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ABSTRACT

Global energy consumption and the related carbon dioxide emissions, which represent a large share of the overall anthropogenic greenhouse gas production, are continuously increasing since most of the energy needs are still provided by fossil fuels, thus constituting one of the main issues to be addressed in the climate change mitigation agenda. To achieve the Paris Agreement's ambitious objectives, an energy transition towards sustainable energy systems based on the new smart energy system (SES) paradigm is needed, thus integrating the various energy sources, vectors and needs within the sectors (electricity, heating, cooling, transport, etc.).

However, optimal planning, design and management of complex integrated systems such as SES require to make use of proper decision support models based on multi-objective optimization techniques, since a sustainability analysis intrinsically involves environmental, economic and social aspects. Furthermore, a SES project involves several stakeholders, each driven by different and often conflicting objectives, which should be considered within such models, to remove some relevant barriers to the energy transition.

Focusing on the improvement of the sustainability of the energy-intensive sectors, the main objective of this thesis is thus the development of a decision support framework based on multi-objective optimization with the aim to support the decision makers in the planning, design and management of integrated smart energy systems, while considering the different involved stakeholders. The proposed model, composed by three main phases (namely investigative, design and decision-making), has been developed by steps via its application on case studies belonging to two main topics concerning the improvement of the sustainability performance of energy-intensive sectors through the implementation of the smart energy system concept. The first main topic is representative of the context of industrial districts and concerns their sustainable energy supply based on technical solutions specifically designed for cluster of firms, allowed by geographical proximity. The other one concerns the synergic integration between industrial and urban areas, through the recovery of waste energy from industrial processes to feed municipal district heating with a carbon-free source. The case studies have been selected, within the opportunities available in the local territorial context, not only because fit for the implementation of the smart energy system concept, but also due to their suitability for the implementation of different phases of the proposed decision support system (DSS).

1 INTRODUCTION

The international context in which this Ph.D. has been developed is initially described in section 1.1, where an outlook on global energy demand and the related greenhouse gas emissions is provided. In section 1.2 the energy transition required to shift towards a world with a lower carbon footprint is presented, with a focus on the leading role of the European Union in promoting climate action. The energy transition needs to be based on a paradigm shift in the way energy in generated and used: in section 1.3 some innovative concepts aimed at developing the sustainable energy systems of the future are presented, together with a brief discussion on the evaluation models available in literature. Lastly, in section 1.4, after the research gaps have been highlighted, the objectives of the thesis are defined.

1.1 Energy and greenhouse gas emissions: the world reference context

The global demand for energy is continuously increasing. In 2017, global energy demand rose significantly compared to 2016 (+1.9%) up to almost 14,000 Mtoe (IEA, 2019). Fossil fuels accounted for 81.3% of energy production in 2017, increasing for the second year in a row, and have even accelerated in 2018. As regards renewable energy sources, hydro slightly increased in 2017 (+0.7%), providing 2.5% of global production, while solar photovoltaic (PV), wind, geothermal, solar thermal increase of production have accelerated in 2017 (+34.8%, +17.7%, +7.0%, +3.4% respectively) but still accounted for less than 2% of global primary energy production together. Finally, nuclear production increased by 1.1% in 2017 compared to 2016, providing the 4.9% share of energy at global level (IEA, 2019).

Concerning electricity generation, the share of power generation from coal is still the most relevant in 2017 (reaching 38.5% of the electricity produced globally). Renewables come second in the electricity mix, and almost reached 25% of the total in 2017. Hydro is still dominant, but its share in the power mix has decreased since the 1970s and recent renewables growth is almost entirely due to the development of wind and solar PV. Generation from gas since 1990 steady increased from 15% up to 23.3% in 2016, and it decreased slightly to 23.0% in 2017. Nuclear production had steadily increased in the 1970s and 1980s up to around 17% of electricity production, and then declining continuously since the 2000s to reach approximately 10%. Power production from oil peaked at almost 25% of power production in 1973 and has been declining since then. From being the second fuel used for electricity production after coal, it has become the fifth, just below 3 % of the global electricity generation in 2017 (IEA, 2019).

Between 1971 and 2017, world total primary energy supply (TPES) increased by more than 2.5 times. Its structure changed, especially in terms of the relative shares of oil and gas. While still the dominant fuel in 2017, oil fell from 44% to 32% of TPES.

Conversely, natural gas grew from 16% to 22%. The share of coal represented 27% of world TPES in 2017, though it has fluctuated significantly, registering a constant increase between 1999 and 2011, influenced mainly by increased consumption in China. In the same time frame, nuclear grew from 0.5% to 4.9% (IEA, 2019).

Energy demand has evolved differently across the main world regions between 1971 and 2017. In 2017, China accounted for 22% of global TPES while the United States for almost 16%. India and the Russian Federation ranked third and fourth respectively. Japan was in fifth position, but with the lowest energy intensity of the five top energy consumers. Together, these five countries accounted for more than half of the global TPES in 2017. It's worth noting that non-OECD countries account for a continuously increasing share of the world energy consumption (72% in 2017). United States accounted for 16% of TPES with 4.3% of the world's population. Conversely, China and India consumed 22% and 6% of global energy respectively, but each accounted for 18% of the global population.

Between 1971 and 2017, total final consumption multiplied by 2.3. The share of energy use of most sectors has been stable. Industry is still the largest consuming sector (accounting for 37%). However, energy use in transport significantly increased, from 23% of TFC in 1971 to 29% in 2015-2017. The residential sector ranked third in 2017, with 21% (IEA, 2019).

Total final consumption has soared in non-OECD Asia including China since the early 2000s to account for 34% of global in 2017, corresponding to a level of 3,317 Mtoe. In the OECD the generally increasing trend came to an end with the 2008 global economic crisis, with total final consumption oscillating around a plateau of 3,600 Mtoe (38% of global TFC) for several years. It has rose again in 2014, reaching 3,711 Mtoe in 2017, its highest level since 2008 (IEA, 2019).

Global energy-related carbon dioxide (CO_2) emissions, which represent a large share of the overall anthropogenic greenhouse gas (GHG) production, are growing coherently to energy consumption since most of the energy needs are still provided by fossil fuels.

Energy-related GHG emissions are indeed mainly due to CO2 emissions from fuel combustion (32.31 GtCO2 in 2016) (IEA, 2018a), which represent around 90% of energy-related emissions and over two thirds of total GHG emissions in 2015, thus constituting one of the main issues to address in the climate change mitigation agenda. They have more than doubled since the early seventies and increased by around 40% since the year 2000, generally linked to increased economic output; in 2017 CO2 emissions increased by around 1.5%, led by China, India and the European Union.

Diverging trends can be observed in different regions of the world. Traditionally, industrialised countries have emitted the large majority of anthropogenic GHGs. Since the early 2000s, Asia dominated global trends, reaching 17.4 GtCO2 in 2016, twice the level of the Americas and three times that of Europe, with China alone accounting for more than one half of the Asian emissions in that year, followed by India with 12% (IEA, 2018a). Asia is still growing at a remarkable pace.

In Europe, emissions decreased since 2000 (UK -29%, France -20%, Italy -23%, Spain -14% and Germany -10%). Emissions also decreased significantly (-16%) in the US although overall levels in the Americas are counterbalanced by other regions (e.g. Mexico +24%, Brazil +43%) (IEA, 2018a).

Africa accounted for around 3.5% of global emissions in 2016, but observed an emission doubling from 1990, passing the billion tons in 2012. Oceania accounted for about 1.5% of global totals.

For what concerns the consuming sectors, electricity and heat generation represents the largest emitting sector, accounting for 42% of global emissions. Since electricity is allocated mainly to industry and is followed by buildings, in 2016 the industry sector accounted for more than 6 GtCO2 (19% of global emissions), with around three quarters of emissions in industry from Asia (IEA, 2018a).

It's worth noting the primary importance of the energy-intensive industrial sectors, as e.g. metals and minerals accounted for more than one third of industrial energy consumption and more than a half of emissions is due to their heavy reliance on coal. Moreover, between 2000 and 2016, energy consumption of the iron and steel sector increased by 80% (200 Mtoe), while its CO2 emissions almost doubled, reaching 1.8 GtCO2 (IEA, 2018a).

The average carbon intensity of the global energy supply (CO2/TPES), which is generally driven by the relative weights of the various sources within the energy mix, was 2.4 tCO2/toe in 2016 (IEA, 2018a). Coal and oil cause together almost 80% of CO2 emissions. Coal, due to its heavy carbon intensity, is the largest source of emissions globally (44%), with emissions from coal strongly driven by China and Asia region; in America and Africa, oil accounted for almost half the emissions. In Europe, coal, oil and gas almost equally contributed to the total.

About natural gas an expanded role in the global energy mix is foreseen, with a 1.5% annual rate of growth in natural gas demand to 2040, together with the doubling of trade in liquefied natural gas (LNG). As regards coal, marked regional contrasts in the coal demand outlook emerge, as countries with flat or declining overall energy needs are making important step in shifting from coal to lower-carbon alternatives, while developing countries (e.g. in Southeast Asia) need for multiple sources of energy to satisfy a fast growth in consumption, thus they exploit this low-cost source of energy, even if pursuing others at the same time. China is moving from the latter group of countries to the former, so that a decline of its coal demand in the future is foreseen (IEA, 2018a).

The long-term future of coal is linked to the commercial availability of improved coal plant efficiency and of carbon capture and storage (CSS) technologies, since only abated coal use is compatible with a deep decarbonisation.

1.2 Developing a low-carbon world: the energy transition

Since the energy sector accounts for about three quarters of global GHG emissions, it represents the key action field in which to concentrate mitigation efforts to shift towards a low-carbon world, with the aim to achieve global climate goals.

Binding commitments to reduce GHG emissions were first set under the Kyoto Protocol's first period (2008-2012), requiring participating industrialised countries to restrain greenhouse gas emissions relative to 1990 by about 5% over the period. A second commitment period (2013-2020) has been set by the Doha Amendment to the Kyoto Protocol, with a thirty-eight Parties' agreement, although without reaching its ratification threshold. It's worth noting that Kyoto Protocol second commitment period targets covered only around 13% of global CO2 energy-related emissions in 2016, despite its extensive participation of 192 Parties (IEA, 2018a).

An important improvement in the coverage of countries taking action to address GHG emissions, which laid the groundwork for the Paris Agreement, is represented by the Copenhagen Accord and Cancún Agreements, when developed and developing countries submitted voluntary emission reduction targets for 2020, with the participating Parties producing over 80% of global GHG emissions.

The 2013 United Nations Decade of Sustainable Energy for All (2014-2024) aimed at setting for the various stakeholders a common and coordinated global action plan to take further action to effectively move the world towards the objective of sustainable energy for all (United Nations, 2013). The document also identified the opportunity of synergies to be realized as a result of the strong nexus between energy and other development factors such as water, food, health, poverty, etc.

Moreover, on September 2015, United Nations established a new plan of action for people, planet and prosperity, with the document "Transforming Our World: the 2030 Agenda on Sustainable Development" (United Nations, 2015), identifying 17 integrated Sustainable Development Goals (SDGs) and 169 targets. Within the Agenda, in particular, concerning climate and energy, Goal N°13 claims "*Take urgent action to combat climate change and its impacts*", while acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change. Moreover, Goal N°7 establish to "*Ensure access to affordable, reliable, sustainable and modern energy for all*".

In December 2015, the global community adopted the first international climate agreement to extend GHG mitigation obligations to all countries, both developed and developing: the historic *Paris Agreement*, which includes mitigation actions to be adopted in time period beyond 2020.

The Agreement came into force 4 November 2016 (United Nations, 2018), with almost two hundred signatories of which the majority have also formally joined or ratified the agreement.

The Paris Agreement is founded on Nationally Determined Contributions (NDCs) made by countries, which are intended to outline their "highest possible ambition" to address climate change, including reducing GHG emissions. NDCs are updated every five years, each new NDC representing a progression from the previous one. Current NDCs cover the period from 2020 to 2030 or 2025, and most of them include quantitative targets of GHG emissions reduction. An important point is that Countries that have submitted an NDC represent over 96% of global CO2 emissions. Since the Agreement's adoption and entry into force, countries have focused on the implementation of their commitments under the agreement, also through the negotiation of a "Rulebook", which includes rules and guidelines for emissions accounting and transparency of mitigation action and financial support.

The long-term goals of the Paris Agreement are ambitious: the limitation of temperature rise to "well below 2°C above pre-industrial levels" and pursue efforts to limit the rise to 1.5°C. To achieve these goals, countries "aim to reach global peaking of GHG emissions as soon as possible" and " to undertake rapid reductions thereafter" to "achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century", which means achieving net-zero emissions by this time.

The achievement of many of the Paris Agreement countries' targets would slow the foreseen rise in global energy-related CO2 emissions, but is not enough to limit global warming to less than 2 °C. According to some studies (IEA, 2016a), in fact, the commitments are globally enough to limit the increase in global CO2 emissions to an annual average of 160 million tonnes if a full implementation is pursued, which represents a marked reduction compared with the average annual rise of 650 million tonnes registered since 2000. Nevertheless, a continued growth in energy-related CO2 emissions, up to about 36 gigatons in 2040, means that the Paris Agreement's targets wouldn't allow to reach a peak in emissions as soon as possible.

The five-years review mechanism built into the Paris Agreement is then fundamental for countries to increase the ambition of their climate goals, in order to guarantee a step-change in the rate of energy efficiency and decarbonisation improvement.

It must be highlighted that the 2°C pathway is very tough, and the road for a reasonable chance of remaining within the temperature threshold goal of 1.5 °C requires a broad energy transition, i.e. a rough transformation of the energy system. The more ambitious the target for limiting global warming, the earlier the point of net-zero emissions must be reached (likely at some point between 2040 and 2060). The challenges to achieve such a scenario are immense: all residual emissions from fuel combustion should either be captured and stored or offset by technologies that remove carbon from the atmosphere, thus requiring the employment of every known decarbonisation option. This would require significant reallocation of capital investment related to the energy sector, shifting from fossil fuels towards renewables and other low-carbon and carbon capture and storage technology, besides further improvements in energy efficiency. The changes already in progress in the energy sector, demonstrate the potential of low-carbon energy, in turn giving credibility to meaningful action on climate change.

Since electricity covers an ever-larger share of the growth in final energy consumption (from around 25% over the last 25 years, electricity accounts for almost 40% of additional consumption and even for two-thirds in some predicted scenarios to 2040 (IEA, 2016a)) the frontlines for a relevant emissions reduction reside in the power sector. The adoption of the following measures seems to be essential. Firstly, a strong push for greater electrification and efficiency across all energy end-uses; a massive deployment of renewable energy sources and carbon capture and storage technologies, and a robust and concerted clean energy research and development effort by governments and companies.

Although representing a small share in total power demand, the foreseen rise of electricity consumption in road transport as electric cars gain consumer appeal (the worldwide stock of electric cars near-doubled in 2015 the 2014 levels) is emblematic of this trend. In the World Energy Outlook scenarios, a rise to more than 150 million electric cars in 2040, and an even more rose up to some 715 million electric cars by 2040 are foreseen (IEA, 2016a), if supportive policies including tighter fuel-economy and emissions regulations as well as financial incentives become stronger and widespread. Moreover, renewables are predicted to break free: nearly 60% of all new power generation capacity to 2040 is expected to come from renewables (IEA, 2016a), also due to a competitiveness without any subsidies, gained thanks to a rapid deployment which brings lower costs. Renewables also gain ground in providing heat, the largest component of global energy service demand, mainly in the form of bioenergy for industrial heat in emerging economies in Asia.

In the WEO-2016 “450 Scenario” (IEA, 2016a) the power sector is depicted as widely decarbonised: the average GHG emissions intensity of electricity generation drops to 80 grams of CO2 per kWh in 2040, compared with 335 g CO2/kWh in the main scenario, and with 515 g CO2/kWh today. Nearly 60% of the power generated in 2040 is projected to come from renewables, almost half of this from wind and solar PV. In the four largest power markets (China, United States, European Union and India), variable renewables become then the main source of power generation, around 2030 in Europe and around 2035 in the other three countries, with only a small increase in subsidies and a small extra cost to consumers thanks also to a more efficient energy use in household electricity.

The World Energy Outlook (WEO) 2018 report by International Energy Agency (IEA) updates the exploration of different possible future scenarios, providing beside a so-called “Current Policies Scenario”, two key scenarios: the “New Policies Scenario” and the “Sustainable Development Scenario”, analysing the levers that causes them and the complex energy system interactions.

The “New Policies Scenario” foresees a global energy demand growth by more than 25% to 2040 due to an extra world population, mostly added to urban areas in developing countries, if continuous improvements in energy efficiency are pursued thanks to sustainability concerns. A shift in energy consumption to Asia is expected, transversal to all sources, technologies and investments: the situation of the early 2000s, when Europe and North America accounted for more than 40% of global energy demand and developing economies in Asia for 20%, is expected to be completely reversed by 2040 (IEA, 2018b). The New Policies Scenario is thus characterised by a slow upward trend concerning energy-related CO_2 emission, reaching around 36 GtCO2 to 2040, which is far from complying with what scientific knowledge would require to reach climate goals.

The so-called “Sustainable Development Scenario” is focused on a broad transformation of the global energy system with the aim to achieve the sustainable development goals, with the goal of halving energy-related GHG emissions to 2040 at around 18 GtCO2, and it is based on an integrated strategy involving all energy sectors and low carbon technologies (IEA, 2018b).

In this scenario, a strong energy efficiency improvement is pursued, with the aim to keep overall demand in 2040 at today’s level. The power sector deploys low-emissions generation technologies, and at the same time the share of renewable energy sources in the power mix rise from one-quarter today to two-thirds in 2040 (including both direct use and indirect use, e.g. renewables-based electricity), providing the main provision of universal energy access. Simultaneously, electrification of end-uses grows in a remarkable way, but also the direct use of renewables to provide heat and mobility increases (IEA, 2018b).

Electricity, therefore, covers a special role, being increasingly the “fuel” of choice in economies that are relying more on lighter industrial sectors, services and digital technologies. Its share in global final energy consumption is set to rise further from the current 20%.

The convergence of policy support and technology cost reductions for renewable energy technologies, digital applications and the rising role of electricity as energy vector represents a crucial factor for meeting many of the world’s sustainable development goals, putting the power sector in the vanguard of emissions reduction efforts.

The electricity system is thus experiencing its most radical transformation since its creation, as it is required to operate differently in order to ensure reliable supply, given the rapid growth in variable renewable sources of generation. The rise e.g. of solar photovoltaic (PV) and wind power gives exceptional importance to the flexibility of the power systems’ operation. Structural changes to the design and operation of the power system are needed to ensure the integration of high shares of RES. Cost reductions for renewables, will not be enough to allow an efficient decarbonisation of electricity supply. A careful review of market rules and structures is required to ensure that the power system can operate with the necessary degree of flexibility. In addition to the need for a strengthening of the grid, incentivising system-friendly deployment of wind and solar, and ensuring the availability of power plants ready to dispatch at short notice, the deployment of further measures such as effective demand response and energy storage as part of a suite of system integration tools would become essential to avoid wind and solar installations having their operations curtailed in times of abundant generation, thus allowing a deep decarbonisation of the power sector. Even in the New Policies Scenario, mainly conventional power plants guarantee the system flexibility, supported by storage systems and demand-side response.

Affordability, reliability and sustainability are then closely interlinked, and the adoption of a comprehensive approach to energy policy is needed. Policy makers need to ensure that all key elements of energy supply, including electricity networks, remain reliable and robust.

It must also be pointed out that the inter-dependencies between energy and water are expected to rise in the coming years, as water is essential for energy production (the energy sector is responsible for 10% of global water withdrawals, mainly for power plant operation as well as for production of fossil fuels and biofuels) and on the other side energy is used to supply water to consumers (around 4% of global electricity consumption is used to extract, distribute and treat water and wastewater, along with 50 Mtoe of energy): up to 2040, the amount of energy used in the water sector is foreseen to more than double (IEA, 2016a).

Indeed, there are several connections between the new United Nations Sustainable Development Goals (SDG) on clean water and sanitation (SDG 6) and on affordable and clean energy (SDG 7). A proper management of energy-water nexus is thus pivotal for the successful realisation of many development and climate goals. There are also many opportunities for energy and water savings that can improve both systems, if approached in an integrated manner.

Moreover, a rapid energy transition requires an acceleration of investment in cleaner, smarter and more efficient energy technologies. More than 70% of the $2 trillion required in the world's energy supply investment each year, across all sectors, either comes from state-directed entities or responds to a full or partial revenue guarantee established by regulation (IEA, 2018b). Frameworks adopted by the public authorities also determines the rate of energy efficiency improvement and of technology innovation.

Given the above, it seems clear that government policies will play a crucial role in determining which path will be followed concerning the long-term future of the energy systems.

1.2.1 Europe as an energy and climate action leader in the world

European Union, with the awareness that the clean energy transition away from fossil fuels towards a carbon-neutral economy is one of the greatest challenges of our time, is strongly committed to lead the fight against climate change.

Back in 2009 the EU was the first to set ambitious energy and climate targets through the adoption of the 2020 climate and energy package. It set three key goals in terms of: 1) 20% GHG emission reduction, 2) 20% increase of the renewable energy sources share in the energy mix, and 3) 20% improvement of the energy efficiency, compared to the levels of the 1990 reference scenario (Council of the European Union, 2007).

Ten years later, the EU is going to achieve the 2020 objectives, and following up the relevant contribution provided to the Paris Agreement, has push to move further ahead in leading the global energy transition setting more ambitious energy and climate targets within the 2030 EU's energy strategy.

The EU has adopted a new ambitious framework called the "*Clean energy for all Europeans*" package, with the aim to give all Europeans access to secure, competitive and sustainable energy, thus ensuring a clean and fair energy transition at all levels of the economy. This set of new rules defines the legislative parameters for the coming years, also enabling the necessary investments. Moreover, the establishment of the EU "Energy Union" provides a framework for a consistent approach in all policy areas. Within the package, more ambitious targets have been set (European Union, 2019), which establishes a cut in GHG emission of at least 40%, an energy efficiency improvement up to at least 32.5% (according to the principle of "energy efficiency first") and an increase of the RES share to at least 32% by 2030 to foster an acceleration of clean energy uptake in all sectors.

Each country will decide how it contributes to these EU objectives by drafting a National Energy and Climate Plan (NECP) for 2021-2030, outlining also a long-term strategy for at least the next 30 years.

The revised *Energy Efficiency Directive* sets targets and foster energy labels, to encourage industry to innovate and invest, since energy savings are depicted as the easiest way of saving money and reducing GHG emissions. The efficiency improvement of households, transport and industry across EU are expected to give an important contribution to meeting the Paris Agreement goals (The European Parliament and the Council of the European Union, 2018a).

Within the Clean energy for All Europeans package, particular emphasis is also given to improving energy performance in the building sector with the *Energy Performance of Buildings and Energy Efficiency Directive* (The European Parliament and the Council of the European Union, 2018b): this sector is crucial to the clean energy transition, as buildings are responsible for approximately 40% of final energy consumption and 36% of CO2 emissions in Europe (the largest single energy consumer of the EU) and has vast potential for energy efficiency gains since about 75% of building stock is energy inefficient and around 35% of EU's buildings are over 50 years old. By pushing the renovation of buildings, also exploiting all smart technologies available (as automation and control systems) but also e-mobility infrastructures such as e-charging points in buildings, this sector can contribute to the development of a carbon-neutral and competitive economy.

The revised *Directive on the promotion of the use of energy from renewable sources* (The European Parliament and the Council of the European Union, 2018c) is supported by a new policy framework in order to provide long-term certainty for investors, put consumer at the centre of the energy transition with a clear right to produce own renewable energy, increase market integration of renewable electricity, accelerate the uptake of RES in the heating/cooling and transport sectors.

The EU has also adopted new rules aimed at making Europe's electricity market fit for the challenges of the clean energy transition, strengthening consumers rights and increasing security of supply: the revised *Regulation on the internal market for electricity* (The European Parliament and the Council of the European Union, 2019a), the revised *Directive on common rules for the internal market for electricity* (The European Parliament and the Council of the European Union, 2019b), a new risk preparedness regulation and an enhanced role for the established *European Union*

Agency for the Cooperation of Energy Regulators (ACER) (The European Parliament and the Council of the European Union, 2019c). Some of the most relevant objectives of the new rules are to allow electricity to move freely throughout the EU electricity market (cross-border trade and cooperation), to enable more flexibility to integrate an increasing share of renewable energy, and to foster more market-based investments. The integration of renewables into the energy system could indeed be eased by regional integration, as testified by the European Union's aim to achieve an "Energy Union". The new rules provide also a stable enabling framework that should facilitate and encourage private investment in the clean energy transition.

Moreover, one of the most important aspect of the Clean energy for All Europeans package is to put consumer at the centre of the clean energy transition. Since the energy transition is strictly linked to socio-economic considerations, the concept of access to energy has been reinforced. Thanks to the new rules, consumers will be able to participate actively, as individuals or joining in local and renewable "*energy communities*", either to produce their own energy, store it or sell it onto the grid.

Citizens can thus benefit from incentives and provisions for renewable energy production and self-consumption. Estimates suggest that by 2030, energy communities could own some 17% of installed wind capacity and 21% of solar (European Union, 2019). Moreover, by 2050, almost half of EU households are expected to be producing renewable energy. Indeed, the shift to a more decentralised energy system where consumers play an active role means more democracy, and more opportunities for citizens to take their own decisions on which type of energy they want to use.

The benefits of the clean energy transition should go far beyond the reduction of greenhouse gas emissions. The clean energy transition would require enormous investments for this economic transformation, thus bringing also opportunities for growth and jobs in Europe, fostering industrial competitiveness and driving research and innovation, that would reasonably contribute to the creation of a strong industrial basis and make the EU a global technology leader. At the same time, cleaner and smarter energy would mean improved health and a better quality of life.

To improve energy efficiency, increase the production and deployment of renewables, in order to reduce greenhouse gas emissions and meet the Paris Agreement commitments, over the next decade Europe is foreseen to need up to 180 billion € per year of public and private funds to be mobilised, generating up to 1% increase in economic growth over next decade and creating 900,000 new jobs in Europe linked to the clean energy sector (European Union, 2019).

While an important amount of the investment will come from public funding (20% of EU spending is currently used for fighting climate change, but EU is already looking to increase the level up to at least 25% under the next financial period 2021 to 2027) most of it is expected to come from private sources. The Clean energy for all Europeans package is an important step also in establishing a stable policy framework and a clear direction for the next decade, thus reducing the risk for investors and providing a clear perspective looking further ahead.

The EU's Clean energy for all Europeans package for 2030 represents one of the most advanced legislative frameworks in the world to transform the energy sector and decarbonize the economy.

With the aim to fix a clear long-term decarbonisation strategy for 2050, the European Commission, in the context of the COP24 climate talks in Katowice in December 2018, presented its "2050 Long-Term Climate Neutrality Strategy". This proposal, a document replacing the 2011 "Roadmap for moving to a competitive low carbon economy in 2050" (the so-called "2050 Roadmap") presents options on how to decarbonise the whole EU economy and will be the basis of discussions in the coming years.

The road to a climate-neutral economy will require further improvements in energy efficiency (savings of up to 50% by 2050), renewables (to be 80% of electricity alongside nuclear energy), transport (widespread of electric cars and low carbon fuels) (European Union, 2019). Moreover, new decarbonised technologies should be developed as well as new markets for the new technologies needed in a clean, decarbonised world should be created: more recycling and decarbonised production processes in industry, infrastructure, the new digital economy (a digitalised and connecting Europe) and the bioeconomy. The extra investment needed to decarbonise the economy has been estimated at around €550 billion per year, up from approximately 400 billion euros today, demonstrating the opportunities that come with this widespread "re-industrialisation".

1.3 Future sustainable energy systems: concepts and evaluation models

From the above discussion, it can be derived that to achieve the Paris Agreement's ambitious objectives, a transition toward sustainable energy systems based on a new paradigm is needed.

In the following a literature review of concepts, technology approaches and evaluation models aimed at developing the sustainable energy systems of the next future is presented.

As anticipated, decentralization is recognized to have a key role for the implementation of a sustainable energy system, especially to allow the integration of a large share of RES towards the development of a total renewable energy system, as reported in (Sperling et al., 2011).

Moreover, the concept of distributed generation has been depicted as the power paradigm for the new millennium (Borbely and Kreider, 2001). Within distributed generation, combined heat and power (CHP) and moreover combined cooling, heat and power (CCHP) represent indeed one of the most performing technical solutions aimed at the improvement of energy efficiency on the generation side.

Cogeneration technologies and efficient district heating and cooling (DHC) networks could provide remarkable environmental benefits due to their improved energy conversion and to the use of waste heat and renewable energy sources. Moreover, CCHP and DHC could also allow to link the thermal and electric energy systems, thus playing an important role in the development of integrated sustainable energy networks (IEA, 2014).

One of the concepts that are well suited to the new paradigm of the energy systems is thus “sector coupling”, i.e. an approach which binds together power and end-use sectors. The concept “encompasses the co-production, combined use, conversion and substitution of different energy supply and demand forms (electricity, heat and fuels), while creating new links between energy carriers and the respective transport infrastructure” (Olczak and Piebalgs, 2018). As a result, sector coupling may bring benefits to the whole energy system. First, it could allow the exploitation of the rising share of variable renewable energy through the integration in the power sector, rather than cutting down the excess as currently happens. For example, sector coupling could enable the use of the excess electricity in electrolysers to produce green hydrogen (electrolysis) and synthetic methane (methanation), which can be stored on a large scale and over longer periods, thus replacing fossil fuels in many end-use applications through an indirect electrification of processes such as transport, heavy industry, and so on, e.g. Power-to-Gas (P2G) or Power-to-Heat (P2H) etc., representing also a source of seasonal flexibility (Olczak and Piebalgs, 2018).

The sector coupling approach might be further improved and integrated. Mancarella proposed the “Multi Energy System (MES)” concept (Mancarella, 2014), while the “Smart Energy System (SES)” concept has been settled in (Lund et al., 2017).

According to the latter, the future challenge will be the integration of the various energy sectors (electricity, heating, cooling, transport, etc.) into the so-called smart energy system, which is defined as “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” (Lund et al., 2017).

Smart energy systems could play also an important role in facilitating a cost-effective integration of renewable energy sources and in fostering end-user’s participation to support power system operation and development. In this context, focusing on the smart concept, smart infrastructures should play a key role in the task of improving energy efficiency as reported in (Lund et al., 2014) and more recently in (Connolly et al., 2016). In the European Commission's strategy for a competitive, sustainable and secure energy in fact, the need for high efficiency cogeneration, district heating and cooling is highlighted, thus promoting projects with smart electricity grids along with smart heating and cooling grids (European Commission Directorate General for Energy, 2011).

As anticipated, energy efficiency should be at the centre of the energy policy of any country since it is far from fulfilling its potential (IEA, 2016b).

Focusing on the energy-intensive sectors, geographical proximity could give the opportunity to obtain collective sustainability benefits significantly greater than the sum of the separate ones, e.g. through the implementation of synergistic energy efficiency measures at the system level.

Aiming at the identification of energy efficiency measures designed to improve sustainability performances of the energy-intensive sectors, the following geographic boundary levels could be considered (Cecelja et al., 2015):

- endogenous: when focusing on a single entity (e.g. a single productive activity);
- exogenous: when focusing on multiple subjects (e.g. an industrial zone);
- urban-industrial system: integration of an industrial district into the neighboring urban territory.

An industrial zone is a restricted area characterized by the presence of many production activities. A homogeneous industrial district is a socio-territorial entity characterized by the presence of both a community of people and a cluster of businesses in a naturally and historically delimited area. In (Chertow, 2000) industrial symbiosis (IS) is defined as a resource-optimization strategy by which two or more firms share energy, water and materials in a collective approach offered by geographic proximity. Moreover, the same author proposes among the industrial symbiosis models the eco industrial park, that involves a conscious effort by private firms to share energy and resources to meet goals such as cost reduction, emission reduction, revenue upgrades and business expansion (Chertow, 2008).

Concerning the building sector, which accounts for a large share of total energy consumption and GHG emissions (Mattinen et al., 2014) as already discussed, district heating and cooling networks should play an important role in the implementation of future sustainable energy systems (Connolly et al., 2014). Besides representing a measure of heat supply efficiency, indeed, the integration of district heating networks (DHN) in urban Smart 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 (Lund et al., 2014).

Among the energy efficiency measures, energy recovery from the waste heat discharged by industrial processes represents one of the greatest opportunities to reduce the consumption of primary energy and the related emission of greenhouse gases. Various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat (US Department of Energy, 2010). Sources of waste heat include hot combustion gases discharged into the atmosphere, heated products from industrial processes and heat transfer from hot equipment surfaces.

Energy recovery should become a common practice to implement since its positive impact on the efficiency of production processes due to the reduction of operating costs, the increase of the plant productivity and the reduction of the pollutant emission. The operational, energy, economic, environmental and social benefits related with energy recovery fully embrace the sustainability concept in its triple bottom line dimensions (Elkington, 1998).

Since industrial energy consumption constitutes a large share of the total and a huge potential for industrial waste heat recovery has been detected in Europe within the identification of local heat demand and supply areas (Miró et al., 2015; Möller et al., 2018), the integration of industrial waste heat into Smart Energy System represents indeed a main opportunity to accomplish the EU climate and energy goals, as European governance is integrating energy efficiency and the recovery of waste heat into its energy policies.

The integration of industrial waste heat has been given 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. 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 (see (Liew et al., 2018)). Further developments led then to the Locally Integrated Energy Sectors (LIES) conceptualisation, to include renewable energy sources as well as other sources and consumers (Perry et al., 2008), a precursor concept of SES.

Then, to improve the sustainability performance of the energy-intensive sectors, a paradigm change from the traditional approach towards the concept of smart energy system is needed.

However, a smart energy system represents an integrated system characterized by technical complexity and high investment cost, involving several stakeholders aiming at different, often conflicting, goals. Optimal planning, design and management of integrated systems such as SES require then to make use of proper decision support models based on multi-objective optimization techniques, as a sustainability analysis is intrinsically a multi-objective optimization problem because it involves environmental, economic and social aspects.

In the following, a literature review of models aimed at the optimization of energy systems involving distributed generation through combined cooling heat and power, renewable energy sources and district heating (DH) networks, thus belonging to the topic of smart energy systems development, is presented.

About distributed generation based on combined cooling heat and power, many models aim at the optimization of design and operation of CCHP systems, though they are focused far more on the endogenous level than on the exogenous one. Among these, Arcuri et al. focused on the optimal design through mixed integer non-linear programming (Arcuri et al., 2007). In (Rong and Lahdelma, 2005) a model for the evaluation of cost-efficient operation of a trigeneration system is developed and in (Bischi et al., 2014) a model for CCHP operation planning that minimizes costs is proposed. Li et al. focused on the sensitivity analysis of energy demands of a hospital facility (Li et al., 2008).

Evolutionary algorithms too have been successfully used to optimize design and operation of CCHP systems at the endogenous level. In (Wang et al., 2010) the optimization of both plant capacity and operation is focused. In (Kavvadias and Maroulis, 2010) the optimization of equipment size and pricing tariff schemes is investigated, while in (Hajabdollahi et al., 2015) a model for the optimization of the operational strategy is proposed.

Widening the perspective to renewable energy sources, in (Nema et al., 2009) a review of hybrid renewable energy systems is provided. Recently, the work by Li et al. focused on the optimal configuration design and operation of a RES integrated CCHP systems through an evolutionary multi-objective optimization model characterizing the system reliability, system cost, and environmental sustainability (Li et al., 2018).

To mention some of the few available models adopting a system approach, moving from traditional solutions for single enterprises to technical solutions specifically designed for clusters of firms, a Mixed Integer Linear Programming (MILP) model capable of solving small scale examples of energy production plant based on CHP and with heating micro-grids for an industrial area, has been developed for design purposes (Reini et al., 2011). However, the only objective function is the minimization of the total annual cost for purchasing, maintaining and operating the whole trigeneration system. Moreover, Meneghetti and Nardin focused on the design optimization, from a facilities management perspective, of a CCHP system integrated with district heating and also renewable technologies such as a concentrated solar power unit serving a cluster of firms, developing a mixed-integer programming model aimed at the optimization of the economic objective function (Meneghetti and Nardin, 2012).

Concerning district heating networks (DHN), 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, obtaining then fluid distribution and thermal gradients within the network and its components.

