. For these reasons, this work focused on lettuce waste generated in the food processing stage, that can ensure both a high compositional homogeneity and large amount in a reduced number of locations (i.e. the industrial plants). The first step has been thus the collection of data relevant to the amount of lettuce waste generated during fresh-cut processing. Official data report that in Italy the fresh-cut lettuce market (ML) amounts up to about 105,300 tons/year [211]. Of that, 60% is represented by whole-head lettuces, mainly iceberg lettuce [212]. A survey conducted in a large Italian fresh-cut company revealed that at least 35% of lettuce head weight is wasted (%WL), mainly due to initial operations of external leaves and core removal [213]. Based on these data, the total amount of waste generated in 1 year in Italy by the fresh-cut processing of whole-head lettuce (WL) has been quantified in about 23,000 tons (eq. (1)).

$$WL = 0.60 \cdot M_L \cdot \%_{WL} \tag{2.29}$$

Similarly, the total amount of whole-head lettuce waste generated by the large fresh cut company considered in the survey has been evaluated. In this company, about 20,000 tons of lettuce are processed into fresh-cut derivatives. Considering 60% of the total processed lettuce to be represented by whole-head lettuces and 35% waste production, the company would manage every year about 4200 tons of whole-head lettuce waste. In this work, for the treatment of this waste, an industrial park integrating traditional lettuce waste management strategies with innovative valorisation options has been proposed. Based on information collected from the producers, lettuce waste is commonly subjected to: (i) anaerobic digestion to produce digestate (fertilizer), biogas and, in turn, energy (by means of the cogeneration unit) [214]; (ii) composting to produce fertilizers [215]; (iii) carbonisation to produce biocarbon [216]. According to recent studies on the innovative valorisation of lettuce waste, the latter could be subjected to: (i) blanching and high pressure homogenisation to produce fresh juices [207]; (ii) ultrasoundassisted extraction to produce antioxidant polyphenolic extracts [208]; (iii) air-drying and grinding to produce vegetable flour intended for functional bakery products [205, 206]; (iv) water substitution with ethanol and supercritical-CO2-drying to produce biodegradable expanded materials for packaging or solvent adsorption applications [209]. In addition, side activities for the purification and recycling of spent resources such as ethanol residue and wastewater have been hypothesized. Real industrial processes have been considered for the process design of traditional waste management strategies (i.e. composting, anaerobic digestion and carbonisation) and side activities (i.e. wastewater treatment, ethanol recycling). Such processes, in fact, present high technological readiness levels (TRL), being actual processes, already applied on an industrial scale [217]. By contrast, innovative lettuce waste valorisation strategies, based on the production of functional beverages, antioxidant extracts,

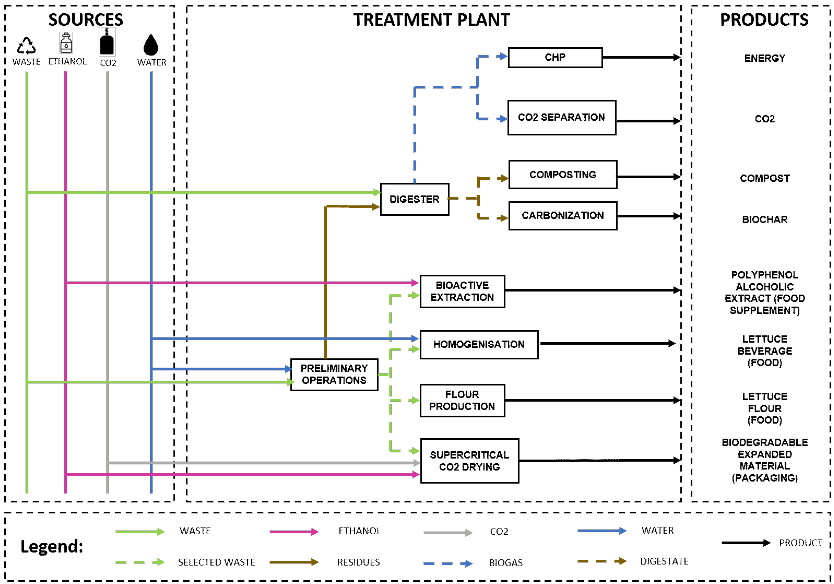


Figure 2.3: Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorization strategies of lettuce waste [2]

vegetable flour and biodegradable materials by means of innovative technologies, present a low TRL. For this reason, process design has been based on processes carried out on a laboratory scale and escalation factors of similar existing plants [30]. The yields of each lettuce waste process have been estimated as % ratio of final output as compared to the initial amount of raw materials entering the process. To this aim, industrial yields of traditional lettuce waste management options have been retrieved from relevant literature [218, 219]. By contrast, in the case of innovative valorisation strategies, laboratory results have been scaled up under the assumption that the same yields and performances would be obtained on an industrial scale, given the same processing conditions [220]. For example, the yield of air-drying and supercritical-CO2-drying resulted of 5%, due to 95% moisture content of lettuce waste [209]. Similarly, in the ultrasound assisted extraction of lettuce polyphenols, about 20% of solid residue has been retained in the filtration step, leading to 80% yield [208]. The hypothesized industrial park is represented in figure 2.3, where the flow diagram of the different processes involved in traditional lettuce waste management options, innovative valorisation strategies, and side activities, as well as their interactions are reported. In the case of traditional management options, lettuce waste would be straight directed to the proper industrial facility. By contrast, the implementation of the innovative valorisation strategies would require a preliminary selection of lettuce waste, to remove spoiled and bruised parts.

The latter would be managed by means of composting, anaerobic digestion or carbonisation. On the contrary, the selected lettuce waste could be exploited as raw material to produce different valorisation outputs. It must be noted that the need for lettuce waste selection introduces a high uncertainty in the amount of lettuce waste available for innovative valorisation strategies, since the initial condition of lettuce waste depends on unpredictable factors, such as weather and cultivation conditions. Possible interactions among the different processing steps involved in traditional and innovative valorisation strategies have been also identified. In fact, the integration of innovative strategies in the existing waste management framework is surely most likely to represent the real scenario of lettuce waste valorisation [201]. In particular, the attention focused on the possibility to reduce the need for outsourcing of energy, water and raw material of a valorisation process by using the waste streams of other processes integrated in the industrial park.

2.2.3.2 Energy demand

Data relevant to nominal energy demand of lettuce waste valorisation plants, integrated into the designed industrial park, have been collected. Laboratory-scale data have been directly derived from experimental activity, while industrial-scale data have been obtained from company surveys. In particular, data relevant to traditional lettuce waste management strategies have been collected from sector experts, engaged in the planning of local industrial activities. By contrast, in the case of innovative valorisation strategies, that are not present in the current industrial practice, data have been determined through scaling factors from similar existing plants and equipment [30]. Collected data have been elaborated to obtain energy functions, describing all the possibilities from a small laboratory scale up to large industrial ones. Regression equations describing the variation of absorbed nominal power (P_i) as a function of maximum plant capacity (tons of processed raw material or semi-finished product, WLi) have been obtained and compared based on the correlation coefficient R2 (Microsoft® Excel 2016). Functions in the form of equations 2.30 and 2.31 have been obtained and the equation presenting the highest R2 has been selected.

$$P_i = mW_{Li} + q \tag{2.30}$$

$$P_i = mlog\left(W_{Li}\right) + q \tag{2.31}$$

Such functions allow estimating absorbed P_i of specific plants and equipment as a function of W_{Li}, where i represents a generic operation. Thus, they represent a flexible tool to describe a wide range of possible scenarios, according to the available lettuce waste amount.

2.2.3.3 Environmental impact evaluation

Energy saving and consequent reduction of greenhouse gas emissions have been set as indexes of the environmental advantage of the designed lettuce waste valorisation industrial park. This has been attributed to the biogas produced form anaerobic digestion of lettuce waste, which can be used as sustainable resource to partially fulfill the energy requirements of the industrial park, contributing to reduce the emissions of greenhouse gases. In addition, the recycle of resources other than energy within the industrial park would allow reducing the need for outsourcing. As an example, the carbon dioxide deriving from the co-generation unit involved in the conversion of biogas from anaerobic digestion in methane, could be used in the supercritical-CO2-drying of lettuce waste. Moreover, the digestate and the biogas-based energy deriving from anaerobic digestion could be entirely recycled for lettuce cultivation and electrical supply of plants and equipment present in the industrial park, respectively. Primary energy saving (PES) and the carbon dioxide emission reduction has been quantified based on the biomethane-derived energy, obtained from lettuce waste anaerobic digestion $CH_{4,AD}$. The environmental analysis is discussed in details in section 2.2.7.

2.2.3.4 Economic analysis

Total cost of investment C_{TOT} has been calculated following equation 2.32 as the sum of equipment cost (C_E, EUR), cost attributed to civil work (C_{CW}, EUR) and to plant design (C_{PD}, EUR).

$$C_{TOT} = C_E + C_{PD} + C_{CW} \tag{2.32}$$

Since CE varies depending on the process scale, functions (in the form of equations 2.30 and 2.31), expressing C_E as a function of equipment power, have been obtained.It must be noted that for low TRL technologies, cost estimation presents a ±30% accuracy, due to possible failures in inflation projection and cost growth, due to unpredictable events related to the high complex process and unproven technology [221]. According to sector experts' opinion, C_{CW} has been set equal to 2/3 of C_E and C_{PD} has been considered as 2% of C_E.

In addition to CE, the costs associated with daily operation and maintenance of the industrial park (CO&M) have been calculated according to equation 2.33:

$$C_{O\&M} = C_M + C_W + C_U + C_{RM} + C_{WS} \tag{2.33}$$

where C_M (EUR) is the cost derived from C_E; C_W (EUR) is the cost of workforce required for plant operation; C_U (EUR) is the cost of utilities; C_{RM} (EUR) is the cost of raw materials; C_{WS} (EUR) is the cost of waste stream management. The revenues deriving from the plant operation R (EUR) are obtained from selling the valorisation products in the market while the operation cost C_{ope} are represented by the operation and maintenance cost $C_{O\&M}$. TEE incentives for saved energy have been considered as possible sources of economic revenues [222] and calculated following equation 2.34:

$$R_{TEE} = PES \cdot V_{TEE} \tag{2.34}$$

where VTEE (V) is the value of the incentives, based on current updates [223]. In order to calculate the value of R, the outputs of both traditional and innovative lettuce waste management options have been individuated.

2.2.4 IV step: wastewater treatment

Wastewater treatment consumes 0.5÷2 kWh electric energy per m^3 of treated water, depending on the selected technologies and plant scheme [224]. The AS biological process is the highest electricity consumer in WWTPs (10.2÷71% of total plant electricity consumption) [225], due to the need for continuously supplying oxygen to the basins, sustaining the aerobic degradation of the organic matter. In medium- and large-scale plants, AS systems account for 50÷60% of the total electricity need, followed by the sludge treatment (15–25%) and recirculation pumping (15%) sections [226]. Research has actually focused on aeration optimization: the idea of increasing aeration efficiency by water looping through a piping, including a venturi aspirator, was recently proposed [227], achieving an aeration efficiency in the range of submersed aerators.
In this chapter a multi-decisional modelling approach has been applied while implementing demand response (DR) to wastewater treatment in order to improve WWTP energy and economic balance considering alternative solutions. In order to enhance the economical performances of the plants, since it counts for the majority of the total plant energy need, it has been decided to focus on the reduction of expenses for aeration through the implementation of a compressed air tank. Recently, compressed air energy storage (CAES) have gained attention, due to their great power range and high energy density, making them an available solution in those contexts where the traditional storage technologies, such as pumped hydroelectric energy storage (PHES), cannot be implemented. In [228], a way to decrease the energy dependency in CAES was investigated, taking advantage of transient flow. Differently from typical utilization of CAES, that includes a power production regulation purpose, as proposed by Abbaspour [229], in the present chapter the compressed air storage (CAS) has been considered as an oxygen buffer for the wastewater treatment proccess. The idea is to reduce treatment process expenses through DR application by compressing air to the tank during low energy demand periods (off-peak) to make it available during high demand periods (peak load). Such a dual utilization of CAS system has not been found in the literature. Moreover this approach, reducing the dependance from the energy market, helps WWTPs gaining a more active role into future smart energy systems.

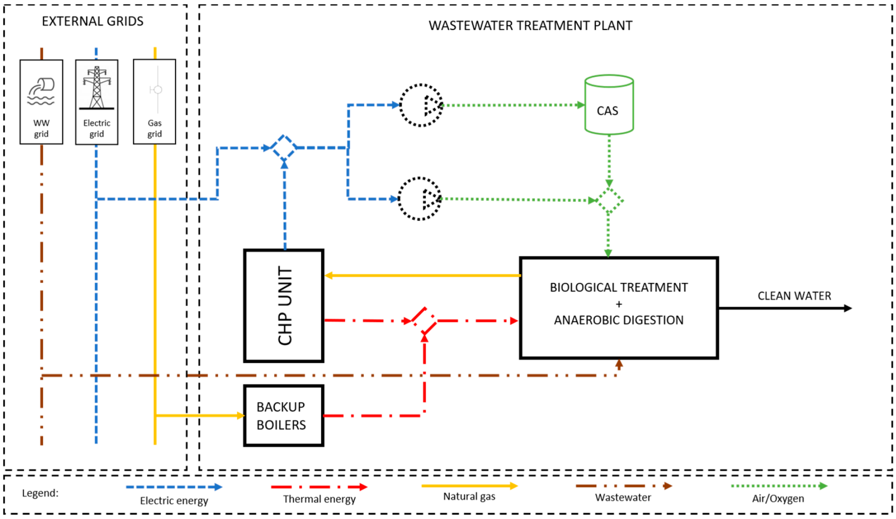


Figure 2.4: Wastewater treatment plant process flow [3]

2.2.4.1 System configuration

Based on a load shift approach, a DR and net zero energy (NZE)-oriented system was proposed for WWTPs. As previously introduced, the aeration during biological wastewater treatment accounts for more than 30% of the plant's total energy consumption. Instead of shifting wastewater treatment to periods characterized by lower energy costs (leading to the need for large storage tanks or equalization basins, not always practically feasible) [225], the possibility of storing the air necessary for the biological treatment was considered. This solution (schematically represented in figure 2.4) allows one to store energy in a compressed air tank during low energy cost (off-peak) periods, utilizing it when the cost increases (peak periods). Furthermore, the possibility to use the electricity from biogas (locally produced in AD process) by cogeneration was analyzed. This second scenario would allow one to cover a significant share of the process electrical load, while the heat production could be used to entirely cover plant heat demand.

2.2.4.2 Biological treatment unit

The oxygen injected in the biological phase ($O_{2,cons}$) was supposed to coincide with the oxygen consumed by biomass, estimated by considering a simplified approach (eq 2.35), as proposed in [230]. The operating parameters of the activated sludge process in equation 2.35 were set as follows, considering typical full-scale plants in the analyzed territory, where a significant influent dilution is observed in sewers due to aquifer infiltration: mean influent COD concentration (COD_{in}) = 250 mg/L, mean effluent COD concentration (COD_{out}) = 50 mg/L (corresponding to 80% COD abatement), hydraulic retention time (HRT) = 7 h, solid retention time (SRT) = 15 d, biomass concentration in the biological basin (X) = 3.5 g volatile suspended solids (VSS)/L. The factor 1.42 represents COD conversion factor for biomass [30].

$$O_{2,cons} = (COD_{in} - COD_{out}) - \frac{HRT \cdot X}{SRT} \cdot 1.42 \tag{2.35}$$

From the calculated oxygen need and considering oxygen share in the air (20%), it was possible to determine the total injected air flowrate. To evaluate the energy consumption of the biological treatment, the specific operating capacity of oxygen diffusers (fine bubbles) was estimated as 1.2÷1.5 kg O_2/kWh (data given from specialized companies in the field). Finally, total plant energy consumption was calculated considering that the electricity consumption for oxygen insufflation is 30÷70% of the total plant energy need, as emerged from relevant literature studies.

