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DEVELOPMENT OF AN ENVIRONMENTAL AND ECONOMIC OPTIMIZATION MODEL FOR DISTRIBUTED GENERATION ENERGY SYSTEMS

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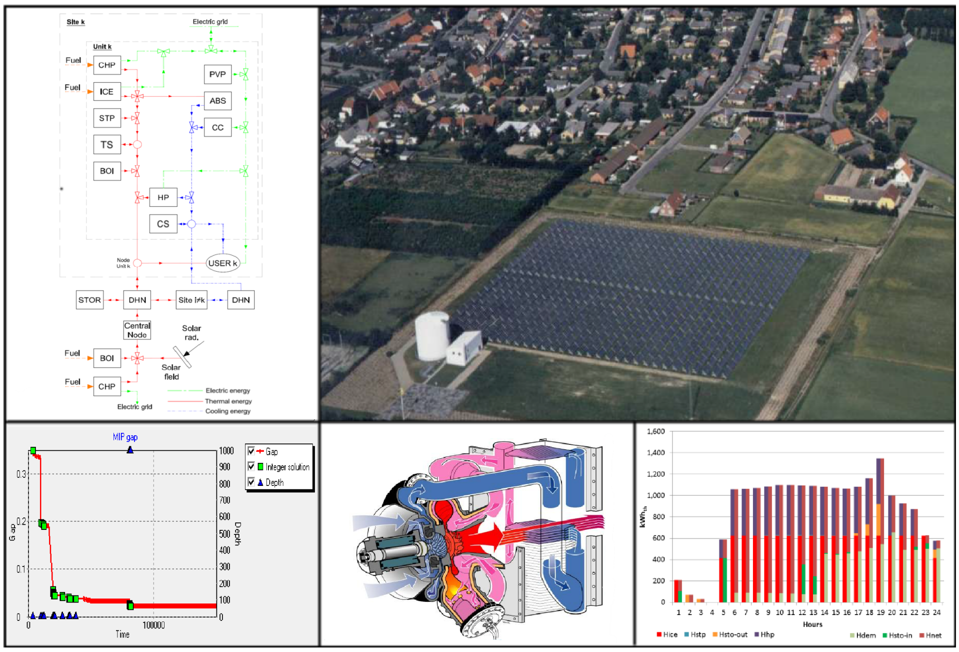

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COVERART

Top-left: Superstructure of the energy system including several energy components, central solar field and seasonal storage.

Top-right: Picture of a real Solar District Heating System.

Button-left: GAP trend during an optimization.

Button-center: Microgas-turbine.

Button-right: Optimal operation maganegement of electric amounts during a winter day.

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Abstract

The reduction of pollutant emissions is one of the current main targets fixed by the most important international authorities. The reduction of the energy needs in the residential-tertiary sector can help achieving this goal, as it represents one of the dominant energy consuming sectors in industrialized societies. However the adoption of an energy system still depend on technical and economical evaluations, while environmental considerations are not taken into consideration yet. For this reason, a development of a tool for the selection of an energy system which allows the reduction of the overall costs containing in the meanwhile the pollutant emissions could help reaching the environmental targets.

The paper proposes a methodology for the Multiobjective optimization of a Distributed Generation Energy System. Such a system is normally constituted by several users connected to each other and to a central unit through a District Heating Network. Furthermore, each unit can be equipped with an internal production unit for the production of its energy needs. Therefore, the determination of the optimal energy system requires the simultaneous optimization of the synthesis, design and operation of the whole energy system. The total annual cost for owning, operating and maintaining the whole system is considered as economic objective function, while the total annual operation CO_2 emissions is considered as environmental objective function.

An optimization MILP model for the optimization of tertiary sector Distributed Generation Energy Systems is developed and is applied to a real case study, made up of nine tertiary sector users located in a small town city center situated in the North-East of Italy. A preliminary energy audit allowed the determination of the users' energy needs.

The energy system is optimized for different configurations in order to understand how different components affect the optimal solution.

Acknowledgments

Although this dissertation work took a lot of hard work and dedication on my part, it would not have been possible without the help and contributions of several people.

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Last but not least, my most important thanks is to my wife Federica, to whom the dissertation is dedicated, for following me in the States, for her incredible patience and inexhaustible support during the last year, particularly on those days I spent more time with my computer than with her. She is the main reason I achieved this goal. Thank you.

Contents

Nomenclature

Notation	**Description**
δ_c	Cooling loss percentage.
δ_t	Thermal losses percentage.
Δt	Difference between outlet and inlet temperatures $[K]$.
η_{boi}	Boiler (BOI) efficiency.
$\eta_{boi,c}$	Central BOI efficiency.
$\eta_{el,ref}$	Electric efficiency of reference.
$\eta_{th,ref}$	Thermal efficiency of reference.
$\boldsymbol{\psi_{boi,c}}$	Additional variable for the centralized BOI.
ρ_p	Medium density $[\frac{kg}{m^3}]$.
$\boldsymbol{\tau}$	Additional variable for the District Heating and Cooling Network (DHCN) network (binary).
$\boldsymbol{\xi}_{ice,c}$	Additional variable for the centralized Internal Combustion Engine (ICE).
A_p	Diameter of the pipeline $[m^2]$.
$\boldsymbol{C_{abs}}$	Cold produced by the Absorption Chiller (ABS) $[kWh]$.
c_{abs}	ABS investment cost $[e]$.
$C_{abs,lim}$	ABS operation limits $[kW]$.
c_{boi}	BOI investment cost $[e]$.
$c_{boi,f}$	BOI fixed investment cost $[e]$.
$c_{boi,v}$	BOI variable investment cost $[e/kW]$.
$\boldsymbol{C_{cc}}$	Cold produced by the Compression Chiller (CC) $[kWh]$.
c_{cc}	CC investment cost $[e]$.
c_{hp}	Heat pump (HP) investment cost $[e]$.
C_{dem}	User cooling demand $[kWh]$.
$c_{el,bgt}$	Electricity cost $[e/kWh]$.
$c_{el,inc}$	Photo-voltaic panels (PV panels) incentive $[e/kWh]$.
$c_{el,sol}$	Electricity income $[e/kWh]$.
$c_{fue,boi}$	BOI fuel cost $[e/kWh]$.
$c_{fue,chp}$	Combined Cooling Heat and Power (CHP) fuel cost $[e/kWh]$.
$c_{fue,ice,c}$	Central ICE fuel cost $[e/kWh]$.