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 in (Aringhieri and Malucelli, 2003). DH simulation was also used to analyse the performance of different real-time control strategies from a management perspective (Wernstedt et al., 2003). The design, analysis and optimization of DHN is the objective of the in-house software developed in (Ancona et al., 2014), 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 in (Koiv et al., 2014). 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 (Guelpa et al., 2017). They also investigated the optimal operating conditions of DHN with a special focus on the role played by the pumping power required (Guelpa et al., 2016).

However, the computational complexity of the above models makes them not suitable for large real-world networks serving hundreds of users (Bordin et al., 2016). 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 (Larsen et al., 2004).

In (Bordin et al., 2016) 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 is developed. The model considers steady state conditions of the hydraulic system and considers the main technical requirements of the real-world application.

Another modelling approach focused on optimal design and operation of DHN for the economic optimization, is based on simple network configurations, or avoid detailed simulation tools of the DHN thanks to simplified assumptions. In some papers, DHN is even modelled as a black box, only accounting for the end users' overall heat demand (Aëšberg and Widén, 2013).

The simulation model developed in (Sartor et al., 2014) deals with the optimal operation of CHP plant connected to a DH network, focusing far more on the facility side than on the network. 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 (Mertz et al., 2016). 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 drop) 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, in (Vesterlund et al., 2017) 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. The mixed-integer linear optimization problem formulated (Haikarainen et al., 2014) 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.

Multi-objective optimization approach has also been adopted to account for different objective functions while optimizing the 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 in (Fazlollahi et al., 2015). In (Morvaj et al., 2016) the optimal design and operation of distributed energy systems as well as optimal heating network layouts for different economic and environmental objectives is investigated. A mixed integer linear programming model was used for multi-objective optimization to minimize total cost and carbon emissions. In (Pavičević et al., 2017) 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 is developed.

A GIS (geographic information system) planning method for assessing the costs of DH expansions has been developed in (Nielsen, 2014), 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.

Concerning the DH networks based on industrial waste heat, in (Gebremedhin, 2014) it is highlighted that it should be able to exploit as much as possible of the available carbon free source, which depends on the overall size and features of the selected users' basin.

Lastly, the importance of taking both the socio-economic and consumer-economic approaches into account when expanding existing and building new DH systems has been outlined (Grundahl et al., 2016).

1.4 Research gaps and objectives of the thesis

The above analysis of the literature shows that in recent years many models have been developed with the aim of optimize the design and operation of energy systems based on CCHP, RES and DH.

Given the boost towards such a sustainable energy transition, the single entity's boundaries would be overcome in favour of synergies, in order to allow sustainability benefits otherwise not reachable.

Nonetheless, these models focused far more on the endogenous level than on the exogenous one. Research has been focused mainly on the techno-economic optimization of distributed generation system to be implemented within a single entity, such as e.g. a CHP plant installed within an industrial facility or a CCHP plant serving a hospital, rather than on a Smart Energy System designed to serve an industrial district or a cluster of productive activities integrated within the neighbouring urban context. Just a few works, such as e.g. (Meneghetti and Nardin, 2012) suggest the adoption of such a system perspective, although an overall sustainability analysis performed by considering a multi-objective optimization approach is still lacking in these works.

This main issue has been highlighted also in (Boix et al., 2015), where a lack of multi-objective optimization studies applied to the design of sustainable industrial districts that provide complex integrated systems for energy supply and recovery, renewable sources and distribution networks (i.e. Smart Energy System) is pointed out.

Moreover, a lack of comprehensive frameworks for planning and design of the integration of industrial clusters with urban areas and RES has been highlighted (Liew et al., 2018) together with the need for greater research commitment to the investigation of the sustainability factors involved.

Furthermore, as the energy system becomes increasingly decentralised, moving from the broad perspective (e.g. European) to the local one based on the smart energy system concept, an integrated infrastructure planning approach will gain indeed growing importance (Olczak and Piebalgs, 2018). Because of the high capital-intensity and long-term pay-back periods typical of the above-mentioned sustainable energy supply systems, also due to the relevant changes required (especially in complex brown field contexts), the adoption of proper decision support models by the decision makers would be required before endorsing the relevant investments expected in this sector.

Finally, a SES project, especially when based on the synergy between industrial and urban areas, most likely involves several stakeholders, each driven by different, often conflicting, objectives. To name a few, industrial companies, end users, citizenship, policy makers and private investors might represent some of the main actors involved. Therefore, to foster smart energy systems, research efforts should also be focused on considering the different involved stakeholders within the models developed for planning, design and management. As evidenced by the above literature review, this aspect has so far been little developed, but is crucial to remove some relevant barriers to the energy transition, since the adoption of a system approach is required in a smart energy system context.

1.4.1 Objectives of the thesis

Focusing on the improvement of the sustainability of the energy-intensive sectors, the main objective of this thesis is thus the development of a decision support framework based on multi-objective optimization with the aim to support the decision makers in the planning, design and management of integrated smart energy systems, considering the different involved stakeholders.

The structure of the main contents of the thesis is outlined in Figure 1.1. In Section 2 the proposed decision support framework based on multi-objective optimization is presented.

The proposed model is then developed by steps via its application on case studies belonging to two main topics concerning the improvement of the sustainability performance of energy-intensive sectors through the implementation of the SES concept, as represented in the scheme of Figure 1.1. The case studies have been selected, within the energy-intensive sectors opportunities available in the local territorial context, not only because fit for the implementation of the smart energy system concept, but also due to their suitability for the implementation of the different phases of the proposed DSS.

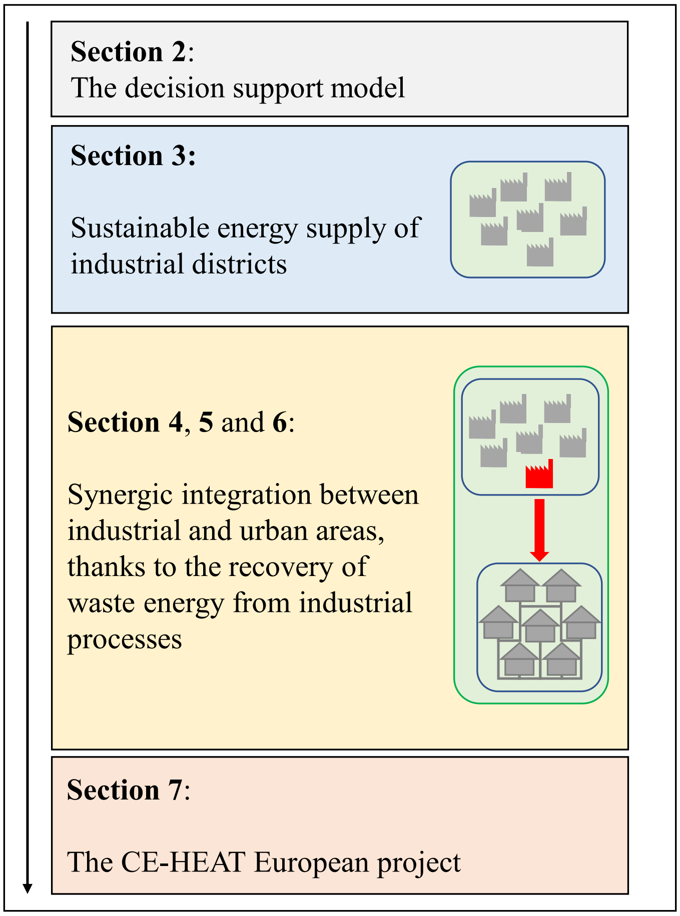


Figure 1.1 Outline of the structure of the thesis

As anticipated, sustainability performances of industrial districts could be substantially improved through the exploitation of the potential benefits offered by geographical proximity, when synergies between companies are established.

Then, the first main topic concerns the sustainable energy supply of industrial districts. In Section 3 the developed decision support framework has been applied to the planning and design of smart energy system solutions specifically designed for clusters of firms, thus considering distributed renewable sources (RES), centralized tri-generation (CCHP), thermal energy storage systems and energy distribution micro-grids.

The context of industrial districts is particularly suitable for the development of the "investigative" (data) phase of the proposed method for decision support, due to the need for the collection, processing and analysis of the data related to energy consumption and production for the considered cluster of companies. Moreover, the SES concept applied to the district's sustainable energy supply is intrinsically a multi-objective optimization problem, thus constituting a suitable test case for the first implementation of the "design" (evaluation) phase of the proposed DSS.

The considered case study concerns an industrial district of the food sector, which is suitable for the implementation of the above described smart energy system concept in its general configuration because of the simultaneous and relevant presence throughout the year of both electric, heating and cooling power demand, due to the particular process's energy requirements (refrigeration rooms, heating, ventilation and air conditioning, equipment and lights, process hot water, etc.).

The developed framework, beside including indicators for monitoring the improvement of the sustainability performance and energy efficiency of the industrial area (and/or the single companies), has proven to represent an effective tool that could help industrial districts' managers and/or institutions dealing with territorial energy planning in identifying the most suitable smart energy system configuration.

The other main topic concerns the synergic integration between industrial and urban areas (see Figure 1.1), and constitutes the object of sections from 4 to 6.

Indeed, the energy-intensive industrial sector could hide relevant opportunities for the implementation of energy efficiency measures to be exploited not only inside the company itself (the endogenous level) according to the traditional approach, but also by overtaking its boundaries towards the external integration based on the smart energy system concept.

Due to the relevance of both its energy requirements and energy efficiency opportunities among the most energy-intensive productive sectors, and because of its huge presence in both the European and the local territorial context, often at a useful distance from urban areas, steel industry based on electric arc furnace (EAF) steelmaking process has been identified as suitable case study for the improvement of sustainability through the recovery of waste energy from industrial process to feed municipal district heating with a carbon-free source.

After providing a comprehensive analysis of the literature on the technologies for the recovery of waste heat from the EAF steelmaking process, in Section 4 a conceptual framework for the different possible exploitation options of the recovered energy is proposed, ranging from the internal use to the external integration into smart energy system. The framework is aimed at helping in the identification of different potential waste heat recovery scenarios to be investigated by means of DSS tools such as the developed one.

As can be derived from the above identification of the gaps existing in the scientific literature, the need to find answers to the following scientific questions arises. Given the opportunity to exploit industrial waste heat recovery through its integration into an urban district heating, is it possible to plan a DHN that simultaneously meets the objectives of the different stakeholders involved, obtaining a win-win solution from a sustainability perspective? And even more, is a compromise solution necessary between the economic and the environmental goals?

To address this task, in Section 5 the developed decision support model based on evolutionary multi-objective optimization is applied to the planning and design of a municipal DHN fed by the waste energy recovered from an EAF steelmaking industrial process, in a typical European city brown field context.

The case study is particularly suitable for the development of the “design” (scenarios) phase of the proposed method for decision support. In fact, the selection of both the most suitable set of end users, city areas and consumer types to be served by the waste heat based DHN requires the identification of different scenarios to be analysed through the developed DSS tool. Moreover, the considered context is also suitable for the development of the “decision making” phase, due to the involvement of different stakeholders, each of them bearer of different goals, thus requiring accounting for different weighting for the decision-making criteria.

The model proves to be able to foster the integration of industrial waste heat recovery into smart energy system, providing to decision makers (policy makers, bodies responsible for territorial energy planning, investors, etc.) a tool that allows the analysis of the different stakeholders involved in a waste heat-based DH municipal energy supply, highlighting the trade-off as well as win-win situations to be exploited.

Concerning the opportunity to implement an efficiency measure such as the recovery of process waste heat in the energy-intensive industrial sectors, also facility managers face indeed the challenge of making the optimal strategic choice among the several waste heat recovery exploitation options identified within the above-mentioned conceptual framework. If only the company’s goals are considered, the different options for the exploitation of the recovered energy could be both synergistic and conflicting, depending on the context. Moreover, the overcome of company’s boundaries in favour of synergies (as investigated in Section 5) might not necessarily represent the best option from the facility manager perspective. The economic objective represents the main driver, although environmental objectives are becoming increasingly important, also due to the increasing value of green marketing. A deeper insight on the sustainability performances of each waste heat recovery option is thus required, in order to allow the facility manager to select the most suitable one and to decide which project to endorse.

To further develop it, in Section 6 the proposed decision support model based on evolutionary multi-objective optimization is applied to an EAF steelmaking case study with a surrounding urban area belonging to a context representative of the typical European climate, with the aim to prove its ability in helping the company’s facility manager in the selection of the most suitable waste heat recovery exploitation option, thus integrating the analysis presented in Section 5 and completing the investigation of the second main topic (see Figure 1.1).

Among the several options identified by the conceptual framework of Section 4, only the two belonging to the Smart Energy System approach, i.e. electricity generation through an ORC unit and the external integration of the recovered energy into an urban DH network have been considered.

The proposed multi-objective model proves to allow the facility manager to make informed decisions on the optimal configuration of the recovery system (technology selection and their possible combination), its optimal sizing and operational strategy definition.

Lastly, the identification of the optimal industrial waste heat recovery option among several possible ones is also the subject of a European research project. The CE-HEAT project, funded by the Central European Program and involving nine partners belonging to Austria, Czech Republic, Croatia, Germany, Italy, Poland and Slovenia, aims to increase energy efficiency (in a circular economy perspective) and to reduce greenhouse gas emissions through the exploitation of industrial waste heat as an energy source. One of the main objectives of the project is the development of an online toolbox for the preliminary assessment of different waste heat recovery options, based on the exploitation of different technologies, thus providing the various stakeholders involved in a waste heat recovery project an overview of the economic and environmental impact of their choices and allowing a more conscious comparison between different waste heat recovery options and selection of the most suitable one.

The developed model has also been applied, in a simplified form, to support the implementation of the CE-HEAT project's online decision support toolbox, proving its potential also as a general procedure to be followed to address the development of online IT tools, as described in Section 7.

2 THE DEVELOPED MULTI-OBJECTIVE DECISION SUPPORT SYSTEM

The conceptual scheme of the developed decision support system (DSS) is structured in five main phases, as represented by the flowchart of Figure 2.1 and presented below.

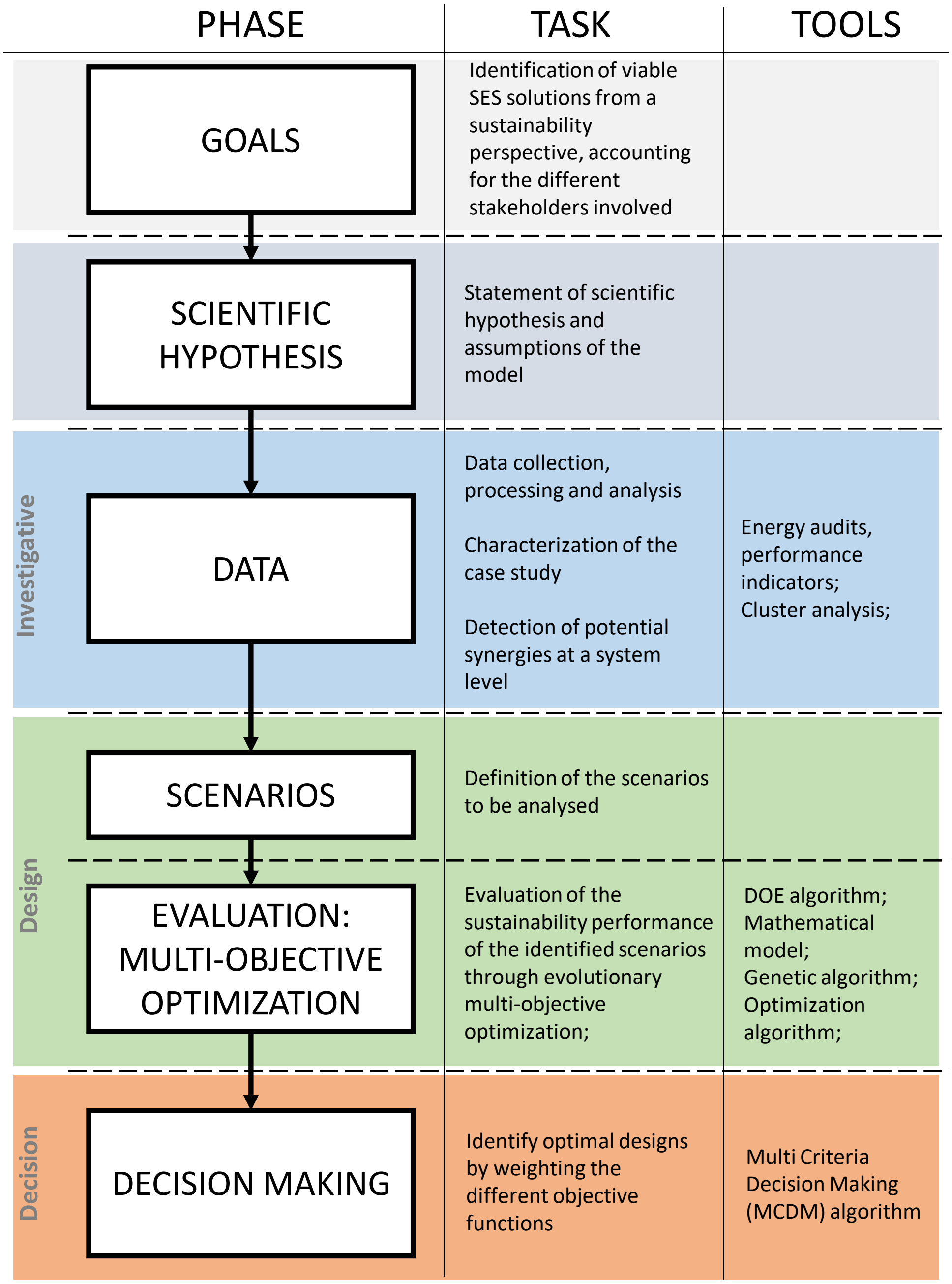


Figure 2.1. Framework of the developed Decision Support System

The three typical phases of a DSS are highlighted: 1) the investigative phase (data collection aimed at the characterization of the specific case study), 2) the design phase (simulations, performed through a several steps procedure) and 3) the decision phase (Mattiussi et al., 2014). It's worth noting that the developed procedure is meant to be applied at the system level, such as a smart energy system context, nonetheless it can be applied also to the endogenous one (i.e. internal with respect to the considered entity).

Once the goal of the work has been defined and once scientific hypothesis and assumptions of the problem have been stated, the next phase consists of the data collection and analysis.

2.1 The investigative phase: data collection and analysis

The investigative phase consists of the acquisition of all the information (specific of the considered case study) needed to perform the evaluation through the DSS. It's worth noting that the level of detail of the available input data concurs to determine the level of accuracy of the evaluation made through the proposed decision model.

The required input data typically regards the characterization of users' energy demand and consumption behaviour. In case of industrial districts, the conduction of energy audits at companies is required in order to characterise their energy consumption behaviour, but also to identify possible industrial waste heat sources and/or potential heat sinks. If a district heating network is concerned, beside the local climate data, the characterization of the DH users (heat demand, consumer types, involved city areas, etc.) is required. Moreover, the characterization of energy supply sources is needed. Lastly, energy generation and distribution infrastructures must be characterized for every considered technology from a technical (configuration, sizing and design, etc.) and economic perspective (collection of investment cost data, typically varying with the capacity, operation and maintenance costs, etc.).

The identification of physical, technical, economic, financial, regulatory, and territorial constraints, both generic and specific of the case study, belongs to the same phase. Some of them will then be included as constraints in the mathematical model of the smart energy system, while others will represent constraints of the multi-objective optimization model, as it will be described in the next sections.

The performance of some economic indicators must satisfy threshold values which are usually fixed e.g. by entrepreneurs when evaluating energy efficiency investments to be endorsed or required by lenders when evaluating infrastructural investments. Also, the real territorial context is accounted, e.g. by considering the different intended use of urban areas, thus imposing some constraints to the optimization problem.

The data collection phase is typically followed by data processing, as the evaluation of performance indicators could be relevant to obtain a deeper insight concerning sustainability behaviour. These indicators should be compared with the reference performance indicators derived from literature or field studies. Alternatively, the comparison can be done through theoretical performance indicators resulting from an analytical modelling of the considered productive process, if information from the literature are not available.

The energy performance indicators, besides allowing to conduct a benchmark analysis, are useful to identify, within the industrial districts and urban areas, possible clusters of energy-intensive users, thus highlighting the potential for energy efficiency measures implementation, and also allowing to detect potential synergies at a system level, which give feasibility to smart energy system solutions.

2.2 The design phase: scenarios development

The identification of the different alternative scenarios to be analysed, represents the next phase.

Concerning the evaluation of different possible configuration for energy supply of a smart energy system, the alternative scenarios could derive from the selection of different combinations within a list of available technologies to implement, such as distributed energy generation technologies, e.g. combined cooling heat and power (CCHP), renewable energy sources (RES) etc., or different possible technologies for the exploitation of waste heat recovery such as heat exchangers (HE), organic Rankine cycle (ORC), or even absorption chiller (AC) if an industrial waste heat recovery project is under examination.

Moreover, also different potential options considering the final users of the SES (e.g. different city area to be served by a waste heat based DHN) could be considered.

The possible scenarios are then identified and some of them are eliminated according to the constraints imposed to the problem. The presence of technical and/or regulatory constraints and of boundary conditions in the considered case study, implies the exclusion of some of the potential scenarios to be analysed from the initial list. The exclusion of a given scenario is performed automatically by the model throughout a check step based on conformity to the constraints and boundary conditions imposed to the problem; the next scenario is then selected and analysed by the model.

2.3 The design phase: evolutionary multi-objective optimization

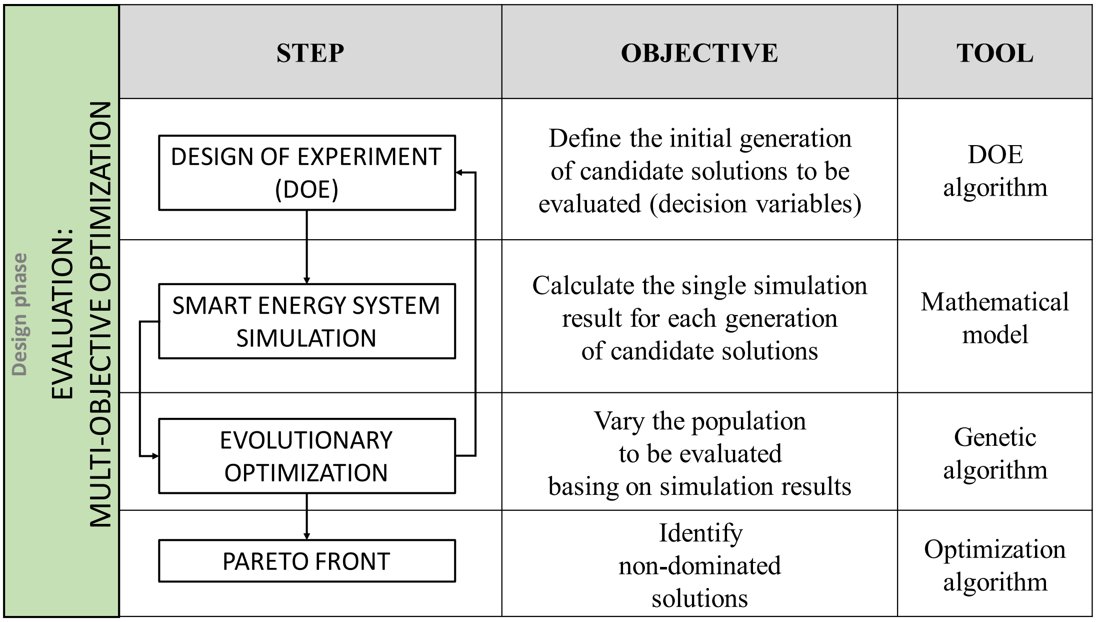
The evaluation of the set of selected scenarios through an iterative evolutionary multi-objective optimization model, integrating different tools as represented in Figure 2.2., completes the "design" phase and represents the core of the proposed decision support method presented in Figure 2.1.

The mathematical model identifies the solutions to the problem that guarantee the achievement of certain target functions. The objective functions of the multiobjective optimization problem are typically selected within a list of relevant aspects, according to the stakeholders' requirements, specifically for the considered case study. In the context of a sustainability analysis, at least the following objective functions should be considered: maximization of the economic (e.g. minimum payback period, maximum internal rate of return, etc.), environmental (e.g. minimum greenhouse gas emissions) and energetic (i.e. maximum primary energy savings) performances.

Within the mathematical model, the identification of the decision variables of the multiobjective optimization problem is relevant. Typically, the decision variables are the critical dimensions which could affect the decision making, i.e. technical features of the energy system (such as e.g. the capacity of the energy generation units and of thermal energy storage system), and the main economic flows on which to act to meet the objectives of the various stakeholders involved in a smart energy system project (such as e.g. in the case of a waste heat recovery project, the remuneration of the thermal energy recovered from an industrial process and the specific selling price of the heating to the DHN end users).

The imposition of the constraints identified during the data collection phase, such as the ones due to technical (e.g. the illogical combination of technologies from a technical point of view) or regulatory compliance reasons, reduces the number of possible scenarios to be evaluated through the evolutionary multiobjective optimization procedure.

Furthermore, it could be interesting to perform a sensitivity analysis on some critical parameters, mainly the economic ones, such as e.g. the specific cost/prices of the energy vectors.



STEP	OBJECTIVE	TOOL
DESIGN OF EXPERIMENT (DOE)	Define the initial generation of candidate solutions to be evaluated (decision variables)	DOE algorithm
SMART ENERGY SYSTEM SIMULATION	Calculate the single simulation result for each generation of candidate solutions	Mathematical model
EVOLUTIONARY OPTIMIZATION	Vary the population to be evaluated basing on simulation results	Genetic algorithm
PARETO FRONT	Identify non-dominated solutions	Optimization algorithm

Figure 2.2. Evolutionary multi-objective optimization procedure. Adapted from (Simeoni et al., 2018)

According to (Mattiussi et al., 2014) an iterative, evolutionary multi-objective optimization consists of a four steps procedure: Design Of Experiment (DOE), mathematical modelling, optimization and definition of the Pareto front.

First, in the design of experiment (DOE) step, the initial population (i.e. the set of sample values to be assigned to the decision variables) required to execute simulation and optimization phases is defined. This set of sample values obtained from a combination of the considered decision variables, allow a first-time resolution of the algorithm.

Based on the results obtained from the first resolution, the algorithm will vary the population through the isolation of the individuals which are most suitable for achieving the goals of the problem. Is thus important for the initial population to be meaningful of the case study to be analysed and to allow to occupy with regularity the entire range of values assumed by the variables.

Good general references for quasi-random sequence generation are provided in (Niederreiter, 1992). The most used techniques for generating sequences of values, among the several, are the random generation, the stratified generation, the Latin hypercube generation and the generation based on the Sobol's sequence, which is described in (Bratley and Fox, 1988). The simulation results presented in the next chapters of the thesis have been obtained through the pseudo-random sequence based on the Sobol's generators. The latter DOE technique has been chosen as it has proven to allow the obtainment of a satisfying uniformity of the sequence of values in the multidimensional space, avoiding gaps and aggregates of points, which instead can occur in the case of random techniques (Maaranen et al., 2004).

At each iteration, a simulation of the smart energy system is then conducted to evaluate the objective functions for the given candidate solution, and a new set of candidate solutions, namely offspring population, is generated for the next iteration by applying genetic operators (Vesterlund et al., 2017), through a criterion based on the ranking of the objective function values.

Then, attention must be paid on the optimization algorithm, whose tasks are the selection of the generated population set based on the solutions of the problem, their hierarchical sorting based on the affinity with the objectives of the problem and finally to establish which of them must be reproduced (Mattiussi et al., 2014).

Evolutionary algorithms (see e.g. (Poloni and Pediroda, 1997)) are meta-heuristic optimization algorithms based on the characteristics of the population, which make use of biology-inspired mechanisms such as mutation, reconnection/crossover, natural selection and survival of the strongest individual (Darwin's Theory of Evolution) to refine the selection of possible solutions to the problem in an iterative way. The advantage, therefore, in the use of evolutionary algorithms is to allow the solution of the problem without the need to provide a large number of information on the objectives set, guaranteeing the possibility of solving a good number of problem categories with good performances.

Evolutionary algorithms are particularly effective in addressing the multi-objective optimization problems typical of the sustainability analysis of energy systems, which are too complex to be solved by means of any traditional method because they involve the optimization of several, usually conflicting, objectives.

The work cycle of an evolutionary algorithm could be described through the following steps:

1. A population of individuals with a random genome is created by defining the DOE;
2. By implementing these individuals within the calculation model, the value of the objective functions is determined;
3. Through the objective functions, each candidate solution is assigned a ranking value based on its adequacy for solving the problem;
4. Solutions having low adequacy are filtered and those having a high degree are allowed, to consent their entry into the reproduction section with greater probability, then implementing a selection process;
5. In the reproduction phase, it is possible to create a new series of individuals by varying or combining the genotypes of the selected individuals;
6. The process iterates starting from the second step, in the absence of further indications.

The attribution of the degree of adequacy is called *fitness assignment*. The most spread *fitness assignment* method is based on the Pareto optimization method, which argues that it is possible to define a front of solutions that can be achieved through the "trade-off' between the objectives, i.e. the compromise between equally desirable but conflicting options (Goldberg, 1989). This yields not a single optimal solution but a set of equally important optima, the Pareto front.

The solutions to the multi-objective problem are compared using the notion of Pareto Domain, that is, a particular solution x, to which a vector u is associated, is said to dominate (x < y), or is better, of another solution y to which a vector v is associated if the first is characterized by performances at least as good as the second in all the objectives, and there is a goal in which it presents better performances. The set of all the vectors that respect the Pareto Domain rule are defined as feasible solutions to the problem, or again, Pareto front.

Several studies have been carried out concerning evolutionary multiobjective optimization and ranking schemes based on the definition of Pareto optimality (Fonseca and Fleming, 1995). Among the methods to determine the best way to use the Pareto concept, the one proposed in (Goldberg, 1989) is to produce the best results and the greatest application. It consists in assigning rank 1 to all non-dominated individuals and removing them from the population, subsequently identifying new non-dominated individuals, assigning rank 2 and removing them from the population until complete cataloguing. Based on this method, Fonseca and Fleming proposed a slightly different approach, in which the rank of an individual corresponds to the number that dominates it (Fonseca and Fleming, 1993). In this way, all those not dominated are characterized by the same rank, while the others are penalized on the basis of the density of the population present in the corresponding region of the trade-off surface; the algorithm iterates this process until all the individuals are catalogued. This algorithm patented by Fonseca and Fleming in 1993 takes the name of MOGA (Multi Objective Genetic Algorithm). More recently, the latter has been evolved in the MOGA-II as reported in (Poles, 2003, 2001).

The Pareto optimization method has been chosen for the proposed iterative evolutionary multiobjective optimization model embedded in the developed decision support method. The evolutionary algorithm selected in this research work is the above mentioned MOGA-II, which is available in the software used for the implementation of the DSS model.

2.4 The decision-making phase

The purpose of the developed decision support method is to allow the decision maker to understand what the consequences of its choices can be and then to make informed decisions. Optimization results are useful to the decision maker for a comparison between possible solutions, in order to highlight the correlation existing between the decision variables considered in the analysis and the economic, energetic and environmental objective functions of the optimization problem.

The decision making phase, where e.g. the selection of the most suitable smart energy system configuration, sizing and operation strategy definition can be performed, based on the analysis of the optimization results, represents the last phase of the decision support method (see Figure 2.1). A review of decision-making methods applied to sustainable energy planning is provided in (Pohekar and Ramachandran, 2004).

Among the available decision-making methods, the multiple criteria decision making (MCDM) tool has become popular in operational research concerning the field of energy planning and management in complex scenarios due to the flexibility it provides to decision makers while considering multiple criteria and conflicting objectives simultaneously. A review on multi criteria decision making methods in sustainable energy decision-making is provided in (Wang et al., 2009), where the different stages such as criteria selection, criteria weighting, evaluation and final aggregation are reviewed. Moreover, the criteria of energy supply systems are summarized from technical, economic, environmental and social aspects and the weighting methods of criteria are classified into categories. More recently, an insight into various MCDM techniques applied to sustainable energy decision making, with focus on renewables, is provided in (Kumar et al., 2017).

In the last phase of the developed DSS, the decision making is meant to be performed through the multiple criteria decision making (MCDM) tool. The criteria are weighted based on the goal of each favoured stakeholder and the related objective functions, according to the suggestions provided by a panel of experts which should be composed by members representative of the different stakeholder categories.

As described, Pareto multi-objective optimization consists in determining all solutions to the problem that are optimal in the Pareto sense. The preferred solution, that is the most suitable one to the decision maker according to its objectives, is selected from the Pareto set. In this sense, multi-objective optimization could be considered as the analytical phase of multi criteria decision making (MCDM) process (Ngatchou et al., 2005).

3 PLANNING AND DESIGN OF SUSTAINABLE ENERGY SUPPLY FOR INDUSTRIAL DISTRICTS

As already highlighted, concerning the improvement of the sustainability performances of the energy-intensive industrial sector, relevant opportunities could be unlocked if single company's boundaries were overtaken towards the establishment of synergies allowed by geographical proximity, thus exploiting the potential benefits offered by the implementation of the smart energy system concept.

Institutions dealing with territorial energy planning need to embed smart energy systems planning in policy strategies to meet environmental goals, but also industrial districts facility managers and investors, face indeed the challenge of making the optimal strategic choice, selecting the most suitable solution when deciding to endorse a project.

This task requires to make use of tools able to provide a deep insight on the sustainability performances of different potential smart energy system configuration (i.e. technology selection, their possible combination, optimal sizing, etc.) and operational strategy definition through the evaluation of technical, economic, environmental and energetic objective functions, thus allowing a conscious comparison between different SES options and the selection of the most suitable one.

Within the context of sustainable energy supply of industrial districts, the developed decision support framework has then been applied to the planning and design of smart energy system solutions specifically designed for clusters of firms, thus considering distributed renewable sources (RES), centralized tri-generation (CCHP), thermal energy storage systems and energy distribution micro-grids.

The considered case study, selected within the opportunities belonging to the energy-intensive sectors available in the local territorial context, concerns an industrial district of the food sector. It is particularly suitable for the implementation of the above described smart energy system concept in its general configuration because of the simultaneous and relevant presence throughout the year of both electric, heating and cooling power demand, due to the particular process's energy requirements (i.e. rooms refrigeration, heating, ventilation and air conditioning, lights and equipment, process hot water, etc.).

In this first development step of the proposed DSS framework, beside the "goal" and the "scientific hypothesis" phases, effort has been put on the development of the "data" and of the "multi-objective optimization" phases, as highlighted in Figure 3.1 where the proposed model, already presented in Section 2 in its general features, is represented as regards its application to the sustainable energy supply of industrial areas.