2.2.4.3 Compressed air storage

The basic idea on which the proposed approach is based is the shift of the peak aeration load to low energy cost periods, introducing a storage system able to sustain the aeration during peak energy cost periods. In order to evaluate the economic convenience of the proposed technology, the energy required to compress the air in the tank, E_{compr} (kJ), is calculated as follows (eq 2.36):

$$E_{compr} = P_{storage} \cdot V \cdot ln\frac{P_{@}}{P_{storage}} + (P_{storage} - p_{@}) \cdot V \tag{2.36}$$

where V represents the storage tank volume (m3), $P_{storage}$ is the pressure inside the tank (MPa), and $P_{@}$ (MPa) is atmospheric pressure

2.2.4.4 Anaerobic digestion unit

The sludge production ($\dot{m}_{sludge}$) was calculated using equation 2.37, considering full-scale WWTPs' characteristics in the investigated area: a specific sludge production of 40 g suspended solids (SS)/m^3 (psludge) was used for the successive calculations. Biogas yield from excess sludge (Q_{CH4}, (m^3 CH_4/h)) was obtained from equation 2.38, considering typical specific methane production (Y_{CH4}, 250 NmL CH_4/g VS) vs. the concentration of excess sludge (2.3% w/w) in medium-scale local $WWTP$s [231].

$$\dot{m}_{sludge} = \frac{Q \cdot p_{sludge}}{\%VS \cdot 10^6} \tag{2.37}$$

$$Q_{CH4} = \dot{m}_{sludge} \cdot \%VS \cdot Y_{CH4} \tag{2.38}$$

The mean electric and thermal efficiencies of the downstream combined heat and power (CHP) unit for biogas cogeneration were assumed respectively as 35% and 43%, consistently with relevant literature studies [232, 233].
The heat load has been considered equal to the one deriving from the anaerobic digester needed to maintain the operating temperature of the biological processes inside the digester. Under the hypotheses of heat balance the energy flux required to maintain the digester temperature at the desired value must be equal to the heat losses, so it can be computed as the sum of the heat losses through digester walls (H_{loss}, (W)) and the thermal energy needed for sludge heating (H_{sludge}, (kJ/h)), calculated using equations 2.39 and 2.40, following the approach proposed in [234]:

$$H_{loss} = k_{air}A_{sup}\left(t_{dig} - t_{soil}\right) + k_{soil}A_{base}\left(t_{dig} - t_{soil}\right) \tag{2.39}$$

$$H_{sludge} = \dot{m}_{sludge}cp_{sludge}\left(t_{dig} - t_{s0}\right) \tag{2.40}$$

The specific heat capacity of sludge (cps) was estimated as 3.62 kJ/kg °C [52], while air (t_{air}) and soil (t_{soil}) temperature were obtained from regional climate data [235]. Air (k_{air}) and soil (k_{soil}) heat transfer coefficients were taken from [234]. The digester operating temperature, t_{dig}, was set at 35 °C (optimum mesophilic range [236]), while the mean influent sludge temperature, t_{s0}, was supposed to be 15 °C, consistently with regional climate data [235]. The geometrical characteristics of the digester (base area, A_{base}, (m^2), and lateral area, A_{sup}, (m^2)) can be considered as known data deriving from the specific case study considering the real characteristics of the analyzed full-scale reactor, or computed through resizing from similar plant assuming a $shapefactor$ to maintain ration between height and diameter of the reactor.

2.2.4.5 Environmental impact evaluation

The compressed air tank implementation shifting the load from high price to lower price hours and not acting on the total energy consumed for the process air pumping doesn't affect the environmental performances of the interventions. As a consequence only the effects deriving from the biogas production and its exploitation have been taken into account. The primary energy savings and the carbon dioxide emissions avoided can be calculated from the yearly production of biogas $Q_{CH4,year}$ obtainable from the hourly production Q_{CH4}. From this value the PES and avoided GHG emissions can be computed as described in section 2.2.7.

2.2.4.6 Economic analysis

For the economic analysis, it is necessary to evaluate the capital cost of the introduced technology and the reduction in operating costs that can be achieved. The capital costs for compressed air storage installation were calculated using the data reported in [237]. A linear correlation between the installed compressor power (W) and the compressor cost (C), obtained through specialized surveys, was considered in this basic approach. Equations in the following form were obtained for both components (compressor and storage tank):

$$C_i = W_i \cdot c_i + q \tag{2.41}$$

The total investment cost (C_{TOT}, (EUR)) is defined as the sum of the capital costs of the installed components. The revenues are defined as the avoided cost for energy purchase, that comes from the load shift due to the compressed air storage. The reduction in operating costs is consequently defined as the difference between the energy cost (purchased in the scenario without air storage) and the effective cost with storage implementation:

$$R_{ope} = C_{av,CHP} + C_{av,tank} + R_{TEE} - C_{compr} - C_{O\&M} \tag{2.42}$$

In equation 2.42, $C_{av,CHP}$ (EUR/y) is the avoided cost through biogas utilization, $C_{av,tank}$ (EUR/y) is the avoided cost through the air storage tank, C_{compr} (EUR/y) is the cost to compress the air inside the tank, and $C_{O\&M}$ (EUR/y) is the operation and maintenance system cost. R_{TEE} (EUR/y) is the share of revenues coming from primary energy saving, due to biogas exploitation from AD. CHP-related variables are set to 0 in the scenario where AD is not considered (Scenario 1). An average economic value of current Italian White certificates, equal to 250 EUR/ton of oil equivalent (toe), has been considered in this basic economic analysis for biogas valorization. The economic analysis has been carried on as reported in section 2.2.8.

2.2.5 V step: waste collection modelling

In order to reduce environmental impact deriving from waste also the collection phase must be taken into account. In the literature several studies approached this topic trying to reduce the impact and emission of garbage trucks by optimizing the collection routes [238, 239]
The aim of this chapter is the development of decision support model to help identifying the optimal solution for the waste collection vehicle fuel by comparing diesel, methane and full electric vehicle based on energy, environmental and economic performances.

2.2.5.1 Collection routes modelling

The impacts evaluation of the waste collection has been computed based on the total distance covered by the waste collection fleet. The total distance is function of the total number of trips needed that depends on the number of municipalities served by the company, on the number of waste fractions collected in every town and on the capacity of the collection trucks. In order to estimate the total number of trips requested to the collection vehicle fleet the following assumptions have been made:

- every waste share is collected individually: following current regulations regarding waste management mixage of different waste shares in order to limit contaminations due to hazardous materials must be avoided in every step of waste treatment, leading to separated collection phases;
- every municipality is served individually:

Following the above mentioned assumptions the mathematical model for the collection routes can be developed. The model receives as input the yearly total amount of waste collected for every waste share. This must be available for all the considered municipalities. Given the total amount of waste to be collected m_{waste}, knowing the capacity of the collection trucks V_{truck}, is possibile to determine the number of requested trips through the following equation:

$$n_{trip} = \frac{m_{waste}}{V_{truck}} \tag{2.43}$$

where n_{trip} represents the number of trips requested to collect the m_{waste} waste share amount with V_{truck} capacity collection trucks. In the case of a number of trips lower than 12, the number of trips will be set equal to 12 imposing a monthly frequence since in the current most common waste collection contracts with the municipalities waste collection company plan a minimum collection frequency due to degradation processes occurring in the waste mass. As a consequence of the above mentioned assumptions the number of requested trucks is equal to the number of daily collection trips. Defining as $n_{day,coll}$ the number of days in a year when collection happens, the number of vehicles is given by:

$$n_{trucks} > \frac{n_{trip}}{n_{day,coll}} \tag{2.44}$$

The smaller number that satisfy the condition is adopted.
While considering waste collection service of multiple waste shares erogated in different municipalities equation 2.43 must be applied to all.
Since the main objective of this study is to identify the optimal fuel solution both on the economic side and on the energy and environmental one, in order to take into account the differences in efficiencies between the considered drive technologies due to different driving cycles, that leads to reduction in energy consumption and environmental emisions, the collection routes have been divided in two phases: a *Transportation* phase that considers the trip of the truck from the deposit to the town where collection takes place, and from the town to the treatment plant once the collection is completed, and a *Collection* phase that considers the trip within the town borders where the actual waste collection from the trash bins takes place.
So the model receives as inputs the distances between the towns where waste collection takes place for every waste share and the plants where the truck are stored for the night and the plants of treatment of every waste share. The total distance covered along the year during the trasportation phase to collect all the waste produced from the considered area depends on the distances just considered and the number of trips calculated previously (equation 2.43), and can be computed through the following:

$$km_{transp} = \sum_i km_{transp,i} \tag{2.45}$$

whre i is the generic town and $km_{transp,i}$ the distance of the generic town from the plant.
Regarding the *Collection* phase, the other phase constituting the collection route when the actual waste collection take place, covered distances calculation two different approaches have been considered in the model depending on which data have been available in the specific analyzed case. The first approach consist in calculating the collection distances km_{coll} from the total covered distance for the collection km_{TOT}, obtained during data gathering in the specific case,

Table 2.1: Fuel specific consumptions

Fuel	Coll	Trans	Unit	Ref
Diesel	0.71	0.37	l/km	[242]
CNG	0.916	0.46.3	$l_{eq,diesel}/km$	[242]
Electric	0.9	0.4	kWh/km	[243]

by subtracting from it the *trasnportation* share of the covered distance:

$$km_{coll} = km_{tot} - km_{transp} \tag{2.46}$$

The second approach consists in introducing an approximation making the assumption that al the routes are composed by *transportation* and *collection* phase by the same ratio. This ratio, as reported in different literature [240, 241], can be assumed as equal to 20%/80% *collection/transportation*. Once the ratio is defined the *collection* distance can be computed by multiplying the *transportation* distance by the overmentioned ratio.
For the calculation of fuel and energy consumption deriving from the activity of waste collection specific fuel and energy consumption have been considered. This approach permitted to utilize different values of specific consumption for every phase in which the waste collection have been divided in order to take into account the effects of differents driving cycles on the consumption. A literature review as been carried on. The values of the consumption factor found are reported in table 2.1.
Once the specific consumption factor has been selected the fuel or energy total consumption can be computed:

$$cons = cons_{spec} \cdot km_{TOT} \tag{2.47}$$

In order to allow comparison between all the considered fuel and drive technologies, the following assumptions have been considered:

- every vehicle has the same weight, and the average weight during the collection has been considered: this allows to assume the same fuel consumption for both the trip before and after collection;

- all the vehicles have the same waste capacity.

2.2.5.2 Waste treatment plant

As introduced before since the considered technologies are methane fed vehicles and full electric vehicles also, an organic waste treatment plant has been considered in the model too. This because the produced biogas coming from the anaerobic digestion of organic waste can be either sent to upgrading in order to produce biomethane to be fed into the CNG waste collection vehicles, or sent to CHP for the production of heat and power to cover the internal loads deriving from the operation of the plant and to charge the batteries of full electric waste collection vehicles.

The plant receives organic waste that after a preliminary selection is mixed with water to obtain a sludge appropriately fluid to be pumped into pipes and sent to treatment into the anaerobic digester. As explained in the previous section (2.1.2) through processes operated by specialized bacterias the organic fraction of the waste treated is scomposed and turned into a gaseous product called biogas composed mainly by methane CH_4 and carbon dioxide CO_2 (on average in a 60/40 % ratio).

Due to the high content in methane CH_4 of the biogas the possibility of utilize this to fed and engine to produce electric energy and heat through CHP has been considered. This energy output coming from the cogenerator can be used to cover the energy loads of the plant reducing the request of energy otherwise obtained through traditional fossil fuels sources, adopting so a circular economy perspective that allows the recovery of energy from waste. Defined the size of the engine P_{CHP}, the thermal $\eta_{CHP,th}$ and electric $\eta_{CHP,el}$ efficiencies of the cogenerator expressed as functions of the size P_{CHP} ([244]), the electric and thermal energy possibly obtainable from the cogeneration of the available biogas $biogas_{CHP}$ are calculated:

$$E_{el,CHP} = \eta_{CHP,el} \cdot biogas_{CHP} \cdot 0.6 \cdot Hi_{CH4} \leq P_{CHP} \tag{2.48}$$

where 0.6 is the percentage of methane constituting the biogas, and

$$E_{th,CHP} = E_{el,CHP} \cdot \frac{\eta_{CHP,th}}{\eta_{CHP,el}} \tag{2.49}$$

The thermal load L_{th} is computed upon the assumption of assuming it equal to the one needed by the anaerobic digester, since the remaining heat load due to indoor heating of the offices can be considered negligible compared to the one requested by the anaerobic digestion process. So the thermal load is computed based on the total amount of sludge sent to anaerobic digester deriving from the organic waste mass entering the plant, calculating the heat power requested to heat the entering sludge mass to the operation temperature of the digester

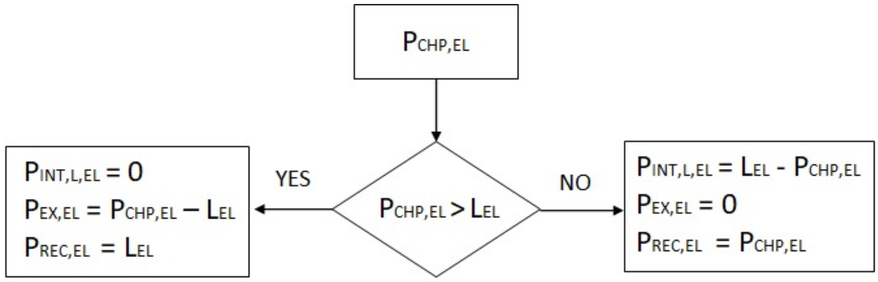


Figure 2.5: Flowchart of the electric balance equation

(through the eq 2.40) and the heat power to compensate the heat losses through the walls of the digester (through the eq 2.39). Both equations are explained in detail in 2.2.4.4
Regarding the electric load L_{el} the possibility to be computed in two different ways has been considered, based on the availability of case specific data from the company or not. When case specific data regarding electric consumption of the plant are available from the company, these can be simply adapted and imported into the model. While when not available, a rescaling from literature data of similar plants based on the plant treatment capacity (available data at [245]) has been considered. This has not been applied to the thermal load because the latter is much more location dependant (in particular temperature dependant) than the electric load and this would have led to a more precise and articulated resizing operation.
These loads must be covered every moment along the operation period. In those moment when the energy coming from the cogenerator $E_{CHP,\cdot}$ is not able to cover the load entirely energy from the grid must be bought to compensate this. Applying this concept to the electric load L_{el} the following balance expression must be satisfied:

$$E_{CHP,el} + E_{int,el} - L_{el} - L_{EV} - E_{CHP,el,sold} = 0 \tag{2.50}$$

where $E_{int,el}$ represents the total electric energy bought from the grid as integration, L_{EV} is the load requested for charging the EV constituting the garbage collection fleet and $E_{CHP,el,sold}$ is the surplux energy coming from the cogenerator after covering the load that is sold to the grid. Equation 2.50 must be satistied at every time step of the simulation. The application of this balance equation for every time step is reported in figure 2.5.