Notation	**Description**
C_{hp}	Cold produced by the HP $[kWh]$.
c_{ice}	ICE investment cost $[e]$.
$c_{ice,f}$	ICE fixed investment cost $[e]$.
$c_{ice,v}$	ICE variable investment cost $[e/kW]$.
c_{inv}	Investment annual cost $[e/y]$.
$c_{inv,c}$	Central unit annual investment cost $[e/y]$.
$c_{inv,u}$	Site annual investment cost $[e/y]$.
c_{man}	Maintenance annual cost $[e/y]$.
c_{mgt}	Micro Gas Turbine (MGT) investment cost $[e]$.
$\boldsymbol{C_{net}}$	Cooling energy transferred through the pipeline $[kWh]$.
c_{net}	DHCN annual investment cost $[e/y]$.
$c_{net,f,c}$	Fixed cost of the DHCN pipeline $[e/m]$.
$c_{net,f,c}$	Fixed cost of the central District Heating Network (DHN) pipeline $[e/m]$.
$c_{net,v}$	Variable cost of the DHCN pipeline $[e/kW \cdot m]$.
$c_{net,v,c}$	Variable cost of the central DHN pipeline $[e/kW \cdot m]$.
COP_{cc}	CC Coefficient of performance.
c_{ope}	Operating annual cost $[e/y]$.
$c_{ope,c}$	Central unit annual operation cost $[e/y]$.
$c_{ope,u}$	Unit annual operation cost $[e/y]$.
c_p	Specific heat $[\frac{kj}{kg \cdot K}]$.
c_{pvp}	PV panels investment cost $[e/m^2]$.
c_{stp}	Solar thermal panels (ST panels) investment cost $[e/m^2]$.
$c_{stp,c}$	Central ST panels investment cost $[e/m^2]$.
c_{tot}	Total annual cost $[e/y]$.
$\boldsymbol{C_{ts}}$	Cooling energy storage input $[kWh]$.
c_{ts}	Thermal Storage (TS) investment cost $[e/kWh]$.
$c_{ts,c}$	Central TS investment cost $[e/kWh]$.
$\boldsymbol{E_{bgt}}$	Electricity bought from the network $[kWh]$.
E_{cc}	Electricity required by the CC $[kWh]$.
$\boldsymbol{E_{hp,c}}$	Electricity required by the HP when producing cold $[kWh]$.
E_{dem}	User electricity demand $[kWh]$.
$\boldsymbol{E_{hp,h}}$	Electricity required by the HP when producing heat $[kWh]$.
E_{hp}	Electricity required by the HP $[kWh]$.
$\boldsymbol{E_{ice}}$	Electricity produced by the ICE $[kWh]$.
$\boldsymbol{E_{ice,c}}$	Electricity produced by the centralized ICE $[kWh]$.

Notation	Description
$E_{ice,lim}$	ICE operation limits $[kW]$.
em_{el}	Electricity carbon intensity $[kg_{CO_2}/kWh]$.
$em_{f,boi}$	BOI fuel carbon intensity $[kg_{CO_2}/kWh]$.
$em_{f,cen}$	Central CHP fuel carbon intensity $[kg_{CO_2}/kWh]$.
$em_{f,chp}$	CHP fuel carbon intensity $[kg_{CO_2}/kWh]$.
$\boldsymbol{E_{mgt}}$	Electricity produced by the MGT $[kWh]$.
em_{lim}	Emission limit in the ϵ-constrained optimization $[kg_{CO_2}/kWh]$.
em_{tot}	Total annual CO_2 emissions $[kg]$.
E_{pvp}	Electricity produced by the PV panels $[kWh]$.
$\boldsymbol{E_{sol}}$	Electricity sold to the network $[kWh]$.
f_{abs}	ABSamortization factor $[y^{-1}]$.
F_{boi}	Fuel required by the BOI $[kWh]$.
f_{boi}	BOIamortization factor $[y^{-1}]$.
$F_{boi,c}$	Fuel required by the central BOI $[kWh]$.
f_{cc}	CCamortization factor $[y^{-1}]$.
f_{hp}	HPamortization factor $[y^{-1}]$.
F_{ice}	Fuel required by the ICE $[kWh]$.
f_{ice}	ICEamortization factor $[y^{-1}]$.
$F_{ice,c}$	Fuel required by the centralized ICE $[kWh]$.
F_{mgt}	Fuel required by the MGT $[kWh]$.
f_{mgt}	MGTamortization factor $[y^{-1}]$.
f_{net}	DHCNamortization factor $[y^{-1}]$.
f_{pvp}	PV panelsamortization factor $[y^{-1}]$.
f_{stp}	ST panelsamortization factor $[y^{-1}]$.
f_{ts}	TSamortization factor $[y^{-1}]$.
GAP	Percentage difference between real and relaxed objective functions.
H_{abs}	Heat required by the ABS $[kWh]$.
$\boldsymbol{H_{boi}}$	Heat produced by the BOI $[kWh]$.
$\boldsymbol{H_{boi,c}}$	Heat produced by the central BOI $[kWh]$.
$H_{boi,lim,c}$	Centralized BOI operation limits $[kW]$.
H_{dem}	User thermal demand $[kWh]$.
H_{hp}	Heat produced by the HP $[kWh]$.
H_{ice}	Heat produced by the ICE $[kWh]$.
$H_{ice,c}$	Heat produced by the centralized ICE $[kWh]$.
H_{los}	Thermal loss through the pipeline.
H_{mgt}	Heat produced by the MGT $[kWh]$.
$\boldsymbol{H_{net}}$	Thermal energy transferred through the pipeline $[kWh]$.

Notation	Description
$\boldsymbol{H_{net,c}}$	Thermal energy transferred through the pipeline of the central DHN $[kWh]$.
$H_{net,lim}$	Size limits of the pipelines $[kWh]$.
$\boldsymbol{H_{ric}}$	Thermal energy received from the network $[kWh]$.
H_{stp}	Solar panel thermal production.
$H_{stp,c}$	Centralized solar field thermal production.
$\boldsymbol{H_{ts}}$	Thermal energy storage input $[kWh]$.
$\boldsymbol{H_{ts,c}}$	Thermal energy storage input $[kWh]$.
Kc_{abs}	ABS Performance curve linearization coefficient.
Kf_{ice}	ICE Performance curve linearization coefficient.
$Kf_{ice,c}$	Centralized ICE Performance curve linearization coefficient.
Kh_{ice}	ICE Performance curve linearization coefficient.
$Kh_{ice,c}$	Central ICE performance curve linearization coefficient.
K_{hp}	HP Performance curve linearization coefficient.
$K_{los,net}$	Thermal loss coefficient $[\frac{1}{C}]$.
$K_{los,ts}$	Percentage thermal loss coefficient.
K_{stp}	Unitary thermal production.
l_p	Length of the pipeline $[m]$.
$\boldsymbol{O_{abs}}$	ABS operation (binary).
obj_{currl}	Current Objective Function.
$obj_{relaxed}$	Relaxed Objective Function.
$\boldsymbol{O_{boi,c}}$	Central BOI operation (binary).
$\boldsymbol{O_{hp,c}}$	HP cold operation (binary).
$\boldsymbol{O_{hp,h}}$	HP heat operation (binary).
$\boldsymbol{O_{ice}}$	ICE operation (binary).
$\boldsymbol{O_{ice,c}}$	Centralized ICE operation (binary).
p_c	Pipeline cooling loss per unit length km^{-1}.
p_t	Pipeline thermal loss per unit length km^{-1}.
$p_{t,c}$	Pipeline thermal loss per unit length km^{-1} of the central DHN pipeline.
Q_{net}	Thermal energy stored in each pipeline $[kWh]$.
$\dot{Q}_p$	Heat transferred by a DHCN pipeline $[kWh]$.
$\boldsymbol{Q_{ts}}$	Thermal energy stored in a thermal storage $[kWh]$.