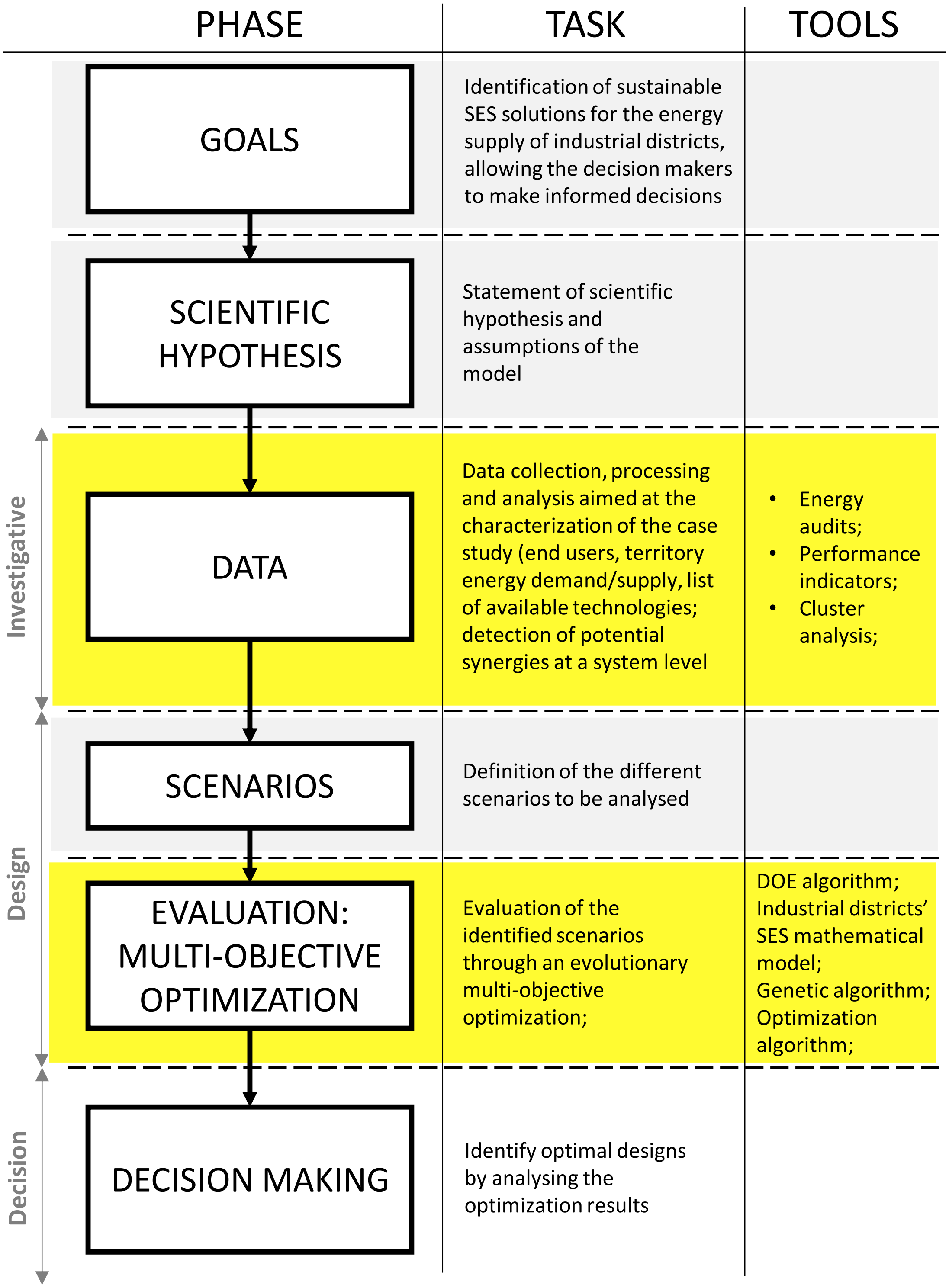


Figure 3.1 Development of the proposed DSS: application to planning and design of sustainable SES solutions for industrial districts

The context of industrial districts is indeed particularly suitable for the development of the "investigative" (data) phase of the proposed method for decision support, due to the need for the collection, processing and analysis of the productive process features, and of the data related to energy consumption and production for the considered cluster of companies (energy audits).

Moreover, the SES concept applied to the district's sustainable energy supply is intrinsically a multi-objective optimization problem, thus constituting a suitable test case for the first implementation of the "design" (evaluation through multi-objective optimization) phase of the proposed DSS. The development of the "scenario" and of the "decision-making" phases is instead presented in the following sections of the thesis.

The data collection phase consists of the acquisition of all the required input information (case-study specific) needed to perform the evaluation through the DSS. In the industrial districts' context, the conduction of energy audits at companies is required in order to obtain a deep characterization, also but not exclusively about their energy consumption behaviour. As already outlined, the data collection phase is then typically followed by data processing, as the evaluation of some performance indicators could be relevant to obtain a deeper insight especially concerning companies' sustainability behaviour. These indicators should be compared with the reference performance indicators derived from literature or field studies, if available, as described on the left branch of Figure 3.2. Alternatively, if information from the literature cannot be obtained, the comparison can be done through theoretical performance indicators resulting from an analytical modelling of the considered productive process.

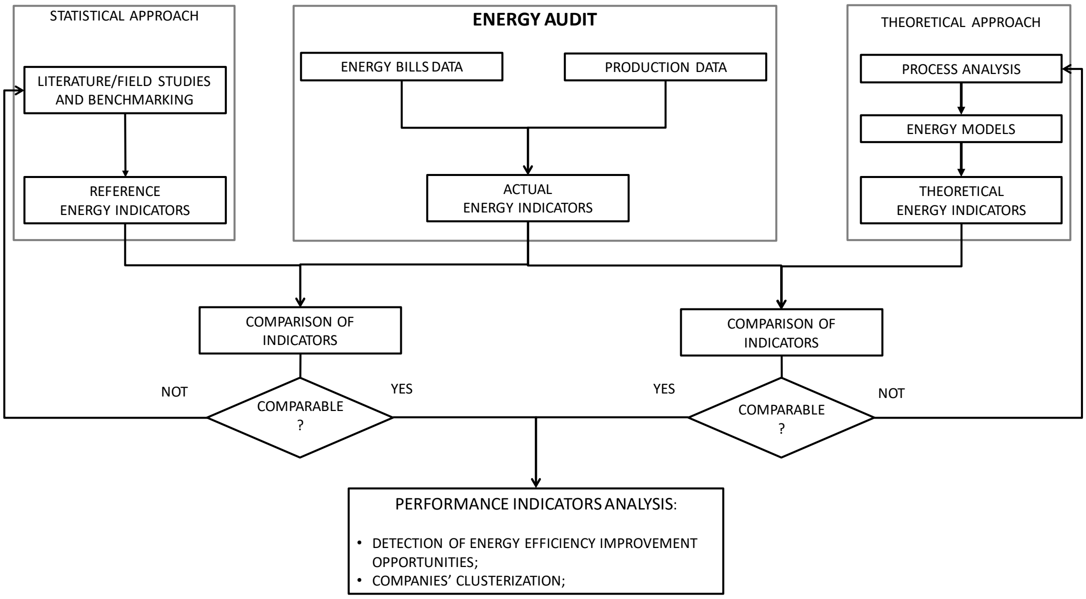


Figure 3.2 Data collection and analysis through energy audits and performance indicators (adapted from (Simeoni et al., 2018))

The developed DSS, by including energy performance indicators, allows to conduct a benchmark analysis and, in this sense, could also represent a useful tool for monitoring the improvement of the sustainability performance and energy efficiency of both the whole industrial area and/or the single companies.

The following performance indicators are considered in this work. The Energy Performance Indicator (EPI) is defined as the ratio of the total annual consumption of each kind of energy e to the total annual production of the company, e.g. expressed in tonnes of product (Equation (3.1)). Consequently, the Cost Performance Indicator (CPI) is defined, once known the specific cost c_e of the considered of energy vector (Equation (3.2)). The Primary Energy Performance Indicator (PEPI) evaluates the primary energy consumption related to the company's production (Equation (3.3) estimated through the primary energy conversion factor ξ_e. Concerning the environmental aspect, several performance indicators could be considered, in order to account for different pollutants. However, in this work, a single environmental performance indicator has been considered, concerning the GHG emissions. The Greenhouse gas Emission Performance Indicator (GEPI) is defined as the ratio of the total annual carbon dioxide emissions for each kind of energy e to the total annual production of the company (Equation (3.4)).

$$EPI_e = \frac{E_e}{production}\left[\frac{kWh_e}{t\,pr}\right] \tag{3.1}$$

$$CPI_e = \frac{E_e \cdot c_e}{production}\left[\frac{EURO}{t\,pr}\right] \tag{3.2}$$

$$PEPI_e = \frac{E_e \cdot \xi_e}{production}\left[\frac{toe}{t\,pr}\right] \tag{3.3}$$

$$GEPI_e = \frac{E_e \cdot \mu_e}{production}\left[\frac{t\,CO_2\,eq}{t\,pr}\right] \tag{3.4}$$

Besides highlighting the potential for the implementation of energy efficiency measures, the analysis of energy performance indicators is also useful to identify, within the industrial district, possible clusters of energy-intensive companies, thus allowing to detect potential synergies at a system level, which give feasibility to smart energy system solutions.

In the context of analysis of sustainable energy supply for industrial districts, the considered stakeholders are single companies, and the following objective functions have been considered: maximization of the economic (e.g. minimum payback period, maximum internal rate of return, etc.), environmental (e.g. minimum greenhouse gas emissions) and energetic (i.e. maximum primary energy savings) performance.

In subsection 3.1 the mathematical model developed for the multiobjective optimization of SES solutions for the sustainable energy supply of industrial district is described. In subsection 3.2 the Italian food industrial district case study is presented, and in subsection 3.3 the obtained results are presented and discussed.

The results obtained with this work were published in the article Simeoni, P., Nardin, G. and Ciotti, G. (2018) 'Planning and design of sustainable smart multi energy systems. The case of a food industrial district in Italy', *Energy*, 163, pp. 443–456. doi: https://doi.org/10.1016/j.energy.2018.08.125.

3.1 Industrial districts' smart energy system modelling

Typically, according the conventional energy supply approach based on separate production (SP), the electricity needed by firms is supplied by the national electricity grid, thermal energy needs are provided by natural gas-fired boilers and the cooling energy needs are satisfied by electric chillers.

In the case of application to industrial districts of the smart energy system concept, in its general configuration, the design should combine distributed generation from renewable energy sources, trigeneration technologies (combined cooling, heat and power), energy storage systems and energy distribution networks. This general configuration, which has been formalised in the mathematical model, is represented in Figure 3.3. It can be scaled to simplified configurations depending on the industrial context considered (e.g. if only cogeneration is needed instead of trigeneration).

The proposed configuration of the smart energy system is based on a centralized CCHP plant which is like a conventional one, but with some relevant differences (see Figure 3.3). The extent of the required generation capacity implies to install multiple components in parallel (power generation units, absorption and electric chillers, back-up boilers, etc.). Energy storage systems are essential to maximize the efficiency of the smart energy system; in this case, only thermal energy storage (hot and cold water) has been accounted. Finally, district energy distribution networks (heating, cooling and electricity) supply every kind of energy need to the district's companies. The SES main power station is connected to the external energy supply grids, i.e. the electric power grid, which provides the integration of the CCHP, and the natural gas pipe, as a traditional CCHP system. The proposed cooling system, which has been defined "*Cold Switch Set*" (CSS), adopts the combination of electric chiller and absorption chiller. To maximize energy conversion efficiency performances (i.e. the maximum exploitation of the fuel's primary energy), in the case of a stable presence of the cooling needs during the year, the potential excess thermal energy produced by the CHP following the companies' electricity demand can be used to cover the cooling load through the absorption chiller, contributing to the optimization of the CHP operation.

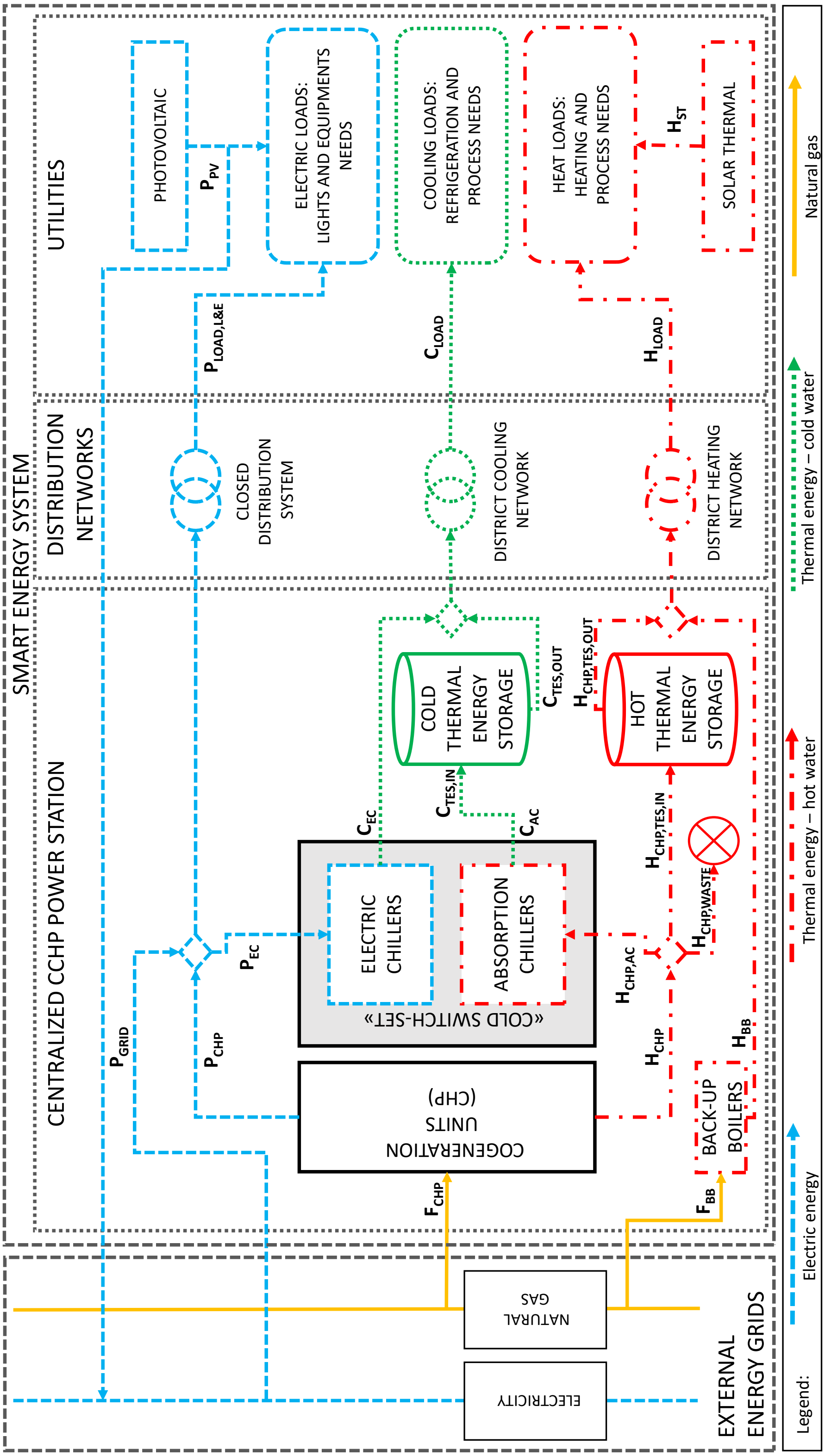


Figure 3.3. Industrial district's smart energy system layout and energy flows. Adapted from (Simeoni et al., 2018)

Distributed renewable energy sources complete the industrial district SES generation layout. In this research, solar distributed renewable energy sources based at the individual companies have been selected because they are a wide applicable and spread technology. In future developments of the research, other non-programmable RES would be considered and different SES layout including the possibility of electricity storage would be investigated.

The energy balance constraints that describe the energy flow diagram of the SES represented in Figure 3.3 are the following, where P, H, C represent respectively the electric, heating and cooling power respectively produced and consumed at the given time t.

$$P_{CHP,t} + P_{GRID,t} - P_{EC,t} - (P_{LOAD,L\&E,t} - P_{PV,t}) = 0 \tag{3.5}$$

$$H_{CHP,t} - H_{CHP,AC,t} - H_{CHP,TES,IN,t} - H_{CHP,WASTE,t} = 0 \tag{3.6}$$

$$C_{EC,t} + C_{AC,t} = C_{CSS,t} \tag{3.7}$$

For the electric energy, the power generation of the CHP units $P_{CHP,t}$ and the integration from the main grid $P_{GRID,t}$, must equal the electric load for light and equipment $P_{LOAD,L\&E,t}$ and the electric chillers load $P_{EC,t}$, after considering the power production of the individual utility's solar photovoltaic plant $P_{PV,t}$ as in Equation (3.5). Concerning the thermal energy, the heat recovered from the prime movers $H_{CHP,t}$ must increase the hot thermal energy storage (TES) level $H_{CHP,TES,IN,t}$ or produce cooling energy through the absorption chiller $H_{CHP,AC,t}$ if no dissipation $H_{CHP,WASTE,t}$ is necessary. The cooling energy produced by the absorption chiller $C_{AC,t}$ is sent to the cold thermal energy storage vessel.

The introduction of the hot and cold TES systems, with buffering and storing purposes, entails the following energy balances, respectively reported in Equation (3.8) and Equation (3.9), since the difference of the thermal energy send to the TES (subscript "IN") and taken from them (subscript "OUT") must equal the accumulation in the energy storage systems, having a heat capacity of mC_p, dependent on the storage vessel volume V_{TES} and on its temperature T, given the heat transfer fluid physical properties and specifications.

$$H_{CHP,TES,OUT,t} + H_{BB,t} - (H_{LOAD,t} - H_{ST,t}) = 0 \tag{3.8}$$

$$C_{TES,OUT,t} + C_{EC,t} - C_{LOAD,t} = 0 \tag{3.9}$$

The fuel energy consumption F_{CHP} and the recovered waste heat $H_{CHP,t}$ of the power generation units (PGU) can be evaluated as reported in Equation (3.10) and Equation

(3.11) respectively, in which $\eta_{CHP,th}$ is the efficiency of the heat recovery system and $\eta_{CHP,el}$ the PGU's electrical efficiency:

$$F_{CHP,t} = \frac{P_{CHP,t}}{\eta_{CHP,el}} \tag{3.10}$$

$$H_{CHP,t} = P_{CHP,t} \cdot \frac{\eta_{CHP,th}}{\eta_{CHP,el}} \tag{3.11}$$

The conversion of fuel to thermal energy in the auxiliary boiler, the conversion of electrical energy to cooling in the electric chiller and the conversion of heat to cooling energy in the absorption chiller are defined by the followings Equations (3.12-3.14), where η_{BB} is the efficiency of the boiler fuelled by natural gas, COP_{EC} and COP_{AC} are the coefficient of performance of the electric and the absorption chillers respectively, $C_{EC,t}$ is the cooling power produced by the electric chiller, $C_{AC,t}$ is the cooling power produced by the absorption chiller. $H_{BB,t}$ represents the thermal power produced by the back-up boilers at a given time t.

$$H_{BB,t} = \eta_{BB} \cdot F_{BB,t} \tag{3.12}$$

$$C_{EC,t} = COP_{EC} \cdot P_{EC,t} \tag{3.13}$$

$$C_{AC,t} = COP_{AC} \cdot H_{CHP,AC,t} \tag{3.14}$$

Therefore, the on-site fuel consumption of the smart energy system $F_{SES,t}$ can be calculated as in Equation (3.15):

$$F_{SES,t} = F_{CHP,t} + F_{BB,t} \tag{3.15}$$

Calculation is based on daily energy load profiles, which are function of the working schedule and day type, i.e. working or non-working day. Usually non-working day profiles are smoother, closer to base load and with less hourly variations. Historical energy consumption data for at least one year, from energy audit, are necessary for designing of a trigeneration plant. The presented energy system can be described by a simple hour by hour energy model. The time horizon of the calculations is one year (t = 1, ... ,8760).

3.1.1 Constraints

The total installed capacity of each equipment is determined by the relative maximum design value deriving by the total requirements of the industrial district, concerning the upper limits, and by the minimum commercially available items capacity as concerns the lower limits. These constraints are embedded in the optimization algorithm of the simulative approach.

3.1.2 Assumptions

Some important assumptions relative to the CCHP plant are required. CHP efficiency is affected by its capacity factor, that is the ratio of the actual power produced at a given time *t* to its nominal power. In this analysis, the generation efficiency of the PGU is assumed to be constant. The efficiency drop of CCHP equipment at partial load operation are then neglected to simplify the analysis and calculation, because a detailed simulation of the CHP operation is not the main purpose of this study. Moreover, the minimum technical limit of the CCHP system is also neglected, for the same reason.

To correctly model SES operation and to optimally size its equipment, the efficiencies of some commercially available reciprocating engines varying with their capacity (represented in

Figure 3.4), are instead accounted in this study.

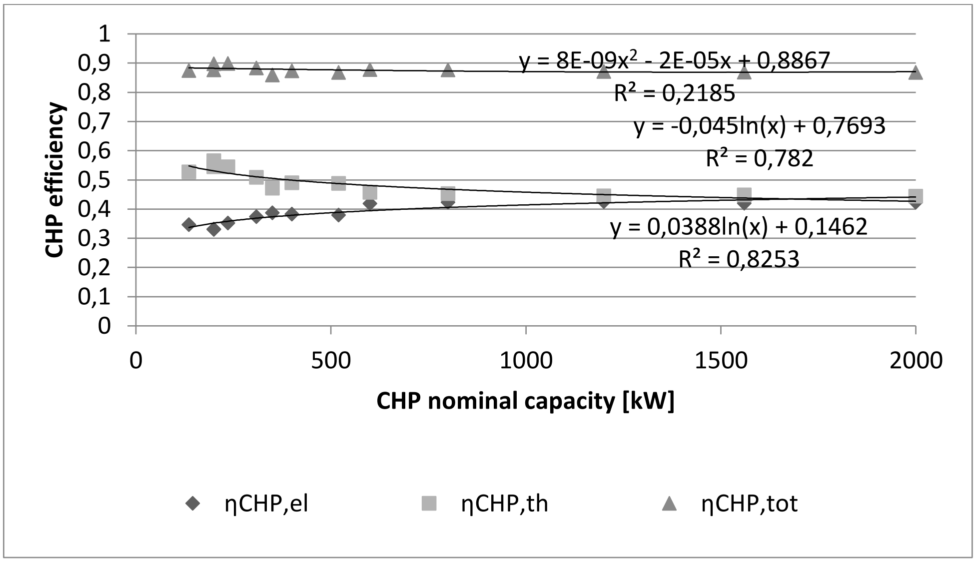


Figure 3.4. CHP efficiency curves (Simeoni et al., 2018)

Moreover, the parasitic electric energy consumption of the system, mainly due to the district's thermal energy distribution networks pumps, is neglected here.

It is important to point out that the energy produced by the renewable sources is assumed to be consumed with priority over the fossil energy and the energy which is bought from the main electric grid. Any excess photovoltaic energy production is sold to the network (e.g. during non-working days, etc.) as represented in Figure 3.3.

3.1.3 Industrial district's SES optimal design: decision variables

Design and operation of distributed generation CCHP plants is affected by operation strategy, which is mainly dependent on each kind of energy needs. In literature, cogeneration systems are typically designed by either covering a constant part of energy (base load), the so called "continuous operation", or by following the evolution of the electrical or heat load (Chicco and Mancarella, 2007). Strategies can be changed during the year to better match to the seasonal load coincidence. Since the conventional load following strategies do not allow to fully exploit the potential benefits in a trigeneration system of a smart energy system context, in this study the chosen operation strategy for the centralized CCHP system is the electric equivalent demand following (Kavvadias and Maroulis, 2010). The system operates to cover the electricity load and the electricity needed for the electric chiller minus the electricity that is conserved by the operation of the absorber in order to cover the cooling load. The CCHP system excess heat production can in fact be stored for delayed use, and/or be used to satisfy the cooling load through the absorption chiller, with the benefit of reducing the total electric load. Heating energy demand is then integrated by backup boilers.

In the proposed multi-objective model, the nominal capacity of cogeneration units P_{CHP_nom}, which influences the ratio of the cogenerated electric power to total electric power demand of the industrial district, is optimized. The reason is that optimizing the size of CCHP power generation equipment is fundamental to plant capital cost and operation mode. The definition of this decision variable implies that its range of variation is between 0 and 1. The capacity of the electric and absorption chillers and backup boilers is instead assigned based on maximum requirements.

To evaluate the electric power and the heat generation potential of distributed renewable energy sources such as photovoltaic and solar thermal respectively, the gross surface area of the rooftops is considered here, assuming an exploitation factor to obtain the net area available for the installation of the solar plants. The considered techniques are conventional polycrystalline silicon photovoltaic panels and flat plate thermal solar collectors. Hourly solar irradiance data for the case study's specific site are considered within the model to evaluate the energy generation potential of the solar sources.

In the presented model, the capacity of the solar photovoltaic and solar thermal plants is also optimized. The reason for optimizing the capacity of these renewable energy generation equipment is that their sizing is important to capital cost and operation mode, since economic, environmental and reliability implications should be considered (Karki and Billinton, 2001). Two further decision variables are thus defined. *PV_R* represents the ratio of the photovoltaic installed area on the total area covered by solar source (photovoltaic and thermal), and SAUF (Solar Area Utilization Factor) represents the share of the total rooftop net available area exploited for the installation of solar source. Both parameters imply an occupied rooftop area, once the technology is selected and the installation specifications are given.

Because of their important role in a smart energy system context, in this study the storage systems' capacities V_{TES} (both hot and cold TES) are also optimized, thus representing decision variables of the optimization problem.

3.1.4 Evaluation criteria

To carry out the analysis, an existing conventional system based on separate production (SP) is taken as the reference to compare to the proposed smart energy system (SES).

To quantify the potential technical, economic, energetic and environmental benefits of the SES compared to SP, the following evaluation criteria are considered.

3.1.4.1 Economic evaluation

The costs associated with the smart energy system operation concern the fuel costs and maintenance costs.

Fuel costs are related to the supply to the prime movers and the auxiliary boilers and the costs of the electricity imported from the grid. Excess electricity that is exported to the grid can also be taken into consideration, if selling is permitted in the regulatory context specific of the case study. Thus, energy tariffs could heavily affect a trigeneration investment. The optimal design must consider the pricing policy applied. The most common energy pricing schemes that are used worldwide are reported in (Kavvadias and Maroulis, 2010). In this study, to simplify the calculations, the volumetric fees only are considered. These results in any case in a precautionary approach since the maximum power demand of the SES from the main grid will be lower than in the SP case.

Maintenance cost is mainly due to the operation of the cogeneration units and is accounted as a specific cost based on the generated electric energy, while maintenance costs of the backup boilers and of the absorption and electric chillers can be neglected, as discussed in the case study section. The following Equation (3.16) gives the annual operating costs AOC, where $c_{O\&M}$ represents the specific cost of operation and maintenance, c_F the specific cost of fuel, $c_{el,GRIDIN}$ the specific cost of electricity bought from the grid (volumetric charges of electricity), $c_{el,GRIDOUT}$ is the specific price of electricity sold to the grid and $c_{H,WASTE}$ is the specific cost of heat dissipation (i.e. the operating cost of a cooling tower). All specific costs are expressed in EUR/kWh.

The annual operational profit (AOP) of the investment (Equation (3.17)) is obtained as the difference between the annual operating costs AOC of the proposed SES solution and the traditional SP one.

Economic evaluation is carried out with the Standard Pay-Back (SPB) and with the Net Present Value (NPV) method which are usually recommended for mutually exclusive investments (Biezma and San Cristóbal, 2006) and can be used successfully for sizing cost-reducing investments (Piacentino and Cardona, 2008). In Equation (3.18) *N* is the expected lifetime of the project (service lifetime of the equipment) and *i* represents the discount rate.

$$AOC = c_{O\&M,CHP} \cdot \sum_{t=1}^{8760} P_{CHP,t} \cdot dt + c_F \cdot \sum_{t=1}^{8760}\left(F_{CHP,t} + F_{BB,t}\right) + c_{el,GRIDIN} \cdot \sum_{t=1}^{8760}\left(P_{GRIDIN,t}\right) \cdot dt - c_{el,GRIDOUT} \cdot \sum_{t=1}^{8760}\left(P_{GRIDOUT,t}\right) \cdot dt + c_{H,WASTE} \cdot \sum_{t=1}^{8760}\left(H_{WASTE,t}\right) \cdot dt \tag{3.16}$$

$$AOP = AOC_{SP} - AOC_{SES} \tag{3.17}$$

$$NPV = -CapCost + \sum_{L=1}^{N} \frac{AOP}{(1+i)^L} \tag{3.18}$$

The capital cost *CapCost* depends on the nominal capacity of the smart energy system equipment, i.e. CHP units, absorption chillers, backup boilers, electric chillers, thermal energy storage vessels, energy distribution networks, solar thermal and PV plants. The investment costs for some commercially available prime movers suitable for the industrial districts CCHP main generation plant (total power generation capacity approximately lower than 20 MW, parallel multi-generation configuration is considered) have been collected, leading to the interpolation functions in the form $y=ax^2+bx+c$ shown in Table 3.1 together with the other SES components, where *y* represents the capital cost of the component, expressed in EUR, and *x* represents its nominal capacity. The investment costs related to the district energy distribution networks depend on their design, which is function of the maximum load required by the single company to be served, which in turn determines the technical specifications (i.e. diameter) of pipes and cables, once the characteristics of the energy carrier are established. The design of the network is also dependent on the relative distance between the firms and the main centralized generation plant. The evaluation is then conducted considering specific costs per unit of length, varying with the diameter of the pipe’s section, and including the cost of the excavation for pipe laying. Fixed costs for the centralized pump system and heat exchangers located at individual companies are considered. According to this, the investment costs related to the energy distribution networks can be considered a fixed value for a given case study, and therefore does not constitute an optimization parameter in this model. It is important to emphasize that the location of the CCHP plant, once satisfying the technical and regulatory constraints of the area, should be chosen according to an optimization criterion, e.g. the minimization of the energy losses due to transport along the distribution network.

Table 3.1. SES components investment cost: interpolation function coefficients (Simeoni et al., 2018)

Component		CHP	AC	EC	BB
Interpolation	a	- 0.0896	0.0138	0.0106	0
function	b	735.37	150.53	113.79	26
coefficients	c	133785	87929	30936	8700
R^2		0.9864	0.9975	0.9807	
validity range of *x*	(kW)	100 ÷ 3000	150 ÷ 1000	300 ÷ 1500	1000 ÷ 5000

The capital cost of the solar photovoltaic plant is dependent on the total installed power capacity and can be evaluated through a specific capital cost**.** Similarly, the capital cost of the solar thermal plant is evaluated considering a specific capital cost depending on the collector’s surface area. The considered specific capital costs of the renewable solar technologies is 1,200 EUR/kW$_{nom}$ and 800 EUR/m^2 for the solar PV and the solar thermal respectively.

Because of the relevant investment costs associated to the realization of a smart energy system project, beside the traditional economic indicators above mentioned, financial indicators such as Debit Service Coverage Ratio DSCR are considered (Equation (3.19)).

$$\mathrm{DSCR} = \frac{\mathrm{AOP}}{\left[(\mathrm{i}+\mathrm{k})\cdot\frac{\mathrm{CapCost}}{\mathrm{SPB}}\right]} \tag{3.19}$$

Usually, investment parameter DSCR must meet the demands of the lenders, who require the compliance with a maximum threshold value (e.g. greater than 1.3) as a constraint, which is so imposed in the optimization algorithm.

3.1.4.2 Primary Energy Saving evaluation

The advantage of a SES compared to conventional SP from a reduction of global primary energy consumption perspective, can be evaluated through the primary energy saving ratio (PESR) as defined by (Mancarella and Chicco, 2009a), i.e. the ratio of the energy saving guaranteed by the adoption of the SES solution in comparison to the energy consumption of the conventional SP (Equation (3.20)).

$$PESR = \frac{E_{SP} - E_{SES}}{E_{SP}} \tag{3.20}$$

The primary energy consumption of the reference separate production case is calculated from the following Equation (3.21), after considering the conversion coefficients for the main electricity grid and natural gas presented in Table 3.2.

$$F_{SP} = \frac{P_{tot}}{\eta_{GRID}} + \frac{H_{tot}}{\eta_{BB,SPS}} + \frac{C_{tot}}{COP_{EC,SP} \cdot \eta_{GRID}} \tag{3.21}$$

Table 3.2 Primary energy conversion factors and carbon dioxide emission factors for the considered energy vectors (Simeoni et al., 2018).

primary energy		carbon dioxide emissions	
ξ_{GRID} (TOE/kWh$_{el}$)	ξ_F (TOE/Sm$^3_{CH4}$)	μ_{GRID} (MgCO$_2$-eq/kWh$_{el}$)	μ_F (MgCO$_2$-eq/Sm$^3_{CH4}$)
1.87E-04	8.20E-04	4.22E-04	1.94E-03

Primary energy consumption of the SES is calculated from its total fuel consumption and the total electricity imported from the main grid for integration. In some countries, the compliance with mandatory values of the primary energy saving (PES) parameter defined below gives access to financial incentives, which must be considered in the economical evaluation, e.g. the Italian "*Titolo di Efficienza Energetica (TEE)*", which corresponds to one tonne of oil equivalent of primary energy saving. Thus, according to the Italian regulation, the following constraints must be met, resulting in the operation under the so-called high efficiency cogeneration "*C.A.R.*" regime:

1. $\eta_{CHP} > 0.75$
2. $PES = \left(1 - \frac{1}{\frac{CHP\,H\eta}{Ref\,H\eta} + \frac{CHP\,E\eta}{Ref\,E\eta}}\right) \times 100\% > 10\,\%$

These constraints are thus embedded in the optimization algorithm of the simulative approach.

3.1.4.3 Emissions evaluation

The pollutant emissions reduction achievable through the installation of the SES in place of SP can be estimated comparing the environmental performances of the two configurations element by element (Chicco and Mancarella, 2008; Mancarella and Chicco, 2008)). The considered environmental criterion is the emission reduction ratio (ERR), defined for the carbon dioxide specie as in Equation (3.22):

$$ERR = 1 - \frac{CDE_{SES}}{CDE_{SP}} \tag{3.22}$$

The amount of greenhouse gas emissions associated with the operation of the smart energy system (CDE_{SES}) and those associated with the SP (CDE_{SP}) are calculated through the proper emission factors of the fuel $\mu_{CO2,F}$ and of grid electricity $\mu_{CO2,GRID}$, reported in Table 3.2 for the Italian electricity production system and for the natural gas combustion. As already anticipated, CO_2 only is considered here, but also local pollutants could be considered (Mancarella and Chicco, 2009b).

3.2 Application: the case study of a food industrial district in Italy

The developed decision support system has been applied to an industrial district of the food sector, located in the North-East of Italy. The considered case study consists of a cluster of sixteen companies, located in a narrow range, belonging to a Union of about thirty firms whose business is the production of raw ham and its derivatives, starting from the processing of ham legs. According to the Union's regulation, the production can only take place within the territory of the municipality.

The district could be defined *homogeneous*, because it is made up of only industries, but it could be also defined *isotropic*, because district's companies produce the same product by the same type of production cycle. In fact, the Italian Protected Designation of Origin (PDO) product is the same for all the Union's companies and the productive process is compulsorily established by the Italian *Ministerial Decree 16 of February 1993, n.293*.

In addition to their proximity and uniformity, district firms are characterized by high energy need for electricity, heating and cooling: according to the Italian regulation, some of them are considered energy intensive. Rooms conditioning (heating and cooling), and refrigeration of ham processing rooms (slicing, packaging and storage cells), represents the main requirements related to the productive process. Electricity demands for light and equipment constitutes a secondary energy demand. Medium temperature hot water for washing of hams is also required.

According to energy data collected by University of Udine in the past in the considered companies for the analysis of their requirements, it can be derived that the energy demand is quite constant during the whole year, apart from the variations due to climate seasonality, as evidenced in the energy consumption data represented in Figure 3.5, where only the companies belonging to the industrial zone are represented. Some other companies belonging to the Union but located outside the industrial zone are not represented on the map. Due to the presence of all these conditions together, the considered case study represents an interesting opportunity of application of the smart energy system concept in its general configuration to the sustainable energy supply of industrial areas.

The energy supply configuration currently adopted within the industrial district is the conventional SP. Electricity is provided from the national grid, and natural gas boiler and compression electrical chiller located at individual companies satisfy the heating and cooling needs respectively. In a few cases, internal combustion engines are installed for CHP, although they are designed to cover the base load of the company, according to an "endogenous" approach. In this study, for comparison between the baseline and the proposed SES solution, they are neglected.

The hourly energy load profiles of a single company have been assumed to be characterized by a random-like notched trend due to the typical on/off operation of the air-conditioning and refrigeration plants, driven by programmable thermostats. A simplified electric energy load profile related to lights and equipment operation of a typical working day has also been considered. Non-working day profiles were instead considered constant. In the case of a main CCHP generation plant, the aggregated hourly energy load profile of the whole district should be considered, resulting in a more flattened behaviour because of the non-simultaneity of the electric and thermal energy demand.

The proposed SES layout (represented in Figure 3.3), made up of centralized CCHP plant, district energy distribution networks and distributed renewable energy sources could effectively contribute to the reduction of the variance and the contemporaneity of energy loads, thus resulting in the exploitation of the size effect relatively to the capital costs, in the opportunity of the reduction of the plant size, and the increase of its utilization factor.

Figure 3.5. Monthly total energy needs of the considered cluster of firms (Simeoni et al., 2018))

About the proposed SES configuration, the selected prime mover technology is the natural gas reciprocating engine, because of its part-load operation adaptability, its good electrical efficiency and the availability of size ranges. Equipment efficiencies assumed for the two compared configurations, SES and SP, are reported in Table 3.3.