The same approach has been applied to the heat load L_{th}, where the application of the abovementioned approach leads to the following balance

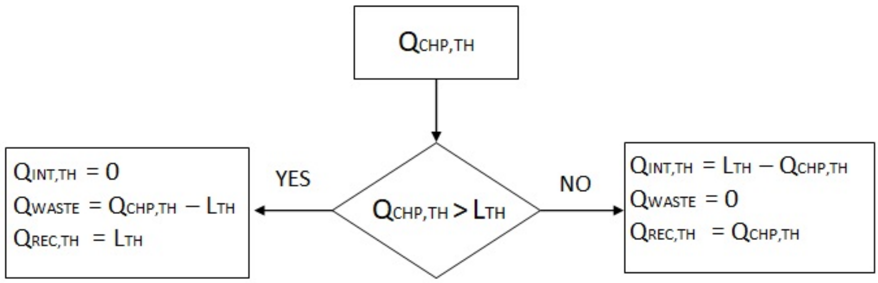


Figure 2.6: Flowchart of thermal balance equation

equation:

$$E_{CHP,th} + E_{int,th} - L_{th} - E_{CHP,th,waste} = 0 \tag{2.51}$$

where $E_{int,th}$ represents the total thermal energy produced through backup boilers utilizing natural gas bought from the grid as integration and $E_{CHP,th,waste}$ is the surplux energy coming from the cogenerator after covering the load that needs to be dissipated. Equation 2.51 must be satistied at every time step of the simulation. The application of this balance equation for every time step is reported in figure 2.6

The amount of natural gas bought from the grid to produce the integration heat energy $E_{int,th}$ through backup boilers can be calculated:

$$CH_{4,BB} = \frac{E_{int,th} \cdot 3.6}{\eta_{BB} \cdot Hi_{CH4}} \tag{2.52}$$

assuming a thermal efficiency of the backup boiler η_{BB} equal to 90%.
Another alternative to the utilization of the biogas is represented by the upgrading, the carbon dioxide CO_2 constituing the biogas is removed through a series of membranes (3 stages) that allow to rise the methane CH_4 content obtaining a gas composed almost entirely (97%) of biomethane. In this context both the possibility to utilize this biomethane to feed the CNG waste collection truck or to be sold to the natural gas grid have been considered. As for the plant load a balance between the requested and produced amounts of methane must be met during the operation period. In the case of surplux or shortage of methane deriving from the upgrading the sold or bought methane amount to/from the grid must be taken into account. The methane balance of the

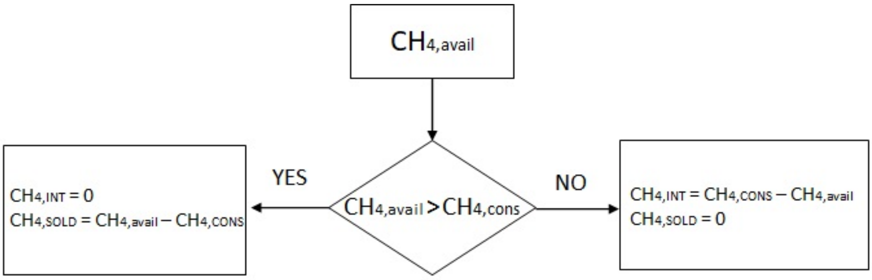


Figure 2.7: Flowchart of the CH_4 balance equation

plant for transportation is represented by the following:

$$CH_{4,avail} + CH_{4,int} - CH_{4,cons} - CH_{4,sold} = 0 \tag{2.53}$$

Equation 2.53 must be satisfied at every time step of the simulation. The application of this balance equation for every time step is reported in figure 2.7

2.2.5.3 Environmental impact evaluation

When carrying on feasability analysis of interventions on waste treatment plant and collection the environmental impact of the different alternatives has to be taken into account when comparing them and represents one of the most important function to look at during the identification phase of the optimal solution. Since different plant configurations have been analyzed, this had the effect of changing the balances of the different energy shares and side products, like the amount of electric energy sold to or bought from the grid and the amount of methane sold to or bought from the national grid, bewteen the plant and the grids, leading to different environmental impacts due to the different energy sources exploited. In this work the primary energy consumption PEC and primary energy saving PES and the carbon dioxide emission reduction $CO2_{red}$ have been chosen as function to compare the environmental performances of the considered alternatives. The primary energy consumption PEC is defined as the consumption of energy deriving from fossil sources expressed in *toe*. The primary energy saving PES is defined as the saving of energy, expressed in *toe*, deriving from the substitution of fossil sources with sustainable sources.

The PEC derives from the utilization of those energy shares bought from the national grids, like the integrated electric energy P_{int}, the methane bought as integration for the loads and vehicles $CH_{4,bought}$ and the diesel for the base diesel trucks scenario. The PES derives from those sustainable energy sources exploited to cover the different loads, like electric energy produced from CHP $P_{CHP,EL}$ and the biomethane produced through anaerobic digestion of waste. The primary energy saving PES and the carbon dioxide emission reduction $CO2_{red}$ are the entities considered for the comparison of the environmental performances of the different alternatives and their computation is explained in detail in section 2.2.7.

2.2.5.4 Cost evaluation

In order to carry on the feasability analysis and identify the optimal scenario a complete comparison is required taking into account also the economical performances of the considered alternatives. As it will be seen in the following chapter 3.5 each alternative differ from the other on the energy side, since different fuel technology for the waste collection have been considered as well as different plant configuration leading to different energy performances, as explained in the previous section. This has an effect also on the economical performances of the alternatives, leading to different operational cost due to the different side products of the plant or higher/lower energy efficiencies, and on the investment cost due to the different components constituing each alternative.
For the investment cost C_{TOT} of the alternatives the cost of the new trucks c_{truck} (different value depending on the fuel technology), the price of the refuelling station C_{pump} for the case of CNG or $C_{charger}$ for the case of EV, and the cost of new battery for EV $C_{battery}$ have been considered. The total cost for the vehicles depends on the number of trucks for the specific technology, the general equation used to calculate this cost is:

$$C_{truck} = \sum_{i} n_{truck,i} \cdot c_{truck,i} \tag{2.54}$$

The total cost of investment C_{TOT} can then be computed as:

$$C_{TOT} = C_{truck} + C_{pump} + C_{charger} \tag{2.55}$$

The operational cost C_{ope} considers all the costs coming from the operation of the plant and the waste collection. For their nature these costs are highly dependant on the alternative considered. For this evaluation the diesel cost

c_{diesel} for refuelling the truck of the base scenario, the cost of electric energy bought from the grid $c_{el,grid}$ to cover the electric load of the plant or to charge the electric vehicles, and the cost of the methane bought from the grid $c_{CH4,grid}$ have been taken into account. The general expression for the operational cost is:

$$C_{ope} = c_{diesel} \cdot cons_{diesel} + c_{el,grid} \cdot cons_{el,EV} + c_{CH4,grid} \cdot cons_{CH4} \quad (2.56)$$

Depending on the analyzed case each term could be present or not.
There are also revenues coming from the operation of the plant that have been taken into account. These are made of the revenues coming from the surplux electric energy produced through CHP sold to the grid $R_{el,CHP}$, the revenues coming from the surplux methane obtained from the upgrading of the biogas produced by the anerobic digester and sold to the grid R_{CH4}, and the revenues coming from reducing the environmental impact of the process like the primary energy saving substituting fossil sources with sustainable one represented by the TEE R_{TEE}, the CO_2 emission reduction expressed by the carbon tax CT R_{CT} and the CIC (italian incentives for advanced fuels):

$$R_{ope} = R_{el,CHP} \cdot p_{el,sold} + R_{CH4} \cdot p_{CH4,grid} + R_{TEE} + R_{CT} \quad (2.57)$$

These costs and revenues are the ones utilized to analyze the economical performances of the alternatives and to carry on the objetive function optimization, as it will be explained in detail in section 2.2.8.

2.2.6 Smart multi energy system model

In this section the complete model of the smart energy system comprising the different subsystems and technologies considered in the previous section has been developed. This SMES model takes into account the collection of waste through gargabe trucks and its transportation to the treatment plant where through anaerobic digestion is treated and turned into an energy source by producing biogas that can be sent either to upgrading to enhance its methane content for utilization as advanced fuel or to the cogeneration engine to produce thermal and electric energy. Beside the waste treatment plant, a wastewater treatment plant has been considered. The sludge would be treated in an anaerobic digester in this case as well in order to extract the energy content from it, and then the obtained biogas would be sent to cogeneration for heat and electricity production. This two treatment plants form the so called waste treatment HUB, having similar energy requests and outputs. Due to their similarities this two plants can share their surplux energy coming from the cogenerators to help each other covering their respective loads.Following a wholesale food market has been integrated in the system. The food market due to its nature can be considered as an user of the system while not as an energy source. This because of the acitivities that take place in it. The food market is characterized by cold energy loads for the goods conservation and preservation that by the integration in the SMES with the waste treatment HUB can be covered by the surplux energy from the cogeneration. Moreover the food waste produced in the market can be sent for treatment in the HUB allowing also this material exchanges between the different elements of the system.

At last the integration in the system of a DHCN as been added. The network when integrated in the system can act both as a source or as an user of the system. This due to its huge heating (or cooling) basin that allows the network to integrate heating or cooling energy when the energy coming from the other sources is not sufficient to cover the loads, or to "absorb" the surplux energy coming from the HUB by reducing the amount of energy integrated through its traditional sources to cover its internal load.

A scheme of the plant is reported in figure 2.8.

The mathematical model of the plants and their interaction are reported in the following sections.

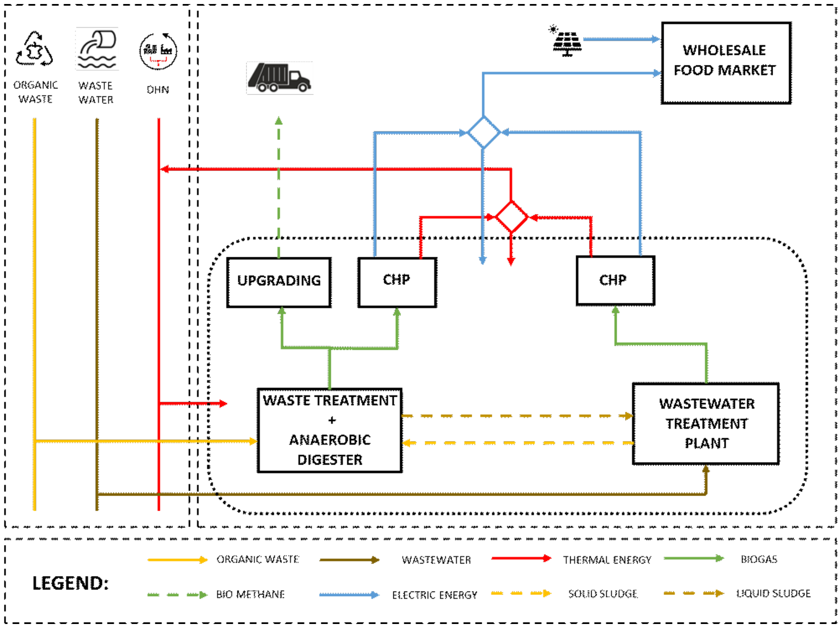


Figure 2.8: SMES process flow scheme

2.2.6.1 Waste treatment plant

The model of the waste treatment plant takes into account the routes for the waste collection phase and its transportation to the treatment plant. The treatment of the waste through anerobic digestion has been considered with the production of biogas to upgrade or sent to cogeneration. Since the model and the plant layout and operation have already been explained, in order to avoid repetition its preferable to refer to section 2.2.5 for further details.
Due to the connection with the wastewater treatment plant the possibility of exchange not only energy but matter as well has been considered. Most "solid" sludges that would interfere with the operation of the wastewater treatment can be sent for treatment to the waste plant.

2.2.6.2 Wastewater treatment plant

The model of the wastewater plant receives in input the amount of wastewater to be treated. The model takes into account the anaerobic digestion of the sludges to produced biogas and a biogas fed cogenerator to cover the internal

loads of the plant. Since the model and the plant layout and operation have already been explained, in order to avoid repetition its preferable to refer to section 2.2.5 for further details.
Due to the connection with the waste treatment plant the possibility of exchange not only energy but matter as well has been considered. The liquid sludges coming from the solids waste treatment can be sent for treatment to the wastewater plant.

2.2.6.3 Food market

The model of the wholesale food market is relatively simple. Due to the activities run inside it the market is characterized just by energy loads since the only energy production is the one coming from photovoltaic panels. The energy coming from the panels has been given the priority to cover the internal loads of the market. So with the system the market will interact through the remaining share of the load not covered by the photovoltaic plant. The electric load of the market derives from the electric chillers necessary to refrigerate the cells where the goods are preserved and the rooms where the food is exposed. The fact that the actual load of the market is constituted by cold energy gives another degree of freedom to the system, since cold energy can be produced both by electric chillers or absorption chillers fed with heat. For this purpose for electric chillers a COP = 2 and for absorption chiller (considering the the low temperature of waste heat) a COP = 0.75 have been considered [246].

2.2.6.4 District heating network

As for the previous plants, for the detailed description of the network and the model representing it it's preferable to refer to section 2.2.1

2.2.7 Environmental analysis

In this section the energy and environmental parameters utilized as environmental function are explained.
When considering the environmental performances of a SMES interventions one parameter to take into account to compared the different configurations

and alternatives is represented by the GHG emissions, usually expressed by the CO_2 emissions. In particular when integrating energy efficiency technology and interventions the reduction in CO_2 emisssions is considered. This may come from waste energy recovery or implementing a more efficient technology. Once the amount of energy recovery and in general the energy consumption reduction it is possible to computed the CO_2 emission reduction by multiplying the amount of energy (electric, thermal and gas, fuel) for its specific emission factor μ ($1.94 \cdot 10^4 tCO_2/Sm^3$ for methane and $4.22 \cdot 10^4 tCO_2/kWh$). The general expression for the emision reduction ca be expressed as the difference of the situation before the intervention and the situation after the intervention, so:

$$CO_2 = \sum_i E_{i,before} \cdot \mu_i - \sum_i E_{i,after} \cdot \mu_i \tag{2.58}$$

where E_i represent the generic energy amount consumed.
In the same way the primary energy saving PES, expressed in toe, deriving from an energy efficiency intervention can be computed by substituting the emission factors with the primary energy factor ξ ($8.2 \cdot 10^{-4} toe/Sm^3$ for methane and $1.87 \cdot 10^{-4} toe/kWh$). So the equation for computing the PES becomes:

$$PES = \sum_i E_{i,before} \cdot \xi_i - \sum_i E_{i,after} \cdot \xi_i \tag{2.59}$$

where E_i represent the generic energy amount consumed. The CO_2 and PES will be utilized during the multi-objective optimization as environmental and energy functions indicators.