Notation	Description
$\boldsymbol{S_{boi}}$	BOI size $[kW]$.
$\boldsymbol{S_{boi,c}}$	Central BOI size $[kW]$.
$S_{boi,lim,c}$	Central BOI size limits $[kW]$.
$\boldsymbol{S_{cc}}$	CC size $[kW]$.
$\boldsymbol{S_{C,net}}$	Size of the cooling pipeline $[kW]$.
$\boldsymbol{S_{cs}}$	Cooling storage size $[kWh]$.
$\boldsymbol{S_{H,net}}$	Size of the thermal pipeline $[kW]$.
$\boldsymbol{S_{H,net,c}}$	Size of the central DHN pipeline $[kW]$.
$S_{hp,lim}$	HP operation limits $[kW]$.
$\boldsymbol{S_{ice,c}}$	Centralized ICE size.
$S_{ice,lim,c}$	Centralized ICE size limits $[kW]$.
S_{pvp}	Size of the PV panels equipment.
$\boldsymbol{S_{stp}}$	Size of the solar equipment.
$\boldsymbol{S_{stp,c}}$	Size of the central solar field.
$\boldsymbol{S_{ts}}$	Thermal storage size $[kWh]$.
$\boldsymbol{S_{ts,c}}$	Central thermal storage size $[kWh]$.
t_{env}	Temperature of the soil [°C].
t_{lim}	Temperature limit for the withdrawal [°C].
$\boldsymbol{t_{pip}}$	Temperature of the medium flowing inside the pipeline [°C].
v_p	Velocity of the medium inside the pipeline $[\frac{m}{s}]$.
$\boldsymbol{V_{ts}}$	Thermal storage volume $[m^3]$.
wgt	Time interval weigth.
$\boldsymbol{X_{abs}}$	ABS existence (binary).
$\boldsymbol{X_{boi,c}}$	Central BOI existence (binary).
$\boldsymbol{X_{cp}}$	Existence of the cooling pipeline (binary).
$\boldsymbol{X_{hp}}$	HP existence (binary).
$\boldsymbol{X_{ice}}$	ICE existence (binary).
$\boldsymbol{X_{ice,c}}$	Centralized ICE existence (binary).
$\boldsymbol{X_{mgt}}$	MGT existence (binary).
$\boldsymbol{X_{net}}$	Existence of a network pipeline (binary).
$\boldsymbol{X_{net,c}}$	Existence of the central DHN(binary).
$\boldsymbol{X_{tp}}$	Existence of the thermal pipeline (binary).

Acronyms

Notation	Description
ABS	Absorption Chiller.
BOI	Boiler.
CC	Compression Chiller.
CHP	Combined Cooling Heat and Power.
COP	Coefficient Of Performance.
CS	Cooling Storage.
DCN	District Cooling Network.
DG	Distributed Generation.
DHCN	District Heating and Cooling Network.
DHN	District Heating Network.
HP	Heat pump.
ICE	Internal Combustion Engine.
MGT	Micro Gas Turbine.
MILP	Mixed Integer Linear Programming.
PES	Primary Energy Saving.
PV panels	Photo-voltaic panels.
ST field	Solar thermal field.
ST panels	Solar thermal panels.
TL	Thermal Limit.
TS	Thermal Storage.

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Preface

The evolution of the world is proportionally related to the energy availability, either temporally or geographically. Never before our development has been so dependent to this resource and this aspect is accentuating day by day. The energy availability and cost have become, therefore, strategic and critical elements for the economic development of a country or region.

The growing importance of the energy sector at the global level makes it the strategic key for the economic development of the countries. For each one of them it is important not only to have appropriate access to the sources, but also have the transport possibility of and effective marketing strategies.

Distrubuted Generation Energy systems, dealt with in this PhD thesis, are among the strategic solutions for the reduction of primary energy needs and costs, allowing a sustainable development of the countries.

1

Introduction

Energy has always played an important role in human and economic development and in society's well-being and now the energy word faces unprecedented uncertainty. The global economic crisis begun in 2008-2009, and still going on, threw energy markets around the world into turmoil and the pace at which the global economy recovers holds the key to energy prospects for the next several years. But only governments, and how they respond to the twin challenges of climate change and energy security, will shape the future of energy in the longer term.

An improvement in the general standard of living always entails a higher demand for energy services; until now, this has meant an increase in energy consumption. Since the beginning of the industrial revolution, the rate of energy consumption has been increasing steadily and global energy consumption is likely to keep increasing over the next 50 years unless major breakthroughs in energy efficiency are achieved and/or the cost of energy increases substantially 1.1. To enjoy a decent quality of life and a reasonable level of prosperity, people must be able to satisfy their basic energy needs. It is a fact that per-capita energy consumption is spread very unevenly around the world, with a small percentage of people consuming substantially more than the majority and a large number of people around the globe suffering because they have insufficient energy services to provide a decent quality of life [18] 1.2.

The global growth is strictly related to the per capita energy consumption and to the growth of the energy requirement. So that, it is very important to find new strategy for the energy demand satisfaction, in order to limit the current intensive fossil fuel usage.

Global climate change can be addressed only by international measures. And it can be managed only if we humans bring down our total energy requirements. This can be done partly with greater efficiency, and (this is the hard part) by decreasing usage as well. The adoption of DG energy systems can met at the same time these two targets, but only if they are optimal designed.[16] [19]

1.1 Global Energy Scenario

Future energy trends will be the interplay of a number of different factors, most of which are hard to predict accurately. In the near to medium term, economic factors are the main source of uncertainty surrounding energy prospects. There is also enormous uncertainty

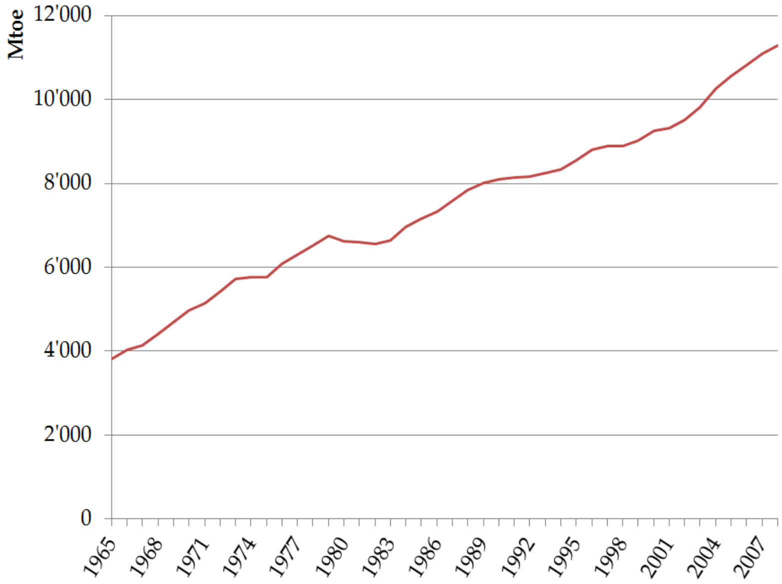


FIGURE 1.1 – World energy consumption in the last 50 years

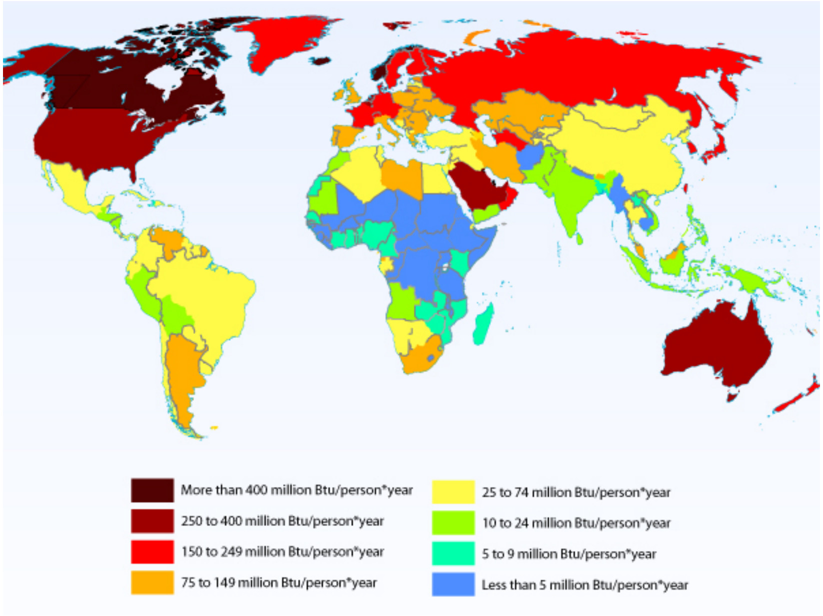


FIGURE 1.2 – Energy consumption per capita, per country (2009)