Table 3.3 Efficiencies of energy system components

η_{GRID}	$\eta_{BB,SP}$	$COP_{EC,SP}$	$COP_{EC,SES}$	$COP_{AC,SES}$	$\eta_{BB,SES}$
0.46	0.90	3.0	5.0	0.80	0.90

CHP heat recovery units and backup boilers supply heat at a temperature of 95 °C. Supply/return temperatures of the district heating and cooling networks have been assumed to be 85/65 °C and 5/12 °C respectively, thus determining the maximum and minimum operating temperatures of the storage systems.

In Table 3.4 the variation ranges of the selected decision variables are reported.

Table 3.4 Variation ranges of the decision variables (Simeoni et al., 2018)

Decision variable	unit	Range of variation	Incremental step
P_{CHP_nom}	kW	0 ÷ 15,000	1,000
PV_R	-	0 ÷ 1	0.1
SAUF	-	0 ÷ 1	0.1
$V_{TES,H}$	m^3	0 ÷ 3,000	100
$V_{TES,C}$	m^3	0 ÷ 3,000	100

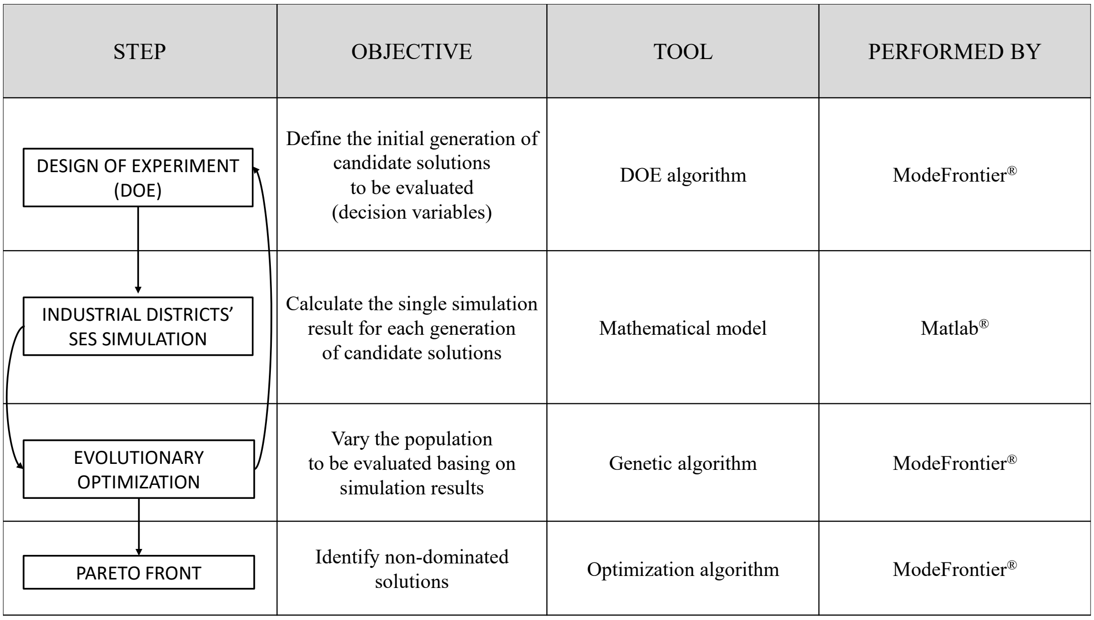
About energy supply costs, an electric energy specific price of 0.15 EUR/kWh_{el} has been accounted. A natural gas price specific cost of $c_F = 0.25$ EUR/Sm^3 has been considered and a lower heating value of the fuel of 9.6 kWh/Sm^3. Lastly, according to the Italian electric energy system regulation, a further tax burden regarding the electric energy consumed by the district's end-users and distributed through the industrial district's private electricity grid, which is defined "Closed Distribution System (CDS)", must be considered. This tax has been considered equal to 0.057 EUR/kWh_{el} for medium voltage electricity supply and must be added to the cost of the electric energy produced by the main power generation plant to be supplied to the companies through the CDS. It is relevant to emphasize that the Italian electric system regulation provides for the possibility of being released from this tax (i.e. reduced to 5%), e.g. in the case of energy production through a CHP unit, allowing the acquisition of the so-called "SEU" qualification. Nevertheless, it is still not feasible from the regulatory point of view to meet the "SEU" mandatory requirements in the case of cluster of companies, i.e. the so-defined "exogenous" level.

About financial incentives, the bonus provided by the Italian regulation to the primary energy saving projects has been considered, assuming a market value of about 300 EUR/toe.

Concerning operation and maintenance costs, a specific maintenance cost of 0.025 EUR/kWh_{el} has been accounted for the operation of the CHP units, while the maintenance cost of the other SES components has been neglected (e.g. absorption chiller annual maintenance cost could amount to about 1,000 EUR).

About investment costs, the interpolation functions and the specific costs presented in Table 3.1 have been used to evaluate the capital costs of the CCHP plant and of distributed RES. District's SES distribution networks represent a fixed cost, as previously discussed, which amounts for the considered case study to about 2,100,000 EUR for the Closed Distribution System (electricity grid) and to around 2,000,000 EUR for the thermal energy district networks. The total gross area available on the companies' building rooftops is about 29,680 m^2, and a conventional design has been considered regarding the installation of the solar panels, optimized according to the specific latitude and longitude of the site. About the investment financial evaluation, a SES plant lifetime of 25 years has been considered. A discount rate of 4% has been assumed together with an inflation rate of 1.5%.

The four steps procedure of the developed evolutionary multi-objective optimization method, i.e. Design of Experiment (DOE), calculations through the above presented mathematical model, optimization and definition of the Pareto front, have been implemented by use of the software listed in Figure 3.6. The simulation of the energy system through the mathematical model has been performed by Matlab®, interfaced with ModeFRONTIER®, which enables multi-objective optimization through evolutionary algorithm, to perform DOE algorithm, genetic algorithm and optimization.



STEP	OBJECTIVE	TOOL	PERFORMED BY
DESIGN OF EXPERIMENT (DOE)	Define the initial generation of candidate solutions to be evaluated (decision variables)	DOE algorithm	ModeFrontier®
INDUSTRIAL DISTRICTS' SES SIMULATION	Calculate the single simulation result for each generation of candidate solutions	Mathematical model	Matlab®
EVOLUTIONARY OPTIMIZATION	Vary the population to be evaluated basing on simulation results	Genetic algorithm	ModeFrontier®
PARETO FRONT	Identify non-dominated solutions	Optimization algorithm	ModeFrontier®

Figure 3.6. Software used for the implementation of the evolutionary multi-objective optimization procedure (Simeoni et al., 2018)

3.3 Results and discussion

3.3.1 Performance indicators analysis

The application of the developed DSS to the case study started with the processing of companies' production and energy consumption data available, which provided the energy performance indicators presented in Figure 3.7. EPI analysis suggested the identification of three kinds of energy consumption behaviour, leading to companies' classification in three main clusters: "*artisanal*", "*industrial*" and "*industrial energy-intensive*".

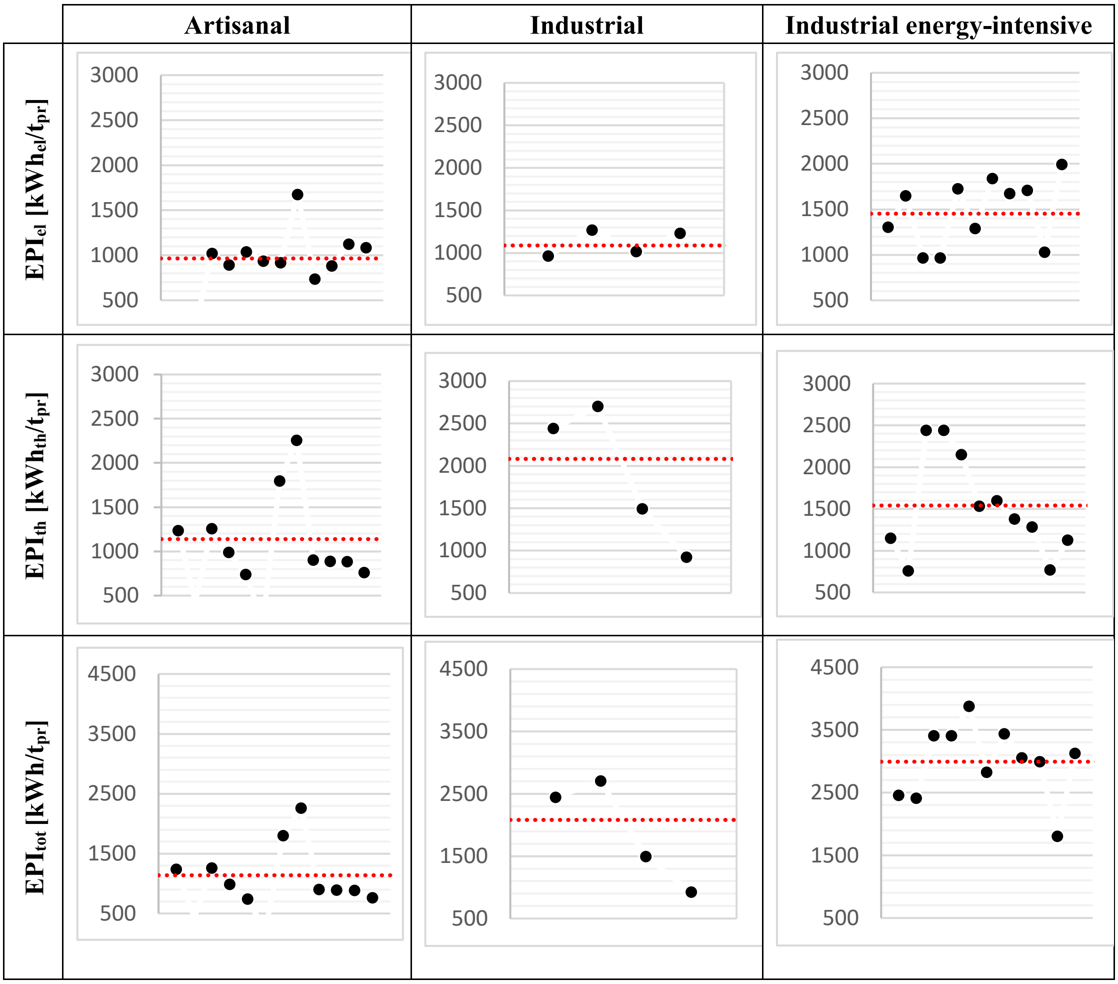


Figure 3.7 EPI comparison: single firm (dots) and cluster average values (straight line). (Adapted from (Simeoni et al., 2018))

The analysis of data and performance indicators of the companies confirmed the presence within a restricted area of the industrial zone of a group of companies belonging only to the industrial clusters, many of which energy-intensive, thus highlighting the opportunity of improving the sustainability of the food industrial district through the implementation of a sustainable energy supply solution based on the smart energy system concept.

3.3.2 Smart energy system design: conventional approach

If a conventional SES design approach was adopted, the most suitable configuration would be chosen based on engineers' experience. This could lead to the installation of five natural gas-driven reciprocating engines of the nominal power of about 3 MW_{el} each, to guarantee a good elasticity of operation and backup spare capacity, for a total capacity of 15 MW_{el}, since the total installed capacity of the generation units must assure the satisfaction of most of the industrial district's total electric load, granting at the same time the exploitation of most of the recovered thermal energy. From the analysis of the hourly energy load profiles of the annual type days, a maximum amount of about 5.6 MW_{th} of heat power could be available for the absorption chillers operation, so around 4.5 MW_{co} total installed capacity should be selected for these components, if a non-dissipation strategy concerning the CHP thermal energy is pursued. Nonetheless, centrifugal electric chillers and back-up boilers should grant the coverage of the peak requirements of the whole district, then an installed capacity of around 10 MW for both cooling and heating is determined. It is important to note that the exploitation of the total net area available for the installation of PV and thermal solar would imply a substantial increase of the SES investment cost, without assuring the reliability of energy supply (Gharavi et al., 2015). For that reason, if a conventional approach based on economic goals was adopted, it would lead to the sacrifice of solar RES with respect to CHP technology, because of capital costs reasons. The calculation relative to the yearly operation of the above described SES configuration provided the results presented by the radar diagram of Figure 3.8, in which the three axes represent the considered sustainability parameters, and where the green triangle is referred to the performance of the smart energy system compared to those of the traditional separate production (plotted in red).

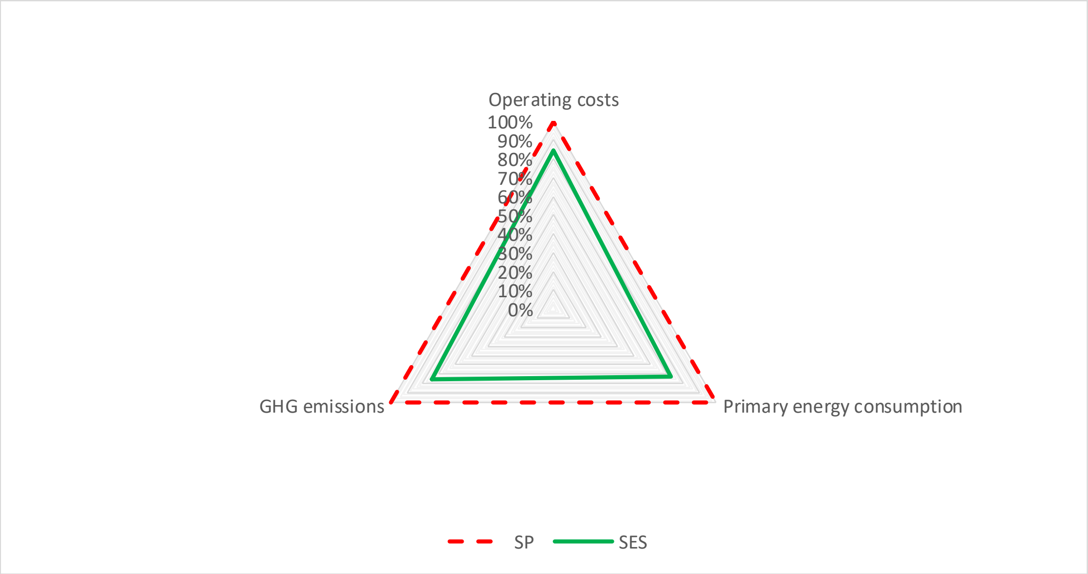


Figure 3.8 Sustainability performances of the two compared solutions (Adapted from (Simeoni et al., 2018))

3.3.3 *Smart energy system design: evolutionary multi-objective optimization approach*

The evolutionary multi-objective optimization approach of the developed DSS method has then been applied, with the aim to prove its potential in supporting the decision-making process for facility managers and strategic energy planning, providing a deeper insight concerning the correlations between the decision variables and the objective functions of the problem and to investigate the trade-off between them.

To solve the optimization problem a personal computer of 16 Gb of RAM, i7 4770 3.40 GHz processor has been used. The algorithm was run with a 500 individuals' population and 200 generations, resulting in 100,000 total evaluated designs, enough to obtain the convergence of the process around the best solution.

In the bubble chart of Figure 3.9 the optimization results regarding the CHP nominal capacity decision variable are represented.

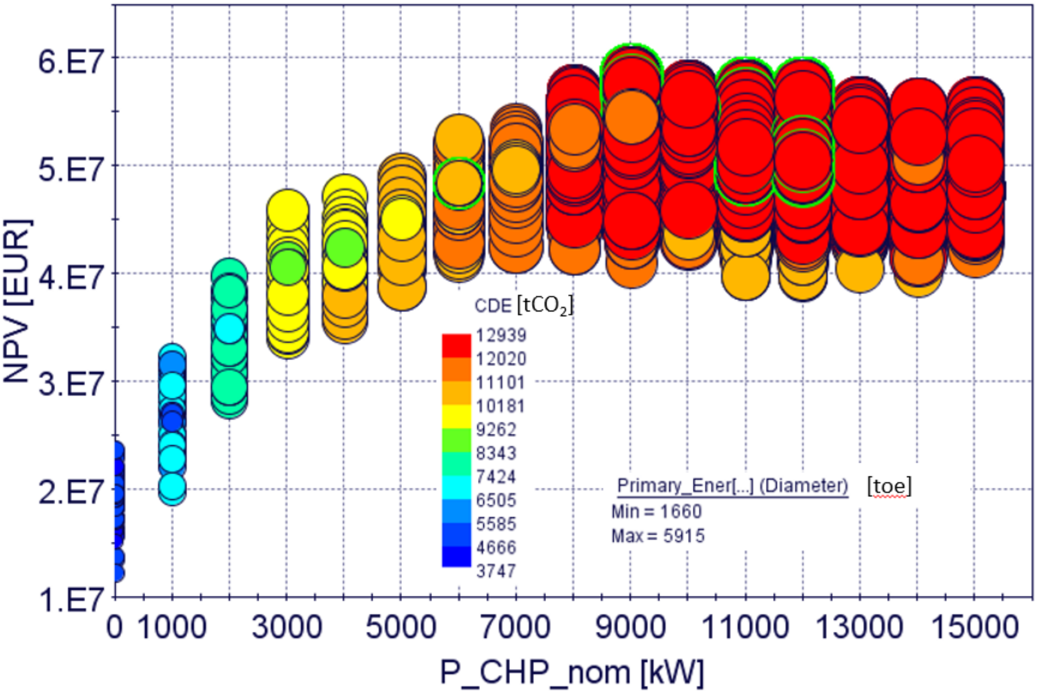


Figure 3.9 Effect of the nominal size of the CHP plant on economic, environmental and energy performances. Adapted from (Simeoni et al., 2018)

As can be observed from the graph, until a cogeneration units' nominal capacity of around 9 MW is reached, the higher the CHP size, the higher the reduction of CO_2 emissions and primary energy saving. Analyzing the Pareto fronts, which are highlighted with by green circular outlines in the chart, the best economic performance (in terms of maximum NPV) is reached if a CHP nominal capacity of around 9 MW is selected, guaranteeing at the same time remarkable environmental and energetic benefits. Due to the influence of the simultaneity factor indeed, a further increase of the PGUs nominal capacity up to the district peak power demand would worsen the economic performance, since the CHP constitutes the major portion of the investment cost. Although, optimal solutions have been identified by the model at 11 and 12 MW of CHP nominal size, where at the expense of a slightly worse economic performance (NPV around 1.3 MEUR lower), a small increase (around 1%) of CDE reduction and of PES can be obtained.

The wide range of NPV values for the Pareto optimal design is due to the different possible configurations of the smart energy system, since e.g. for a P_{CHP_nom} of 11 MW and a maximum exploitation of the net available area covered by the solar source (13,356 m^2), a decrease of the share of photovoltaic PV_R from 1.0 to 0.3 implies a higher investment cost for the smart energy system (+6.8 MEUR, 40% higher) and accordingly a longer payback period (4.7 years instead of 3.3). It is therefore interesting to analyze the impact of the solar sources on the SES performance. The bubble chart of Figure 3.10 represents the correlations between the two decision variables PV_R and SAUF and their influence on the economic and environmental performances of the smart energy system, where optimization results have been filtered for a given nominal size of the CHP of 9 MW.

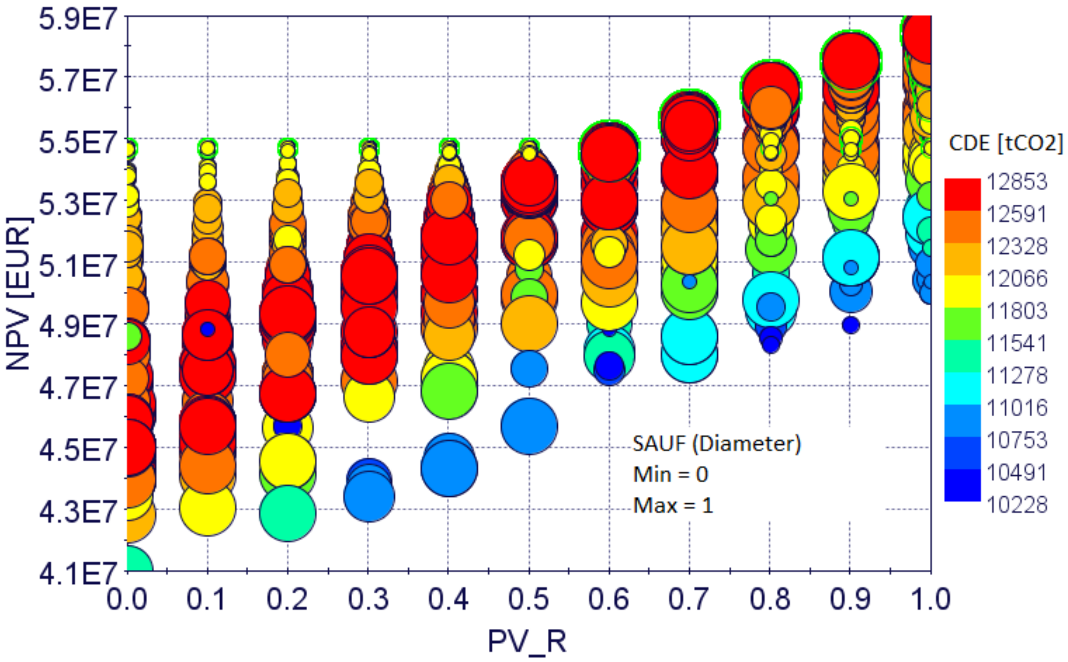


Figure 3.10 Effect of the photovoltaic share and of the total area covered by the solar sources on the economic and environmental objective functions, for a given nominal power of CHP of 9 MW. Adapted from (Simeoni et al., 2018)

As evidenced by Pareto designs, which have been outlined by green circles in the chart, if the economic objective function is being pursued (i.e. NPV maximization) higher values of the total rooftops area covered by the solar sources should be chosen (SAUF equal to 1.0) together with a predominance of the photovoltaic technology (values of the PV_R decision variable above 0.6). This option, which implies an investment cost of 15.2 MEUR, would also lead to a remarkable CO_2 emission reduction performance of 12,593 tCO_2. It can be observed that CO_2 emissions decrease both for lower and higher ratio of the PV on the total area covered by solar source. Although, for the same value of total area destined to the solar sources, solutions characterized by a predominance of the solar thermal source over the photovoltaic one do exist: in this case, despite the environmental performance is similar (less than 1% difference), the economic one is worse (around 10 MEUR higher investment cost, 22% lower NPV). Since the minimization of the SES investment payback period is one of the objective functions, especially when a facility manager perspective is adopted, optimal Pareto solutions which provide for a small use of the solar RES could be the choice, due to the avoided capital cost of solar plants: interesting NPV around 55 MEUR could be obtained, while the worst environmental and energetic performances of 11,803 tCO_2 emission and 5,424 toe of primary energy savings respectively are recorded, which corresponds to a worsening of 6% if compared to the Pareto solution characterized by the best NPV.

As regards TES capacity decision variable, Pareto multi-objective optimization results show that a hot water storage of 1,500 m^3 can assure the achievement of remarkable environmental and energetic performances, without significantly affecting economic performance. About the cold thermal energy storage, optimization results evidenced that the arrangement of the Pareto front is found at values close to zero of the TES volume. This is due to the exploitation strategy of the cold TES, which has been assumed to be activated only when excess energy from the absorption chiller is produced, which is negligible if compared to the cooling energy produced through the electric chillers.

While in this first application of the developed DSS to the sustainable energy supply of industrial districts, only thermal energy storage has been included in the smart energy system layout, a more detailed characterization of other RES options together with electrical energy storage would be performed in future developments of the research, investigating its impact on the SES performances.

Despite the remarkable environmental and energetic potential benefits of the smart energy system solution compared to the traditional separate production (about 12,500 tCO_2/year of GHG emission savings, together with about 5,700 toe/year of primary energy savings), a certain inconsistency between these two sustainability performances and the economic one has emerged. This could be unexpected because of the financial incentives (TEE) granted to such energy saving projects, and is mainly due to the tax added on the electricity distributed through the industrial district's private Close

Distribution System and consumed by companies, which in the considered case study accounts for a total close to 2.3 MEUR/year. If compared to the amount of financial incentives granted thanks to the primary energy saving (around 1.7 MEUR/year), it can be stated that this tax could undermine and overcome the advantage of the financial incentives (TEE) provided for such energy saving projects. Moreover, due to the relevant SES investment cost of more than ten million euros, this could cause a lack of financial appetite for private investors, despite an interesting NPV of above 50 million EUR at plant's end of life. Thus, research suggests that some regulation adjustment might be studied so that the solution providing the largest energy saving and GHG emission reduction could be rewarded, thus granting the consistency between the different sustainability performance objectives in the context of industrial districts' SES sustainable energy supply.

3.4 Final considerations

In this section the proposed decision support framework has been applied with the aim to prove its potential in supporting the decision makers in the planning and design of sustainable energy supply for industrial areas.

This first application of the proposed model to a case study has been focused on the development of its "investigative" (data collection, processing and analysis, particularly as regards performance indicators) and its "design" (Pareto evolutionary multi-objective optimization) phases, to which the context of industrial districts is particularly suitable.

The proposed method has been applied to an Italian food industrial district case study, which has been selected within the opportunities belonging to the energy-intensive sectors available in the local territorial context, because particularly suitable for the implementation of a smart energy system concept in its general configuration because of the simultaneous and relevant presence throughout the year of both electric, heating and cooling power demand, due to the particular process's energy requirements. The considered SES layout combines RES, CCHP through absorption chiller, energy storage systems and district distribution networks (heating, cooling and electricity) serving a cluster of firms.

The developed framework has proved to represent an effective tool that could aid decision makers in identifying the most suitable smart energy system configuration. Results showed that the multi-objective optimization carried out on economic, environmental and energetic objective functions allows the investigation of the trade-off between the different objective functions and the analysis of how sustainability performances change based on the selected smart energy system configuration, so that it can act as a decision support tool to identify the most viable layout through the proper sizing of CCHP and RES. It also provides design suggestions such as the identification of the optimal capacity of thermal energy storage systems.

Furthermore, the application to the case study proves that the SES concept can really represent a main opportunity to industrial districts either from the sustainability and the competitiveness perspective. Thus, the developed tool can be used not only in the system design phase, but also as a support to plan regional development.

Lastly, research suggests that some financial incentives or regulation adjustments could be studied so that a smart energy system solution providing remarkable potential benefits from the energy savings and the GHG emission reduction perspectives could consistently improve its economic attractiveness.

4 ENHANCING SUSTAINABILITY OF THE ENERGY-INTENSIVE INDUSTRIAL SECTORS: OVERTAKING INTERNAL BOUNDARIES TOWARDS A SMART ENERGY SYSTEM INTEGRATION

As presented in the introduction section, industry is responsible for a large share of total greenhouse gas emissions related to energy consumption, and some industrial sectors are particularly energy intensive. Indeed, the latter could hide relevant opportunities for the implementation of energy efficiency measures to be exploited not only inside the company itself, according to the traditional approach (endogenous level), but also by overtaking its boundaries towards the external synergic integration between industrial and urban areas based on the smart energy system concept. Waste heat recovery in energy intensive industries represents one of the greatest opportunities to reduce their primary energy consumption thus increasing their competitiveness and sustainability.

In this thesis, also due to the relevance of both its energy requirements and energy efficiency opportunities among the most energy-intensive productive sectors, and because of its huge presence in both the European and the local territorial context (often at a useful distance from urban areas), steelmaking industry based on electric arc furnace (EAF) melting process has been identified as suitable case study for the investigation of the potential for sustainability improvement which could be unlocked through the overcoming of company's internal boundaries towards a smart energy system integration, through the recovery of waste energy from industrial process to feed municipal district heating with a carbon-free source.

In subsection 4.1 a comprehensive overview on the technical solutions for the recovery of waste heat from the EAF steelmaking process is initially provided.

A conceptual framework for the identification of the different possible exploitation strategies for the recovered energy is then proposed in subsection 4.2, ranging from the traditional approach based on its internal use to the smart energy system concept based on the external integration of the resource. The framework is aimed at helping in the identification of different potential waste heat recovery scenarios to be investigated by means of the proposed DSS model.

The investigation of the decision-making challenges involved with the implementation of such waste heat recovery based SES concept represent then the subject of the next sections 5 and 6 of the thesis.

A summary of this work was published in the article: "Nardin G, Ciotti G, Dal Magro F, Meneghetti A, Simeoni P. Waste heat recovery in the steel industry: better internal use or external integration? In: Conference Proceedings of the 23th AIDI Summerschool "Francesco Turco". Sept. 12-14, 2018, Palermo (AIDI2018.123)".

4.1 Energy efficiency in the steel industry: overview of technical solutions for waste heat recovery

In 2012, the steel industry consumed about 5% of all primary energy produced worldwide contributing to 7% of all global CO_2 emissions due to a high share of coal in the fuel mix (Laplace-Conseil, 2013). World steel production increased from 28 million tons in 1950 to nearly 1.6 billion tons in 2015 (Word Steel Association, 2016). Although recently significant improvements have been achieved, this sector has a great potential to further reduce both energy consumption and greenhouse gas emission. In particular, steelmaking process adopting electric arc furnace (EAF) represents one of the most employed technology and accounts for the 28% of the worldwide steel production (Rizwan Janjua, 2013), and releases as waste heat from 15% to 35% of the total energy provided to the process (Kirschen et al., 2009). Figure 4.1 shows a typical energy balance of an EAF.

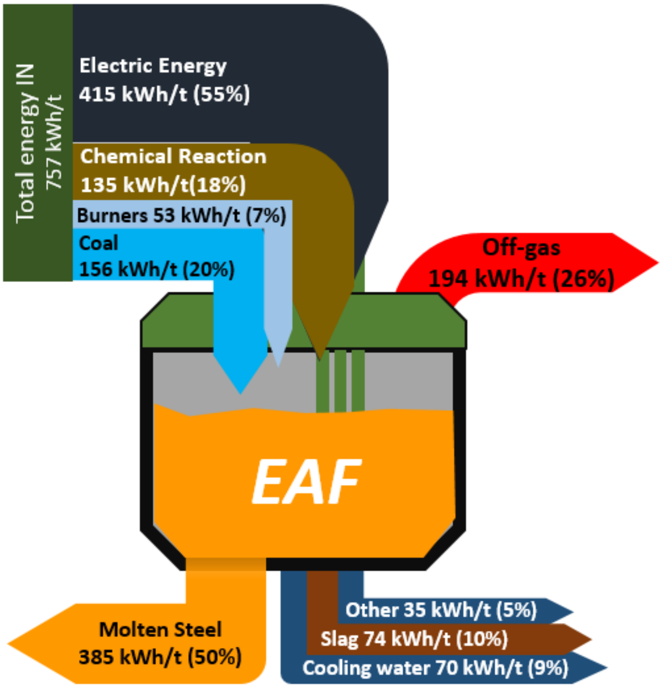


Figure 4.1: Energy balance of an electric arc furnace (Santangelo et al., 2015)

The furnace off-gas, which is characterised by an average temperature of about 750 °C and an average specific energy content of about 200 kWh/t, represents the main waste heat source in the steelmaking process based on EAF (Born and Granderath, 2013).

Since typical production capacity of EAF furnace varies from 50 to 300 t/h, a waste heat recovery potential ranging from 10 to 60 MW can be estimated.

This section proposes an overview of the available waste heat recovery technologies, highlighting advantages and criticalities of available energy recovery solutions, with the aim of identifying the best options for future heat recovery projects in energy intensive industries.

In

Table 4.1 a classification of current technologies for waste heat recovery from EAF process is reported, as derived from a literature review of journal and conference papers, as well as technical reports. The proposed classification of energy recovery solutions is based on the adopted heat recovery approach, which can be direct or indirect, while distinguishing between the potential end uses of the recovered energy, which can be internal or external to the industrial facility. Technologies based on direct heat recovery recirculate the waste heat of the off-gas directly into the EAF process, while indirect energy recovery technologies recover the waste heat by employing a heat transfer fluid (HTF).

Table 4.1: Current technologies for waste heat recovery from electric arc furnace (adapted from (Nardin et al., 2018))

Recovery approach	**Sub-category**	**Use**	
		Internal	**External**
Direct	Continuous charge	Scrap preheating	-
	Discontinuous charge	Scrap preheating	-
Indirect	Steam	Internal processes	Industrial symbiosis
		-	District heating
		Power generation - Steam Turbine - ORC Turbine	Electricity grid
	Hot Water	Power generation - ORC Turbine	Electricity grid
		-	District heating

It is worth noting that current heat recovery solutions focus just on high temperature waste heat because no opportunity to exploit low temperature waste heat exists within the steelmaking plant. Furthermore, low temperature waste heat currently represents a cost for the steel industry, which must spend further energy to dissipate it. The opportunity to recover such low temperature waste heat and to transfer it to an external user, such as a district heating network, could represent a huge chance to achieve higher exploitation of the waste heat and, thus, better performances. In the following subsections a detailed description of each category is provided.

4.1.1 Direct heat recovery technologies

Concerning the first approach, many technologies have been developed for the internal use of the recovered heat, such as e.g. scrap preheating. In direct heat recovery technologies, the waste heat is recovered by preheating the scrap before its charging into the EAF furnace. The type of scrap charging further classifies such technologies into two groups: continuous and discontinuous charge (see

Table 4.1). Two technologies are mainly used to directly recover the heat in discontinuous charging: shaft furnace and twin-shell. The shaft furnace is available in two main arrangements: single and double shaft (Schmidtt, 1997). In the single shaft furnace, the shaft is situated on top of the EAF, and is water cooled and refractory lined. The double shaft consists of two EAF furnaces, each one with a shaft and one common electrode mast and set of electrodes to serve both furnaces. The twin-shell technology is similar to the double shaft technology, including two EAF vessels with a common arc and power supply system (U.S. Environmental Protection Agency, 2012). Consteel®, Ecoarc® and EPC® might be accounted as the main technologies for direct heat recovery in continuous scrap charging.

Consteel® technology conveys the process off-gas into a tunnel where the scrap is pre-heated and continuously fed into the EAF by means of a charge conveyor (Memoli and Bianchi Ferri, 2007). The off-gas enters the tunnel at around 750°C and leaves it at around 500°C, leading to a heat recovery efficiency of about the 34%. The upgraded version of Consteel® technology consists of wider conveyors and a different tunnel profile to improve the heat exchange as well as a new tunnel section equipped with burners, to enhance the input of chemical energy (Giavani et al., 2012). Ecoarc® technology continuously fed the scrap into the preheating shaft where it is constantly in contact with the molten steel in the furnace; during the melting phase the furnace including the shaft is tilted backwards (Yamaguchi et al., 2000). The preheating chamber with its telescopic feeder and the charging deck where a hopper operates are the two main components of the EPC® technology. In this case, the preheating chamber is installed beside the EAF upper shell and the preheated scrap is charged continuously by the telescopic feeder system into EAF for melting (Rummler et al., 2012).

Direct energy recovery technologies have significant advantages (Lawrence Berkeley National Laboratory, 2010), such as the reduction of the tap-to-tap (TTT) cycle time, the decrease of power requirements, and the reduction of CO2 emissions (Tenova Spa, 2011). Nevertheless, the technical challenges related both to the EAF intermittent process and pollutant emissions limit the profitability of such heat recovery solutions. A broad adoption of these technologies has been hindered by the difficulties related to the increased plant complexity, surface oxidation of the charge and its partial melting as well as high emission factors for dioxins (Remus et al., 2013).

Concerning the economic aspect, it is worth noting that information about the investment costs for these technologies are difficult to find as they derive from private negotiations between suppliers and customers.

4.1.2 Indirect heat recovery technologies

Indirect energy recovery technologies employ an HTF, such as steam or hot water (see Table 4.1), to recover the waste heat of the EAF off-gas. Such technologies requires a thermal energy storage system to provide a constant heat supply to the downstream systems (Steinparzer et al., 2012).

In current state-of-the-art EAF fume treatment plant (Remus et al., 2013) off-gas are cooled down to around 600°C through water cooled ducts (WCD). A quench tower is usually installed downstream to quickly reduce off-gas temperature down to 200°C in order to allow bag filters operation while preventing dioxins production. The heat absorbed by the cooling water, whose temperature increases from around 30°C to 50°C, is typically dissipated into the atmosphere by means of evaporative towers, thus representing an additional operative cost, as already outlined.

Technologies such as Clean Heat Recovery® (Santangelo et al., 2015), employ superheated water to recover the EAF waste heat and to feed an Organic Rankine Cycle (ORC) system. This system has been implemented by Danieli Officine Meccaniche Spa in the ABS steel plant in Italy. In order to mitigate the issues related to the temperature fluctuations of EAF off-gas, an innovative tank of superheated water, called Thermal Stabilizer Unit (TSU), has been developed to smooth the thermal power fluctuations thanks to a proper mix of the hottest water with the coldest one.