2.2.8 Economical analysis

In this section the economic parameters utilized as economic function and their computations are explained. The difference between the R_{ope} and the C_{ope} of the considered DHN solution represents the expected cash flow CF (EUR/year) of the investment.

$$FC = R_{ope} - C_{ope} \tag{2.60}$$

Economic evaluation is carried out by conventional performance measures such as standard pay back (SPB), defined as the time requested to recover the total investment cost C_{TOT} through the yearly cash flow FC:

$$PB = \frac{C_{TOT}}{FC} \tag{2.61}$$

Another performances indicator is the net present value (NPV) calculated as the sum of discounted cash flows at the present time for the considered time period (usually the lifetime of the project), as follows

$$NPV = \sum_{i=0}^{30} \frac{FC_i}{(1 + k_{discount} + infl)^i} \tag{2.62}$$

The expected lifetime of the project (service lifetime of the equipment) in the case of a DHN should be at about 30e50 years [247]. The internal rate of return (IRR) is also an important econoimc performance indicator to take into account. It's defined as the discount rate for which the net present value NPV is equal to zero:

$$IRR \quad | \quad NPV = \sum_{i=0}^{\mathrm{inf}} \frac{FC_i}{(1 \cdot IRR)^i} = 0 \tag{2.63}$$

Because of the relevant investment costs associated energy systems infrastructure, a financial indicator such as the debt service coverage ratio (DSCR) should be considered, to allow an evaluation of the investment also from an investment fund perspective. DSCR should satisfy the lenders, who usually require the compliance with a threshold value, which has been therefore imposed as a constraint in the optimization algorithm.

$$DSCR = \frac{FC}{\frac{C_{TOT} \cdot (k_{discount}+infl) \cdot (1+k_{discount}+infl)^y}{(1+k_{discount}+infl)^y - 1}} \tag{2.64}$$

2.2.9 Multi-objective optimization

During the multi-objective optimization the optimal solution that satisfy the target objective funtions of the smart energy system are identified. Usually the objective functions are chosen within the most relevant aspects of a smart energy system implementation, and so the following objectives are considered: maximization of the economic, environmental and energy performances. The optimization variables are chosen between the ones that can be directly modified by the stakeholders during the design or operation of the system, to identify the configurations and costs variables that optimized the performances. There could be some variables not under the direct conrol of the stakeholders, just like costs defined by the markets. These variables can be object of a sensitivity analysis to evaluate their effect on the intervention performances. According to Mattiussi a multi-objective optimization consists of four steps, namely: design

of experiments (DOE), mathematical modelling, optimization, definition of the pareto fronts [192]. First the DOE, the selections from the alternatives space from which the optimization algorithm will start, has to be defined. The choice of the DOE algorithm may depend on the kind of analyisis to carry on. For multi-objective optimizations a Sobol algorithm is reported as the most suitable.
For multi-objective optimization evolutionary algorithm are particularly efficient, due to their work cycle:

- starting from the DOE individuals the objective functions are evaluated;
- ranking the individuals based on the objective functions and from the one having great adequacy the next generation of individuals is generated;
- the next generation of individuals is analyzed and the process iterates until convergence.

From the solutions given by the multi-objective algorithm the pareto fronts are obtained. A solution x is said of pareto if there's no another solution y with better performances on a objective function without reducing the performances related to another objective function. The set of all the solution that satisfy this condition represent the pareto front.

2.3 Decision phase

The decision phase consists in comparing the alternatives obtained during the design phase to allow the decision makers an informed decision making process showing them the effects of their choices. As method for decision making and comparison of the various alternatives the multi-criteria decision making (MCDM) method has been adopted. This method consists in weigthing the criteria base on the interests of the different stakelhoders involved in the interventions or on the various objective when just one decision maker is present. In this way the pareto solutions identified in the previous phase are compared and the most suitable according to the weights is selected.

3

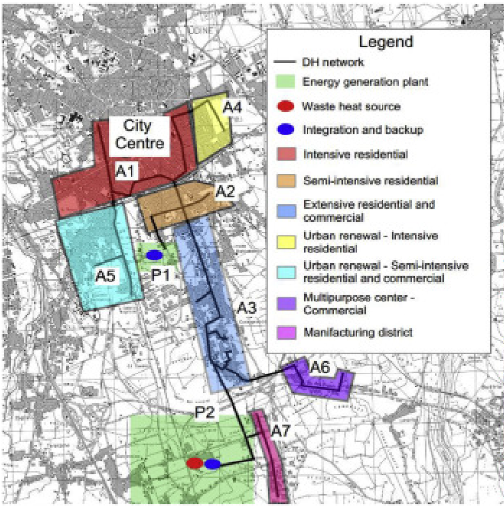
Results

In this chapter the results obtained from the testing and application of the subsystem are reported. In section 3.1 the results of the application of the DHN are reported. In section 3.2 are reported the results of the waste heat recovery technology comparison. The results coming from the investigation of food waste recovery are analyzed in section 3.3. In section 3.4 the result of the investigation of the wastewater plant are reported, and the results coming from the analysis of the waste collection model are investigated in section 3.5. Finally the results of the application and optimization of the SMES model to a case study are discussed in detail in section 3.6.

3.1 I step: waste heat fed DHN implementation

3.1.1 Case study

The proposed model has been applied to the city of Udine, located in North-Eastern Italy, a typical example of a European small town with about 100,000 inhabitants and an average population density of approximately 1750 inhabitants/km^2 . It comprehends both high- and low-density populated areas. Concerning the waste heat source, the opportunity was identified in a steel casting company located about 5 km south of the Udine city centre [248], which operates scrap melting through two electric arc furnaces (EAF). The main city areas to be potentially connected to DHN have been selected according to the same atlas. One and two dwelling buildings in low heat density areas such as suburban single-family houses and small villages have thus been excluded because unfavourable [249]. Through the analysis of the municipality regulatory plans and on-site inspections, most of potential consumers in the neighbourhood have been recognised as residential, but there are also some



City area	Residential	Public administration	Schools	Health and care	Commercial	Manufactures
A1	●	●	●			
A2	●	●	●	●		
A3	●				●	
A4	●					
A5	●				●	
A6					●	
A7					●	●

Figure 3.1: Udine case study: DHN layout and main city areas characterization [1]

schools, public institutions and administrative offices, as well as commercial buildings, one small healthcare facility and a few industrial consumers. An overview of the considered city areas to be potentially connected to the DHN is given in figure 3.1. Currently the investigated area has no DH infrastructure and individual boilers are adopted for space heating and hot water, mainly fed by natural gas, for a maximum installed power which can be roughly estimated in approximately 200 MW. Natural gas is considered as reference fossil fuel, with a lower heating value of 9.6 kWh/Sm^3 . As the reference scenario, the case with end users connected to a new DH network, designed without including waste heat recovery from the steel industry, thus replacing boilers with DH substations, is considered. The DHN energy generation plant can only count on HOB. The waste heat recovery infrastructure is composed, instead, by a heat exchanger close to the steel casting facility, as well as a pumping system, and a transportation pipeline which brings the waste heat to the end users. With the aim of testing the developed model, five alternative waste heat-based DH system scenarios have been analysed in this section, including all the main city clusters, which are characterised by the presence of consumer types as represented in figure 3.1. In scenario S1, the user basin served by DH is composed by the two highest-density residential areas next to the city centre A1 (intensive) and A2 (semi-intensive) as reported in figure 3.1. Some other consumer types such as schools, public administration offices and a small health care facility are also present. The waste heat recovery infrastructure is added to the network layout: a heat exchanger close to the steel casting facility and a transportation pipeline. The peak covering and back-up plant P1 is located next to the city centre main basin. It must be highlighted that the locations where to install the DH peak

Table 3.1: Analyzed scenarios

Scenario ID	Connected areas	H[MW]	L_{DH} [km]
S1	A1, A2	107	13.2
S2	A1, A2, A3	127	14.3
S3	A1, A2, A4, A5	187	15.8
S4	A1, A2, A3, A4, A5, A6, A7	195	21.4
S5	A1, A2, A3, A4, A5, A6, A7	190	21.4

integration and back-up plant have been selected within the available areas according to the municipality general regulatory plan, as indicated by the blue dots in figure 3.1, as suitable for brown field contexts. Scenario S2 considers the supply of the recovered energy to the users located along the way to the city's main basin (the one of S1): some commercial buildings, beside many extensive residential ones, characterise this area A3. Because of the long-time horizon which characterizes a DHN project, Scenario S3 considers a possible future expansion of the city centre to the nearby areas A4 and A5, currently characterised by a need for urban redevelopment, which are planned to be semi-intensive residential. In this scenario as in S1, a remote heat recovery facility brings the waste heat to the user basin next to the city centre, where the peak integration and backup facility P1 based on HOB is installed. Scenario S4 aims at investigating how the further connection to the DH network layout of A6 and A7 clusters, located nearby the steel foundry and composed mainly by commercial consumers and industrial manufacturers respectively, can enhance the exploitation of the available waste heat. Scenario S5 considers the same user basin as the one of S4, but with a different characterization of the urban redevelopment areas A4 and A5. This scenario investigates the effects of considering more commercial buildings instead of semi-intensive residential ones. An overview of all the considered scenarios, with the overall nominal heat demand H and DH network length L_{DH} is presented in table 3.1. The waste heat power available for recovery H_{avail} has been estimated up to 25 MW [22], in the form of hot water at above 90 °C, quite constant given the 24 h per day 7 days per week operations of the steel plant. An availability factor of 80% has been considered to account for steel plant downtime due to maintenance. DH network supply/return temperature are assumed constant at 85/65 °C. The specific investment costs for the pipeline system reported by Nielsen [189], ranging from 281 EUR/m for a 48 mm diameter to 1946 EUR/m for a 813 mm diameter insulated pipe, have been used to evaluate the DH network installation. About DH natural gas fired HOB, a nominal specific investment cost of 0.06 MEUR/ MW, a fixed O&M cost of 2000 EUR/MW/year and a variable O&M cost of 1.1 EUR/MWh have been accounted. Concerning TES, an average specific cost of 300 EUR/m^3 for steel tanks for storage capacity

Table 3.2: Variation range of the decision variables

Decision variables	unit	Range of variation	Incremental step
$c_{energy,rec}$	EUR/MWh	1÷ 30	1
p_{user}	EUR/MWh	5÷ 95 ([250])	5
V_{TES}	m^3	0 ÷ 20000	1000

up to 7000 m^3 and of 200 EUR/m^3 for concrete tanks for storage capacity up to 20,000 m^3 have been accounted [247]. The specific energy costs were estimated according to the current Italian energy market prices and considered constant throughout the simulated heating season: $c_f = 0.25 EUR/Sm^3$, $c_{TEE} = 300 EUR/TEE$, $c_{carbontax} = 5$ EUR/tCO2. In table 3.2 the variation ranges of the decision variables are reported. A specific cost for surplus heat dissipation (i.e. thermal energy available from recovery but exceeding the users' demand) of 4 EUR/MWh has been considered. Lastly, an emission factor of 1.94E-03 tCO2-eq/Sm^3 CH4 and a primary energy conversion factor of 8.20E04 toe/Sm^3 CH4 have been considered for the natural gas combustion. Simulations were run using hourly average external temperatures for the whole heating period, i.e. from 15 October to 15 April, according to the Italian regulation.

3.1.2 Results

The multi-objective optimization problem for the case study described in section 3 has been solved as explained in Fig. 1 using a 16 GB RAM, i7 4770 3.40 GHz PC. A population of 1000 individuals and 250 generations were adopted, resulting in 250,000 total evaluated designs, sufficient to obtain the convergence of the process in about 12 h. For the considered waste heat recovery scenarios the diagrams on the left side of figure 3.2 represent the hourly operation profiles of the DH system encompassing the whole heating season; in these diagrams the integrated (blue line), recovered (green line), stored (red line) and dissipated (yellow line) energy are plotted together. The diagrams on the right side of the same figure show the load duration curves related to the entire DHN's seasonal heat demand. The share of coverage by each energy source (recovered energy and HOB integration) and the surplus energy dissipation are also plotted in the form of duration curves, where the recovered energy is obtained as the sum of instant availability at the steel company heat exchanger and the heat power provided by TES. As it can be noticed from the graphs, given the amount of available waste heat power from industrial recovery, the larger the basin, the greater the waste heat source exploitation and, thus, the primary energy saving and the GHG emission reduction. Primary energy saving maximization implies the maximization of the total amount of recovered energy but also the minimization of the energy to be dissipated because of excess of availability. The recovered energy is, in facts, increasing from S1 to S5 (see the green area in figure 3.2, right side), and consequently less energy needs to be dissipated (see the yellow area in figure 3.2). At the same time, the increase in the number of DH users requires more energy from integration (represented by the blue area in figure 3.2, right side). A greater demand allows a better exploitation of the waste heat source, as highlighted by the red line in the hourly load distribution plots of figure 3.2, left side, representing the available heat that can be stored in TES system to be used later, when needed. TES system should be continuously charged during lower heat demand periods and discharged during the higher ones, according to the DH system heat requirements. An undersized DH user basin would lead to high dissipation, once TES maximum capacity is reached, since the heat load is not high enough to exploit the stored energy. Given the amount of industrial waste heat available for recovery, the DHN user basin selected in S4 allows a satisfactory exploitation of the waste heat source and, thus, a significant primary energy saving. The scenario with the largest basin seems to be also the most environmentally friendly one, allowing to achieve the better GHG emission reduction performance, and at the same time the economic indicators for the involved stakeholders are very good, despite the higher capital cost of the infrastructure due to the enlargement of the DH network.

3.1.2.1 MCDM analysis

Scenario S4, with its 25 km long DH network and about 195 MW nominal heat capacity of connected users, allows to achieve remarkable PES and GHG emission reduction performances. At the same time the economic indicators for the involved stakeholders are positive, despite the demanding capital cost of the infrastructure of about 39.7 MEUR. In order to allow a conscious decision making process, the linear algorithm of the multi criteria decision making (MCDM) tool of the modeFRONTIER® software has been applied on the solutions belonging to the Pareto front, for this most environmental-friendly scenario. First, the definition of weights to be assigned to the different stakeholders' objective functions has been done by pushing towards design solutions favourable for every single involved stakeholder, i.e. DH facility manager (and at the same time the investors), consumers, the industrial waste heat source and public authorities pursuing environmental goals. The software MCDM tool provides a ranking of the solutions, among which only the first

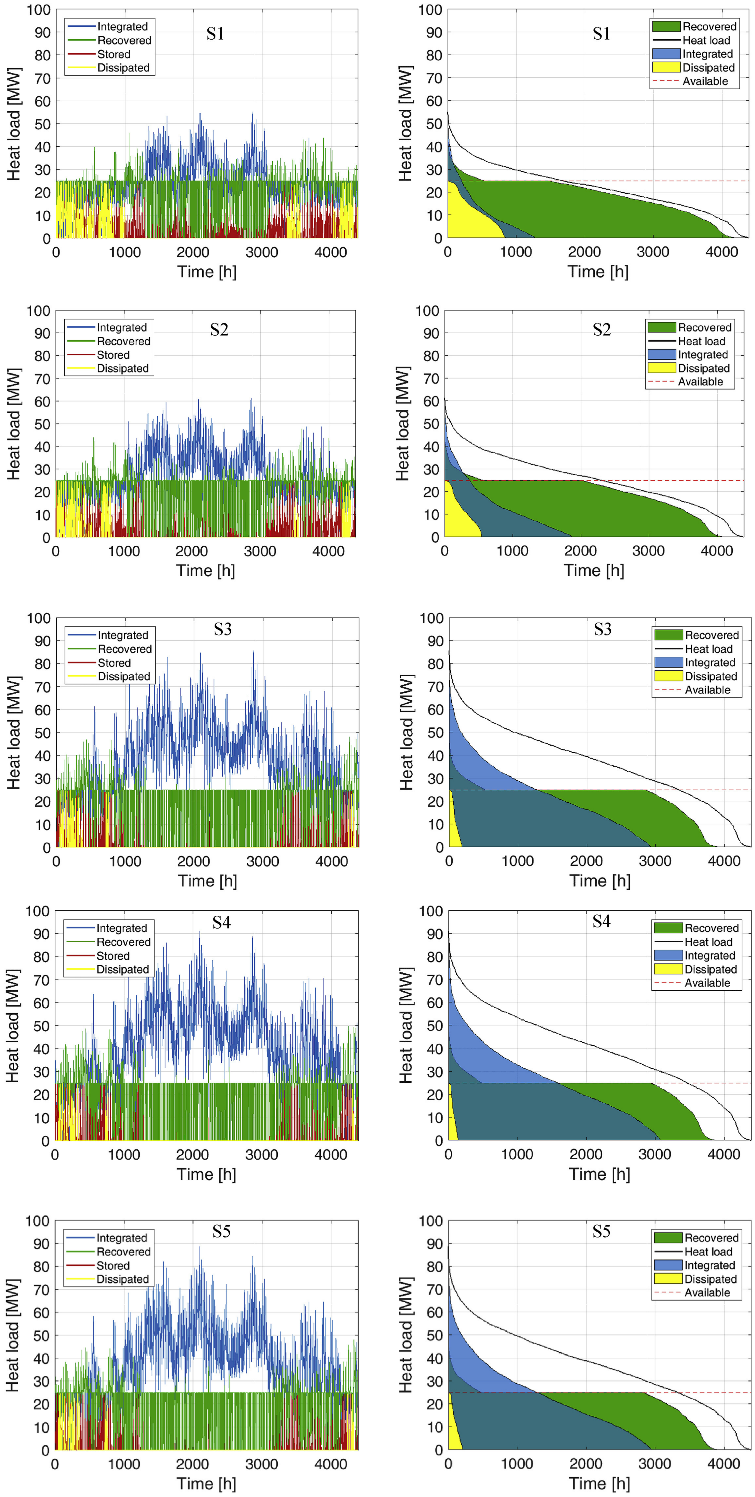


Figure 3.2: DHN energy system simulation. Hourly profile (left side) and duration curves (right side) for scenario 1 to 5 [1]