about the outlook for energy prices, the size of energy resources and their cost, and the prospects for new energy-related technology, especially in the longer term. But government policies are arguably the biggest source of uncertainty to the next future. Governments around the world have expressed a will to take decisive action to steer energy use onto a more environmentally and economically sustainable course, although the measures needed to bring this about, the way in which they are to be implemented and their timing are often unclear. Most governments will act, but how, when and how vigorously are far from clear. What they do to tackle critical energy-related problems holds the key to the outlook for world energy markets over the next quarter of a century.

The World Energy Outlook 2010 [1] considers three different possible future scenarios and they derive from different underlying assumptions about policy. In this way, it provides insights into what policy can achieve and what the absence of policy action or delay in implementing policies would mean for energy markets, energy security and the environment.

With reference to Fig. 1.3 the Current Policies Scenario takes into consideration only those policies that had been formally adopted by mid-2010. The New Policies Scenario takes account of the broad policy commitments that have already been announced and assumes cautious implementation of national pledges to reduce greenhouse-gas emissions by 2020 and to reform fossil-fuel subsidies. The third scenario, the 450 Scenario, assumes implementation of the high-end of national pledges and stronger policies after 2020, including the near-universal removal of fossil-fuel consumption subsidies, to achieve the objective of limiting the concentration of greenhouse gases in the atmosphere to 450 parts per million of CO_2 equivalent and global temperature increase to 2°C.

In the New Policies Scenario, which takes account of both existing policies and declared intentions, world primary energy demand is projected to increase by 1.2% per year between 2008 and 2035, reaching 16750 million tonnes of oil equivalent (Mtoe) (+36%). Demand increases significantly faster in the Current Policies Scenario, in which no change in government policies is assumed, averaging 1.4% per year over 2008-2035 (+48%). In the 450 Scenario, in which policies are assumed to be introduced to bring the world onto an energy trajectory that provides a reasonable chance of constraining the average global temperature increase to 2°C, global energy demand still increases between 2008 and 2035, but by a much reduced 22%, or an average of 0.7% per year.

Fossil fuels remain the dominant energy sources in 2035 in all three scenarios, though their share of the overall primary fuel mix varies markedly, from 62% in the 450 Scenario to 79% in the Current Policies Scenario, compared with 74% in the New Policies Scenario and 81% in 2008 (Fig. 1.4). These differences reflect the varying strength of policy action assumed to address climate-change and energy security concerns. The shares of renewables and nuclear power are correspondingly highest in the 450 Scenario and lowest in the Current Policies Scenario. The range of outcomes, and therefore the uncertainty with respect to future energy use, is largest for coal and non-hydro renewable energy sources.

Non-OECD (Organisation for Economic Co-operation and Development) countries generate the bulk of the increase in global demand for all primary energy sources (Fig. 1.5). OECD oil demand falls by 6 mb/d (millions of barrel per day) in 2009-2035, but this is offset by a 19-mb/d increase in the non-OECD (international bunker demand also rises

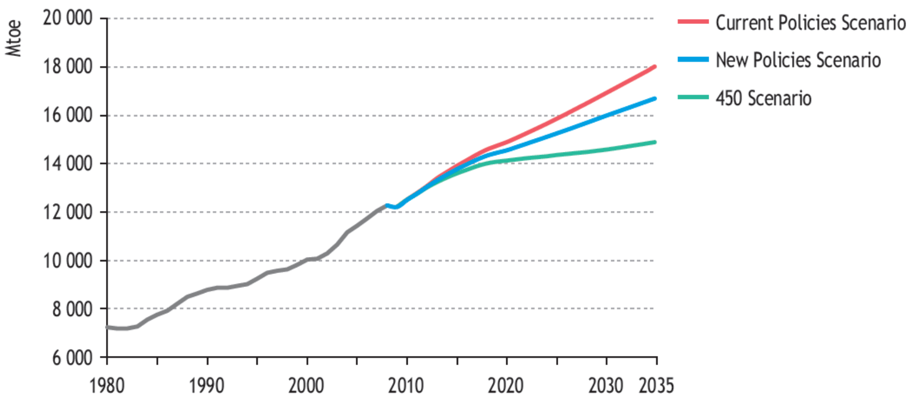


FIGURE 1.3 – World Promary Energy demand by scenario [1]

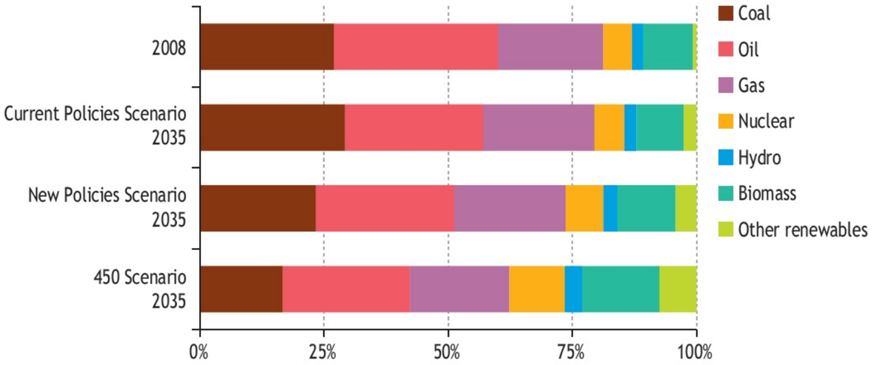


FIGURE 1.4 – Shares of energy sources in world primary demand by scenario [1]

by almost 3 mb/d). Oil demand increases the most in China (7.1 mb/d), India (4.5 mb/d) and the Middle East (2.7 mb/d) as a consequence of rapid economic growth and, in the case of the Middle East, the continuation of subsidies on oil products. By 2035, China overtakes the United States to become the largest oil consumer in the world. Having reached a peak of 46 mb/d in 2005, oil demand in the OECD continues to decline, reaching 35 mb/d in 2035, due to further efficiency gains in transport and continued switching away from oil in other sectors. Oil demand in the United States declines from 17.8 mb/d in 2009 to 14.9 mb/d in 2035.

Non-OECD regions are responsible for the entire net increase in coal demand to 2035. China alone accounts for 54% of the net increase; although coal's share of China's energy mix continues to decline, more than half of its energy needs in 2035 are still met by coal. Most of the rest of the growth in coal demand comes from India and other non-OECD Asian countries. Driven by policies to limit or reduce CO_2 emissions, coal use falls sharply in each of the OECD regions, particularly after 2020. By 2035, OECD countries consume 37% less coal than today.