Hot water could be also used to feed district heating networks with a supply temperature of around 90°C. However, to the best of author's knowledge, recovered heat by hot water has not been used to feed district heating yet.

Some other systems, e.g. SMS Siemag AG (Ester, 2009) and Tenova iRecovery® (Born and Granderath, 2013), are based on steam generation through evaporative cooling of the off-gas ducts. Currently, evaporative cooling represents the best solution for off-gas heat recovery because of its flexibility. In fact, the generated steam can be exploited in many ways, serving both internal and external users. According to (Born and Granderath, 2012), in most European countries steam generated by heat recovery allows the achievement of a cost saving of 25 € per ton of generated steam, if the internal use of the generated steam is concerned (such as its application to carry out secondary metallurgy process, for example steel degassing by means of steam-driven vacuum pumps). The recovered steam could be also used to drive turbines for energy conversion. The electricity generated by the turbines can then be used within the same steelmaking plant (i.e. self-consumption) or sold to the electricity grid (i.e. external use). The steam can also be used directly to feed an external user such as a district heating network (Trunner and Steinparzer, 2015).

The most successful and spread waste heat recovery system based on steam generation is the iRecovery®, which has been firstly developed (iRecovery® Level 1) by Tenova from the well-known evaporative cooling system within the GMH EAF revamping project, where about 20 t/h of steam are continuously produced to feed internal users (Schliephake et al., 2011). The main advantage of this solution is the operational stability, which is enabled by the constant temperature of water evaporation, and the robustness to the off-gas temperature peaks. Such a robustness is due to the spare capacity of the boiling water/saturated steam mixture flowing in the cooling system. This system is able to cool down the off-gas up to 600°C. Considering an average inlet off-gas temperature of 750°C, a heat recovery efficiency of about 21% can be estimated. In waste heat recovery systems based on steam generation, Ruth's steam accumulators are used as TES systems.

At ESF steel plant in Riesa (Germany), the presence of more favourable conditions in terms of steam demand gave Tenova the opportunity to develop the iRecovery® Level 2 technology (Baresi, 2012; Bause et al., 2015) to further exploit the off-gas waste heat. In this case, the off-gas is cooled down to 200°C, leading to a heat recovery efficiency of approximately 75%. This opportunity has been accomplished by adding a waste heat boiler located downstream the evaporative cooling ducts and installed on the primary EAF off-gas line, bypassing the existing quenching tower. Critical problems such as dioxins de novo synthesis and the extremely high dust concentration required remarkable design efforts.

Due to its technical features and energy performances as well as to the many references worldwide, Tenova iRecovery® might be rewarded as the current best available technology within the EAF indirect heat recovery options. The general layout of such an indirect waste heat recovery approach based on steam production is represented in Figure 4.2.

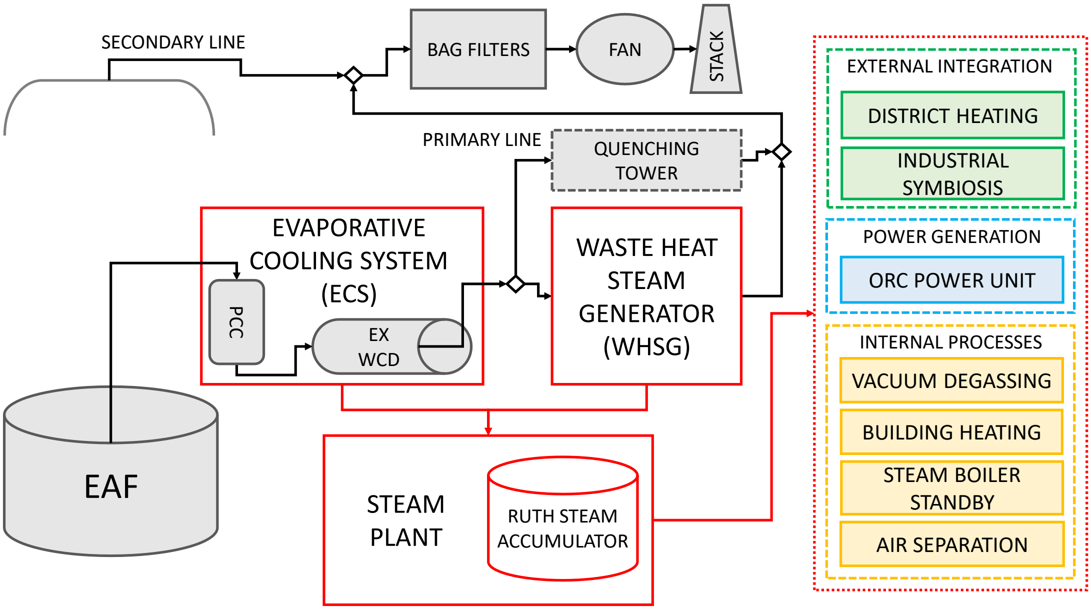


Figure 4.2 Waste heat recovery through steam production: benchmark plant layout and different possible uses of the recovered energy (Nardin et al., 2018)

For what concerns power generation technologies, two main options are available: steam and ORC turbine. When adopting these technologies in EAF waste heat recovery systems, steam turbine could be cost-effective when the electric nominal power is higher than 15 MW, while ORC turbine becomes economically viable at much lower values. ORC turbine's specific capital cost could be considered approximately 1,000 € per kW of electric nominal power (data provided by local supplier).

About the application of indirect heat recovery technology, both technical and strategic issues should be carefully evaluated when overcoming the industrial facility's boundaries towards the external integration of the recovered energy, as will be investigated below. Thus, a system perspective should be adopted to guarantee the success of the project.

4.1.3 *Innovative heat recovery technologies*

Finally, it is worth mentioning also those solutions which have been proposed and analysed in literature, but are still in their development phase, with no actual application to refer to. Innovative heat recovery technologies (see Table 4.2) can be considered as an evolution, mainly aimed at increasing the energy conversion efficiency (in particular, power generation efficiency).

Table 4.2 Innovative technologies for waste heat recovery from EAF (adapted from (Nardin et al., 2018))

Recovery approach	Sub-category	Use	
		Internal	External
Indirect	PCM-based devices	Power generation - Steam Turbine - ORC Turbine	Electricity grid
	Molten salt	Power generation -Steam Turbine	Electricity grid

Two main innovative solutions have been proposed: the first one using molten salt as HTF and the other one employing phase change materials (PCM).

The use of molten salt as heat transfer and storage media has been tested in a pilot plant installed in a Simetal EAF Quantum (Steinparzer et al., 2014).

Besides sensible energy storage system (e.g. hot water tank, molten salt), latent heat storage technologies exploiting phase change materials (PCMs) are considered to be a promising solution able to store energy as latent heat and release it at a constant temperature during phase transition (Agyenim et al., 2010). According to (Farid et al., 2004), latent heat storage is one of the most efficient ways of storing thermal energy. Unlike sensible heat storage, latent heat storage provides much higher storage density with a smaller temperature difference between storing and releasing heat. However, in (Kenisarin, 2010) it is highlighted that such technologies for recovery of high-temperature waste heat have not been given great attention despite their large potential. Latent heat storage systems for high-temperature waste heat recovery in steel industry have been proposed in (Maruoka et al., 2004), where metals, such as lead and copper, are adopted as PCM in order to supply constant heat to an endothermic reaction. Another system exploiting metals as PCM has been proposed in (Nardin et al., 2014). In this case, the aim of the system is to reduce the variability of the off-gas temperature to allow an efficient downstream energy recovery with traditional technologies such as a steam Rankine cycle. The smoothed temperature profile of the heat transfer fluid constitutes a more favourable condition at the turbine inlet, thus increasing the its efficiency due to reduced partial load operations. Furthermore, excessive oversizing of the turbine to face high steam temperatures is avoided, with benefits on investment costs. In (Dal Magro et al., 2017), the smoothing system is coupled with steam production by means of carbon dioxide as HTF. However, such promising solutions, even if patented (Nardin, 2012), are just at a developing phase, with no actual plants implementing them.

4.2 A conceptual framework for the identification of suitable waste heat recovery exploitation strategies

The previous section has highlighted the potential and limits of available waste heat recovery technologies concerning the EAF steelmaking sector. Direct heat recovery technologies allow the reduction of TTT cycle time and the decrease of power requirements. However, the deployment of such a technology is mainly limited by both the increased plant complexity and dioxin emission factors. Indirect heat recovery technologies do not improve the performance of the EAF process but result to be more flexible. In fact, due to their intrinsic flexibility, they can feed both internal (e.g. power generation) and external (e.g. district heating) users.

Involving external users into the deployment of industrial waste heat recovery projects could allow a full recovery of the waste heat, thus representing a huge chance to achieve better sustainability performances, not only for the industrial sector.

In Figure 4.3 a conceptual framework for the identification of the different waste heat recovery strategies is proposed. It could also represent a quick decision support tool to exclude non-viable options for a given case study and to select the suitable ones, according to the boundary conditions. Two important criteria are considered in this framework: the potential demand from external users and the decision to implement electricity generation. The potential demand could be both thermal and/or electric energy, while the external users could be the electrical grid, surrounding industrial activities as well as private and public buildings (to be served by a DHN). The potential demand is related to the location of the steelmaking plant, which affects the cost of the infrastructure (e.g. district heating network) required to transfer the heat to the potential end-users, and to the climate conditions of the considered geographical context, which particularly affects the heat demand of buildings. The potential demand is considered high when external users can absorb entirely or almost completely the waste heat recovered in the steelmaking plant and are relatively close to it. This condition usually happens when the steelmaking plant is located inside an industrial park or is close to an urban centre. On the contrary, the potential demand is low when external users can absorb just a small amount of the recovered heat or the steelmaking plant is located too far away from potential energy consumers.

In many cases, the opportunity of electricity generation could be considered also as a flexible way to exploit the excess recovered energy, since the need for electric energy is often large in energy-intensive industrial processes. This aspect has been accounted as represented in the left-side of the framework. With this concern, it must be outlined that market value of the electricity (buying/selling price of the electricity as well as incentives rewarding power generation from heat recovery) should be considered in order to evaluate this option.

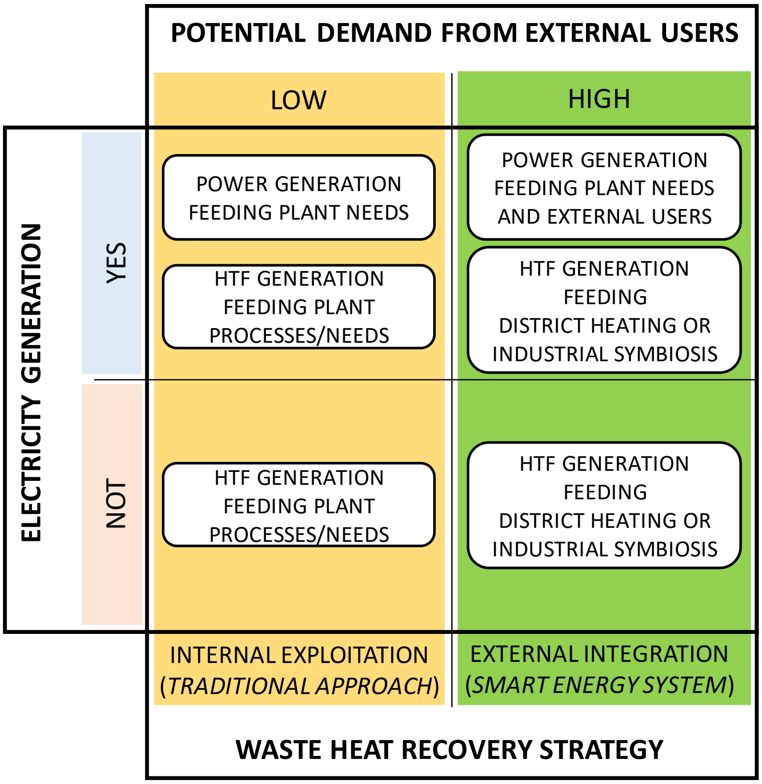


Figure 4.3: Conceptual framework for the identification of different waste heat recovery exploitation strategies

When the presence of potential demand from external users is low and no electricity generation is provided, internal use of the recovered waste heat through HTF generation feeding industrial plant's processes and needs represents the best option for waste heat recovery. If e.g. a steam-based heat recovery is adopted, an internal process such as steel degassing could be fed. However, since electricity can be used in most of internal processes, power generation could be considered as preferable over the direct use of steam. In this case, electricity generation should be added to the HTF exploitation for internal use, as represented in the top left quadrant of the detection framework.

In the case of high potential demand from external users, the overcoming of the individual industrial facility's boundaries to embrace an energy recovery exploitation strategy based on the Smart Energy System concept could open the doors to a relevant enhancement of the sustainability performances.

If no electricity generation is considered, the proposed framework recommends the adoption of an indirect heat recovery technology to satisfy the thermal energy demand of external users such as nearby industrial facilities (thus adopting an industrial symbiosis approach) or a district heating network in case of the presence of external users characterized by a relevant building heating demand. If the DH network already exists, the solution can be more easily implemented. However, the simultaneously presence of a great amount of waste heat and a significant thermal power demand can even trigger the realization of a network from the scratch.

The external integration of the recovered industrial waste heat requires the active involvement of both public institutions and private stakeholders, which should cooperate in order to create the proper conditions for mutual benefits. It is worthwhile to highlight that district heating can exploit low temperature waste heat sources (e.g. cooling water) more significantly than internal recovery solutions where limited applications can be found, thus allowing to reach a better overall energy efficiency.

Moreover, when the electricity generation strategy is chosen, the deployment of a multi energy system serving both internal needs and external users is allowed. In this case, SES configuration provides an indirect waste heat recovery technology feeding both an ORC unit for power generation and a district heating network and/or industrial symbiosis.

To provide some case studies, the Riesa project (Bause et al., 2015) represents a successful example of implementation of the SES approach through an industrial symbiosis option for the exploitation of the recovered energy, since the steam generated by the waste heat recovery system of the steelmaking plant is sold to a different industrial activity to feed its tyres production plant, which is located in the neighbourhood. Moreover, part of the generated steam is used to supply an ORC power production unit for self-consumption. Another interesting example of industrial waste heat recovery based on the SES approach has been implemented in Brescia (Italy) at the ORI Martin steel shop, where a new Consteel® EAF has been installed together with a iRecovery® Level 2 waste heat recovery system coupled with an ORC unit connected to the national grid (Monti et al., 2015). During the winter, the waste heat recovery system feeds the existing municipal district heating network and generate electricity with the eventual surplus of recovered energy, while during the summer only electricity is generated. Depending on the energy market regulation and subventions, the electric energy can be self-consumed as in the Riesa plant, or both self-consumed and sold to the national grid as in Brescia plant.

To fully exploit such symbiotic relationship an interaction platform should be developed and grounded on technologies and concepts of Industry 4.0, ranging from power demand matching balancing to demand side management of the multiple involved users.

Finally, the proposed framework is not meant to provide a static positioning within the different recovery strategies. An energy-intensive facility such as e.g. a steel plant can indeed start with an internal exploitation of the waste heat recovered (lower left quadrant). Then, electricity generation can be added, in order to exploit the eventual residual waste heat, to further increase the energy recovery efficiency. Depending on external conditions, which can change over time, indirect recovery can later embrace external users, thus shifting to the right quadrants. Therefore, evolutionary paths are provided within the framework, leading an industrial facility to dynamically change its positioning.

4.3 Final remarks

A conceptual framework for the identification of the suitable exploitation strategies for industrial waste heat recovery has been proposed with the aim of identifying the different possible options for future heat recovery projects in steelmaking industry as well as other energy intensive industries. The framework is based on the potential demand from external users as the main criterium, while considering also the opportunity to generate electricity by installing a power unit fed by the recovered energy.

Therefore, internal use or external integration should be evaluated based on the actual context where the waste heat is available. However, recent projects highlight a trend towards an exploitation strategy based on the smart energy system approach. The single industrial plant's boundaries are overcome in favour of symbiotic synergies, which could allow a wider exploitation of the recovered energy, otherwise difficult to reach by internal use only. Therefore, the research effort has been focused on empowering smart energy systems by means of the development of new system design solutions as well as the creation of collaborative platforms for the involvement of the different stakeholders involved in such projects, as presented in the following Section 5.

Given an industrial waste heat recovery opportunity, the selection of the most suitable strategy to pursue, requires the adoption of proper decision support models, able to allow a deep investigation of the sustainability performances of each different option, and moreover enabling the analysis of the correlations between the objective of the various stakeholders involved and the critical parameters on which to act to reach a win-win solution. Such models would allow the decision makers (industrial facility's managers, investors, but also policy makers) to provide informed decisions. This research tasks constitutes the objects of the next sections of the work.

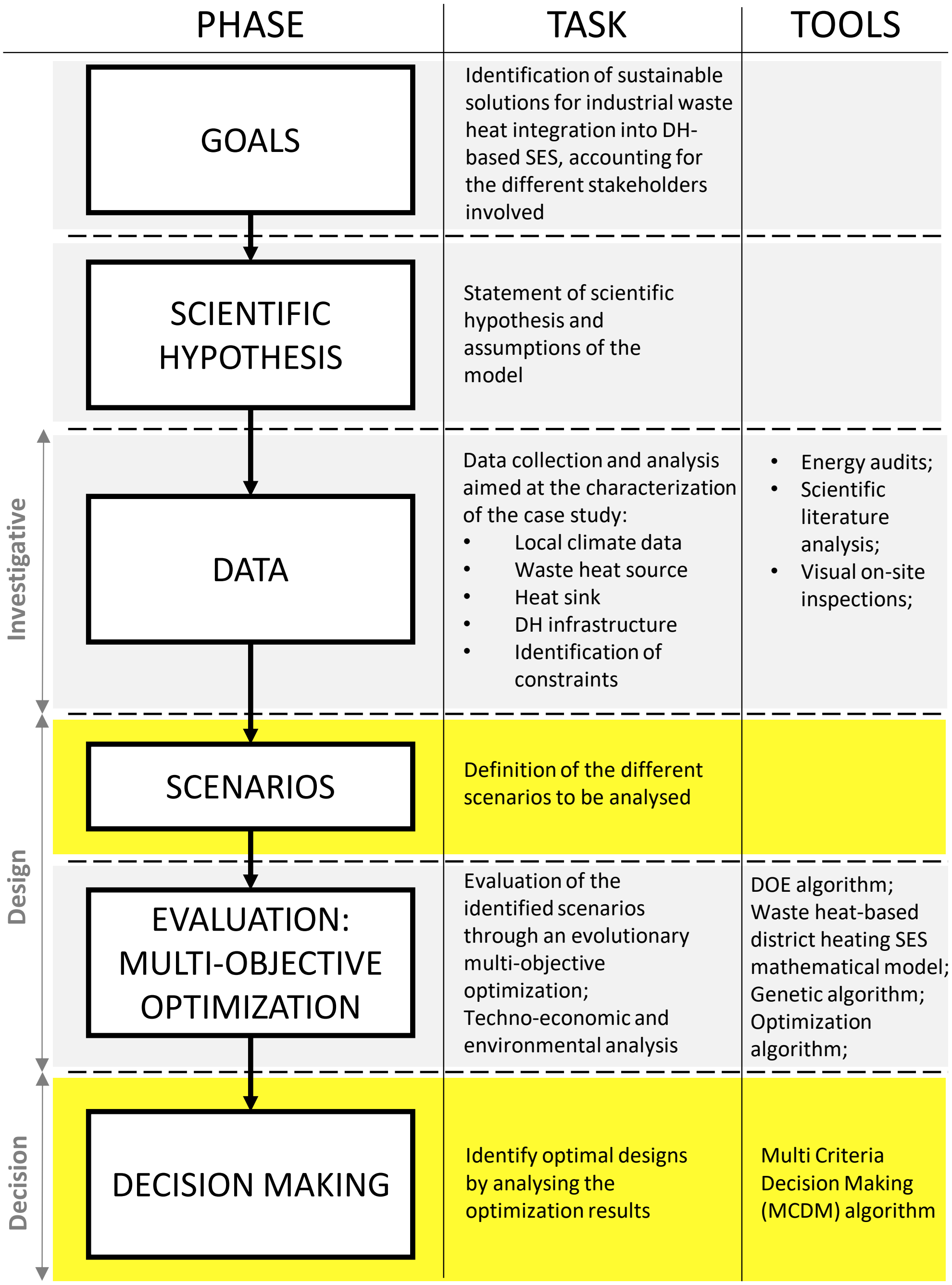
5 FOSTERING ENERGY TRANSITION THROUGH THE ESTABLISHMENT OF URBAN – INDUSTRIAL SYNERGIES: THE INTEGRATION OF INDUSTRIAL WASTE HEAT RECOVERY INTO SUSTAINABLE SMART ENERGY SYSTEMS

The integration of the huge potential for industrial waste heat recovery into smart energy system represents a main opportunity to accomplish the climate and energy goals. A district heating project exploiting industrial waste heat involves indeed several stakeholders, each driven by different and often conflicting objectives. Typically, besides the industrial facility providing the waste heat, the main actors involved in such a project are an energy services provider managing the district heating network, end users (e.g. private buildings or even other industrial facilities), policy makers and investment funds. Each of them is the bearer of different instances, such as profit maximization, minimization of the energy bill cost and minimization of greenhouse gas emissions to name a few. To successfully implement such energy transition strategy based on urban-industrial synergies, all the several stakeholders' conflicting objectives should be considered.

Given then an industrial waste heat recovery opportunity, when the embracement of a strategy based on external integration is pursued, some questions arise, thus requiring the adoption of proper decision support tools to investigate if it is possible to simultaneously meet the objectives of the various stakeholders involved, leading to remarkable economic and environmental performances. Moreover, a model to enable the analysis of the trade-off between the stakeholders' different perspectives, allowing to identify possible win-win solutions for both the industrial sector and the citizenship, is needed. Other issues to address by means of such DSS concern planning suggestions (e.g. the proper selection of the district heating network set of users to fully exploit the available waste energy) but also design directions about the DHN infrastructure and generation plant technical configuration (such as e.g. the thermal energy storage capacity to be selected).

In this section, the developed model for decision support is applied to an Italian case study of a municipal DHN fed by the waste energy recovered from an EAF steelmaking industrial facility, in a typical European city brown field context, to prove its potential in performing a sustainability evaluation of a smart energy system involving the industrial facility as the waste heat source and the urban neighbourhood as district heating network end users.

Besides the "data" and the "evolutionary multi-objective optimization" phases of the proposed method for decision support, already tested and developed within the application to the case study of industrial districts, in this context particular effort has been put in the implementation of the "scenarios" and on the "decision-making" phases, with the aim of completing the development of the method, as highlighted in Figure 5.1, which provides an overview of the particularities of the application of the proposed DSS to the considered context.



PHASE	TASK	TOOLS
GOALS	Identification of sustainable solutions for industrial waste heat integration into DH-based SES, accounting for the different stakeholders involved	
SCIENTIFIC HYPOTHESIS	Statement of scientific hypothesis and assumptions of the model	
DATA	Data collection and analysis aimed at the characterization of the case study: • Local climate data • Waste heat source • Heat sink • DH infrastructure • Identification of constraints	• Energy audits; • Scientific literature analysis; • Visual on-site inspections;
SCENARIOS	Definition of the different scenarios to be analysed	
EVALUATION: MULTI-OBJECTIVE OPTIMIZATION	Evaluation of the identified scenarios through an evolutionary multi-objective optimization; Techno-economic and environmental analysis	DOE algorithm; Waste heat-based district heating SES mathematical model; Genetic algorithm; Optimization algorithm;
DECISION MAKING	Identify optimal designs by analysing the optimization results	Multi Criteria Decision Making (MCDM) algorithm

Figure 5.1. Development of the proposed DSS: application to the synergies between industrial and urban areas based on the integration of waste heat into municipal DH

The selected case study is particularly suitable for the development of the “design” (scenarios) phase of the proposed method for decision support. In fact, the selection of both the most suitable (from a sustainability perspective) set of end users, but also of the different city areas and consumer types to be served by the waste heat based DHN, requires the identification of different scenarios to be analysed through the proposed DSS tool based on evolutionary multi-objective optimization.

Moreover, the considered context is also suitable for the development of the “decision making” phase, due to the involvement of different stakeholders, each of them representing the bearer of different goals, thus requiring accounting for different weighting for the decision-making criteria. Decision-making is then performed through the multiple criteria decision making (MCDM) applied to the Pareto solutions by weighting the various objective functions according to the main goal of each favoured stakeholder.

Once the scientific hypothesis and assumptions of the problem have been stated, the next phase consists of the data collection. In this application context, data collection mainly includes the characterization of the local climate, of the waste heat source, of the heat sink (in particular, characterisation of the DH basin heat demand, of the involved city areas’ consumer types, etc.) and the characterization of the waste heat-based DH infrastructure (sizing and design, collection of investment cost data, etc.).

Moreover, the identification of physical, technical, economic, financial, regulatory, and territorial constraints, both generic and specific of the case study, belongs to the same data collection phase. Some of them are then included as constraints in the mathematical model of the energy system, while others represent constraints of the multi-objective optimization model. To provide a non-exhaustive example, the real territorial context is accounted by considering the different intended use of the urban areas potentially involved in the project and imposing some constraints to the optimization problem. The payback period related to the waste heat recovery infrastructure to be realized within the industrial facility, which implies an investment cost $C_{inv,industry}$ should be repaid through the revenues related to recovered energy selling to the DH system provider and through the avoided cost for waste heat dissipation (e.g. cooling towers operation), and must be lower than a threshold value (indicatively, 5 years is usually fixed by entrepreneurs when evaluating energy efficiency investments to be endorsed). At the same time, a DSCR value greater than a threshold value (typically 1.3) is usually required by lenders when evaluating infrastructural investments.

The model proves to be able to foster the integration of industrial waste heat recovery into smart energy system, providing to decision makers (policy makers, institutions responsible for territorial energy planning, investors, etc.) a tool that allows the analysis of the different stakeholders involved in a waste heat-based DH municipal energy supply, highlighting the trade-off as well as win-win situations to be exploited.

A summary of this work and the results obtained were published in the article: "Simeoni P, Ciotti G, Cottes M, Meneghetti A. Integrating industrial waste heat recovery into sustainable smart energy systems. Energy 2019;175:941–951. doi: https://doi.org/10.1016/j.energy.2019.03.104".

In the following subsection 5.1 a detailed description of the mathematical modelling developed for the multiobjective optimization of SES solutions for the integration of industrial waste heat recovery into municipal district heating is provided. In subsection 5.2 the selected case study involving a steelmaking industry as the industrial waste heat source and the neighbouring city as the heat sink is presented. In subsection 5.3 the obtained results are presented and discussed, while in subsection 5.4 the performed MCDM analysis in described.

5.1 Waste heat recovery integration into district heating. Smart energy 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 set of consumers to which allocate the recovered energy 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 a daily energy profile of the available energy from recovery. Plant downtime can occur due to ordinary and extraordinary maintenance interventions, which has been considered in the developed model by an availability factor (AF). The available recovered energy 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 industrial plant revamping required to implement the heat recovery system, an investment cost for the company that make available the recovered energy.

5.1.1 Assumptions

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 characterisation of the potential sink for the recovered energy 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.

5.1.2 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 based on the correlation between the thermal power required and the outdoor temperature, when only the value of the power installed for every user is known, has been presented by the author in (Ciotti et al., 2016). 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 set of users in the considered hour h of the heating season, can be obtained as in Equation (5.1):

$$L_{th,h} = SF \cdot \sum_w \left(\sum_j H_{w,j} \right) \cdot \frac{\vartheta_{id,w} - \vartheta_{o,h}}{\vartheta_{id,w} - \vartheta_{od}} \quad [MW] \tag{5.1}$$

where $\vartheta_{id,w}$ represents the indoor design temperature, which is fixed for each consumer type w, $\vartheta_{o,h}$ is the hourly average value of the outdoor temperature and ϑ_{od} represents the outdoor design temperature, which is site-specific, according to the national regulations. In order to perform the above evaluation, the following input data should therefore be acquired (Ciotti et al., 2016):

- Indoor design temperature $\vartheta_{id,w}$ and daily heating period for each consumer category w (e.g. residential buildings, schools, etc.) served by the DHN;
- Heat capacity currently installed, distinguished by each consumer category w;
- Average hourly temperature distribution of a typical year (easily provided by the local meteorological agencies).

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 suggested in (Winter et al., 2001) 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 (Winter et al., 2001).

The heat load pattern depends mainly on the building's kind of activity. The following consumer categories have been considered in this study: 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 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 in (Gadd and Werner, 2013), 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.

5.1.3 Energy System configuration and size

An industrial waste heat-based DH project is based on the supply of a portion of the DHN seasonal heat demand through the energy made available from the recovery, 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 heat only boilers (HOB) feed by natural gas 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 and then used when the request is high, without dissipating the surplus energy. Furthermore, TES can flatter the thermal load diagram, then reducing the need for peak load boilers intervention, thus leading to a decrease of fossil fuel requirements. Moreover, TES allow an easier optimisation of the operation, with higher conversion efficiencies and a smoother operation of the plants, which leads to less need for maintenance as underlined in (Verda and Colella, 2011). According to a common setup in most of the renewable powered DH systems, also adopted in the proposed configuration, the HOB is not directly connected to the TES, as they are usually used only for integration purposes, covering peak loads, or as backup units. The developed model calculates by simple energy balances the share of the overall waste heat energy available from the industrial source that can be exploited for district heating 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 Equation (5.2).

$$L_{th,h} - H_{rec,h} - H_{HOB,h} - H_{TES,h} = 0 \tag{5.2}$$

The model is driven by the total space heating demand, as described in Figure 5.2:

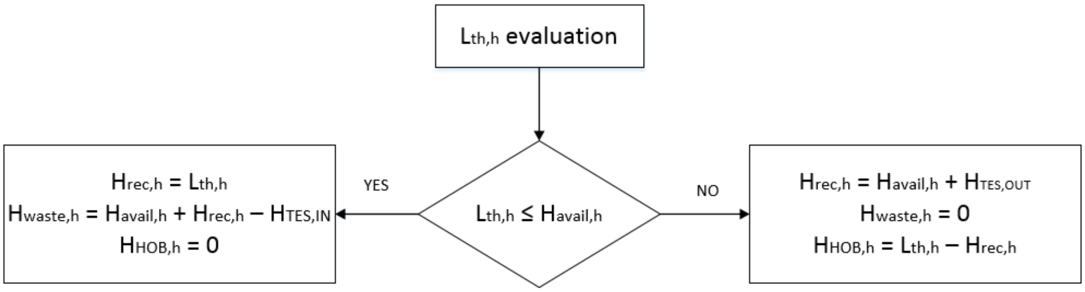


Figure 5.2 Flowchart of the waste heat-based district heating smart energy system model (Simeoni et al., 2019)

Simulations have been based on a time step of 1 hour, given the hourly heat demand profiles as previously discussed.

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, the temperature gap between supply and return temperatures to the tank 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 the storage, which depends on the considered volume once the thermodynamic properties of the fluid are set. 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. Moreover, a constant efficiency of the boilers fuelled by natural gas η_{HOB} at varying loads has been assumed.

5.1.4 *Objective functions*

Since the main goal of this research is the identification of viable solutions for the industrial waste heat integration into Smart Energy Systems from a sustainability perspective, the objective functions of the multi-objective optimization problem have been selected according to the stakeholders' different conflicting objectives, as presented in Table 5.1.

Table 5.1. Goals of the multi-objective optimization model. Adapted from (Simeoni et al., 2019)

Stakeholder	Objective function	Optimization
DH service provider	IRR	maximization
	SPB	minimization
Investors	DSCR	maximization
Industrial waste heat source	SPB	minimization
Citizenship	PES	maximization
	GHG emissions	minimization

Each stakeholder could be indeed the bearer of different instances, such as profit maximization concerning the DH service provider (accounted with the conventional economic indicators such as IRR, NPV, etc.), minimization of GHG emissions if the whole community is accounted, and so on, thus adopting an overall sustainability perspective. The minimization of the heating expenditure (bill cost), which is the goal of the DHN end user, is accounted through one of the main decision variables of the problem, as described in the next subsection 5.1.5 (the specific price of the heating service for the final consumers).

For the assessment of the advantage of a waste heat-based DHN compared to conventional DH fed by fossil fuels from a reduction of primary energy consumption perspective, the Primary Energy Saving (PES) indicator has also been used in the optimization algorithm, calculated as the energy recovered from the waste heat source and actually exploited in the entire calculation period E_{rec}. The only environmental criterion considered in this paper is the carbon dioxide emission reduction CDE, but also local pollutants could be considered in future development. The avoided GHG emissions and PES thanks to the operation of the waste heat-based DH network are calculated through the proper emission and conversion factors of the reference energy vectors.

5.1.5 Decision variables

Concerning decision variables, both technical and economic parameters have been selected for the optimization problem.

Concerning the economic aspect, the main economic parameters on which to act to meet the objectives of the various stakeholders involved in such an industrial waste heat recovery project are the specific cost of the thermal energy recovered from steel industry c_{energy_rec}, and the specific selling price of the heating service to the DHN end users p_{user}. The last two have then been selected as decision variables of the optimization problem.

About technical aspects, the capacity of the thermal energy storage system V_{tes} has been selected as decision variable, since almost all the other technical features of the district heating systems are fixed for a given scenario.

5.1.6 System cost evaluation

The investment cost is composed by two main terms: the energy generation plant (involving the various components such as HOBs, TES, the heat exchanger for the recovery of industrial waste heat, pumps, etc.) and the DHN infrastructure, i.e. pipelines connecting the main generation plant to the end users. Regarding the infrastructure, in DH models, a simplified evaluation of the capital cost of the pipeline is often used, considering an average investment cost per unit length (Pavičević et al., 2017). A detailed model has been developed by (Nielsen, 2014) 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 most likely placed close to or underneath the road network, the latter has been followed to design the DH grid reaching each neighbourhood 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. Once the distribution grid has been sized, the investment costs are estimated, based on specific investment cost per unit length data varying with commercially available diameters provided in (Nielsen, 2014), 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, investments can be much higher in dense cities than in green field development and lower density areas, due to higher costs of digging a pipeline (International Energy Agency, 2013). About heat losses from the network, a calculation based on empirical data obtained from (Nielsen, 2014) 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 technical features such as efficiencies, capacity bounds, and the fixed operation and maintenance costs, according to technical reports (Danish Energy Agency, 2016a). 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 (Pavičević et al., 2017). Storage capacity related specific investment costs have been considered according to (Danish Energy Agency, 2012). A two-step function has been used, assuming each TES type suitable for different storage capacity range: steel tanks up to about 7,000 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). The operating costs associated with the DH system concern mainly the heat energy supply costs, i.e. costs related to the fuel needed to feed heat only boilers and the ones related to the recovered energy, 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 €/MW/year) and a variable O&M (expressed in €/MWh) specific cost based on the generated thermal energy are considered, as reported by (Danish Energy Agency, 2016b). As regards DH network O&M, a fixed energy specific cost (expressed in €/MWh/year) has been accounted, as provided by (Danish Energy Agency, 2016a). The following equation gives the annual operating costs AOC (expressed in €/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 €/MWh, and only volumetric fees of heat supply are considered.

$$AOC = C_{O\&M} + c_f \cdot \sum_{t=1}^{N} F_{HOB,t} + c_{energy\_rec} \cdot \sum_{t=1}^{N} \left(H_{rec,t}\right) \cdot dt + c_{waste} \cdot \sum_{t=1}^{N} \left(H_{waste,t}\right) \cdot dt \tag{5.3}$$

The annual operational profit AOP 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), has been accounted as in Equation (5.4) respectively as specific bonus to be multiplied by the overall carbon dioxide emission savings (c_{carbon_tax}, expressed in €/tCO$_2$-eq) and primary energy consumption savings (p_{TEE}, expressed in €/toe).

$$AOP = p_{user} \cdot E_{user} + c_{carbon\_tax} \cdot CDE + p_{TEE} \cdot PES \tag{5.4}$$

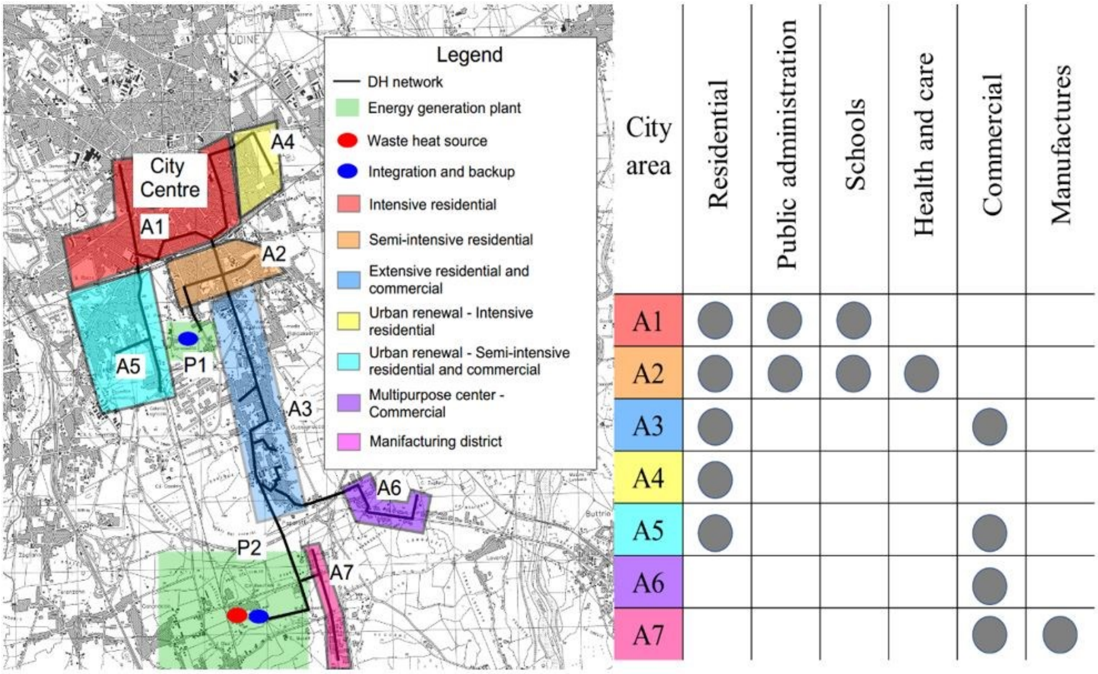
The difference between the AOP and the AOC of the considered DHN solution represents the expected cash flow (CF) of the investment (expressed in €/year), from the DH service provider perspective. Economic evaluation is carried out by the conventional performance indicators already presented in subsection 3.1.4.1, such as standard pay back (SPB), net present value (NPV) and internal rate of return (IRR). The expected lifetime of the project (service lifetime of the equipment) to be accounted in the case of a DHN should be at least 30 years (Energistyrelsen, 2012). Because of the relevant investment costs associated to a district heating 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 (analogously to what presented in Section 3).