Table 3.3: MCDM applied only to Pareto front solutions

	DH	Users	Heat source	Environment
$V_{TES}[m^3]$	19000	19000	20000	20000
$c_{energy,rec}[EUR/MWh]$	11	11	30	18
$p_{user}[EUR/MWh]$	95	29	54	34
$SPB[y]$	2.6	9.9	6	9.4
$NPV[MEUR]$	177	10	48	14
IRR [%]	38.6	9.1	16.2	9.7
DSCR	5.6	1.4	2.4	1.5
$SPB_{steel,industry}[y]$	4.6	4.6	1.7	2.8

classified was selected and reported in table 3.3.

The economic indicators for the favoured stakeholder are at their best. If the DH service provider profit is maximized, this will result in the minimum cost of the recovered energy of 11 EUR/MWh, resulting in the maximum payback period for the steel making company of 4.6 years and the maximum heating price for consumers of 95 EUR/MWh. If end users are favoured, the minimum heating price of 29 EUR/MWh is reached, while keeping at the same level the recovered energy cost of 11 EUR/MWh. While the payback period for the steel making company is still at 4.6 years, the SPB for the DH provider reaches the highest value of around 10 years since the cash flow is not sufficient to counter the higher investment cost in the short term, and the other economic indicators get worse but still acceptable. When the industrial waste heat source goals are pursued, the maximum allowed value of the recovered energy cost (30 EUR/MWh) is selected by the MCDM tool, guaranteeing a short SPB of 1.7 years, while keeping an intermediate level of the heating price for consumers (54 EUR/MWh), reducing their energy bills. The project economics for the DH service provider are not very performing although still compliant with the imposed constraints, with a SPB of six years and an IRR of 16%. If the environmental performance is being pursued, the exploitation of about 89,675 MWh of recovered energy is reached in the whole heating season, around 98% of the total potential for energy recovery made available from the steel casting facility. This solution leads to a total annual CO2 emission saving of around 18,900 tCO2 if compared to the reference scenario where only gas fired DH HOBs are used for covering the heat demand. A TES capacity of 20,000 m^3 has been designed to allow this performance. The analysed scenario allows a wide range of solutions regarding price and energy cost policies.

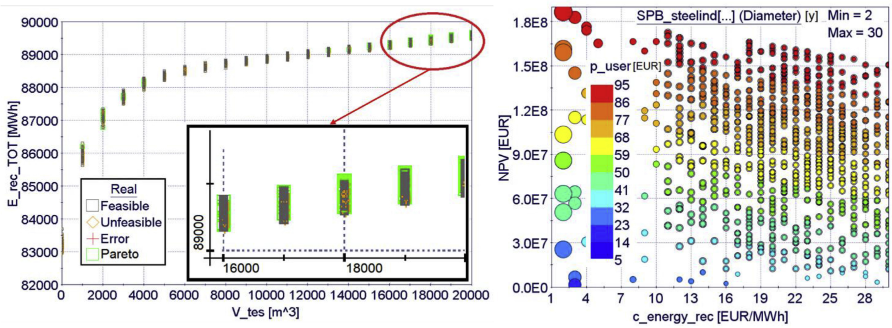


Figure 3.3: Pareto front for scenario 4. TES capacity versus total recovered energy (left side) and bubble diagram, represeting the relation between the economic decision variables and their influence on the project's economics (right side) [1]

3.1.2.2 Pareto fronts

The graphs of figure 3.2 refer to a TES capacity of 20,000 m^3 since, according to simulation results, as shown by the Pareto front (marked in green) of the scatter diagram on the left side of figure 3.3, the optimization pushes towards the highest values of the storage capacity when the maximization of the PES objective function is being pursued, disregarding the minimization of the investment cost. From a design perspective a V_{TES} of around 7000 m^3 is enough to obtain relevant environmental performances. Further storage volume does not guarantee significant improvements of the primary energy saving together with affordability. These main results could help decision makers in the plant design phase, giving important indications about component sizing, such as TES capacity. The multi-objective optimization results regarding the influence of the two economic decision variables, i.e. the specific cost of recovered energy and the heating prices for the consumers, on the trade-off between the economic performance for the DHN service provider (NPV) and for the waste heat source, are presented in the bubble diagram of figure 3.3, where the Pareto front has been marked by black circles. Looking at the spread of solutions that are generated, it can be noticed that there are feasible solutions (i.e. solutions which satisfy the imposed constraints), which could satisfy both DH service provider and the steel casting facility, while keeping the consumers' space heating bills at competitive levels through a conscious choice of DH heating service price. This would lead to a win-win solution from a sustainability and competitiveness perspective, for each involved stakeholder. It's worth noting that the Pareto multi-objective optimization pushes towards a specific cost of recovered energy greater than 10 EUR/MWh up to around

Table 3.4: Range and step of variation of the considered decision variables

Variable	Unit	Range	Step
HE power	(kW)	20-10000	100
HP power	(kW)	30-1200	30
ABS power	(kW)	100-4000	100
DH power	(kW)	100-20000	1000
ORC power	(kW)	500-4000	200
T (ABS,ORC, HE, DH)	(°C)	200-700	100
T (HP)	(°C)	20-60	5
T (cascade)	(°C)	0 400-700	100
Grant	(%)	0-50	10
TEE	(EUR/TEE)	100-400	100
Electricity cost	(EUR/kWh)	0.025-0.2	0.025
Thermal energy cost	(EUR/kWh)	0.03-0.12	0.01
DH length	(km)	0.5-10	2

30 EUR/MWh (the maximum allowed value) while keeping at a competitive price the heating service for consumers, from above 40 EUR/MWh (markedly below the maximum allowed value of 95 EUR/MWh).

3.2 II step: multiple waste heat recovery technologies

The implementation of the CE-HEAT project's online decision support tool, aimed at helping final users in the decision-making process through a conscious comparison between different waste heat recovery options, based on the information contained in the atlas developed by APE FVG, represents the final goal of this work. The development of a database of the input and output of the multi-objective optimization model provided by this research represents one of the project's preliminary activities. In table 3.4 the range and step of variation of the decision variables selected for the realization of the database are reported. The calculation performed through the developed mathematical model allowed the production of a database in a proper format in order to make it suitable for the online waste heat recovery evaluation tool implementation. Every considered scenario lead to a single spreadsheet file. A potential investor can first check the waste heat cadastre for interesting waste heat sources. It is true that sources with high power, high temperature and continuous emission profile guarantee higher recovery opportunity, but sources physically located nearby energy demand could be preferred as the reuse of energy is easier. After

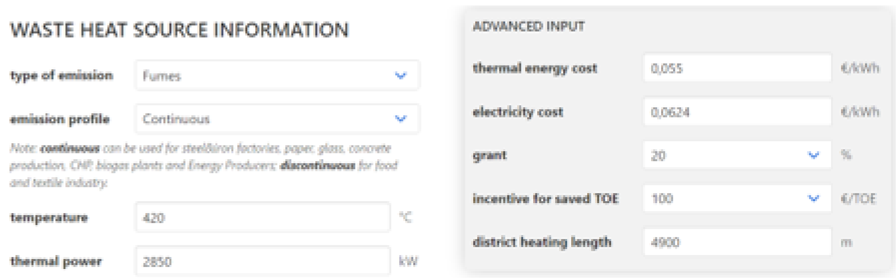


Figure 3.4: Screenshot of the online toolbox interface [4]

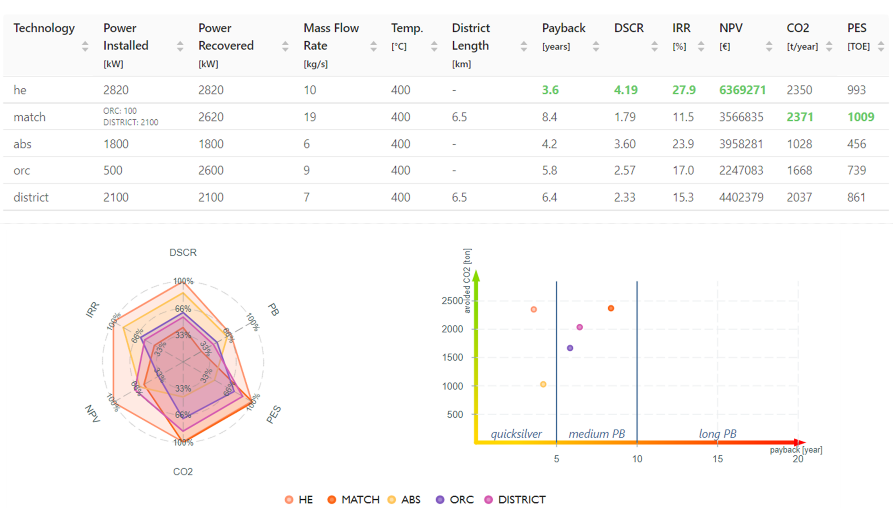
choosing the source, the investor can access data concerning the waste heat available in the cadastre. It is also possible to measure distances between the source and a potential energy demand. These data should be then used in the Decision Support System to assess different opportunities under an economic and technical point of view, as described in the previous paragraph. Policy makers can make use of the DSS jointly with the waste heat cadastre to find waste heat sources available in their territories and assess the energy wasted in that area. Policy makers need to embed energy recovery planning in policy strategies to meet environmental goals. Recoverable waste heat sources, should be selected within the waste heat cadastre and data used in the DSS. Policy makers, by setting different grants and incentives for saved *toe*, can define which incentive schemes should be developed to make waste heat recovery bankable.

Once the input variables are selected by the online toolbox user (see figure 3.4), the program will provide the decision support suggestions in terms of sustainability performance indicators and graphs (see figure 3.5).

3.3 III step: valorisation of food waste

3.3.1 Case study

Aiming to optimize the treatment and valorisation plant configuration, different designs have been investigated. An overview of the analysed DOE, describing variable range variation and incremental steps, is reported in table 3.5. As explained in section 2.2.3.1, lettuce waste availability for a typical Italian



Technology	Power Installed [kW]	Power Recovered [kW]	Mass Flow Rate [kg/s]	Temp. [°C]	District Length [km]	Payback [years]	DSCR	IRR [%]	NPV [€]	CO2 [t/year]	PES [TOE]
he	2820	2820	10	400	-	3.6	4.19	27.9	6369271	2350	993
match	ORC: 100 DISTRICT: 2100	2620	19	400	6.5	8.4	1.79	11.5	3566835	2371	1009
abs	1800	1800	6	400	-	4.2	3.60	23.9	3958281	1028	456
orc	500	2600	9	400	-	5.8	2.57	17.0	2247083	1668	739
district	2100	2100	7	400	6.5	6.4	2.33	15.3	4402379	2037	861

Figure 3.5: Comparison between different waste heat recovery options [4]

Table 3.5: Range and step of variation of the considered decision variables

Variable	Unit	Range	Step
W_L	tons/year	$3600 \div 8400$	600
Ope fractions	%	$0 \div 1$	0.1
V_{TEE}	EUR/TEEE	$0 \div 300$	100
$p_{biochar}$	EUR/kg	$0.2 \div 0.9$	0.05
$p_{food,suppl}$	EUR/kg	$4 \div 18$	1
$p_{homogenized}$	EUR/kg	$1.15 \div 6.15$	0.5
p_{flour}	EUR/kg	$0.16 \div 1.6$	0.16
p_{chips}	EUR/kg	$0.03 \div 0.18$	0..03

company has been estimated up to 4,200 tons/year. Nevertheless, W_L has been tested on a wider range, ranging from 3600 to 8400 tons/year. This allowed taking into account the variations of waste amount, which can vary according to unpredictable conditions, including weather, cultivation yield, pests. The fractions of waste material delivered to the different operations involved in traditional treatments and innovative valorisation technologies, ranging from 0 to 1, have been used to optimize the industrial park configuration. A variable value, ranging from 0 to 300 EUR, was set for incentives (TEE), based on most recent updates [223]. As already anticipated, table 3.5 reports the price (p) range of these valorisation products, which was defined based on corresponding market products. In this regard, the choice to use a price range rather than a medium price was based on the extreme variability of their values over time [30, 251]. Considering the high number of considered variables and deriving possible designs, a population of 500 individuals and 250 generation were chosen. The design phase computed a total of 125000 possible scenarios. The latter were then scheduled according to the values assumed by the environmental advantage and economic effort indexes of the multi-objective study, as defined in section 2.2.3.1.