Unlike demand for the other fossil fuels, demand for natural gas increases in the OECD where it remains the leading fuel for power generation and an important fuel in the industrial, tertiary and residential sectors. Collectively, the OECD countries account for 16% of the growth in natural gas consumption to 2035. Developing Asia, again led by China and India, accounts for 43% of the incremental demand, as gas use increases rapidly in the power sector and in industry. The Middle East, which holds a considerable share of the world's proven natural gas reserves, is responsible for one-fifth of the global increase in gas consumption.

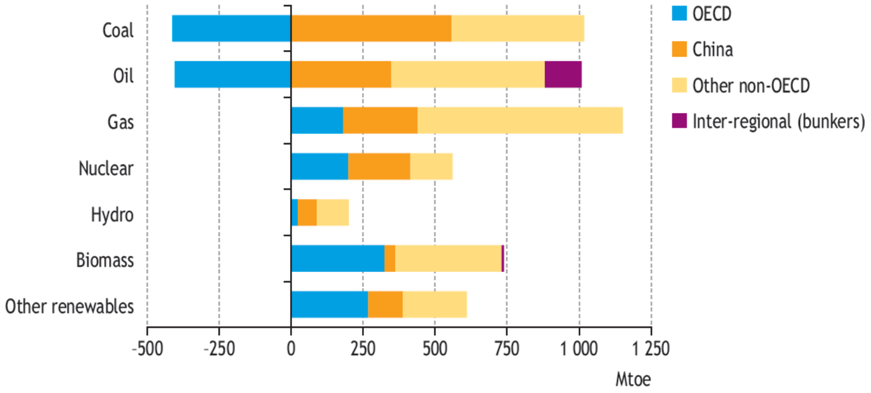


FIGURE 1.5 – Incremental primary energy demand by fuel and region in the New Policies Scenario, 2008-2035 [1]

Fig. 1.6 shows the share of energy final destination in 2010 and it results that industry is the sector which use the more energy (≈33%), the second is transportation (≈29%) and the remaining part is shared between residential (21%) and commercial sectors (18%). These two last sectors are characterized by the same type of energy consumptions and if grouped they account for about 40% of the final energy consumption.

Fig. 1.7 shows the incremental energy demand by sector and by region in the next 20 years and it can be noted that the total final consumption is projected to grow by 1.2% throughout the period 2008-2035. Industry demand grows most rapidly, at 1.4% per year, and by 2035 it will consume around 35% of the total final energy consumption. The World Energy Outlook (2010) [1] reports that over three-fifths of the growth in industrial energy demand comes from China and India, while the Middle East and Latin America also see strong growth in demand. OECD industrial energy demand increases through to 2020 before dropping

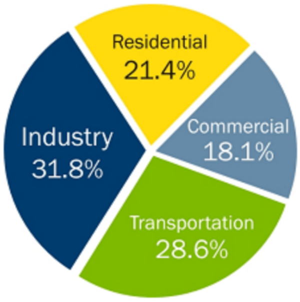
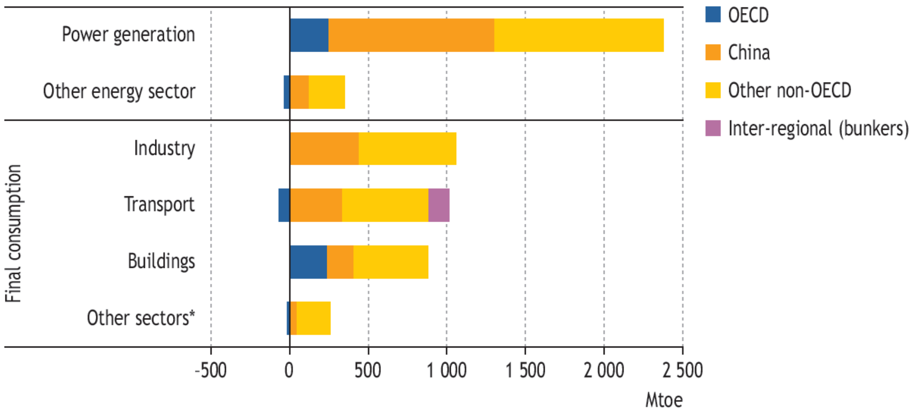


FIGURE 1.6 – Final energy use, 2010 [2]

back to levels similar to today by 2035. The energy consumed by buildings and in general by the residential and tertiary sector grows more gently at a rate of 1% per year. Looking the OECD countries it can be noted that the final energy consumption for industry and transportation will diminish by 2035, while for residential and tertiary sector the energy consumption will increase. This forecast highlight that in terms of primary energy consumption the residential and tertiary sectors can be significantly improved with the adoption of advanced energy supply systems and supply side energy reduction strategies.



* Includes agriculture and non-energy use.

FIGURE 1.7 – Incremental energy demand by sector and region in the New Policies Scenario, 2008-2035 [1]

These figures (Figs. 1.3-1.7) show that in the near future the energy demand will still increase in all scenarios, mainly due to the growth of non-OECD countries. The increasing of the demand is met either by renewable sources or by fossil fuels, so that the CO_2 emissions will increase too. Focusing on Europe, the natural gas will lead the next 20 years, so that it is of basic importance to improve the technologies which use natural gas and find new strategies of exploitation, in order to increase the overall efficiency decreasing at the same time the total usage of natural gas.

1.2 Environmental 2020 Target

Energy is linked to global warming through the emissions of greenhouse gas (GHG). The development and implementation of advanced energy technologies, including cleaner fossil fuels, energy efficiency, renewable energies and technologies which contribute to the reduction of greenhouse gas emissions, are currently top priorities for energy engineering. Current trends in energy consumption and supply, as presented in the previous section 1.1, show a persistent dominance of fossil fuels and oil, gas and coal in the energy mix. This pattern of energy consumption continues to have serious climate change implications since carbon dioxide emissions and the world's temperature are steadily increasing, which could have a potentially catastrophic outcome. To set the world on a different path, a change in energy policy is needed to reduce the growth in GHG concentrations. One aggressive scenario considered by the International Energy Agency (IEA) involves reducing the concentration of GHG to 450 ppm; the IEA estimates that this would limit the atmospheric temperature increase to less than 2℃(450 Policy Scenario, see Fig. 1.3).

According to the guide lines defined by the Kyoto Protocol [20], the EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020, known as the ”20-20-20” targets to kick-start with the reduction of CO_2 emissions. These targets are:

- a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels;
- 20% of EU energy consumption to come from renewable resources;
- a 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

The final goal is to reach a low-carbon supply of energy services at competitive, sustainable and reasonable cost. It is important that the GHG emissions generated by the conversion and use of energy, in particular CO_2 emissions, are drastically reduced in order to meet the 2-degree target.

1.3 Distributed Generation Energy Systems

Distributed Generation Energy Systems can play an important rule to achieve the ”20-20-20” targets allowing a reduction of CO_2 emissions and primary energy usage with economic competitiveness. Since the energy demand in OECD countries is expected to increase for residential and tertiary sector (Fig. 1.7) in the next 20 years, Distributed Generation Energy Systems is one of the possible solution which could contain this increment.

Various definitions exist for Distributed Generation System but in general it can be regarded as a small scale generation system used on-site (and possibly unconnected to the distribution network) and/or connected to distribution networks, irrespective of products, technologies or fuels used (Fig. 1.8). Distributed Generation is a fairly new concept in literature about electricity markets, but the idea behind it is not new at all.