5.2 Case study: EAF steelmaking facility's waste heat integration into an urban DHN

The proposed model has been applied to the city of Udine, located in North-Eastern Italy, which has been selected as suitable case study within the local territorial context because representative of a typical European small town with about 100,000 inhabitants and an average population density of approximately 1,750 inhabitants/km^2. It comprehends both high- and low-density populated areas. Concerning the waste heat source, the selected case study offers an opportunity identified in a steel casting company located about 5 km South of the Udine city centre (Flensburg Halmstad and Aalborg Universities, 2018), 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 (Cooper et al., 2016)., Most of potential consumers in the neighbourhood have been recognised as residential from the analysis of the municipality regulatory plans and on-site inspections, but there are also some 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 shown in Figure 5.3. Currently the investigated area has no DH infrastructure and individual boilers mainly fed by natural gas are adopted for space heating and domestic hot water, for a maximum installed power which can be roughly estimated in approximately 200 MW. Natural gas is then 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, thus replacing boilers with DH substations, is considered, without including waste heat recovery from the steel industry (the energy generation plant can only count on HOB).

The waste heat recovery DHN 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, including all the main city clusters, which are characterized by the presence of the consumer types reported in Figure 5.3.



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

Figure 5.3. Udine case study: DHN layout and main city areas characterization (Simeoni et al., 2019)

Scenario S1 considers a DHN serving the two highest-density residential areas next to the city centre A1 (intensive) and A2 (semi-intensive) as reported in Figure 5.3; 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 composed by the heat exchanger close to the steel casting facility and by the transportation pipeline. The remote heat recovery facility brings the waste heat to the main consumer basin next to the city centre, where the peak covering back-up plant P1 is located. It must be highlighted that the locations where to install the DH peak integration and back-up plant, indicated by the blue dots in Figure 5.3, have been selected within the available areas according to the municipality general regulatory plan, as required in a brown field contexts. Scenario S2 considers the additional energy supply 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 accounts for 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, the peak integration and backup facility P1 based on HOB is installed next to the city centre. 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 aims at investigating the effects of a large share of commercial buildings instead of semi-intensive residential ones with the areas to be rebuilt. An overview of all the considered scenarios, with the related overall nominal heat demand H and DH network length L_{DH} is presented in Table 5.2.

Table 5.2 Analysed scenarios (Simeoni et al., 2019)

Scenario ID	Connected city 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

The waste heat power available for recovery H_{avail} has been estimated up to 25 MW (Nardin et al., 2018), in the form of hot water at above 90 °C, quite constant given the 24 hours 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 pipelines reported in (Nielsen, 2014), ranging from 281 €/m for a 48 mm diameter to 1,946 €/m for a 813 mm diameter insulated pipe, have been considered to evaluate the network's capital cost. About natural gas fired HOB, a nominal specific investment cost of 0.06 M€/MW, a fixed O&M cost of 2,000 €/MW/year and a variable O&M cost of 1.1 €/MWh have been accounted. Concerning TES, an average specific cost of 300 €/m^3 for steel tanks for storage capacity up to 7,000 m^3 and of 200 €/m^3 for concrete tanks for storage capacity up to 20,000 m^3 have been accounted, according to (Energistyrelsen, 2012). 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 €/Sm^3, c_{TEE} = 300 €/TEE, c_{carbon_tax} = 5 €/tCO_2.

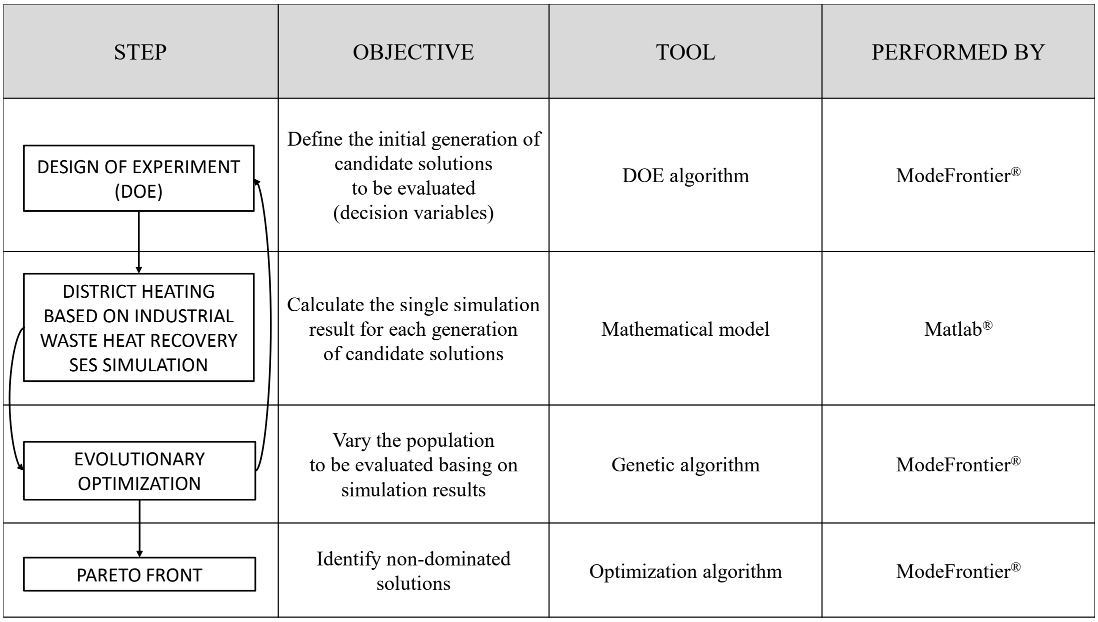
In Table 5.3 the variation ranges of the decision variables of the multi-objective optimization problem are reported.

Table 5.3. Variation ranges of the decision variables (Simeoni et al., 2019)

		unit	Range of variation	Incremental step
Decision variables	c_{energy_rec}	€/MWh	1 ÷ 30	1
	p_{user}(Werner, 2016)	€/MWh	5 ÷ 95	5
	V_{TES}	m^3	0 ÷ 20,000	1,000

A specific cost for surplus heat dissipation (i.e. thermal energy available from recovery but exceeding the users' demand) of 4 €/MWh has been considered. Lastly, an emission factor of 1.94E-03 tCO_2-eq/$Sm^3{}_{CH4}$ and a primary energy conversion factor of 8.20E-04 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.

The four steps procedure of the developed evolutionary multi-objective optimization method, i.e. Design of Experiment (DOE), mathematical model, optimization and definition of the Pareto front, have been implemented by use of the software listed in Figure 5.4.



STEP	OBJECTIVE	TOOL	PERFORMED BY
DESIGN OF EXPERIMENT (DOE)	Define the initial generation of candidate solutions to be evaluated (decision variables)	DOE algorithm	ModeFrontier®
DISTRICT HEATING BASED ON INDUSTRIAL WASTE HEAT RECOVERY SES SIMULATION	Calculate the single simulation result for each generation of candidate solutions	Mathematical model	Matlab®
EVOLUTIONARY OPTIMIZATION	Vary the population to be evaluated basing on simulation results	Genetic algorithm	ModeFrontier®
PARETO FRONT	Identify non-dominated solutions	Optimization algorithm	ModeFrontier®

Figure 5.4 Software used for the implementation of the evolutionary multi-objective optimization procedure (Simeoni et al., 2019)

The simulation of the energy system through the mathematical model has been performed by Matlab®, interfaced with the ModeFrontier® software, which performed DOE algorithm, genetic algorithm and optimization.

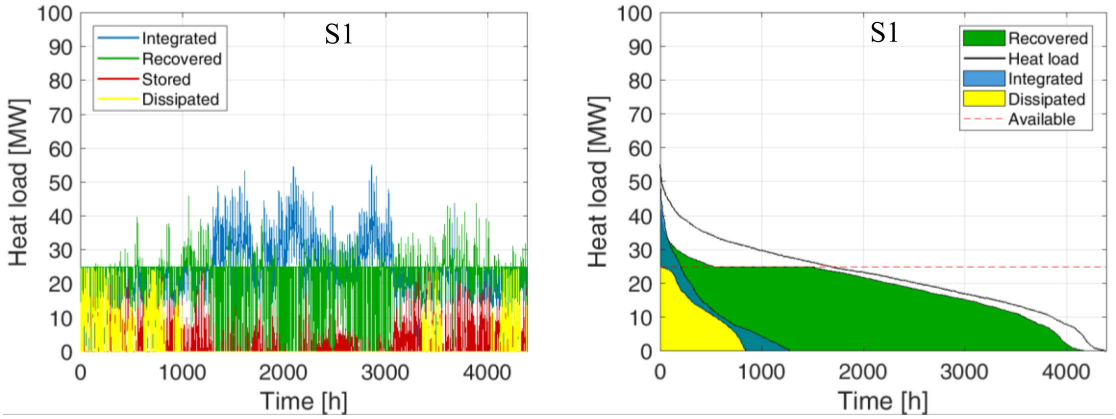
5.3 Optimization results

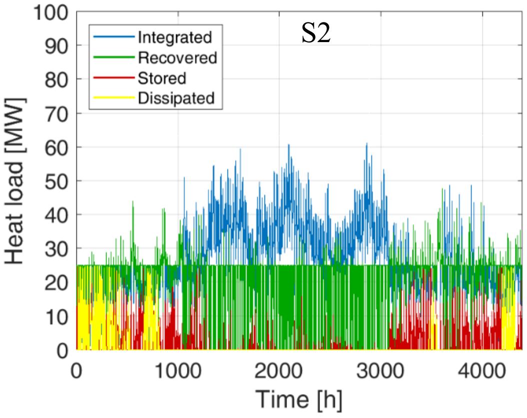
The multi-objective optimisation problem for the case study has been solved by using a 16 GB RAM, i7 4770 3.40 GHz PC. A population of 1,000 individuals and 250 generations were adopted, resulting in 250,000 total evaluated designs, enough to obtain the convergence of the process in about 12 hours.

5.3.1 Primary energy savings: DH infrastructure planning suggestions

The diagrams on the left side of Figure 5.5 represent the hourly operation profiles of the DH system, encompassing the whole heating season, for the considered waste heat recovery scenarios from S1 (top) to S5 (bottom); 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 users' space heating demand coverage related to 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 thermal energy availability at the heat exchanger of the steel company and the thermal energy provided by TES.

The graphs of Figure 5.5 refer to a TES capacity of 20,000 m^3 since, according to simulation results, this design solution allows to achieve the best environmental performance within the considered range.




S2
Integrated
Recovered
Stored
Dissipated
Heat load [MW]
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2000
3000
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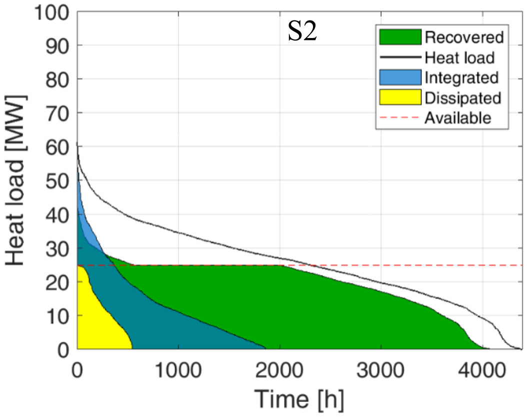
S2
Recovered
Heat load
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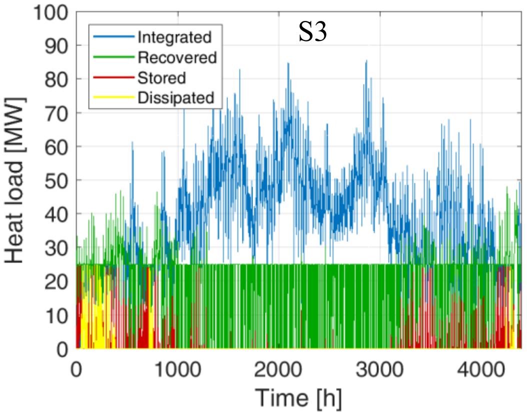
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Heat load [MW]
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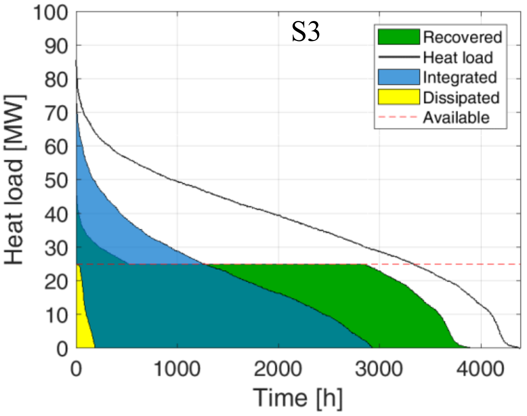
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Heat load
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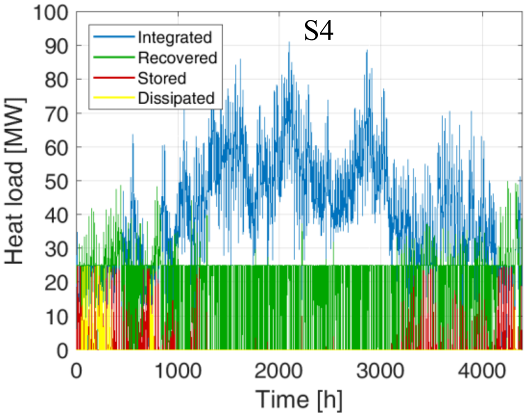
S4
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Dissipated
Heat load [MW]
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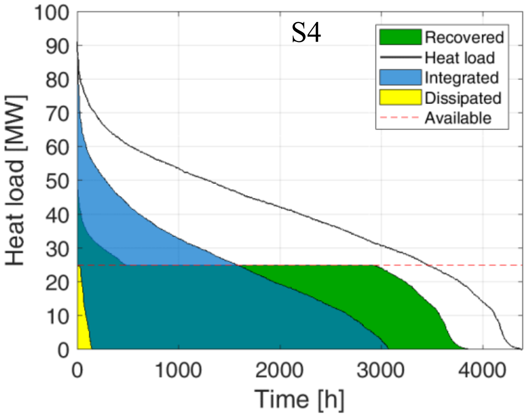
S4
Recovered
Heat load
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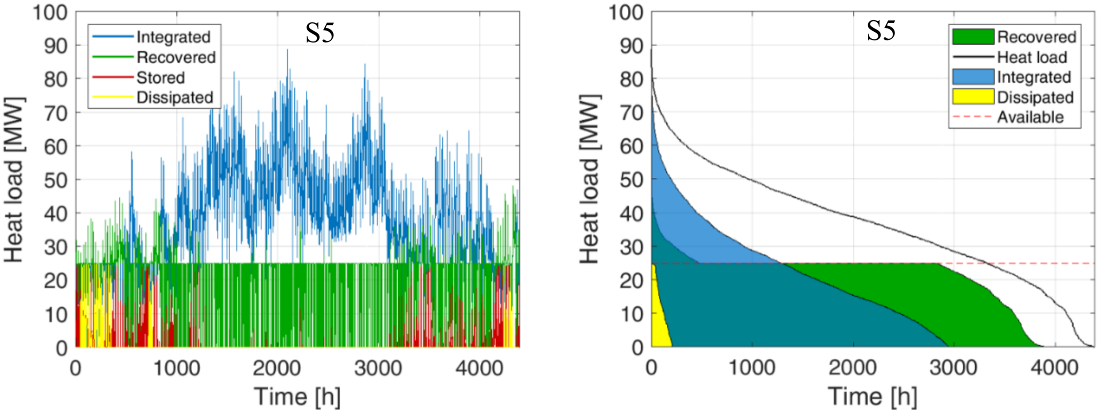


Figure 5.5. DHN energy system simulation. Hourly profile (left side) and duration curves (right side) for scenarios S1-S5 (Simeoni et al., 2019).

As it can be noticed from the graphs, given the amount of available energy from industrial waste heat recovery, the larger the basin, the greater the waste heat source exploitation and, thus, the primary energy saving and the CO_2 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 fact, increasing from scenario S1 to S5 (see the green area in Figure 5.5, right side), and consequently less energy needs to be dissipated through the operation of the cooling towers (see the yellow area in Figure 5.5). At the same time, the increase in the DH load implies the requirement of more energy from integration (represented by the blue area in Figure 5.5, 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 5.5, 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.

5.3.2 *Pareto fronts*

Due to its best environmental performance within the set of analysed scenarios, only the optimization results related to Scenario S4 are presented in the following. According to simulation results related to Scenario S4, as shown by the Pareto front (marked in green) of the scatter diagram of Figure 5.6, the optimization pushes towards the highest values of the storage capacity, although optimal solutions exist also at values of storage capacity below 4,000 m^3. If the maximization of the PES objective function is being pursued disregarding the minimization of the investment cost, the highest values of the TES size should be selected. From a design perspective a V_{TES} of around 7,000 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.

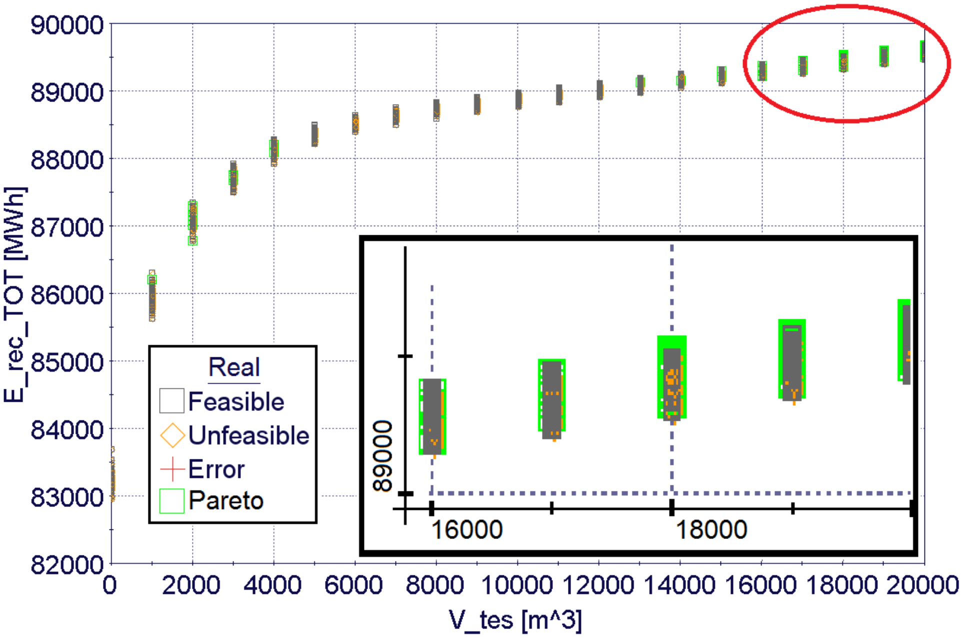


Figure 5.6. Pareto fronts (marked in green) for Scenario S4. TES capacity versus total recovered energy. Adapted from (Simeoni et al., 2019)

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 industrial waste heat source, are presented in the bubble diagram of Figure 5.7, where the Pareto front has been marked by black circles.

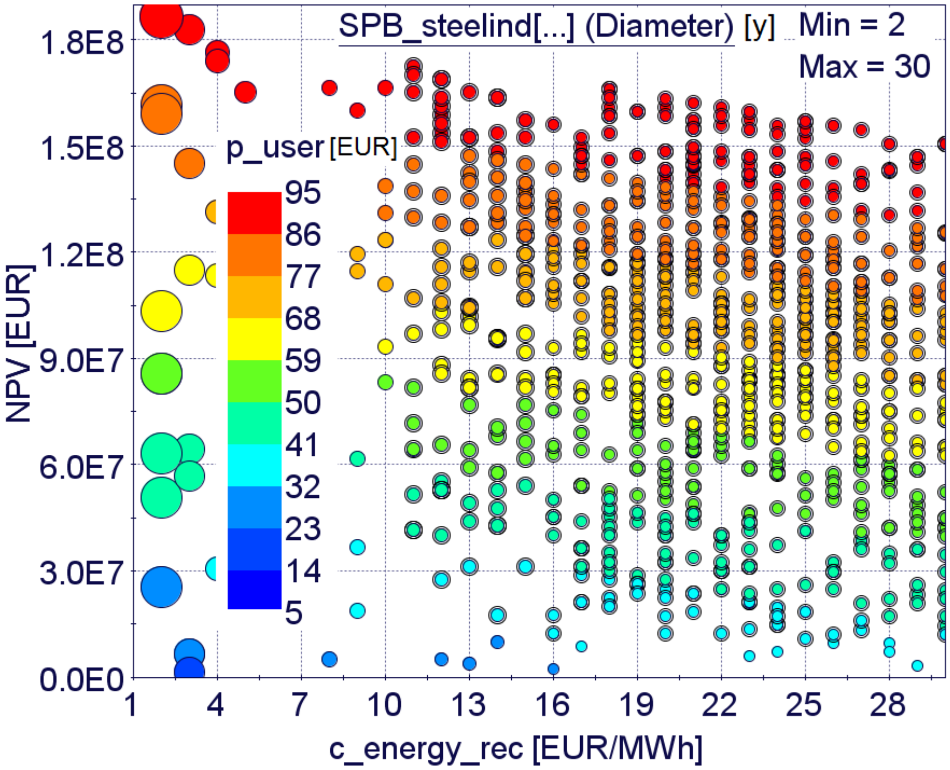


Figure 5.7 Pareto fronts for Scenario S4 (marked in black). Bubble diagram representing the relation between the economic decision variables and their influence on the project's economics. Adapted from (Simeoni et al., 2019)

It's worth noting that the Pareto multi-objective optimization pushes towards a specific cost of recovered energy greater than 10 €/MWh up to around 30 €/MWh (i.e. the maximum allowed value) while keeping at a competitive price the heating service for consumers, from above 40 €/MWh (markedly below the maximum allowed value of 95 €/MWh).

Moreover, as can be observed looking at the spread of results that are generated, there are feasible solutions (i.e. solutions which satisfy the imposed constraints) which could satisfy both the DH service provider and the steel casting facility, while keeping the consumers' space heating bills at competitive levels through a conscious selection of DH service price. At the same time, ambitious environmental targets can be reached. This would lead to a win-win solution from a sustainability and competitiveness perspective, for each involved stakeholder.

5.4 MCDM analysis

As discussed above, 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 M€.

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 MCDM tool of the software provides a ranking of the solutions, among which only the first classified was selected and reported in Table 5.4. The economic indicators for the favoured stakeholder are, thus, at their best.

Table 5.4. MCDM applied only to Pareto front solutions (Simeoni et al., 2019)

Favored stakeholder	design ID	V_{TES}	c_{energy_rec}	p_{user}	SPB	NPV	IRR	DSCR	$SPB_{steel\_industry}$
		[m^3]	[€/MWh]	[€/MWh]	[y]	[M€]	[%]		[years]
DH provider	243827	19,000	11	95	2.6	177	38.6	5.6	4.6
Consumers	12022	19,000	11	29	9.9	10	9.1	1.4	4.6
Waste heat source	3338	20,000	30	54	6.0	48	16.2	2.4	1.7
Environment	2061	20,000	18	34	9.4	14	9.7	1.5	2.8

As discussed in the following, the analysed scenario S4 allows a wide range of solutions regarding price and energy cost policies.

If the DH service provider is considered as favoured stakeholder, thus aiming at maximizing its profit , the minimum cost of the recovered energy of 11 €/MWh should be selected, resulting on the opposite in the maximum payback period for the steel making company of 4.6 years and the maximum heating price for consumers of 95 €/MWh. If instead end users are the favoured stakeholder, the minimum heating price of 29 €/MWh could be considered, while keeping at the same level the cost of the recovered energy of 11 €/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 high 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 €/MWh) is selected by the MCDM tool, guaranteeing a short SPB of 1.7 years, while keeping an interesting level of the heating service price for consumers (54 €/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 CO_2 emission saving of around 18,900 tCO_2 if compared to the reference scenario where only gas fired HOBs are used for covering the heat demand of the DH network. A TES capacity of 20,000 m^3 must be designed to allow this performance.

5.5 Final remarks

The exploitation of industrial waste heat recovery through its integration into an urban DH smart energy system can represent a chance to guide the transition towards sustainability. To successfully implement such a strategy, however, the conflicting objectives related to the different involved stakeholders should be considered (DHN service provider, the industrial waste heat source, residential consumers, public authorities, etc.). Moreover, the brown field is characterised by different potential end users with their different demand profile and features to be combined into the most beneficial set from a sustainable perspective.

In this section of the thesis, with the aim of completing the development of the proposed evolutionary multi-objective optimization model for decision support, it has been applied to a case study of urban-industrial synergy representative of the European context, a municipal DHN in a typical European city brown field context fed by the waste energy recovered from an EAF steelmaking industrial facility. The selected case study was particularly suitable for the development of the “design” (scenarios) phase of the proposed method for decision support, because the selection of both the most suitable set of end users, but also of the different city areas and consumer types to be served by the waste heat based DHN, requires the identification of different scenarios to be analysed. Moreover, the considered context was also suitable for the development of the “decision making” phase, due to the involvement of different stakeholders, each of them representing the bearer of different goals, thus requiring accounting for different weighting for the decision-making criteria.

The model has proved to provide general insights for the development of a SES concept based on waste heat recovery from an energy intensive industry to be exploited to supply a DHN, enabling the investigation of the sustainability performance of such smart energy system projects. The DSS allows to analyse how system configuration and performance change based on the favourite stakeholder, so that it can act as a decision support tool to identify the most viable solution. Moreover, it can allow to identify the public policies needed to sustain the effective transition towards such sustainable energy supply. Thus, the developed tool can be used not only in the system design phase, but also as a support to plan regional development, as the results for its application to the case study of Udine city, in North-Eastern Italy, have underlined.

6 INDUSTRIAL WASTE HEAT RECOVERY PROJECTS: THE FACILITY MANAGER PERSPECTIVE

Concerning waste heat recovery projects, especially in the energy-intensive industrial sectors, facility managers face indeed the challenge of making the optimal strategic choice within the different waste heat recovery options already identified in chapter 4.

The economic objective represents the main driver, although environmental objectives are becoming increasingly important, also thanks to the rising value of green marketing.

Indeed, when both the potential demand from external users and the opportunity to produce electricity represent attractive options, in order to allow the facility manager to select the most suitable waste heat recovery option and to decide which project to endorse, a deeper insight on the sustainability performances of each potential waste heat recovery solution is required.

The developed DSS method has then been applied adopting a facility manager's perspective, with the aim to investigate the economic, energetic and environmental performances of different options for waste heat recovery exploitation, thus allowing a strategic decision making for the endorsement of the related investments. As a result, the model would make it possible to obtain significant suggestions regarding the optimal configuration of the energy recovery system, i.e. the selection of the most suitable option for the exploitation of the recovered energy, even accounting for the possible combination of different technologies, their optimal sizing and the definition of the operational strategy.

Within the various energy recovery options identified within the conceptual framework presented in section 4, in this context only the two energy recovery options based on a smart energy system approach (Figure 6.1) have been considered, in order to provide a deeper insight thus improving the analysis already presented in section 5. Namely, power generation through an ORC unit (both for self-consumption and grid selling) and the exploitation of the generated heat transfer fluid to feed an urban DH network.

Beside their wide applicability and ease of combination, the reason for the research commitment in the investigation of these two options, is from one hand the large need for electric energy typical of the energy-intensive productive processes (i.e. the generated electric energy is very likely to be self-consumed by internal processes) and from the other one the opportunity to allow the external integration of the recovered energy into smart energy systems. As already highlighted in the previous section 5, in fact, external integration of the recovered energy could allow to reach remarkable sustainability benefits both for the enterprise and the surrounding urban/industrial context. As already outlined by the literature review presented in section 4, in fact, these two exploitation options have been widely implemented in almost every industrial waste heat recovery case study, especially concerning the EAF steelmaking sector.

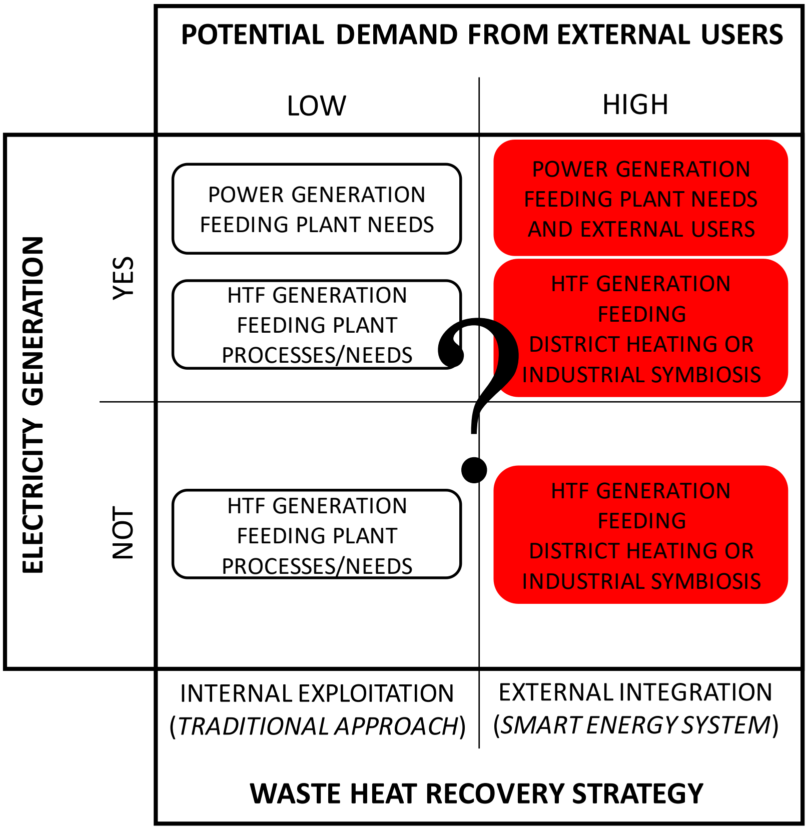
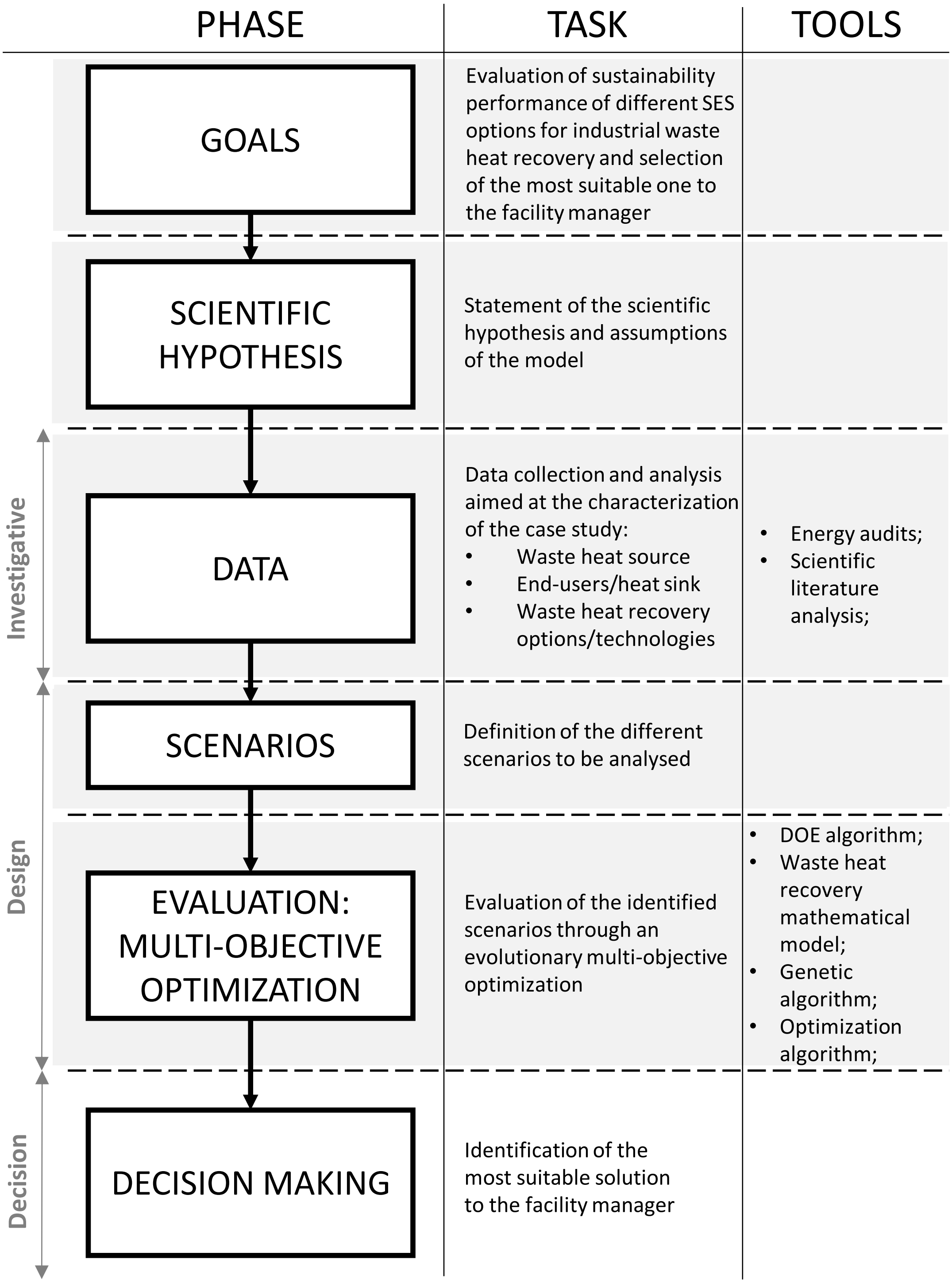


Figure 6.1. Conceptual framework for the identification of different waste heat recovery exploitation strategies: open questions about the selection criteria of solutions enabling a SES approach

With the aim to further refine it, the DSS developed in this thesis has then been applied, as presented in Figure 6.2, to the same context of Section 5 (i.e. an EAF steelmaking facility with a neighbouring municipal DHN case study), in order to investigate the economic, energetic and environmental performances of different options for waste heat recovery exploitation, thus allowing a strategic decision making for the endorsement of the investment for the most suitable option from the facility manager's perspective.