3.3.2 Results

The multi-objective optimization problem for the case study described in section 2.2.3.1 has been solved using a 16 GB RAM, i7 4770 3.40 GHz PC. For the considered waste treatment and valorisation scenarios the charts in figure 3.6 represent the main effect of decision variables on the maximisation of $CO_{2,RED}$ (figure 3.6,a) and the minimisation of PB (figure 3.6,b). In these diagrams a box plot of a low level and a high level, indicated respectively with "-" and "+", of each factor variable are represented. A factor is important if it leads to a significant difference between the means of the two groups, connected by a line. The higher the difference, the more important is the factor. The connecting line can have either a positive or a negative slope: a positive slope indicates a positive correlation between the factor and the response, a negative slope indicates a negative correlation. As it can be noticed from the graphs, as the waste fraction delivered to anaerobic digestion increases, the CO2 emission reduction increases (mean value of 163 tons CO2/year, reaching a maximum value of 208 tons CO2/year), thus leading to primary energy saving. The waste fraction subjected to innovative valorisation has a similar but less pronounced effect, since its related connecting line has a lower positive slope (mean value of 102 tons CO2/year, reaching a maximum value of 140 tons CO2/year). This effect is due to the fact that lettuce waste valorisation leads to the production of

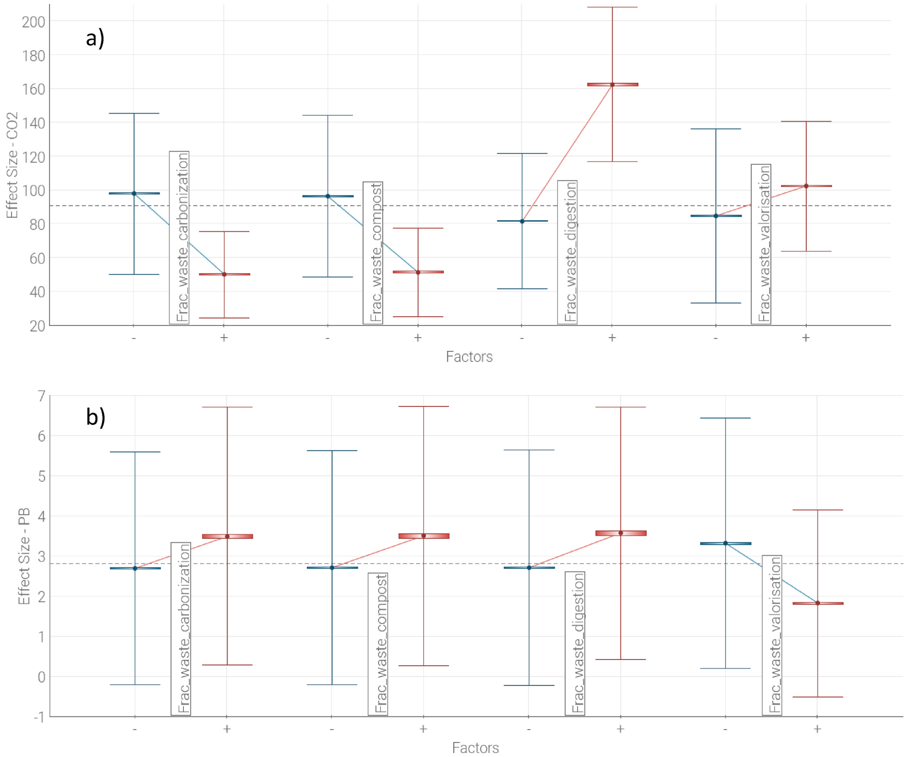


Figure 3.6: Main effect charts of carbonization, composting, anaerobic digestion and valorization on: a) $CO_{2,red}$ and b) PB [2]

innovative sustainable derivatives, which have a reduced environmental impact as compared to traditional ones. On the contrary, an increase in carbonisation and composting fractions leads to a decrease of the CO2 emission reduction of the plant, as it is shown from the negative slope of the connecting lines. Regarding the effects on the considered variables on the economic performances, as the waste fraction delivered to innovative valorisation increases, the PB decreases, while an increase in the waste fraction subjected to traditional treatment fractions leads to a higher PB. This is due to the higher added value and thus market price of the products obtained by innovative valorisation strategies, as compared to those derived from traditional ones (table 3.5).

Table 3.6: MCDM applied to valorization plant solutions

	Environmental	Cost	PB	Trade off
% carbonization	0	70	20	0
% composting	0	0	10	40
% AD	60	20	0	30
% lettuce flour	0	0	0	0
% lettuce homogenate	4	1	0	12
% lettuce bioactive extract	24	9	70	18
GHG emission reduction [tCO2/y]	124.4	39.1	63.1	71.8
PES [toe/y]	55.1	17.3	28	31.8
Investment cost [EUR]	9667276	8502699	10535299	9120427
PB [y]	2.4	3.1	0.3	1

3.3.3 MCDM analysis

Table 3.6 reports four of the scenarios among those obtained by the study. These scenarios were selected based on the achievement of each one of the objectives of the study, i.e. the maximisation of the environmental advantage and the minimisation of the economic effort indexes of the lettuce waste valorisation industrial park.

In these scenarios, the amount of whole-head lettuce waste produced during 1 year from a large fresh-cut company (about 4,200 tons, as discussed in section 2.2.3.1) was considered. As expected, the scenario allowing to maximise the environmental advantage would be the one managing the major part (60%) of lettuce waste through anaerobic digestion to produce biogas. The remaining lettuce waste fraction would be valorised into fresh homogenates, antioxidant extracts and innovative biodegradable materials. However, the C_{TOT} of this scenario would be of 9.7 million EUR and with a PB higher than 2 years (table 3.6). This can be attributed to the high cost of equipment required for implementing innovative technologies such as high pressure homogenisation, ultrasound assisted extraction and supercritical-CO2-drying. Accordingly, the minimisation of C_{TOT} would be reached by managing at least 90% of lettuce waste through traditional options, not allowing a proper valorisation of its rich composition. Moreover, this scenario would also present limited environmental advantages and a PB longer than 3 years (table 3.6). The latter would be minimised to just 4 months by valorising 70% lettuce waste into bioactive extracts. This valorisation strategy, in fact, would highly increase the value chain of lettuce waste, by producing a high-price food supplement (table 3.5). Nevertheless, C_{TOT} would be higher than 10.5 million EUR, while CO_{2RED} and PES would still be half that those realised in the scenario maximising the environmental advantage of the designed industrial park (table 3.6). Therefore, all the scenarios reaching one of the study objectives would present some drawbacks. In this regard, the selection of a specific scenario should be driven by a compromise among the defined economic and environmental objectives. For this reason, a further scenario, deriving from a compromise solution, is presented in table 3.6. In this scenario, 30% of lettuce waste would be valorised by the application of innovative valorisation strategies, based on the production of value-added homogenates and bioactive extracts using high pressure homogenization and ultrasound-assisted extraction, presenting a C_{TOT} lower than 9.1 million EUR and a PB of about 1 year. The remaining 70% lettuce waste would be subjected to traditional management options (composting and anaerobic digestion), contributing to greenhouse gases emission reduction and energy saving of about 72 tCO2/year and 32 toe/year respectively.

3.4 IV step: wastewater treatment

3.4.1 Case study:

The system model has been tested and validated on the plant of Lignano Sabbiadoro (Udine province). The daily pattern of wastewater flowrate was obtained from one-year hourly data of a medium-scale municipal WWTP (86,400 population equivalent (PE), Udine Province), highlighting two distinct peaks at 1 p.m. and 4 p.m. (figure 3.7). The obtained data were consistent with the typical reported 24-h behavior of flowrate in municipal WWTPs [225]. The calculated WWTP peak factor (maximum flowrate in the 24 h period divided by mean daily flowrate) was around 1.1, showing a moderate daily variability. The flowrate daily pattern was assumed to be constant for all the analyzed plant potentialities and any seasonal factor was considered in this first approach. The electricity price pattern in the 24 h time period was calculated considering the mean values of a typical month in Italy [252]. The mean electricity price for industrial users was given by the Italian Authority for energy, gas, water and waste [253].

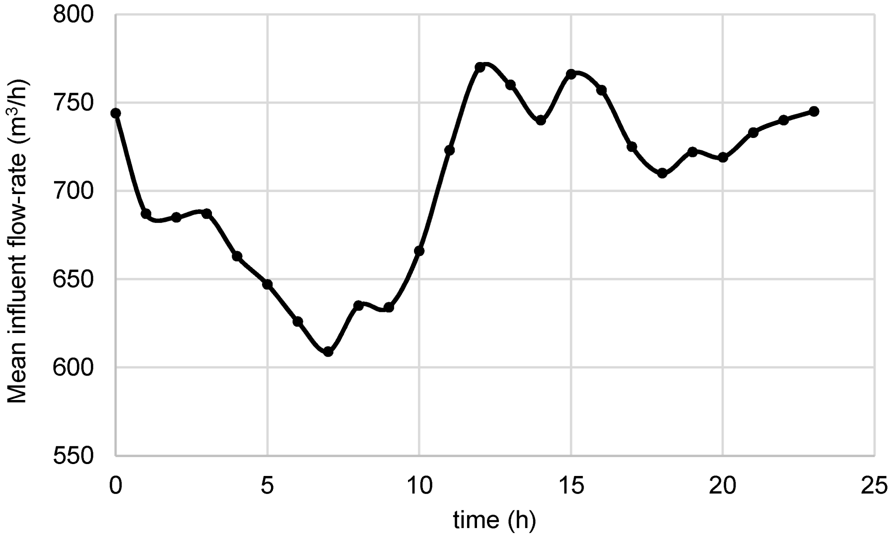


Figure 3.7: Mean 24h behaviour of the influent flow-rate in the analyzed WWTP [3]

3.4.1.1 Optimization model implementation

The mathematical model describing the behaviour of the wastewater treatment plant processes and its ancillary technologies has been developed in MATLAB® and successively implemented in the commercial optimizer modeFRONTIER® for multi-objective optimization during scenario analysis. The selected parameters for the optimization process are summarized in table 3.7. The range of modelled COD concentration was in line with the observed COD values in the analyzed territory, characterized by consistent wastewater dilution, due to mixed sewers and significant infiltrations from the aquifer. A wide range of treated flowrates was considered, to extend the validity of the obtained results to different scale WWTPs. The modelled flowrate range in WWTPs approximately corresponds to plant potentialities of 75,600–225,600 PE, consistent with most of medium scales WWTPs in Friuli-Venezia Giulia region (North-east of Italy). As for compressed air system characteristics, different combinations of pressure and volume were considered, to evaluate the influence of these parameters (both singularly and in combination) on the economic output.

Separate simulations were conducted for scenario 1 (CAS integration without AD) and scenario 2 (CAS integration with AD). Since scenario 1 investigates the implementation of compressed air tank as a DR technology, its implementation affects only the economic performances so the relevant output parameters

Table 3.7: Selected input parameters in the multi-objective optimization model

Parameter	Selected Range	Modelling Step
Influent flowrate	504 ÷ 1504	100
Influent COD concentration	150 ÷ 500	50
Electicity consumptio aeration (% total)	30 ÷ 80	10
CAS volume (m^3)	0.3 ÷ 1000	Variable
CAS pressure (MPa)	0.1 ÷ 35	Variable

Table 3.8: Selected output functions in the multi-objective optimization model

Parameter	Objective Function
NPV (EUR)	Maximization
PES (toe)	Maximization

that were considered in the analysis were common economic indexes (PB, net present value (NPV)) while, in the case of scenario 2, being implemented AD, meaningful environmental parameters (primary energy saving, PES) are considered to measure the effects on environmental performances as well. Since the main goal of this research was the implementation of a new technology in a WWTP following the DR perspective, the multi-objective optimization functions have been selected among those most representative from a sustainable perspective (table 3.8). For the assessment of the economic advantages deriving from the implementation of the analyzed technology, the NPV maximization objective has been identified as the most representative. Regarding the environmental impact, the most meaningful objective was PES maximization.

According to the stakeholders' interests, a constraint of 10 years has been applied to the PB output value.

3.4.2 Result

As previously introduced, two main scenarios have been investigated, the first one involving only introduction of the air storage unit, composed of an air compressor and a storage tank, to allow air accumulation during the off-peak periods and air utilization from the air tank during the peak periods for sustaining aeration in the biological basin. The second approach includes AD introduction, with electricity production in a CHP unit and integration of the produced electricity in the storage system to increase both total energy savings and the use of renewable energy sources. This solution is particularly indicated

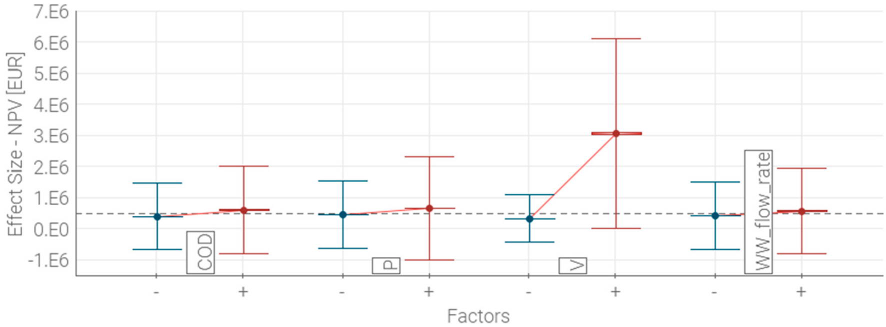


Figure 3.8: Influence of the main input parameters on the NPV of the proposed compressed air storage system (Scenario 1) [3]

in medium and large-scale plants, where AD is typically already implemented. The simulations were carried on as explained before using a 32 GB RAM, i7 4770 3.40 GHz PC. A population of 500 individuals and 250 generations was adopted, resulting in 125000 total evaluated designs for both scenarios, sufficient to obtain the convergence of the process in about 2–3 h.

3.4.2.1 Scenario 1: Compressed air storage without anaerobic digestion

In figure 3.8, the influence of the selected input parameters (table 3.7) on the economic convenience of the proposed storage system is summarized. It can be noticed that air tank volume has a strong impact on NPV, with a significant increase in the economic income as the volume increases (up to 1000 m^3). The air storage pressure is shown to have a limited influence on NPV, with a slight increase in the economic convenience as a higher air pressure is selected. As for wastewater characteristics, the influent COD concentration and the wastewater flowrate have a mild effect: a more polluted effluent (meaning a higher internal energy) and a higher plant potentiality are slightly favorable for storage tank installation. Moreover, a linear behavior was encountered by analyzing NPV variation with respect to the influent COD concentration, for the wide chosen range of wastewater flowrates. In the most favorable conditions, PB time was lower than 1 y for Scenario 1, highlighting a significant convenience of air storage system installation, given the actual market economic conditions and the investigated plant characteristics.

The detailed analysis of NPV variation with respect to air storage pressure, reported in figure 3.9, interestingly highlights that NPV increases to a

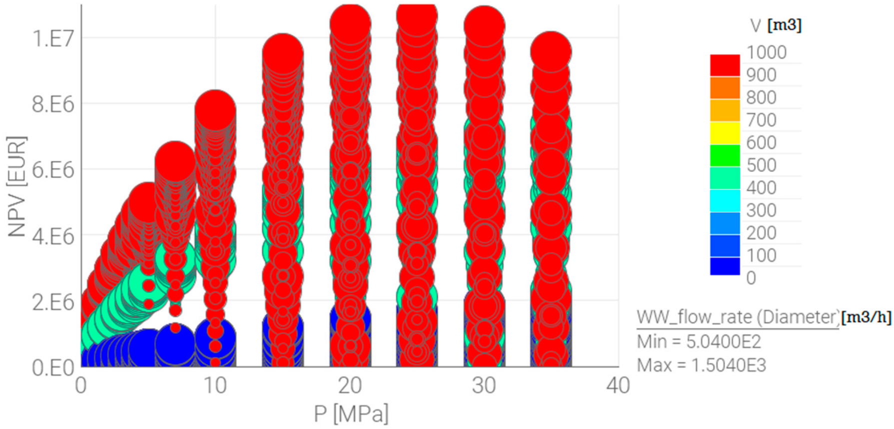


Figure 3.9: Influence of air storage tnak pressure and volume on NPV for different wastewater flowrates [3]

maximum at an intermediate pressure value, while a decrease is observed for a further pressure augmentation (in particular considering larger tank volumes); this is due to the fact that for a higher vessel pressure, the specific compression power increases, leading to higher compression costs.

3.4.2.2 Scenario 2: Compressed air storege with anaerobic digestion

In the second scenario, AD introduction is included, with biogas valorization through the CHP unit, able to supply a share of the needed electricity. The analysis of the influence of single input parameters on NPV value (figure 3.10) shows that a similar behavior to that encountered in Scenario 1 (figure 3.8) is obtained, even if influent wastewater flowrate has a stronger influence, due to the fact that AD becomes more convenient for a higher plant potentiality.