In the early days of electricity generation, distributed generation was the rule, not the exception. The first electricity power plants only supplied electricity to customers in the close neighborhood of the generation plant. Balancing demand and supply was partially done using local storage, i.e. batteries, which could be directly coupled to the DC grid. Later, technological evolutions, such as the emergence of AC grids, allowed for electricity to be transported over longer distances, and economies of scale in electricity generation lead to an increase in the power output of the generation units. All this resulted in increased convenience and lower per unit costs and massive electricity systems were constructed, consisting of huge transmission and distribution grids and large generation plants. Balancing demand and supply was done by the averaging effect of the combination of large amounts of instantaneously various loads. Security of supply was increased

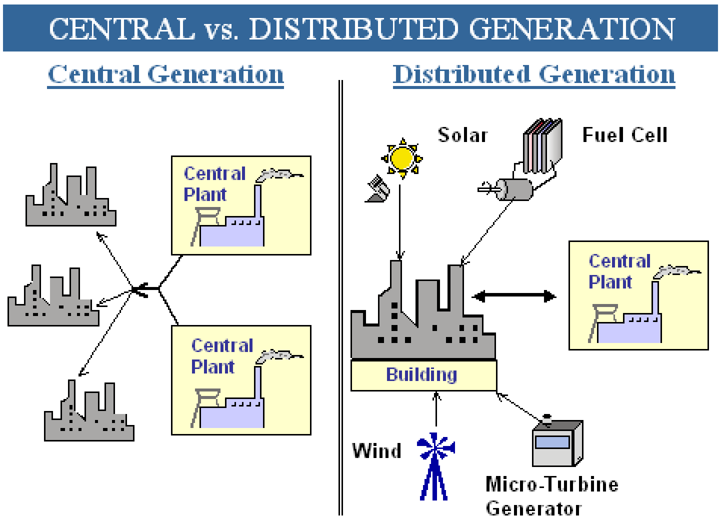


FIGURE 1.8 – Central vs Distributed Generation Energy Systems, [3]

as the failure of one power plant was compensated by the other power plants in the interconnected system. In fact this interconnected high voltage system made the economy of scale in energy generation possible.

In the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for distributed generation. This is confirmed by the International Energy Agency [21], who lists five major factors that contribute to this evolution:

- developments in distributed generation technologies;
- constraints on the construction of new transmission lines;
- increased customer demand for highly reliable electricity;
- electricity market liberalization;
- concerns about climate change.

Distributed generation systems offer various advantages. On a stand-alone electricity basis, DG is most often used as back-up power for reliability purposes, but can also defer investment in the transmission and distribution network, avoid network charges, reduce line losses, defer the construction of large generation facilities, displace more expensive grid-supplied power, provide additional sources of supply in markets, and provide environmental benefits [22]. Furthermore, one of the most important advantages is that DG can operate in conjunction with CHP applications improving the overall efficiency and also, they makes the development of renewable energy system possible, as these energy sources have low energy density. The presence of DG in the network alters the power flows (usage patterns) and thus the amount of losses. Depending on the location and demand profile in the distribution network where DG is connected, and DG operation, losses can significantly decrease because the electricity is produced close to the user.

In addition to the potential network benefits and reliability (security of supply benefits), distributed generation may bring other benefits to power systems. The first is the ability to add generating capacity in a modular fashion and that does not require building new large power plants which will have excess capacity for some time and because of size, may be easier to site and permit, thus completed quicker. In an electricity market environment, distributed generation can offer additional supply options to capacity markets and ancillary services market thereby leading to lower costs and more competition.

For what concerns the thermal generation, the heat has always been produced very closed to the user using fossil fuels or biomass sources, such as wood and it can be stated that the concept of DG has always been applied for thermal generation. Only few exceptions can be found for thermal generation and they refers to Nordic countries where the use of district heating network has been developed since the begin of the XX century [23]. In this case the thermal energy is produced in big centralized thermal plants and fed to the users by large district heating networks.

CHP also called cogeneration, is the simultaneous production of electrical power and useful heat for industrial processes. The heat generated is either used for industrial processes and/or for space heating inside the host premises or alternatively is transported to the local area for district heating. The overall efficiencies of centrally dispatched, large generation facilities are no greater than 55% on average over a year and these are natural gas combined cycle facilities. By contrast, cogeneration plants, by recycling normally wasted heat, can achieve overall thermal efficiencies in excess of 85%. Applications of CHP range from small plants installed in buildings (e.g. hotels, hospitals, etc.) up to big plants on chemical works and oil refineries, although in industrialized countries the vast majority of CHP is large, industrial CHP connected to the high voltage transmission system. From the other hand CHP systems can be installed only close to the thermal users. This implies that they are convenient only if they are not of large size, and consequently that they have to be spread out in the area. The integration of CHP systems with DG systems is called Distributed Cogeneration.

Finally, distributed generation systems may imply lower emissions than traditional fossil-fired power plants for the same level of generation. It depends on technology and fuel source and, of course, this is true if renewable technologies are adopted. The benefits are potentially large in systems where fossil fuels dominate electricity generation, leading to lower CO_2 emissions levels.

DG can contribute significantly to achieve the ”20-20-20” targets, but it is not possible to define general guidelines describing which technologies should be adopted in a distributed energy system, because it highly depends on the boundary conditions of the sites. Furthermore DG systems which are not optimally designed, not only limit benefits, but can produce opposite effects such as increase the environmental pollutant.

1.4 Objectives of the Thesis

DG energy systems may include various kind of technologies, energy resources and can be applied to different scales. As said in the previous section, it is of paramount importance that they are designed for the specific application and taking account of all boundary conditions which could limit or prevent the expected results. The optimal solution turns out to be a compromise of many factors and there are actually almost an infinite number of possible solutions which cannot be considered one by one.

The Thesis proposes a multi objective optimization model for a Distributed Generation Energy System. The proposed model allows the environmental and economic optimization of a system for supplying electricity, thermal and cooling energy to a set of users. It is constituted by various technologies, includes the integration with a district heating/cooling network and a central solar system.

The thesis can be divided into two main parts: the first one I presents the methodological approach adopted and describes the optimization model proposed. The second part (II) refers to a realistic application of the model including a detailed description of the case study, of the optimization steps and of the results. The model is optimized for different configurations, the which complexity increases step by step to understand how different components and system configuration affect the optimal solution.

1.5 Original Contribution and Practical Impact

The originality of the proposed research is that it provides a methodological approach for the optimization of DG energy systems. It gives an optimization model that can be directly applied to a specific case study and it shows how the different kind of components have to be represented in the model in order to maintain the linearity of the model without affecting the obtained results.

The multi objective optimization approach put together the synthesis, design and operation optimization problem in order to allow the inclusion of the DHCN together with the production units located close to the users. When the DHCN can be included in the final configuration, the synthesis-design and operation problems cannot be solved separately. For isolated systems, where the energy required by the user is produced locally, the design of the energy system can be obtained considering the maximum energy required and, eventually the average load required, without defining the operation. For energy systems which include the district heating and cooling network instead, the synthesis-design and operation definition cannot be separated because the energy to be produced by each production site is not known in advance, as the flows through the DHCN are not defined. So that, the synthesis, design and operation optimization must be conduced simultaneously.