In the following subsection 6.1 a detailed description of the mathematical modelling developed for the identification of the most suitable industrial waste heat recovery SES option from a facility manager perspective is provided. In subsection 6.2 the selected case study involving an EAF steelmaking industry as the industrial waste heat source is presented, while in subsection 6.3 the obtained optimization results are presented and discussed.



PHASE	TASK	TOOLS
GOALS	Evaluation of sustainability performance of different SES options for industrial waste heat recovery and selection of the most suitable one to the facility manager	
SCIENTIFIC HYPOTHESIS	Statement of the scientific hypothesis and assumptions of the model	
DATA	Data collection and analysis aimed at the characterization of the case study: • Waste heat source • End-users/heat sink • Waste heat recovery options/technologies	• Energy audits; • Scientific literature analysis;
SCENARIOS	Definition of the different scenarios to be analysed	
EVALUATION: MULTI-OBJECTIVE OPTIMIZATION	Evaluation of the identified scenarios through an evolutionary multi-objective optimization	• DOE algorithm; • Waste heat recovery mathematical model; • Genetic algorithm; • Optimization algorithm;
DECISION MAKING	Identification of the most suitable solution to the facility manager	

Figure 6.2 Further development of the proposed decision support system: application to the evaluation of different waste heat recovery options

6.1 Identifying the most suitable industrial waste heat recovery option from a facility manager perspective: mathematical modelling

6.1.1 *Multi-objective optimization problem*

Since the goal of this work is the identification of the most suitable solution for the industrial waste heat recovery exploitation strategy from a facility manager perspective, the objective functions of the multi-objective optimization problem have been selected according to this stakeholder different conflicting objectives, as presented in Table 6.1.

Table 6.1. Goals of the multi-objective optimization problem

Stakeholder	Objective function	Optimization
Industrial waste heat source: facility manager	IRR	maximization
	PES	maximization
	GHG emissions	minimization

As anticipated, in addition to the economic aspect, also environmental objectives are increasing their importance for companies due both to the rising value of green marketing and to the forecast of a potentially significant increase in the value of CO_2 in the coming years. Thus, beside the main goal represented by profit maximization, which has been accounted with the conventional economic indicators as already presented (i.e. IRR), the minimization of GHG emissions and the maximization of primary energy saving have also been accounted, thus adopting anyway a sustainability approach to the optimization problem.

Primary Energy Saving (PES) indicator is considered as the energy recovered from the waste heat source and actually exploited in the entire reference calculation period. The only environmental criterion considered in this work is the GHG emissions (only carbon dioxide has been accounted), but also local pollutants could be considered in future development in order to provide a deeper comparison of the environmental performance of the different exploitation options. The avoided GHG emissions and PES thanks to the waste heat recovery project are calculated through the proper emission and conversion factors of the reference fuels/energy vectors already presented in the previous sections.

When considering options for industrial waste heat recovery exploitation based on external integration of the waste heat by feeding a urban district heating network and on power generation through an ORC unit for self-consumption and grid selling (see

Figure 6.3), there are basically two main parameters determining a change in the absolute and relative performance of each solution: the nominal capacity of the ORC plant $P_{ORC,nom}$, and the economic valorisation of the thermal energy sold to the external DH network v_{th}.

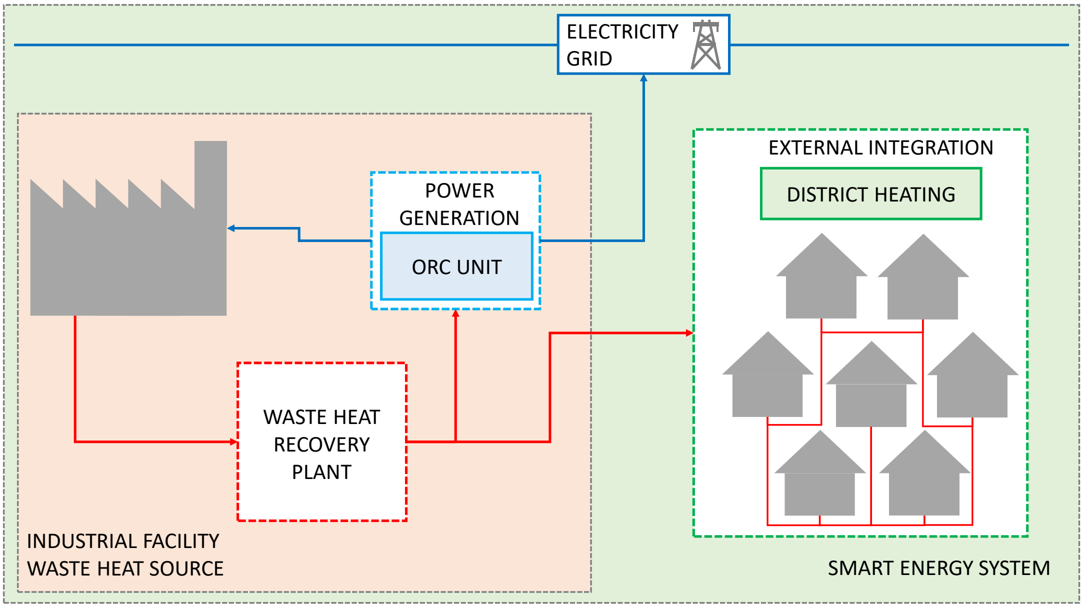


Figure 6.3 Industrial waste heat recovery: suitable options from a facility manager perspective

About the latter, as already investigated in section 5, the economic value of the heat recovered should be indeed negotiated between the company that makes it available and the company that manages the district heating network, thus representing a main decision variable of the optimization problem. The capacity of the external district heating network H_{DH}, which in turn determines the heat load of the network, does not represent a decision variable of the optimization problem from a facility manager perspective, but rather constitute an external condition of the specific case study, then it should be accounted in the definition of the different scenarios to be analysed.

At the same time, the size of the electricity generation plant is subject to optimization. In fact, it may be convenient to install it without considering the district heating option, or instead to select it in combination with external integration, thus creating a solution consisting of the combination of two different recovery options in parallel, or it might even be convenient not to install it at all, then choosing only the integration of the recovered energy into an external energy system.

6.1.2 Assumptions

Since the focus of the present work is a sustainability performance evaluation of the considered waste heat recovery options from a facility manager perspective, rather than a detailed simulation of their physical behaviour, the developed mathematical model is based on the following hypothesis. As regards the external integration of the recovered heat, the same hypothesis already presented in section 5.1.1 exist, thus the DH network could be considered as a black box since only the thermal load of the network determines how much energy from recovery can be allocated to the DH option. Concerning both waste heat exploitation options, steady state conditions of the network operation and of the ORC unit, i.e. no dynamic effects (transient conditions) are considered. Moreover, the efficiency of the considered technologies for the exploitation of waste heat recovered, namely the ORC plant and the heat exchanger serving the external DHN, are assumed to be constant with load changes. The efficiency drops of equipment at partial load operation are neglected to simplify the analysis and calculation.

6.1.3 Algorithm

Since from a facility manager perspective, the main driver for the choice of the different waste heat exploitation options, considering both system configuration and its operation, is represented by profit maximization, the economic value related to each considered solution for the exploitation of the recovered energy has been selected as the only decision criterion in the algorithm of the optimization problem.

The operating conditions can change over time, e.g. the current market values of the electric energy (its specific cost and the value of its selling to the grid) are likely to change over the course of a typical year. For this reason, with the aim to allow the selection of the most suitable recovery option also from the plant operation point of view, the developed algorithm can account for market values of the energy vectors varying during the simulation period.

At every time period of the calculation (the considered time step is one hour), the specific economic values of each alternative exploitation option (respectively v_{DH} for district heating, $v_{ORC,endo}$ for self-consumption of the recovered electricity and $v_{ORC,eso}$ for its selling to the national grid) are evaluated based on the market values of energy vectors and sorted in descending order.

It’s worth noting that also the contribution of incentives provided to primary energy saving interventions (e.g. white certificates TEE) and the economic value of the avoided CO2 emissions, i.e. carbon tax (CT), have been accounted only in the case of power generation through the ORC unit, while concerning the district heating option the DHN service provider has been considered to take advantage of such economic grant, as reported in the following equations (6.1-6.3).

$$v_{ORC,endo} = \left(c_{el} + \xi_{el,grid} \cdot TEE + \mu_{el,grid} \cdot CT\right)\eta_{ORC} \tag{6.1}$$

$$v_{ORC,eso} = \left(v_{el} + \xi_{el,grid} \cdot TEE + \mu_{el,grid} \cdot CT\right)\eta_{ORC} \tag{6.2}$$

$$v_{DH} = (v_{th})\eta_{HE} \tag{6.3}$$

The thermal power H_{avail} made available from the industrial waste heat recovery system is therefore assigned with priority to the option characterized by the highest potential economic value of the unit of recovered energy, granting then profit maximization. Once the energy demand associated with this option is exhausted, in the event of residual availability of thermal power from the industrial waste heat recovery system, it would be allocated to the next option in terms of economic value and so on, thus iterating the cycle as represented in the flowchart of Figure 6.4.

Industrial facility's electric load profile is then considered in order to allow a comparison with the power potentially generated through the ORC unit, since an eventual surplus would be allocated to the next exploitation option in terms of economic value. Similarly, the hourly thermal load profile of the DHN is considered, as already presented in section 5.1.2.

The thermal energy available downstream the waste heat recovery plant $H_{avail,h}$, if not allocated to the various recovery options, is dissipated as it would be in the traditional way, thus representing a cost for the company instead of a revenue (accounted through the specific cost of dissipation c_{waste} as already presented in section 5).

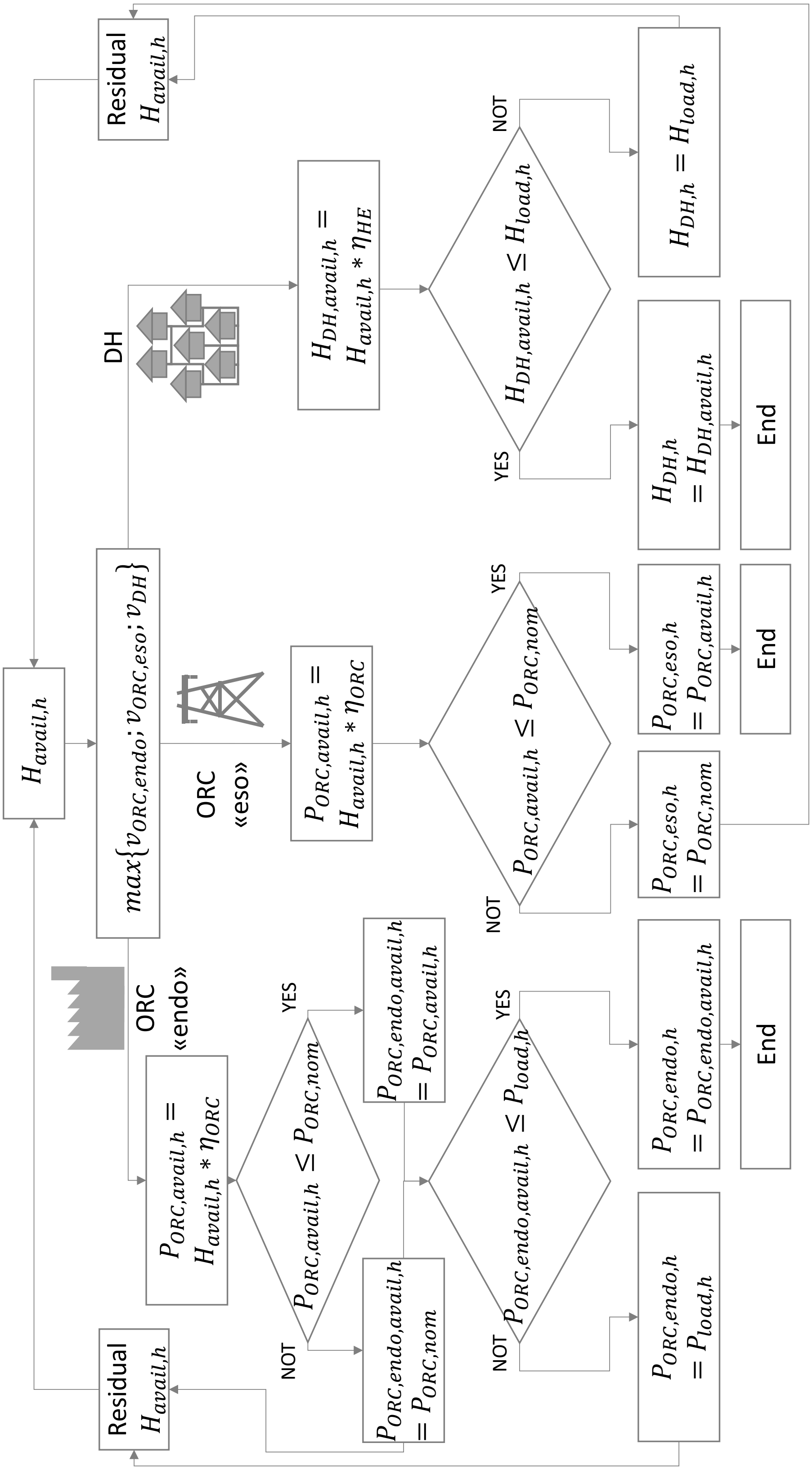


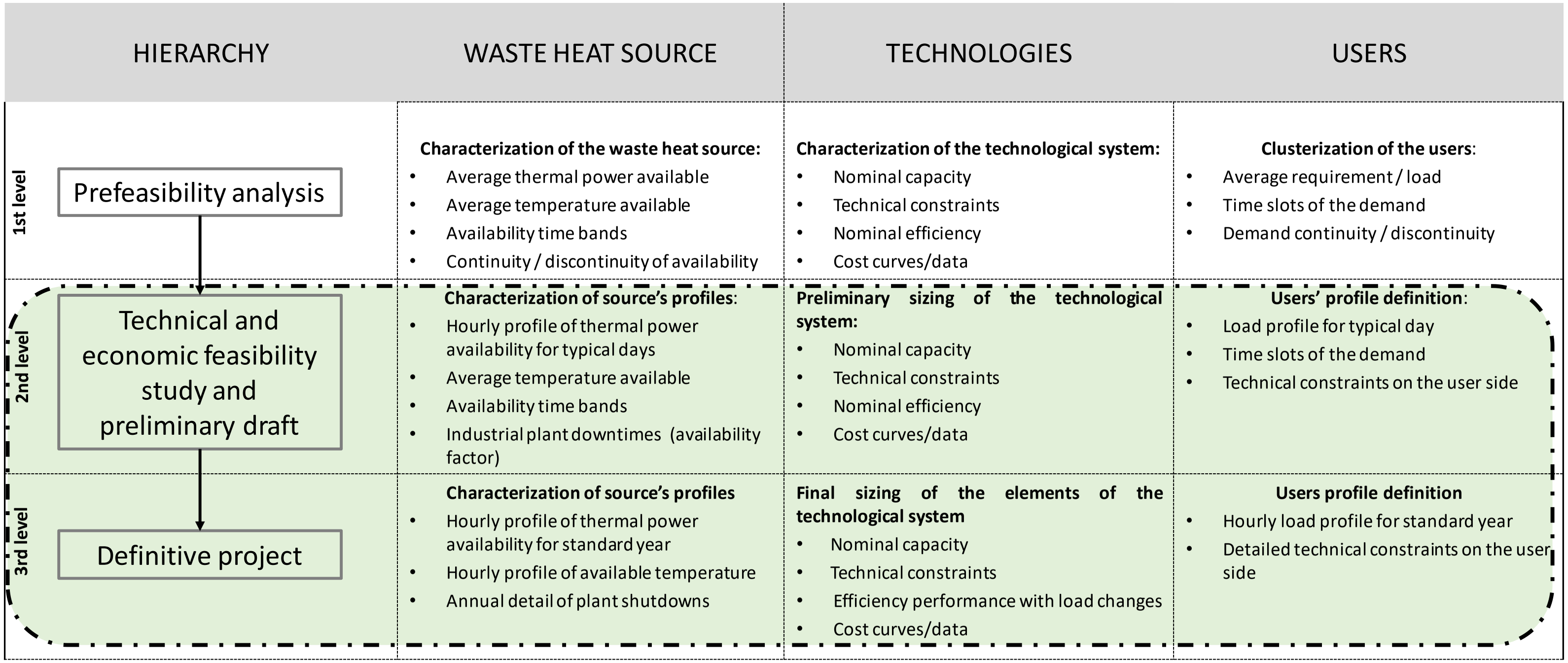
Figure 6.4 Flowchart of the developed waste heat recovery algorithm

6.1.4 Waste heat source and users' demand characterization

In the context of strategic evaluation of industrial waste heat recovery options, when a facility manager perspective is adopted, rather than a pre-feasibility analysis of different waste heat recovery options aimed at highlighting their potential, indeed, a kind of preliminary draft of the project is required.

Relevant research topics must be deeply investigated for each alternative recovery option, such as e.g. the optimal matching between the available waste energy and the energy demand from final users/energy sinks. Because of its influence on the actual exploitation of the recovered energy, this could even determine the feasibility of some exploitation options for the energy recovered and/or increase the sustainability benefits of the project. The characterisation of the potential sink for the recovered heat is a crucial aspect to assess the sustainability of the project for an energy service provider.

With the aim of investigating such aspects, the mathematical model of the DSS should be developed in order to allow a deeper characterization of waste heat sources and final users demand, thus implementing at least the second hierarchical level as presented in Figure 6.5. Concerning the level of detail of the input data needed, e.g. hourly profiles of waste energy availability from the industrial source and of energy demand from the potential sinks/final users are then required.



	HIERARCHY	WASTE HEAT SOURCE	TECHNOLOGIES	USERS
1st level	Prefeasibility analysis	**Characterization of the waste heat source:** • Average thermal power available • Average temperature available • Availability time bands • Continuity / discontinuity of availability	**Characterization of the technological system:** • Nominal capacity • Technical constraints • Nominal efficiency • Cost curves/data	**Clusterization of the users**: • Average requirement / load • Time slots of the demand • Demand continuity / discontinuity
2nd level	Technical and economic feasibility study and preliminary draft	**Characterization of source's profiles**: • Hourly profile of thermal power availability for typical days • Average temperature available • Availability time bands • Industrial plant downtimes (availability factor)	**Preliminary sizing of the technological system:** • Nominal capacity • Technical constraints • Nominal efficiency • Cost curves/data	**Users' profile definition**: • Load profile for typical day • Time slots of the demand • Technical constraints on the user side
3rd level	Definitive project	**Characterization of source's profiles** • Hourly profile of thermal power availability for standard year • Hourly profile of available temperature • Annual detail of plant shutdowns	**Final sizing of the elements of the technological system** • Nominal capacity • Technical constraints • Efficiency performance with load changes • Cost curves/data	**Users profile definition** • Hourly load profile for standard year • Detailed technical constraints on the user side

Figure 6.5 Case study characterisation: hierarchy of the evaluation model

6.1.5 *Waste heat recovery options: technical and economic characterization*

Concerning investment costs related to the waste heat recovery option represented by electricity generation by means of an Organic Rankine Cycle plant, the following cost curve has been considered, where the nominal capacity $P_{ORC,nom}$ is expressed in kW (Lemmens, 2016):

$$c_{ORC} = 9907.5 \cdot P_{ORC,nom}^{-0.267} \tag{6.4}$$

About the external integration of the recovered waste heat, the heat exchanger serving the DHN is assumed to be the only investment cost to be borne by the company, as for the purpose of comparing the different recovery options, the investment cost associated with the waste heat recovery system does not affect the assessments since it must be incurred anyway, although it may actually be relevant. Moreover, such economic information is difficult to obtain because it is often implemented as part of an overall revamping of the industrial plant, and the related costs might be subject to remarkable differences from one case study to another.

The following cost curve has been considered, where the nominal capacity $H_{HE,nom}$ is expressed in kW (Theissing et al., 2010):

$$c_{HE} = 4076.2 \cdot H_{HE,nom}^{-0.71} \tag{6.5}$$

As regards O&M, a fixed cost of 2.4 € per MWh of generated electric energy has been considered (Herzog, 2015) for the ORC unit, while operation and maintenance of the district heating heat exchanger has been assumed to be charged to the DH service provider.

6.2 Application to the context of an EAF steelmaking facility

With the aim of testing the developed DSS model, it has been applied to the steelmaking sector, due to its relevance within the energy-intensive industrial processes as outlined in section 4, allowing to focus at the same time on the local territorial economic context, thus integrating the analysis already presented in the previous sections of the thesis.

A steel casting company which operates scrap melting through an electric arc furnace has been considered as the industrial waste heat source. According to the territory-oriented approach adopted for the selection of the case studies within the research work, the typical climate of North-eastern Italy has been considered in order to allow the investigation of the influence of the climate type representative of the European context (which is characterised by marked differences between the various season) on the performance of the different options for the exploitation of the recovered energy. To further improve the research, in future developments of the work an analysis of multiple scenarios characterised by different climate context would be presented, with the aim to outline the importance of the specific context when the external integration of the recovered energy into a Smart Energy System is considered as one of the main options.

Assuming a EAF capacity of 140 t/h, the thermal power H_{avail} made available from the waste heat recovery plant has been estimated up to around 13.5 MW (Baresi et al., 2014). An availability factor of 80% has been considered to account both for the productive cycle downtimes, and in the remaining 20% the availability is assumed to be halved. Plant downtimes due to maintenance have been neglected because they could influence unequally the two waste heat recovery options depending on the actual period of occurrence. The energy from recovery is available in the form of saturated steam, quite constant assuming the 24 hours per day and 7 days per week operations of the steel plant and thanks to the remarkable buffering capacity features of the steam-based EAF waste heat recovery system already discussed in section 4.

It must be pointed out that the furnace Tap to Tap cycle typically takes around 50 minutes to be completed, which is less than the time step of the simulation, then the profile of thermal power available from recovery could be assumed to be the average value.

To evaluate the performance achievable through an external integration of the recovered energy, an urban DH network of about 200 MW maximum installed power, providing to end users space heating and domestic hot water needs, has been considered as the heat sink. Natural gas is considered as the reference fossil fuel feeding the DH boilers (lower heating value of 9.6 kWh/Sm^3), to be replaced by the thermal energy available from recovery.

The typical hourly electric energy load profile for a steelmaking facility operating an EAF based process has been considered to account for the internal load $P_{load,h}$ (Bause et al., 2015). It's worth noting that due to the high power constantly required by a typical EAF in the "power on" phase of the melting cycle (e.g. 70 MW on average), the energy generated from recovery through the ORC unit is likely to be quite entirely allocated to satisfy the company's internal demand.

The investment costs for the DH infrastructure are assumed to be carried out by the company providing the DH service, comprehending also the pipeline structure required to reach the industrial facility for the connection of the waste heat source to the DH network. Only the investment related to the heat exchanger proving the recovered energy to the DHN, which represent an integrated component of the waste heat recovery plant of the industrial facility, is assumed to be carried out by the steelmaking company.

Concerning equipment efficiency, we considered for the DH heat exchanger $\eta_{HE} = 98\%$ and $\eta_{ORC} = 19\%$ for the ORC unit, both constant with varying load.

The specific energy costs, estimated according to the Italian energy market prices, have been considered constant throughout the simulated plant operation period, i.e. one typical year, for the sake of simplicity. A specific cost for the electric energy bought from the grid c_{el} of 0.055 €/kWh has been considered for the industrial facility, and a valorisation of 0.04 €/kWh has been assumed for the selling of the eventual surplus of electric energy produced by the ORC unit. Moreover, fixed values of the financial incentives provided to the primary energy saving projects and of the CO2 emission savings have been considered (i.e. 250 €/TEE and 8 €/tCO$_2$ for the Carbon Tax).

A specific cost for surplus heat dissipation (i.e. thermal energy available from recovery but exceeding the users' demand) of 4 €/MWh has been considered.

As regards the DH option for the exploitation of the recovered energy, simulations were run accounting for the hourly average external temperatures for the whole heating period, i.e. from 15 October to 15 April, according to the Italian regulation. Out of that period, the DH load is assumed to be due only to domestic hot water needs.

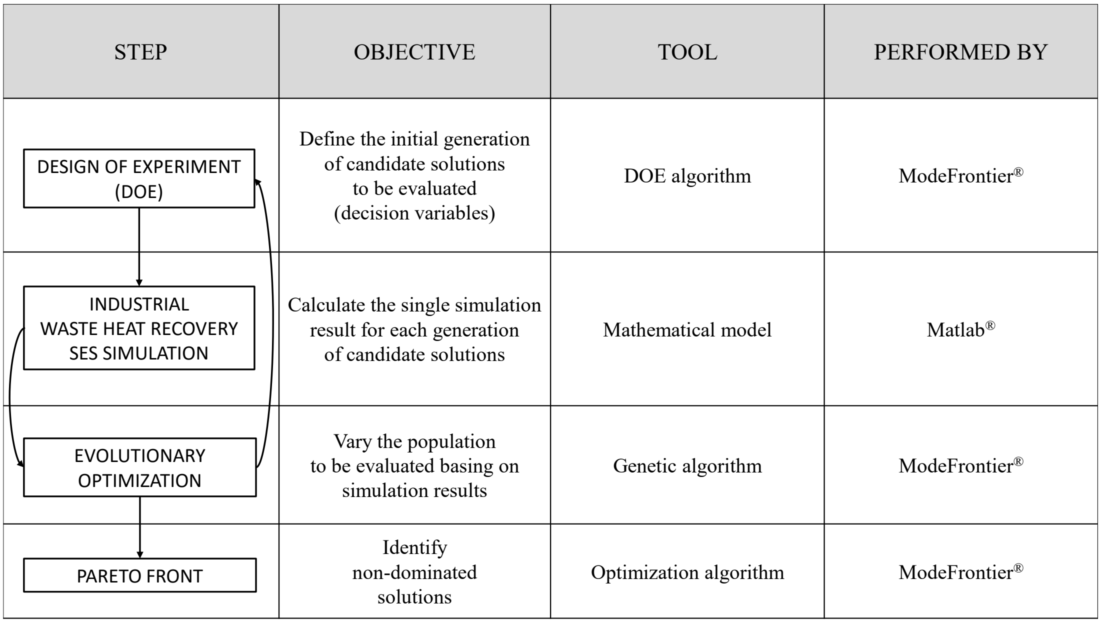
Lastly, the CO2 emission factors and primary energy conversion factors already reported in Table 3.2 have been considered for the involved energy vectors.

In the following table the variation ranges of the decision variables of the multi-objective optimization problem are reported.

Table 6.2. Variation ranges of the decision variables

Decision variable	Unit	Range of variation	Incremental step
v_{th}	€/MWh	1 ÷ 30	1
$P_{ORC,nom}$	kW	0 ÷ 10,000	500

The four steps procedure of the developed evolutionary multi-objective optimization method, i.e. Design of Experiment (DOE), mathematical model, optimization and definition of the Pareto front, have been implemented by use of the software listed in Figure 6.6. The simulation of the energy system through the mathematical model has been performed by Matlab®, while DOE algorithm, genetic algorithm and optimization have been performed by the ModeFrontier® software.



STEP	OBJECTIVE	TOOL	PERFORMED BY
DESIGN OF EXPERIMENT (DOE)	Define the initial generation of candidate solutions to be evaluated (decision variables)	DOE algorithm	ModeFrontier®
INDUSTRIAL WASTE HEAT RECOVERY SES SIMULATION	Calculate the single simulation result for each generation of candidate solutions	Mathematical model	Matlab®
EVOLUTIONARY OPTIMIZATION	Vary the population to be evaluated basing on simulation results	Genetic algorithm	ModeFrontier®
PARETO FRONT	Identify non-dominated solutions	Optimization algorithm	ModeFrontier®

Figure 6.6 Software used for the implementation of the evolutionary multi-objective optimization procedure. Adapted from (Simeoni et al., 2018)

In Figure 6.7 a screenshot of the overall implementation of the multi-objective optimization model in the ModeFrontier® software is provided, highlighting fixed and variable input data to the problem, its output and the design objective represented by the three sustainability objective functions.

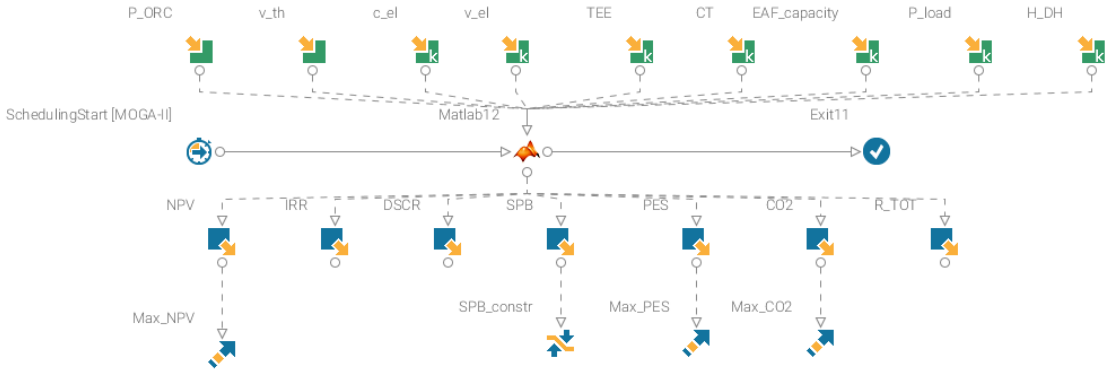


Figure 6.7 Implementation of the multi-objective optimization problem by the ModeFrontier® software: workflow

6.3 Optimization results

The multi-objective optimisation problem for the considered case study has been solved by using a 16 GB RAM, i7 4770 3.40 GHz PC. A population of 100 individuals and 100 generations were adopted, resulting in 10,000 total evaluated designs, enough to obtain the convergence of the process.

6.3.1 Pareto fronts

About the multi-objective optimization results, the influence of the two decision variables on the trade-off between the economic and the environmental performance for the industrial company are represented in the bubble diagram of Figure 6.8, where the Pareto front has been marked by black circles.

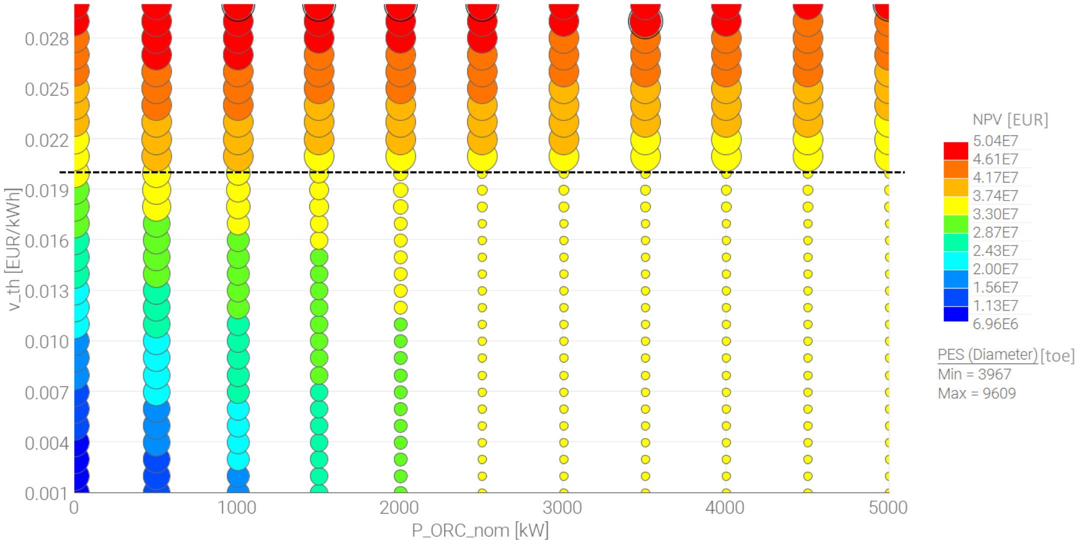


Figure 6.8 Bubble diagram representing the influence of the economic and of the plant design decision variables on the sustainability performance of the waste heat recovery system configuration

Regarding the influence of the economic decision variable, it can be noticed from the graph that the Pareto multi-objective optimization pushes towards the highest value of the selected range. If a value of the thermal energy of 30 €/MWh were agreed with the DHN service provider during the negotiation phase, the economic goal of the steel casting facility could be achieved, as expected. At such value of the recovered energy, the size of the ORC unit seems to have a negligible impact on the economic performance indicator. Nonetheless, for ORC sizes of 1000 up to 5000 kW there are optimal solutions, for both the primary energy saving and the NPV indicators, thus leading to a win-win solution from a sustainability and competitiveness perspective for the industrial stakeholder.

As can be observed from the graph, there is a marked separation line at a thermal energy value of around 20 €/MWh, since above this value the external integration of the recovered energy into the urban DH network becomes the most economically viable option, given the assumptions about the specific value of the electric energy (both self-consumed and sold to the grid). For this reason, different behaviours can be recognized over and under that value.

Moving from the best towards lower values of the economic decision variable v_{th}, if remaining in the field of DH solution priority, remarkable performance of both NPV and PES could however be achieved through a proper selection of the ORC nominal capacity. As can be noticed from the graph, the installation of an ORC unit of around 500 to 1000 kW nominal capacity could allow the achievement of relevant economic revenues even in the event of not fully satisfactory negotiations regarding the sale of the thermal energy, due to the improvement of waste heat recovery revenues during those periods of the year when there is almost no DH load.

When shifting to the field of ORC option priority, a different trend can be observed. The ORC represents in that case the priority destination of the thermal power available, and the DH option is considered only if the company's electric load is exhausted, if the sale of electric energy is less economic efficient with respect to the DH option or when the ORC capacity is not enough to exploit the waste heat recovery potential related to a EAF capacity. Thus, as regards the plant design decision variable, the greater the ORC nominal capacity, the better the economic performance for a given value of the thermal energy sale. A higher ORC size would in fact allow to exploit as much waste energy availability as possible, while keeping still good economic indicators for the company, disregarding the minimization of the investment and operation and maintenance costs of the ORC unit. Once the waste heat availability is saturated, a higher nominal capacity of the ORC would not be exploited, worsening the economic indicator due to the larger investment cost. For the considered EAF capacity of 140t/h, a $P_{ORC,nom}$ of around 2500 kW size would allow to achieve relevant environmental performances together with affordability.

From the primary energy saving perspective, an opposite behaviour can be observed: the greater the ORC nominal capacity, the lower the PES performance when the field of ORC priority is considered. The reason for that is the energy conversion efficiency of the ORC which is less performing if compared to the direct exploitation of the saturated steam to feed the DHN. With the increasing of the ORC size, the contribution of the DH option decreases, thus causing a worsening of the PES indicator.

These main results could help the facility manager in the decision-making phase when the design of the waste heat recovery options is concerned, giving important indications about system configuration and component sizing, such as ORC nominal capacity.

The diagram of Figure 6.9 shows the hourly operation profile, encompassing the entire simulation period (one year), of the waste heat recovery system. Both the considered waste heat recovery options are represented, since according to the multi-objective optimization results a combination of them should be chosen to achieve optimal sustainability performances. The graph refers to a value of the thermal energy sold to the external DHN of 25 €/MWh and to a nominal capacity of the ORC plant of 2.5 MW.

The red line represents the share of the energy made available from the waste heat recovery system which is allocated to the external DH network through the heat exchanger. The blue lines represent the electricity generated by means of the ORC unit thanks to the exploitation of the recovered energy, both for self-consumption ("ORC endo", plotted in light blue) and for sale to the external grid ("ORC eso", plotted in blue).

The total recovered energy is obtained as the sum of the shares allocated to the two exploitation options, to satisfy the energy balance constraint.