Scenario 2 is particularly representative of medium and large-scale plants, where AD is already applied on full-scale, with biogas valorization: the integration of locally produced electricity with air storage system would optimize energy saving. In figure 3.11, NPV and primary energy saving (PES) variation with respect to the influent flowrate was depicted: the maximum obtainable NPV was in the range of 6÷10 MEUR, while PES was in the range of 36÷108 toe/y for the different analyzed plant potentialities. It could be seen that the investigated scenarios had a comparable behavior with respect to the considered

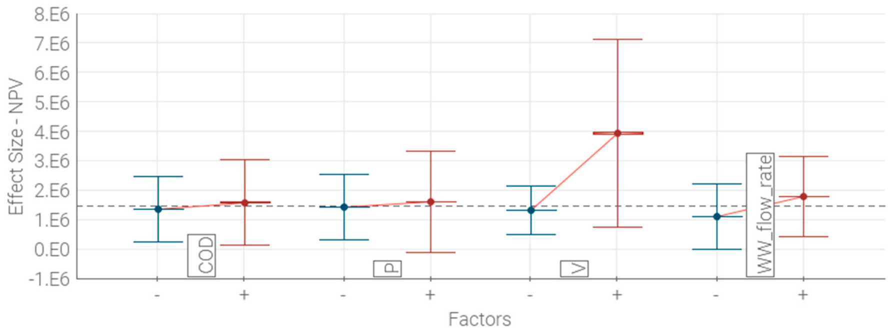


Figure 3.10: Influence of the main input parameters on the NPV of the proposed compressed air storage system (Scenario 2) [3]

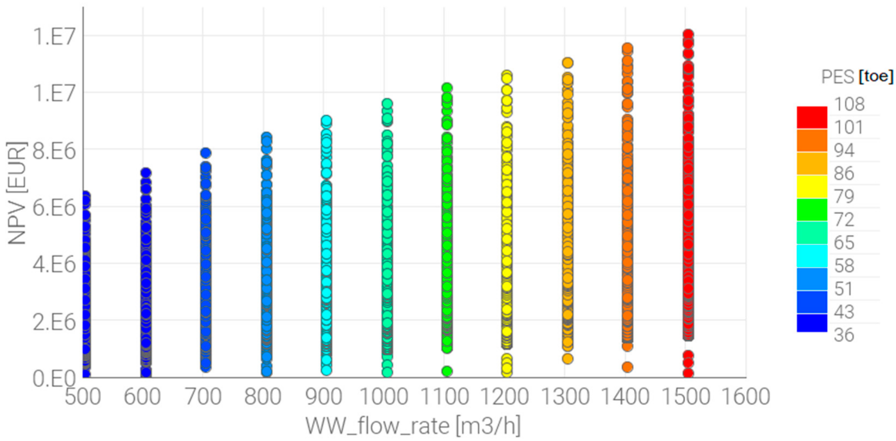


Figure 3.11: Influence of the treated wastewater flowrate on NPV and PES (Scenario 2) [3]

input parameters. The proposed CAS system was shown to be technically and economically feasible. Given the cost-effectiveness of the solution, it is now possible to move on to a more in-depth study to analyze the commercially available technical devices for further system optimization.

3.5 V step: waste collection modelling

The developed waste collection and treatment model has been applied to the Friuli Venezia Giulia region considering the municipalities served by the NET company. The company serves 57 municialities in the region offering separate collection (list of the served municipalities can be found on the company site [254]). The waste share collected are dry waste, paper, plastic, organic waste, glass and metal. The company collects the different waste shares in 2 different plants, one located in the city of Udine and one located in the town of San Giorgio di Nogaro. The distances between the plants and the towns where collection takes place have been obtained through the *Google maps* service. The actual diesel consumption for waste collection has been found on the company site. The amount of each waste share collected yearly in every town considered in the analysis have been obtained from the report written by the region agency for environment protection (ARPAfvg) [255]. In the analysis three different scenarios have been investigated: the first one in which the collection trucks fleet has been considered composed of just methane fed vehicles; the second one in which a fleet composed entirely of full electric trucks has been considered; and the third one in which a mixed fleet methane-electric with a variable composition has been considered.

3.5.1 Validation of the route modelization

First of all before going further with the analysis of the intervention the route model has been validated to test its reliability. For this purpose the model has been applied to the NET case study and the number of vehicles needed to carry out the waste collection in the considered town has been utilized as validation variable. Knowing the amounts of waste collected yearly in each town, the number of days in the year when the collection takes place and the volume of waste that a truck can carry the number of trucks needed is obtained applying equation 2.44. Incrementing the value just obtained of a 5% as a safety margin considering substitution vehicles during maintenance a number of 86 trucks has been otained. In 2018 (last available report from the company) the company reported a number of 86 vehicles. Being the exact number calculated the model can be considered validated.

3.5.2 Results

In this analysis the optimal fleet and treatment plant configuration have been looked for considering as optimization variable the percentage of electric vehicles EV constituting the fleet, the size of the cogenerator P_{CHP} and the fraction of biogas that should go to upgrading instead sent to cogeneration. The effects of

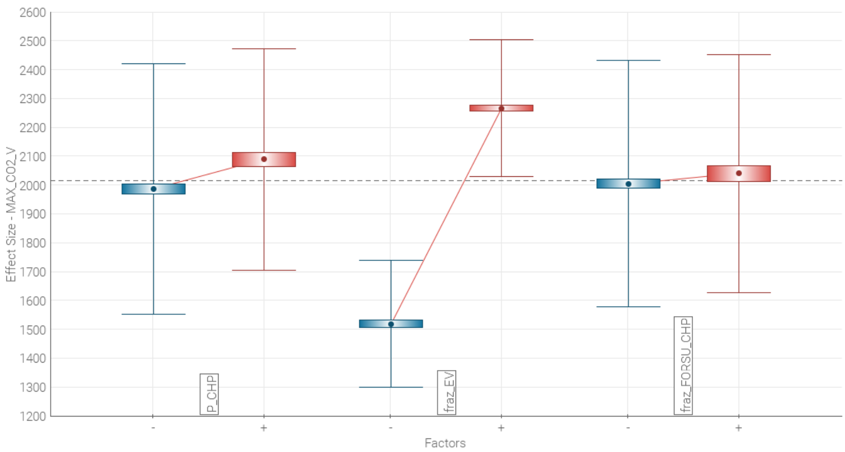


Figure 3.12: Optimization variable effect on CO2

these variables on the carbon dioxide emission reduction are reported in figure 3.12. It can be seen how all the optimization variables have a positive effect on the GHG emissions. In particular the share of EV constituting the fleet has a huge positive effect on the emission reduction meaning that electric trucks have a greater potential in comparison to methane fed vehicles in reducing the

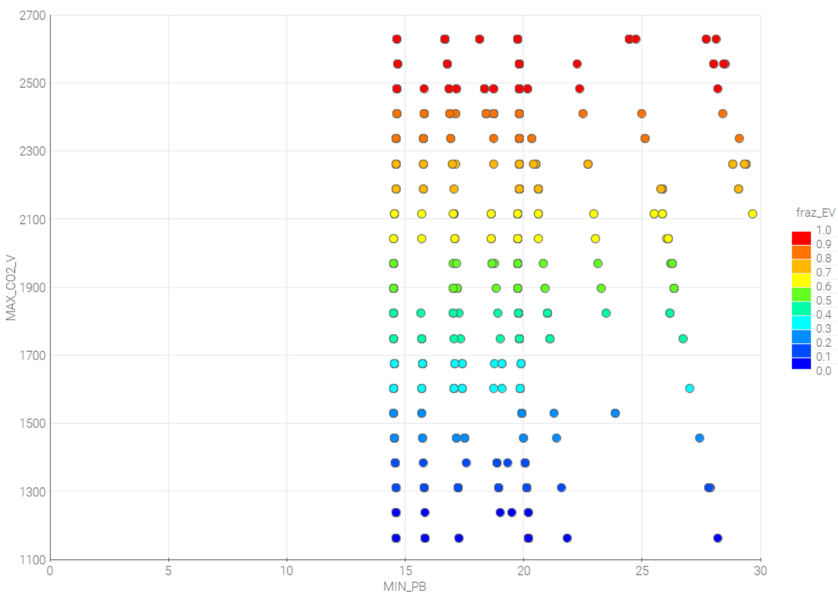


Figure 3.13: Environmental and economic performances

environmental impact of the waste collection. This potential is highlighted also in figure 3.13 where environmental and economical performances are reported as function of the share of EV constituting the vehicle fleet. This figure show also that the environmental performances are not higly affected by the fuel technology, due also to the similar cost of methane fed vehicles and EV considered, being the most relevant cost term.

3.6 Smart multi energy system

3.6.1 Scenario 1: NET + CAFC

The first scenario considers the connection of the waste tratment plant (NET) and the wastewater treatment plant (CAFC) located next to each other in the city of Udine, through an energy and matter exchange in a view of circular economy. The idea is to utilize the surplus, energy and waste, deriving from the operation of each plant to optimize the operation of the other's processes and cover the internal loads of the plants in order to reduce green house gases emissions, leading also to an increment of primary energy saving, thanks to the use of renewable energy sources as the waste.
At first the case of cogeneration of only the FOP share of biogas has been considered. Figure 3.14 reports the yearly behaviour of recovered thermal energy produced by the cogeneration and the heat load requested by the plant. As it can be seen during the winter months the energy produced by cogeneration is not enough to cover the energy request for heating, while in summer months, when the heating load decreases due to the higher temperature there is a surplus of energy. The total amount of thermal energy recovered is more than 7000 MWh, and being recovered from biogas derived from waste it leads to a green house gas emission of 2357.6 tonn of CO2 and a primary energy saving of 1034.5 toe.

Figure 3.15 represents the yearly behaviour of the production of thermal energy deriving also from the cogeneration of the share of biogas deriving from the treatment of FORSU. It can be seen how the energy production is greater than the heat load of the plants along the whole year, leading to a great energy surplus. In this case the amount of recovered energy is almost 8000 MWh leading to a reduction of CO2 emission of 2374 tonnes and a primary energy saving of 1041.1 toe. Comparing the result with the previous case it can be noted that the FOP share of biogas can cover the heat load almost entirely

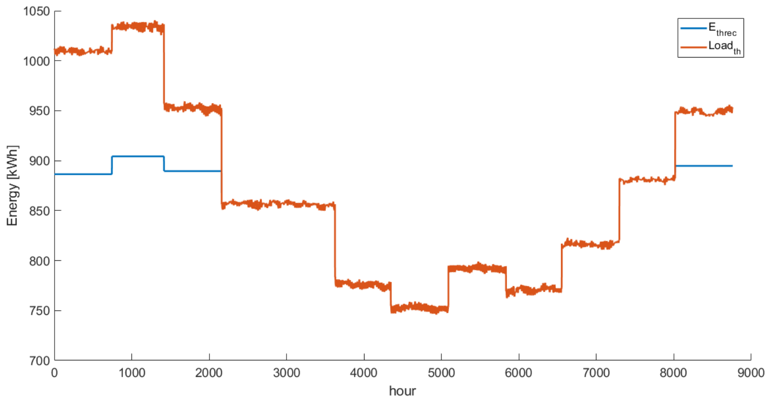


Figure 3.14: Thermal energy yearly behaviour (POF)

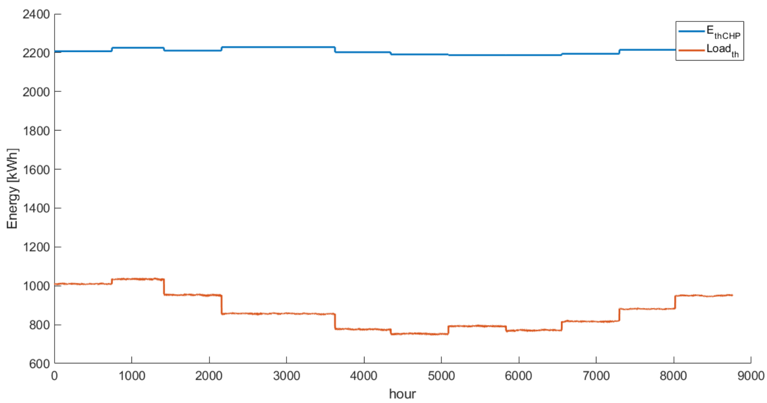


Figure 3.15: Thermal energy yearly behaviour (POF+OFMSW)

by itself. In figure 3.16 the recovered electric energy and the electric energy produced by cogeneration, in the case of utilizing also parto of the FORSU share of biogas, so considering a cogenerator power P_{CHP} of 1499, are reported. It can be seen how the energy produced is more than enough to satisfy the electric energy loads of the plants. The energy recovered is more than 12000 MWh .

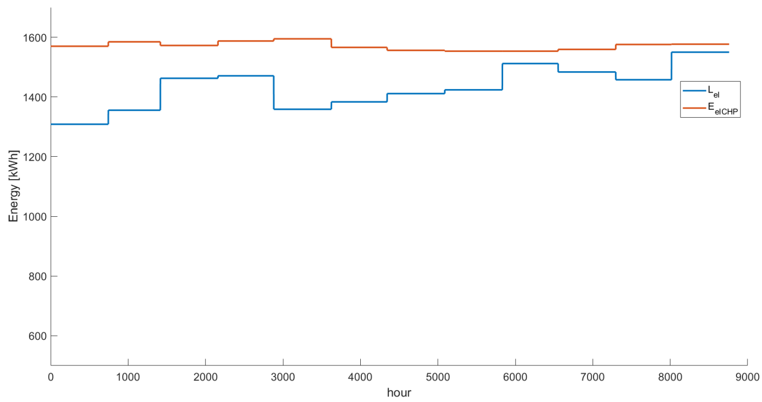


Figure 3.16: Electric energy yearly behaviour (POF + OFMSW)

3.6.2 Scenario 2: NET + CAFC + UDINE MERCATI

As reported previously UDINE MERCATI is the wholesale fruit and vegetable market located in the city of Udine, around 700 meters far from the NET-CAFC hub. It's main energy request is represented by electric energy load for the operation of cooling cells utilized for storage and preservation of goods. As showed in the previous scenario, from the NET-CAFC hub there could be an important surplus of electric energy. The NET-CAFC and UDINE MERCATI symbiosis will represent a virtuous example of industrial symbiosis where UDINE MERCATI will play the role of user absorbing the surplus energy coming from the waste treatment hub reaching energy efficiencies and environmental emission reductions.
In this case the results showed how the electric energy available from the cogeneration of also part of the FORSU share of the biogas could cover almost entirely also the electric load of the chilling cells of UDINE MERCATI. This leads to an energy recovery of more than 13000 MWh total, with 5491.8 tonnes of CO2 emission reduction and 2433.5 toe of primary energy savings.
The results of the optimization of this scenario are reported in the following figures (3.18, 3.19, 3.20, 3.21, 3.22). From figure 3.18 it can be seen how even for high sizes of the cogenerator P_{CHP} no higher PES are achievable. This plateau happens when both the loads of the HUB and the food market are covered, since after that limit no energy can be recovered any further. This is also highlighted by the pareto front (black circles) located at the maximum cogenerator size values before the plateau.
In figures 3.19, 3.20, 3.21, 3.22 the effects of the optimization variables on the