The heterogeneous choice of users (hospital, schools, theater, town hall, swimming pool, etc.) with different kinds of energy demand patterns allows to consider the achieved results not affected by a specific user profile, so that the results are not valid only for the specific case study, but can be extended to other similar cases, which can be easily recognized in other small-medium towns of Europe.

The model proposed wants to give realistic solutions that can be used as a basis for the design of regional distributed energy systems. The operation optimization results, are helpful for the definition of control logic which manage the system once it is in operation. The tool is developed to be utilized by suppliers, consumers, consultants and authorities, which enables all the involved parties to discuss on equal basis before a decision. The tool will lead the parties to understand better the impacts of the different system parameters and thus to make better decisions in often very complex situations.

I

Methodological approach and model description

2

Optimization of Distributed Generation Energy Systems

Energy is a vital input for social and economic development.

Energy sector reform is critical to sustainable energy development and includes reviewing and reforming subsidies, establishing credible regulatory frameworks, developing policy environments through regulatory interventions, and creating market-based approaches. Energy security has recently become an important policy driver, and privatization of the electricity sector has secured energy supply and provided cheaper energy services in some countries in the short term, but has led to contrary effects elsewhere due to increasing competition, resulting in deferred investments in plant and infrastructure due to longer-term uncertainties.

The rapid development of the global economy has increased remarkably the energy requirements all over the world. The demand is being met by fossil fuels so far, but the realization that fossil fuel resources for the generation of energy are becoming scarce and that climate change is related to greenhouse emissions (CO_2 emissions) has increased interest in energy saving and environmental protection [24]. This goal can be reached decreasing the dependence on fossil fuels, increasing the efficiency of existing energy plants and eventually reducing the whole primary energy demand [4]. Not surprisingly these are the "20-20-20" targets and they can be achieved with an optimal adoption of DG renewable energy systems.

As a result of the generalization of agricultural, industrial and domestic activities the demand for energy has increased remarkably, especially in emergent countries. This has meant rapid grower in the level of greenhouse gas emissions and the increase in fuel prices, which are the main driving forces behind efforts to utilize renewable energy sources more effectively. Furthermore, to reach this goal, new efficient technologies for the development of DG are available. Despite the obvious advantages of the use of renewable energy and DG systems, they present important drawbacks. The discontinuity of generation due to the climate dependence, requires complex design, planning, control optimization methods and integration either with traditional energy systems or energy storages. Fortunately, the continuous advances in computer hardware and software are allowing researchers to deal with these optimization problems using computational resources, as can be seen in the large number of optimization methods that have been applied to the renewable and sustainable energy field [25].

DG is the opposite of the conventional situation where power plants are large centralized units. A new trend is developing toward distributed energy generation, which means that energy conversion units are situated close to energy consumers, and large units are substituted by smaller ones [26]. In the last case, distributed energy generation means that single buildings, or small group of buildings, can be completely self-supporting in terms of electricity, heat, and cooling energy. This principle has already been applied for example in hospitals, also with more than one building, that are very dependent on the reliability of electricity supply [27–31].

A lot of research has been made recently toward the development of technological solutions in the context of energy conversion, transportation and storage, and the integration of the various systems [3, 32, 33]. Understanding the link between distributed and centralized energy systems and sustainable development, however, requires more extended consideration in terms of environmental, economic and technological issues, which have all to be taken into account at the same time. Fig. 2.1 shows a DG energy system which includes different energy production units and potential users, connected to each other by transmission grids.

The basic question is: What actually can be decentralized in terms of energy systems and how does decentralization affect the system and its operation? The answer is not trivial and generally not only one solution responds to the question, because it depends on too many variables. But obviously, a convenient decentralization, is more than just locating production units close to the users or substituting large power plants with smaller ones.

A DG energy system may potentially include a lot of components for the transformation, distribution and storage of energy. Energy transformation systems, conventional or renewable, means for example ICE, MGT, ABS, BOI, PV panels, etc. Distribution systems are intended integrated with DHCN, electricity network and heat exchanger, while storage systems are either electricity storages, such as batteries, or thermal storages. Among such a large amount of components and configuration possibility it is obvious that it is not possible to identify a priori which is the best system configuration. So that, the optimization of the system is of crucial importance for a rational use of natural and economic resources and for minimizing their adverse effects on the environment [34]. Moreover, the best solution may vary based on which is the goal that the designer wants to achieve. In fact, the best economic solution does not generally correspond to the best environmental solution and also the solution which involves the lowest investment cost could implies greater operation costs.

This chapter reports a brief overview of the State of the Art, an introduction to the optimization methods available and the limits of the traditional optimization of DG energy systems integrated either with renewable energy sources or energy storage systems.

2.1 State of the Art

The design of DG energy systems is not simple and cannot follow specific steps toward the final solution. In fact there are so many variables that the designer should be aware

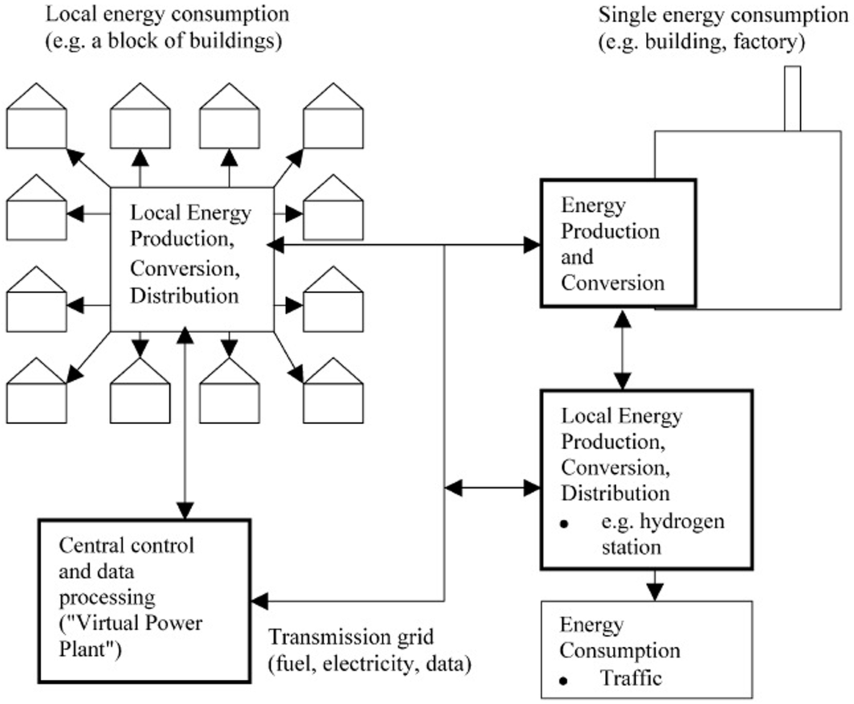


FIGURE 2.1 – An example of a possible Distributed Energy System [4]

that it is almost impossible to consider all of them.

The general approach is to refer to a single expert, or a panel of experts, in the energy system design and they will determine the optimal configuration of the system based on their past experiences. The solution proposed by the experts generally has two characteristics:

- satisfies the energy requirement of the users;
- allows a cost reduction if compared to the conventional solution.

A project which has these two characteristics usually satisfies the client because it responds to the most important deliveries, but there is no certainty that it is the best one and, if the problem is very complicated, it could happen that the new proposed solution is worse than the conventional one. The human mind cannot explore all possible solutions and so, even reaching some better results with respect to the conventional solution, other better solutions could exist. They can be identified only with the help of design support technologies. In general an optimization model can find the best solution from whatever point of view, for all problems and considering all boundary conditions defined by the designer.