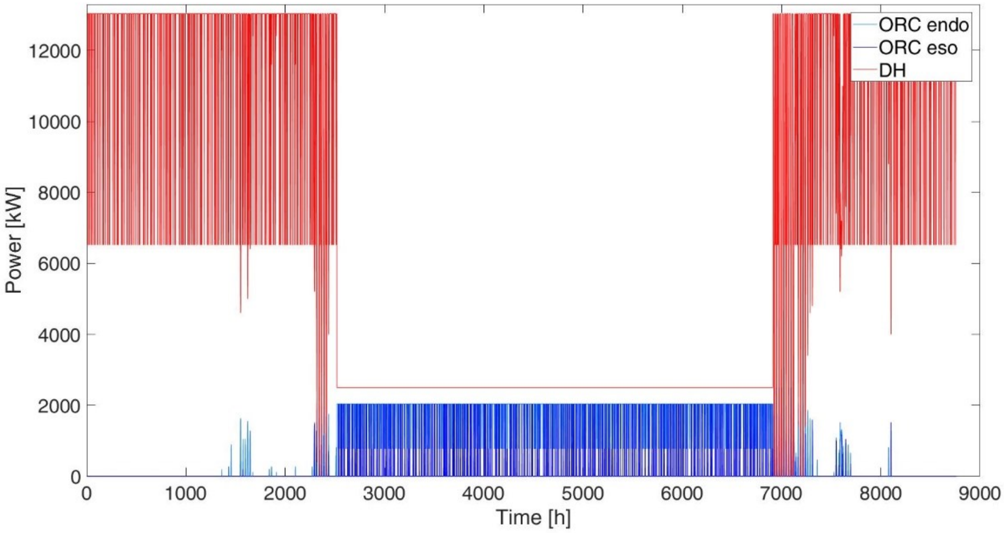


Figure 6.9 Waste heat recovery system simulation. Hourly operation profile of the considered waste heat recovery options for the entire simulation period

As it can be noticed from the graph, which is referred to the case of priority assigned to the external DH integration option (because of economic value ranking reason), given the amount of available waste heat power $H_{avail,h}$ from industrial recovery, the installation of an ORC unit to exploit the eventual surplus thermal energy still available could grant to maximize the primary energy saving and the GHG emission reduction, due to the seasonal climate features of the DH load typical of the considered case study. Since the capacity of the DHN represents an external condition which is fixed for a given case study, a better exploitation of the waste heat source could be only achieved by installing, in combination with the DH heat exchanger, a power generation plant able to convert as much as possible of the surplus energy eventually available after the DH load has been satisfied, thus maximizing the total amount of recovered energy but also minimizing the energy to be dissipated because of excess of availability. This is highlighted in the graph of Figure 6.10, in which a portion of the simulation period is represented (end of the winter/earl spring).

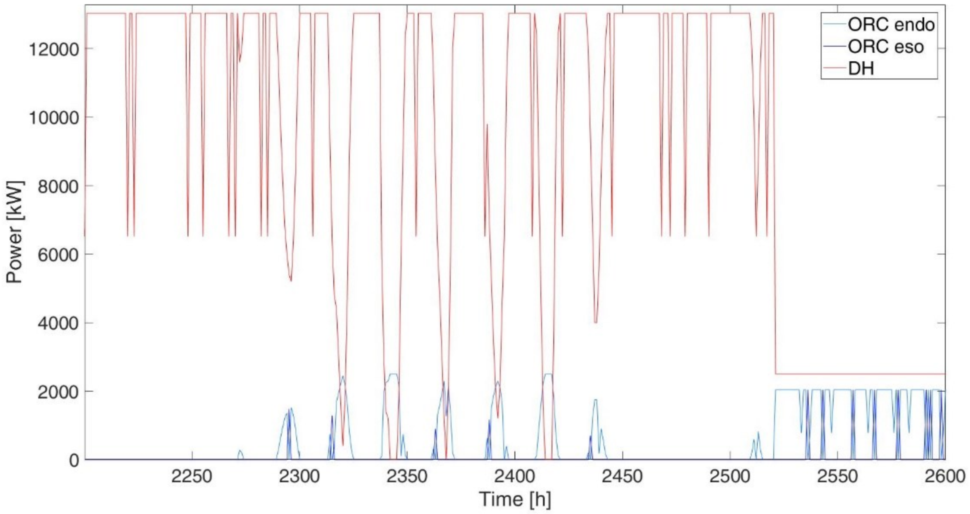


Figure 6.10 Waste heat recovery system simulation. Hourly operation profile of the considered waste heat recovery options for a portion of the simulation period (end of winter)

Given the amount of industrial waste heat available for recovery (roughly 13 MW), as can be noticed by the value of the energy provided to the external DH network during the heating season (i.e. approximately from 15 October to 15 April), which saturates the availability for most of this time, the DHN user basin selected in this scenario allows a satisfactory exploitation of the waste heat source and, thus, significant primary energy saving and GHG emission reduction performance. The installation of an ORC unit of 2.5 MW nominal power capacity allows to exploit the surplus of waste energy availability, which otherwise would be sent to dissipation during the rest of the year because of the seasonal lack of external demand. Thus, as already outlined, without the parallel combination of both the two waste heat recovery options, also in the case of a suitable DH user basin, high dissipation would occur due to the seasonal features of the considered climate. Since the heat load during the warm months (spring and summer) would be only due to domestic hot water needs, it would not be high enough to allow a significant exploitation of the recovered energy in this period of the year. In conclusion, for the considered case study concerning industrial waste heat recovery in the EAF steelmaking sector in the European context, which is characterized by a seasonal climate, the optimal combination of both exploitation options could allow a company to achieve the best sustainability performance, otherwise not reachable with the implementation of only one of the energy recovery solutions.

6.4 Final considerations

Concerning waste heat recovery projects in the energy-intensive industrial sectors, facility managers face the challenge of making the optimal strategic choice within different waste heat recovery options, since the external integration of the recovered energy might not represent necessarily the best option from the company's perspective.

With the aim to integrate the analysis presented in section 5, where the conflicting objectives related to the different stakeholders involved in a waste heat-based DH project have been investigated, in this part of the research only the energy recovery options based on a smart energy system approach (power generation through an ORC unit and the DH external integration) have been considered within the ones identified by the conceptual framework presented in section 4, because of their potential to guide the transition towards sustainability. Indeed, when both a potential demand from external users exists and the opportunity to produce electricity represents an attractive option, in order to allow the facility manager to select the most suitable waste heat recovery option and to decide which project to endorse, a deeper insight on the sustainability performances of each potential waste heat recovery solution is required. The economic objective represents the main driver, although environmental objectives are becoming increasingly important, also thanks to the rising value of green marketing.

The proposed DSS method has then been further developed by means of its application to the adoption of the facility manager's perspective, with the aim to investigate the trade-off between the economic, energetic and environmental performances of both different options for waste heat recovery exploitation, thus allowing a strategic decision making for the endorsement of the related investments.

As the first results for its test application to a case study representative of the typical European climate context have underlined, the developed evolutionary multi-objective optimization model for decision support has proved to provide the facility manager precious suggestions regarding the optimal configuration of the energy recovery system, i.e. the selection of the most suitable option for the exploitation of the recovered energy and the best combination of different technologies, their optimal sizing and the definition of the operational strategy. Moreover, the developed model can be used not only in the system design phase, but also as a support to the facility manager in the negotiation task, providing significant suggestions about the range of values of the thermal energy sale to an external DH service provider which could grant to satisfy the goals of the company that would make available the waste heat.

7 IMPLEMENTING AN IT TOOL FOR DECISION SUPPORT: THE CE-HEAT PROJECT

The exploitation of the huge potential for industrial waste heat recovery detected in Europe represents an opportunity to accomplish the objectives set by the European Union with the aim to fight climate change. In this context, the CE-HEAT project, funded by the Interreg Central Europe Program and involving nine partners from seven Countries, aims to increase energy efficiency in a circular economy perspective and to reduce greenhouse gas emissions through the exploitation of industrial waste heat as an energy source in Central Europe space (Ciotti et al., 2019). The two main objectives of the CE-HEAT project are the preparatory production of a land register of regional waste heat (supported by GIS) and subsequently the development of an online toolbox for the preliminary assessment of investments in waste heat recovery projects.

Concerning the first target, the developed atlas accounts for the industrial facilities spread all over the regions involved in the project and reports a theoretical waste heat potential determined through a bottom up estimation, derived from industries' environmental permits. Waste heat sources are distinguished between hot water or hot exhaust gases depending on the specific industrial process.

The online decision support toolbox is meant to allow a preliminary assessment of investments in waste heat recovery projects and aims at aiding the decision-making process of investors and policy makers to compare different scenarios combining various heat recovery technologies (some of which to be applied inside the considered industrial site and others addressed to the external integration) through the evaluation of technical, economic, environmental and energetic performance indicators.

The developed decision support system (DSS) has then been applied to aid the implementation of such online tool for the decision-making process, as described in the next subsection.

The full version of this work and the results obtained were published in the article "Ciotti G, Cottes M, Mazzolini M, Sappa A, Simeoni P. A decision support system for industrial waste heat recovery: the CE-HEAT project. In: Conference Proceedings of the 24th AIDI Summerschool "Francesco Turco". Sept. 11-13, 2019, Brescia (AIDI2019.71)".

7.1 Applying the developed DSS to the implementation of an online toolbox for the preliminary evaluation of waste heat recovery projects

As anticipated, the objective of the online toolbox is to perform a pre-feasibility analysis of different waste heat recovery options, providing the various stakeholders which could be interested in an industrial waste heat recovery project an overview of the economic and environmental impact of their choices, to allow a more conscious decision-making process.

Given the level of detail of the information available from the atlas provided for the implementation of the decision support toolbox, the latter is meant to be a pre-feasibility analysis of different waste heat recovery options.

Concerning the "data collection" phase, waste heat sources, waste heat recovery technologies and final users are then investigated at a simplified first level of detail, input data are then characterised by the first level of detail reported in Figure 6.5 (i.e. average values of the involved information).

Moreover, the waste heat sources have been modelled with two main clusters, continuous or discontinuous, depending on the features of the industrial process, and similarly as regards final users.

The "evaluation" phase, in this context of application of the proposed DSS, doesn't include evolutionary multi-objective optimization, since the scope of the application of the DSS is to obtain a database of evaluation results to be implemented in the online toolbox, without optimizing the designs. Rather, a techno-economic and environmental evaluation is performed, in order to evaluate the sustainability performances that interest the stakeholders.

For the same reason, the decision-making phase of the developed decision support system has not been applied in this context, since the decision making is meant to be carried on by the end users of the online toolbox while running it.

Decision variables such as financial incentives to be granted by public institutions, and sensitivity analysis on features such as thermal and electric energy costs have been considered.

The toolbox is meant to work this way: once the input data values are selected by the user, the program will provide the decision support suggestions in terms of sustainability performance indicators, displayed by graphs and tables, allowing a comparison of the various waste heat recovery options.

7.2 Waste heat recovery options modelling

The online toolbox considers different options of industrial waste heat recovery, both 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 potential end user of the recovered energy.

Both the availability of waste energy from the industrial source and energy demand of the consumers can be modified by the toolbox's end user, in order to suite the specific features of the considered case study. Given the wide range of industrial activities and processes, the model takes only into account the fluid that is carrying the waste energy (distinguishing between exhaust gases or hot water).

Six different waste heat recovery options have been embedded in the online toolbox: ORC plant to generate electricity, absorption chiller to satisfy 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 a set of buildings located in a narrow range from the industrial waste heat source, and lastly a combination of an ORC unit and of district heating, with the aim to explore the feasibility of a technology cascade system aiming to the maximization of energy recovery.

Concerning the characterization of the availability of the waste heat source, it has been described by a simplified time scheduling which considers 4 time slots per day of 6 hours each, and a Boolean variable which indicates if the heat source is available in the selected time slot. The same approach has been adopted for the characterization of the user demand. To complete the characterization, the input and output temperatures and mass flow rates of the waste heat source and of the end users are required to be selected in order to determine the enthalpy of the heat transfer fluid.

Two different industrial waste heat source clusters have been considered 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 energy intensive industrial sectors such as iron and steel, 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). This has been adopted for e.g. textile and food industries.

The modeling of the considered technology for the exploitation of the recovered energy has been provided by a partner of the CE-HEAT project. Concerning the economic evaluation, cost functions have been used to estimate the capital cost of the considered technologies according to (Bejan et al., 1996). Moreover, also operation and maintenance costs (O&M), engineering costs, costs for civil buildings constructions, and revenues from the sale of the recovered energy have been considered.

The economic analysis is carried out through four different profitability criteria: payback period (PB), net present value (NPV), internal rate of return (IRR), and the debt service coverage ratio (DSCR).

7.3 Results: the database for the implementation of the decision support toolbox

One of the main goals of the CE-HEAT project was the implementation of an online decision support toolbox aimed at helping final users in the comparison of different waste heat recovery options, based on the information contained in the atlas developed by APE FVG. To aid the implementation of such a toolbox, as one of the project's preliminary activities the proposed DSS has been applied as presented in section 7.1 to provide a database composed by input data and output results of the evaluation model.

The evaluation performed through the developed model allowed the production of a database in a proper format in order to make it suitable for the implementation in the online waste heat recovery tool for decision support. Every considered scenario of waste heat recovery option lead to a single spreadsheet file. In Table 7.1 the range and step of variation of the dimensions selected for the realization of the database to be implemented in the online tool are reported.

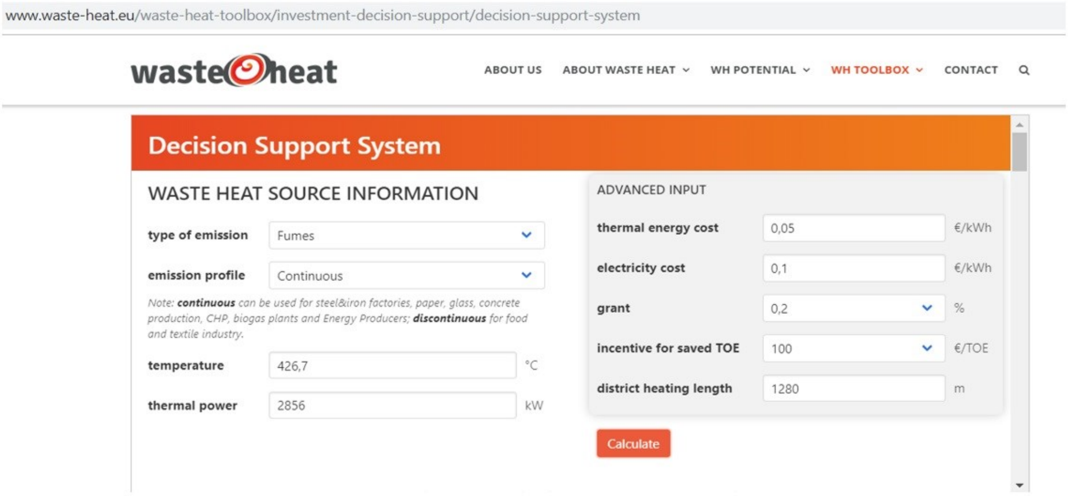
Concerning the intended use of the implemented online toolbox for decision support (Figure 7.1), a potential investor can first check the waste heat cadastre to identify interesting waste heat sources. After selecting a waste heat source, the investor can access data concerning the waste heat available in the cadastre. It is also possible to measure distances between the source and a potential energy sink. These data should be then used in the "Decision Support System" online tool to assess different opportunities for the exploitation of the recovered energy under a technical and economic 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, since they need to embed energy recovery planning in policy strategies to meet environmental goals. Waste heat sources suitable for recovery projects could be selected within the waste heat cadastre and related data could be used in the DSS.

Moreover, policy makers, by setting different grants and incentives for primary energy saving targets, can define which incentive schemes should be developed to make waste heat recovery bankable.

Table 7.1 Range and step of variation of the considered dimensions (Ciotti et al., 2019)

Dimension	Unit	Range	Step
Heat exchanger power	(kW)	20-10,000	100
Heat pump power	(kW)	30-1,200	30
Absorption chiller power	(kW)	100-4,000	100
District heating	(kW)	100-20,000	1000
ORC power	(kW)	500-4,000	200
Temperature (ABS, ORC, HE, District)	(°C)	200-700	100
Temperature (Heat pump HP)	(°C)	20-60	5
Temperature (Match)	(°C)	400-700	100
Grant	(%)	0-50	10
TEE	(€/TEE)	100-400	100
Electricity cost	(€/kWh)	0.025-0.2	0.025
Thermal energy cost	(€/kWh)	0.03-0.12	0.01
District heating	(km)	0.5-10	2



Decision Support System

WASTE HEAT SOURCE INFORMATION

type of emission Fumes

emission profile Continuous

*Note: **continuous** can be used for steel&iron factories, paper, glass, concrete production, CHP, biogas plants and Energy Producers; **discontinuous** for food and textile industry.*

temperature 426,7 °C

thermal power 2856 kW

ADVANCED INPUT

thermal energy cost 0,05 €/kWh

electricity cost 0,1 €/kWh

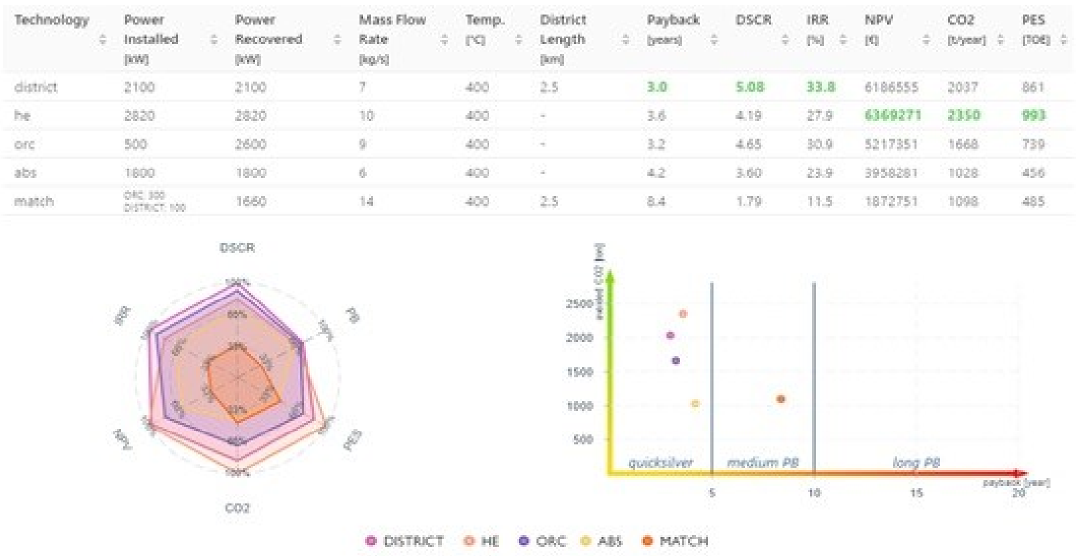
grant 0,2 %

incentive for saved TOE 100 €/TOE

district heating length 1280 m

Figure 7.1 CE-HEAT DSS toolbox’s user interface: input data required (Ciotti et al., 2019)

Once the input data are selected by the online DSS toolbox user, the program will provide the decision support suggestions in terms of sustainability performance indicators and graphs (Figure 7.2).



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]
district	2100	2100	7	400	2.5	**3.0**	**5.08**	**33.8**	6186555	2037	861
he	2820	2820	10	400	-	3.6	4.19	27.9	**6369271**	**2350**	**993**
orc	500	2600	9	400	-	3.2	4.65	30.9	5217351	1668	739
abs	1800	1800	6	400	-	4.2	3.60	23.9	3958281	1028	456
match	ORC: 300 DISTRICT: 100	1660	14	400	2.5	8.4	1.79	11.5	1872751	1098	485

Figure 7.2 CE-HEAT DSS toolbox's user interface: comparison between different waste heat recovery options (Ciotti et al., 2019).

7.4 Final considerations

In the CE-HEAT project, involving partners belonging to Austria, Czech Republic, Croatia, Germany, Italy, Poland and Slovenia, an online toolbox has been implemented to aid the decision-making process of investors and policy makers when comparing, through the evaluation of technical, economic, environmental and energetic performance indicators, various industrial waste heat recovery options based on the exploitation of different technologies.

To implement such tool, a simplified version of the decision support model developed in this thesis has been applied to provide a database of input data and output results of the sustainability evaluation of the different recovery options to be embedded in the online tool.

The developed model for decision support has thus proved to represent also a generalized procedure suitable for the investigation of case studies representative of different contexts with respect to the ones considered in this thesis.

Moreover, the developed model for decision support proved that could be applied also in a simplified version to allow the implementation of user-friendly IT tools aimed at enhancing the perception of the need for a sustainability improvement within the energy intensive contexts.

CONCLUSIONS

Global energy consumption and the related carbon dioxide emissions, which represent a large share of the overall anthropogenic greenhouse gas production, are continuously increasing since most of the energy needs are still provided by fossil fuels, thus constituting one of the main issues to be addressed in the climate change mitigation agenda.

To achieve the Paris Agreement's ambitious objectives, a transition towards sustainable energy systems based on the new smart energy system paradigm is needed, integrating the various energy sectors (electricity, heating, cooling, transport, etc.), energy sources, vectors and needs. Given the boost towards such a sustainable energy transition, the single entity's boundaries would be overcome in favour of synergies, in order to allow sustainability benefits otherwise not reachable.

However, a smart energy system represents an integrated system characterized by technical complexity and high investment cost, involving several stakeholders aiming at different, often conflicting, goals. Optimal planning, design and management of integrated systems such as SES require then to make use of proper decision support models based on multi-objective optimization techniques, as a sustainability analysis is intrinsically a multi-objective optimization problem because it involves environmental, economic and social aspects.

The literature review highlighted a lack of multi-objective optimization studies applied to the planning and design of solutions for the sustainable energy supply of industrial districts that provide complex integrated systems (i.e. Smart Energy System) and, moreover, a lack of comprehensive frameworks for planning and design of the integration of industrial clusters with urban areas and RES.
Furthermore, as an integrated infrastructure planning approach will gain growing importance, the development of proper decision support models to help the decision makers when endorsing the relevant investments expected in this sector would be required because of their high capital-intensity and long-term pay-back periods. Finally, a SES project, especially when based on the synergy between industrial and urban areas, most likely involves several stakeholders, each driven by different, often conflicting, objectives. Therefore, research efforts should also be focused on considering the different involved stakeholders within the models developed for planning, design and management, a crucial aspect to remove some relevant barriers to the energy transition, since the adoption of a system approach is required in a smart energy system context.

Focusing on the improvement of the sustainability of the energy-intensive sectors, the main objective of this thesis was thus the development of a decision support framework based on multi-objective optimization with the aim to support the decision makers in the planning, design and management of integrated smart energy systems, while considering the different involved stakeholders.

The proposed model, described in Section 2, has been developed by steps via its application on case studies belonging to two main topics concerning the improvement of the sustainability performance of energy-intensive sectors through the implementation of the smart energy system concept. The first main topic is representative of the context of industrial districts and concerns their sustainable energy supply based on renewable sources, tri-generation, energy storage and micro-grids. The other one concerns the synergic integration between industrial and urban areas, thanks to the recovery of waste energy from industrial processes to feed municipal district heating with a carbon-free source.

The case studies have been selected, within the energy-intensive sectors opportunities available in the local territorial context, not only because fit for the implementation of the smart energy system concept, but also due to their suitability for the implementation of the different phases of the proposed DSS.

Concerning the first topic, relevant opportunities for the improvement of the sustainability performances of the industrial districts could be unlocked if single company's boundaries were overtaken towards the establishment of synergies allowed by geographical proximity, thus exploiting the potential benefits offered by the implementation of the smart energy system concept. In Section 3 the developed decision support framework has been applied with the aim to prove its potential in supporting the decision makers in the planning and design of sustainable energy supply for industrial areas based on smart energy system concept, involving CCHP, RES, thermal energy storage systems, DHC and electricity distribution networks serving a cluster of firms. This first application has been focused on the data collection, processing and analysis phase (particularly as regards performance indicators) and on the Pareto evolutionary multi-objective optimization phase of the developed procedure.

The considered case study concerned an industrial district of the food sector, which was suitable for the implementation of the smart energy system concept because of the simultaneous presence throughout the year of both electric, heating and cooling power.

Beside including indicators for monitoring the improvement of the sustainability performance and energy efficiency of the industrial area (and/or the single companies), the developed framework has proved to represent an effective tool that could aid decision makers (industrial districts' managers and/or institutions dealing with territorial energy planning and investors) in identifying the most suitable smart energy system configuration. Results showed that the multi-objective optimization carried out on economic, environmental and energetic objective functions allows the investigation of the trade-off between the different objective functions and the analysis of how sustainability performances change based on the selected smart energy system configuration, so that it can act as a decision support tool to identify the most viable layout through the proper sizing of CCHP and RES. It also provides design suggestions such as the identification of the optimal capacity of thermal energy storage systems.

Furthermore, the application to the case study proves that the SES concept can really represent a main opportunity to industrial districts either from the sustainability and the competitiveness perspective. Thus, the developed tool can be used not only in the system design phase, but also as a support to plan regional development.

Lastly, research suggests that some financial incentives or regulation adjustments could be studied so that a smart energy system solution providing remarkable potential benefits from the energy savings and the GHG emission reduction perspectives could consistently improve its economic attractiveness.

Concerning the second main topic, the energy-intensive industrial sector could present relevant opportunities for the implementation of energy efficiency measures (such as e.g. waste heat recovery) to be exploited not only within the company (endogenous level, traditional approach) but also by overtaking its boundaries towards a smart energy system external integration.

Industry is responsible for a large share of total greenhouse gas emissions related to primary energy consumption, and some industrial sectors are particularly energy intensive. Waste heat recovery in energy intensive industries represents one of the greatest opportunities to reduce their consumption of primary energy thus increasing their competitiveness and sustainability. Due to the relevance of both its energy requirements and energy efficiency opportunities among the most energy-intensive productive sectors, and because of its huge presence in both the European and the local territorial context (often at a useful distance from urban areas), steelmaking industry based on electric arc furnace (EAF) melting process has been identified as suitable case study for the investigation, through the application of the developed decision support model, of the potential for sustainability improvement which could be unlocked through the overcoming of company's internal boundaries towards a smart energy system integration, through the recovery of waste energy from industrial process to feed municipal district heating with a carbon-free source.

In Section 4 a comprehensive overview on the available technologies for the recovery of waste heat from the steelmaking process based on electric arc furnace has been provided, and a conceptual framework for the identification of different possible exploitation strategies for the recovered energy in future heat recovery projects in steelmaking industry, as well as other energy intensive industries, has been proposed, ranging from the internal use to the external integration into smart energy system. The aim of the proposed framework is to aid the identification of different potential waste heat recovery scenarios to be investigated by means of the proposed DSS model. The framework is based on the potential demand from external users as the main criterium, while considering also the opportunity to generate electricity by installing a power unit feed by the recovered energy.

Therefore, internal use or external integration should be evaluated based on the actual context where the waste heat is available. However, recent projects highlight a trend towards an exploitation strategy based on the smart energy system approach. The single industrial plant's boundaries are overcome in favour of symbiotic synergies, which could allow a wider exploitation of the recovered energy, otherwise difficult to reach by internal use only. Therefore, the research effort has been focused on empowering smart energy systems by means of the involvement of the different stakeholders involved in such projects.

In Section 5 of the thesis, with the aim of completing the development of the proposed evolutionary multi-objective optimization model for decision support, and moreover to prove its potential in performing a sustainability evaluation of urban-industrial synergy, it has been applied to an Italian case study representative of the European context, a municipal DHN in a typical city brown field context fed by the waste energy recovered from an EAF steelmaking industrial facility.

The conflicting objectives related to the different stakeholders (DHN service provider, the industrial waste heat source, residential consumers, public authorities, etc.) involved in the exploitation of industrial waste heat recovery through its integration into an urban DH smart energy system have been considered.

The selected case study was particularly suitable for the development of the "design" (scenarios) phase of the proposed method for decision support, because the selection of the most suitable set of end users, but also of the different city areas and consumer types to be served by the waste heat based DHN, requires the identification of different scenarios to be analysed. Moreover, the considered context was also suitable for the development of the "decision making" phase, due to the involvement of different stakeholders, each of them representing the bearer of different goals, thus requiring accounting for different weighting for the decision-making criteria.

The proposed DSS model has proved to be able to foster the development of a SES concept based on the integration of waste heat recovery from an energy intensive industry to be exploited by supplying a municipal DHN, allowing the decision makers (policy makers, institutions responsible for territorial energy planning, investors, etc.) to analyse how sustainability performance change based on the favourite stakeholder, highlighting the trade-off as well as win-win situations to be exploited, so that it can help to identify the most viable solution.

Results outlined that is possible to plan an industrial waste heat based DHN that simultaneously meets the objectives of the different stakeholders involved, obtaining a win-win solution for both the industrial sector and the citizenship from a sustainability perspective. Moreover, a compromise solution between the economic and the environmental goals could not be necessary if the district heating network set of users and the city areas to be served are properly selected, in order to fully exploit the available waste energy, thus leading to remarkable economic and environmental performances. The proposed model also provided design directions about the DHN infrastructure and generation plant technical configuration, such as the most suitable thermal energy storage capacity to be selected.

Moreover, the developed model can allow to identify the public policies needed to sustain the effective transition towards such sustainable energy supply. Thus, the developed tool can be used not only in the system design phase, but also as a support to plan regional development, as the results for its application to the case study of Udine city, in North-Eastern Italy, have underlined.

Concerning the opportunity to implement an efficiency measure such as the recovery of process waste heat in an energy-intensive industry, its facility manager faces indeed the challenge of making the optimal strategic choice among the several waste heat recovery exploitation options identified within the conceptual framework.

If only the company's goals are considered, the different options for the exploitation of the recovered energy could be both synergistic and conflicting, and the overcome of company's boundaries in favour of synergies (as investigated in Section 5) might not necessarily represent the best option from the facility manager perspective.

Indeed, when both a potential demand from external users exists and the opportunity to produce electricity represents an attractive option, in order to allow the facility manager to select the most suitable waste heat recovery option and to decide which project to endorse, a deeper insight on the sustainability performances of each potential waste heat recovery solution is required. The economic objective represents the main driver, although environmental objectives are becoming increasingly important, also due to the rising value of green marketing.

With the aim to integrate the analysis presented in Section 5, where the conflicting objectives related to the different stakeholders involved in a waste heat-based DH project have been investigated, in Section 6 the proposed evolutionary multi-objective optimization DSS has then been further developed by means of its application to the adoption of the facility manager's perspective, thus completing the investigation of the second main topic of thesis. The DSS model has been applied to an EAF steelmaking case study with a surrounding urban area belonging to a context representative of the typical European climate, with the aim to prove its ability in helping the company's facility manager in the selection of the most suitable waste heat recovery exploitation option..

The model enables the investigation of the trade-off between the economic, energetic and environmental performances of the considered options for waste heat recovery exploitation, thus allowing a strategic decision making for the endorsement of the related investments. Because of their potential to guide the transition towards sustainability, only the energy recovery options based on a smart energy system approach (power generation through an ORC unit and the external integration of the recovered energy into a municipal DH network) have been considered among the several ones identified by the conceptual framework presented in Section 4.

As the first results for its test application to a case study representative of the typical European climate context have underlined, the developed evolutionary multi-objective optimization model for decision support has proved to provide the facility manager precious suggestions regarding the optimal configuration of the energy recovery system, i.e. the selection of the most suitable option for the exploitation of the recovered energy and the best combination of different technologies, their optimal sizing and the definition of the operational strategy. Moreover, the developed model can be used not only in the system design phase, but also as a support to the facility manager in the negotiation task, providing significant suggestions about the range of values of the thermal energy sale to an external DH service provider which could grant to satisfy the goals of the company that would make available the waste heat.

Finally, the identification of the optimal waste heat recovery option among several possible ones was also the subject of a European research project. The CE-HEAT project, funded by the Central European Program and involving nine partners belonging to Austria, Czech Republic, Croatia, Germany, Italy, Poland and Slovenia, aimed to increase energy efficiency (in a circular economy perspective) and to reduce greenhouse gas emissions through the exploitation of industrial waste heat as an energy source. One of the main objectives of the project was the development of an online toolbox for the preliminary assessment of different waste heat recovery options, based on the exploitation of different technologies, thus providing the various stakeholders involved in a waste heat recovery project an overview of the economic and environmental impact of their choices and allowing a more conscious comparison between different waste heat recovery options and selection of the most suitable one.

To implement such tool, a simplified version of the decision support model developed in this thesis has been applied to provide a database of input data and output results of the sustainability evaluation of the different considered recovery options, to be embedded in the online tool. The developed model for decision support has thus proved to represent also a generalized procedure suitable for the investigation of case studies representative of different contexts with respect to the ones considered in this thesis. Moreover, the developed model for decision support proved that could be applied also in a simplified version to allow the implementation of user-friendly IT tools aimed at enhancing the perception of the need for a sustainability improvement within the energy intensive contexts.

The proposed DSS has revealed to represent a powerful tool to guide the transition towards the enhancement of the sustainability of the energy intensive sectors. It can be applied to different industrial production and climate context and allows to embrace multiple objectives of different stakeholders. Its fully exploitation will be investigated and pursued in the next future research.

NOMENCLATURE

AC	absorption chiller
AF	availability factor
AOC	annual operating costs (EUR)
AOP	annual operating profit (EUR)
BB	backup boiler
CapCost	Capital cost (EUR)
CHP	Combined heat and power
CCHP	Combined cooling heat and power
CDE	carbon dioxide emission savings
CDS	Closed distribution system
CF	cash flow (EUR)
CHP	combined heat and power
COP	coefficient of performance
CPI	Cost performance indicator (EUR/ton_{pr})
DH	District Heating
DHN	district heating network
DOE	design of experiment
DSCR	debt service coverage ratio
DSS	Decision support system
EAF	electric arc furnace
EC	electric chiller
EPI	energy performance indicator (kWh/Mg_{pr})
ERR	Emission reduction ratio
GA	genetic algorithm
GEPI	Greenhouse gas emission performance indicator ($MgCO_{2\text{-}eq}/Mg_{pr}$)
GHG	Greenhouse Gas

GIS	geographic information system
HOB	heat only boilers
HE	Heat exchanger
HP	Heat pump
IRR	Internal rate of return
IS	Industrial symbiosis
IUS	Industrial urban system
MCDM	Multi criteria decision making
MOGA	Multi-objective genetic algorithm
NPV	Net present value (EUR)
ORC	Organic Rankine cycle
O&M	operation and maintenance
PDO	Protected Designation of Origin
PEPI	Primary energy performance indicator (TOE/Mg_{pr})
PES	primary energy saving (TOE)
PESR	primary energy saving ratio
PGU	power generation unit
PV	solar photovoltaic
PV_R	ratio of the photovoltaic area to the total area used for the solar source
RES	Renewable Energy Sources
SAUF	Solar utilization factor of the total net available rooftop area
SEU	Sistema efficiente di utenza
SES	smart energy system
SF	simultaneity factor
SMES	smart multi energy system
SPB	Standard pay back (years)
SPS	separate production system
SS	switch set

ST	solar thermal
TEE	Titolo efficienza energetica - “White Certificates” (EUR/TOE)
TES	Thermal energy storage
TOE	Tonnes of oil equivalent

SYMBOLS

A	area (m^2)
C	cooling power (kW)
C	cost (EUR)
c	specific cost (EUR/kWh) or (EUR/m^3)
E	energy (kWh)
e	given kind of energy vector
F	fuel power (kW)
H	heating power (kW)
I	discount rate
k	inflation rate
L	power (electric, heating, cooling) demand/load (kW)
N	lifetime of the project (years)
P	electric power (kW)
p	specific price (EUR/kWh)
T	Temperature (K)
t	time (h)
V	volume (m^3)
θ	temperature (°C)
η	efficiency
μ	pollutant emission conversion factor
ξ	primary energy conversion factor

SUBSCRIPTS AND SUPERSCRIPTS

avail	available
AC	absorption chillers
BB	Back-up Boiler
c	specific cost
CHP	Combined heat and power
co	cooling
carbon,tax	carbon tax
EC	electric chillers
el	electric
energy	energy
eq	equivalent
f	fuel
grid	electricity grid
GRIDIN	electric energy imported from the external grid
GRIDOUT	electric energy exported to the external grid
h	given hour
id	indoor design
IN	intake of the storage
industry	industry related
inv	investment
j	generic building belonging to the considered consumer category
L&E	Lights and Equipment
load	current load
nom	nominal capacity of the considered component
o	outdoor

od	outdoor desing
OUT	provided by the storage
O&M	operation and management
pr	product
PV	solar photovoltaic
rec	energy recovered
ref	Reference
SMES	smart multi energy system
SP	separate production
ST	solar thermal
TES,C	thermal energy storage, cold
TES,H	thermal energy storage, hot
th	thermal
tot	total
user	user related
w	consumer type
waste	dissipated thermal energy/waste heat

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