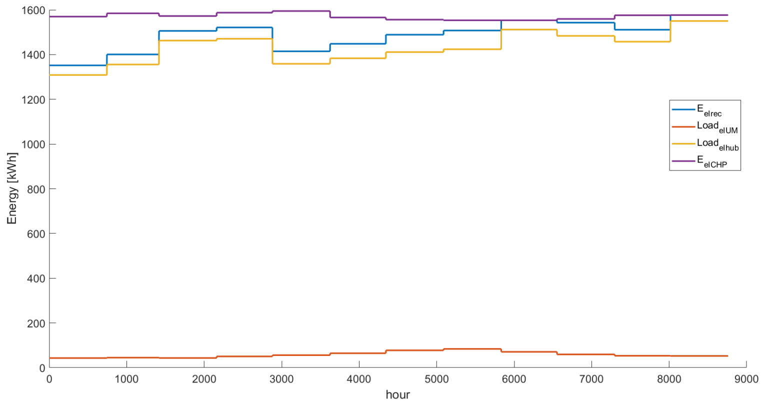


Figure 3.17: Electric energy yearly behaviour (POF+OFMSW)

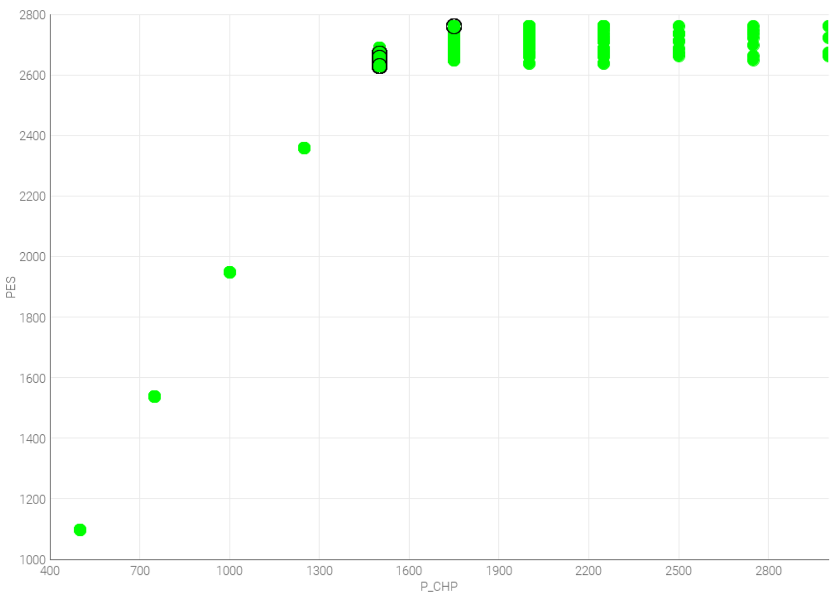


Figure 3.18: PES behaviour over cogenerator size P_{CHP}

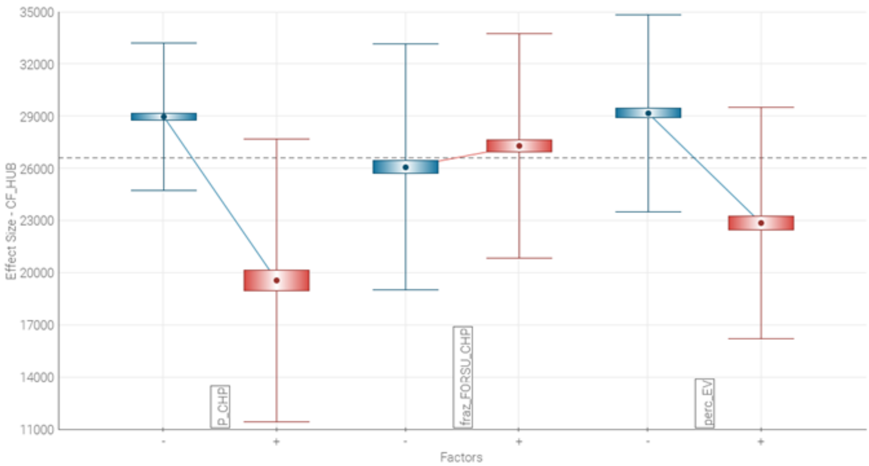


Figure 3.19: Optimization variable effect on CF HUB

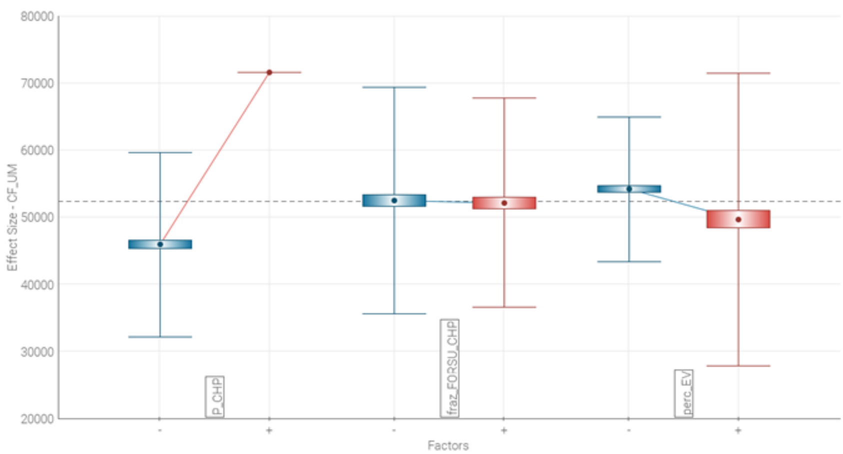


Figure 3.20: Optimization variable effect on CF UM

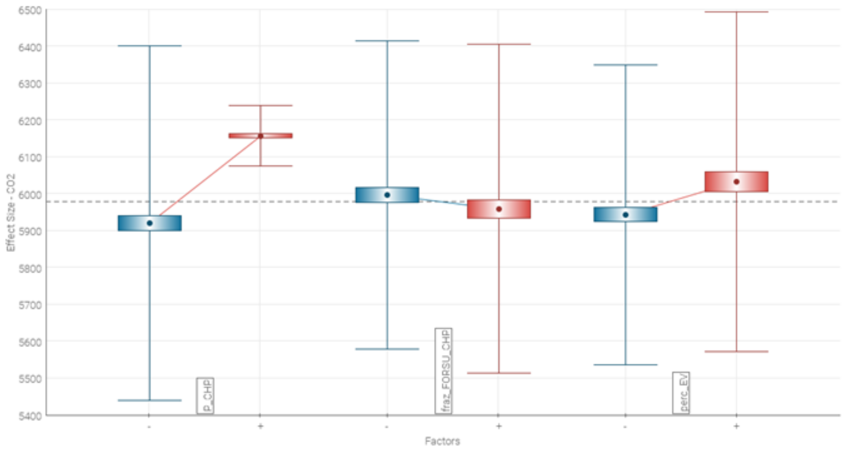


Figure 3.21: Optimization variable effect on CO2

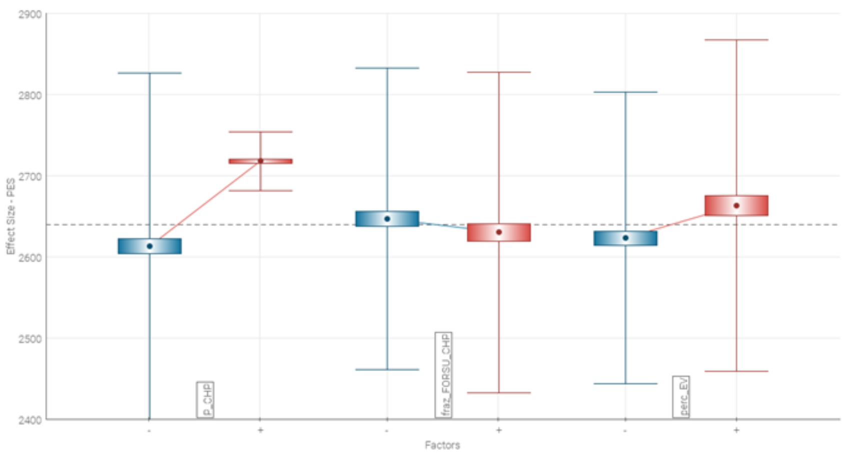


Figure 3.22: Optimization variable effect on PES

objective functions are reported. It can be seen how the cogenerator size P_{CHP} has a negative effect on the economic perfomance of the HUB, while it has a positive one on the economic perfomance of the food market. This may depend on the fact that increasing the cogenerator power also the heat production increases leading to higher dissipation cost for the surplux thermal energy, while higher electricity production from the cogenerator helps covering the food market loads reducing so the need for buying energy from the national grid. The size of the cogenerator has positive effect on the PES and CO_2 emission reduction due to higher recovered energy.

3.6.3 Scenario 3: NET + CAFC + UDINE MERCATI + DH

In the area surrounding the location of NET-CAFC hub a district heating network at the service of the southern basin of the city of Udine has been planned. The network would be fed by waste heat recovered from a steel casting facility located south of the city. An energy integration plant based on methane fed backup boylers is considered for the integration of energy, allowing to cover peaks over the heat availability from the facility. As showed in the results of the first scenario, when the NET cogenerator is fed by only the biogas share deriving from the FOP the produced heat is not enough to cover the heat load of the NET-CAFC plants during the winter months, while when the cogenerator is fed also by the biogas share deriving from the FORSU there's a great surplus of heat energy. This justify the bi-directional communication between the NET-CAFC hub and the planned DHN, considering the hub both as a user of the network when the cogeneration heat production will not be enough and an integration of energy by the network will be needed, and as a sustainable heat source to provide energy to the network, making it more resilient.
The results of the optimization of this scenario are reported in the following figures (3.23,3.24).

From figure 3.23 it can be seen how the implementation also of the DHN allows a greater PES for high cogenerator sizes avoiding the plateau seen in the scenario with only the food market. The graph is characterized by a lower slope because the district heating network operation for heating is limited by the italian legislation to half ot the year (being the plant in Udine from the 15 October to 15 April), so for the rest of the year it works as cooling network. Moreover it can be seen how two pareto fronts are present (highlighted in black circles), that show how good economic performances can be reached even for low sizes of the cogenerator.

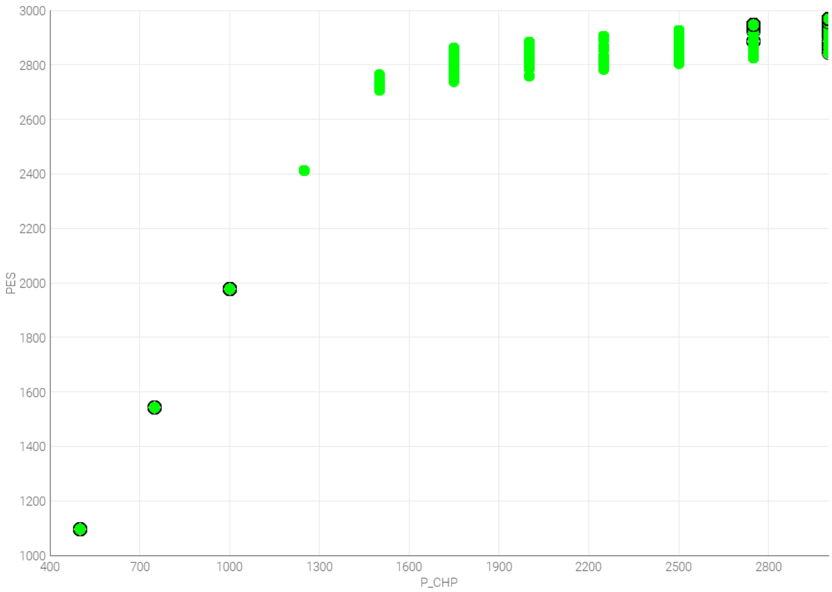


Figure 3.23: PES behaviour over cogenerator size P_{CHP}

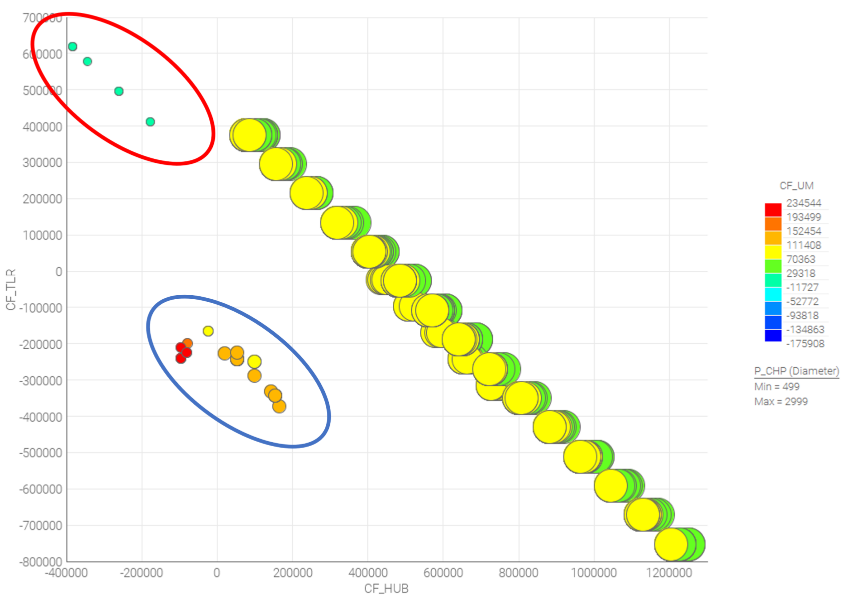


Figure 3.24: Pareto fronts of HUB, food market and DHN economic performances

Figure 3.24 represent a 4D diagram where the third dimension is represented by the colors of the bubbles and the fourth by the dimension. In this diagram only the alternatives constituting the pareto fronts are reported. In the blue circle the pareto front of the food market, in the red circle the pareto front of the DHN while the others represent the pareto of the PES and the HUB. Selecting the alternatives in each pareto the performances of the corresponding stakeholder would be maximized, but reducing at the same time the performances of the other actors. Fors this reason a trade off solution is required.

4

Conclusions

The aim of this thesis was the development of a decision support methodology to assist stakeholders in those interventions in which the implementation of different sustainable and renewable energy sources in smart energy systems is considered, allowing an aware choice of the most sustainable and economical solutions. The work has been based on the identification of the technologies and energy sources available to be implemented in SMES in a circular economy perspective. So different kind of waste have been considered, like heat waste, organic waste (fruit and vegetable waste, organice waste from municipal solid waste and wastewater). While analyzing this kind of interventions great attention should be paid on the data obtained from the literature since the results reliability is highly dependent on the utilized data. For this reason the adoption of a data set should be justified by a precise data analysis requiring so a deep literature review to be performed.
With the collected data models representing this technologies have been developed and combined to form the SMES model, after being validated in various case studies.
Finally, the application of the decision support methodology to the SMES resulted in a tool to guide stakeholders during identification of sustainable and economical solutions when multiple sources are considered. This tool has shown to be exploited for promoting advantageous and virtuous industrial symbiosis opportunities to enhance the environmental and economic performances in waste management. From the acquired results it has been seen how industrial and urban symbiosis represent a fundamental advancement for different sectors, since the implementation of circular economy perspective turned the view on waste materials allowing their energy exploitation and the possibility to considerd these material no more like a waste but like a product or energy source, merging so the food and waste sector allowing a further connection with energy, urban and transportation sector showing opportunities for fossil fuels utilization and *GHG* emission reduction while at the same time enhancing business growth.
Further developments of the work will follow the trend in sustainable energy and technologies development. The integration in the system of electrolyz-

ers and fuel cells would allow the hydrogen implementation in SMESs. This would pose the bases for the implementation of other chemicals to be used as sources or obtained as product enhancing the circular economy introducing also energy-to-chemicals and chemicals-to-energy perspectives.

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