The problem dealing with optimization of energy systems begun with thermoeconomics, which is the first method developed in and, as an exergy-aided cost-reduction method, provides important information for the design of cost-effective energy-conversion plants [35, 36, 15]. The exergy costing principle is used to assign monetary values to all material and energy streams within a plant as well as to the exergy destruction within each plant component. The design evaluation and optimization is based on the trade-offs between exergy destruction (exergetic efficiency) and investment cost for the most important plant components [37].

A review of the open literature shows that the current research works can be grouped in three big groups:

- researches focusing on the optimization of the operation of DG energy systems, going from the optimization of the single component, to the operation of the overall system;
- researches dealing with the optimization of the system synthesis;
- researches focusing on synthesis, design and operation optimization.

Each group can be further subdivided, considering single and multi-objective optimization targets.

Over the last decade an increasing number of papers dealing with energy system optimization have been produced [25]. One of the first optimization model was developed by Henning in 1992 [38], and it consists on a linear programming model to minimize the operating cost of an energy supply system for local Swedish utilities. In 1997 he presented a linear programming model called MODEST [23] for the minimization of capital and operation costs of energy supply and demand side management. Curti et al. [39] proposed an optimization model for aiding the design of a mixed energy production system, including heat pump based district heating, conventional boilers and decentralized heat pump. Yokoyama et al. [40] in 2002 proposed a method for optimal structural design, to determine the structures of energy supply systems in consideration of their multi-period operation. Karlsson [41] has recently presented the MIND method, a decision support for optimization of industrial energy systems.

For a general overview of models, methods and applications of energy systems, the author refers readers to extended reviews presented recently [42, 43, 25, 44]. Among a big amount of researches presented in this field, some common points can be outlined:

- almost all models rely on linear programming (LP) or mixed integer linear programming (MILP). However, some approaches based on meta-heuristics (simulated annealing, genetic algorithms, etc.) have been proposed, but they present some difficulties concerning the determination of search parameters, the treatment of constraints and the judgment of optimality [45–47].
- the researches normally focus only on a specific targets: operation or synthesis optimization, economic and/or environmental optimization, unit or DHN optimization, etc.

To deal with optimization of DG energy systems, including DHCNs and thermal storages, and focusing on different objectives (economic rather than environmental), it is necessary to consider all aspects at the same time, and not in successive steps. This is because the operation optimization hardly affects the optimal synthesis of the system, as well as the economic optimum does not correspond to the the environmental optimum.

Some recent works seem to go in this direction. Chinese proposed a MILP model for the optimization of a DHCN in a DG context [48], Soderman and Petterson [49] presented a structural and operational optimization of a DG energy system, Ren et al. [50] proposed a multi-objective optimization model to analyze the optimal operating strategy of a DER system while combining the minimization of energy cost with the minimization of environmental impact which is assessed in terms of CO_2 emissions, while Carvalho [51] presented a model for the synthesis and operation optimization of residential units, considering environmental and economic aspects.

This work proposes a complete model considering together:

- synthesis, design and operation optimization;
- various energy components (internal combustion engines, microgas turbines, absorption machines, heat pumps, etc.);
- thermal storages,
- solar thermal field and photovoltaic panels;
- economic and environmental optimization.

The incorporation of all this items in the same model allows comparing different configuration options, distributed generation together with centralized generation, the competitiveness of renewable sources and the effectiveness of specific incentive policies. The tool will lead the parties to understand better the impacts of the different system parameters and thus to make better decisions in often very complex situations.

2.2 Problem Formulation

The objective of the thesis is to define an optimization strategy to synthesize a Distributed Energy System Configuration of a set of users, considering its operation. The system can be decomposed in three main parts, as represented in Fig. 2.2:

- Production units;
- District Heating and Cooling Network;
- Energy users.

The production units are units where renewable or fossil fuel sources are transformed in electricity, thermal or cooling energy. The units can be located close to the users to supply directly electricity and thermal energy (cool and cold), or they can be isolated and supply thermal energy to the user through the DHCN. In this case, the electricity

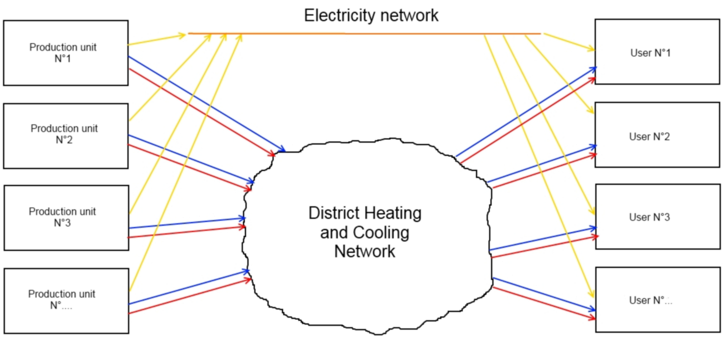


FIGURE 2.2 – Distributed Generation Scheme

produced is sold to the electricity network. The production units should account for the possibility of contain various type of transformation components, such as:

- cogenerators;
- natural gas boilers;
- chillers;
- solar and photovoltaic panels;
- heat pumps;
- fuel cells;
- biomass or biogas systems;
- thermal storages;
- etc.

The optimization procedure will identify which components minimize the objective functions (environmental and economic), their size and where they have to be located.

The District Heating and Cooling Network represents the thermal grid which connects the users to each other. The procedure will determine which are the branches that allow a minimization of the objective functions and the diameter of each pipeline.

The energy users represents the actual consumers of electricity, thermal and cooling energy. The definition of the DG energy system demands does not contain any variable to be optimized.

To solve this problem a reducible structure, known also as superstructure, has to be defined. It will embed all feasible process options and interconnections for the optimal design structure. Even considering only few users and few component kinds the number of configurations to be evaluate is large. Additionally, considering variable operating modes and energy costs, the number of alternatives could then reach up to infinite. Fortunately, the number of feasible solutions can be really reduced into a few ones when the complete set of constraints is immersed in the optimization model.

The optimization variables can be grouped in three categories:

1. Synthesis variables: which define the configuration of the energy system
    - Location of the components;
    - Network branches;
2. Design variables: which define the size of the adopted components
    - Size of the components;
    - Size of the network branches;
3. Operation variables: which define the optimal operation of the energy systems
    - Load of each single component in each time interval;
    - Internal unit energy flows in each time interval;
    - Energy flows through the DHCN in each time interval.

The optimization procedure determines the optimal value of each single decision variable in order to minimize the objective functions of the problem.

2.3 Optimization Methodology

As widely discussed in the previous paragraph, optimization techniques can help to define the best energy system for a set of users. An optimization is the selection of the best solution (with respect to some criterion) among a set of possible alternatives.

In the simplest case, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values within an allowed set and computing the value of the function. Operations research provides advanced analytical methods to help make better decisions [52]. Based on mathematical sciences, such as mathematical modeling, statistical analysis, and mathematical optimization, operations research allows to define optimal or near-optimal solutions to complex decision-making problems. Because of its focus on practical applications, it has been applied to various disciplines, such as industrial engineering and operations management, economy and organization science [53]. Among various specific applications, operations research has been used also in the field of energy systems [5].

The optimization of a DG energy systems consists of two major elements: posing the problem as a set of mathematical statements amenable to solution and defining a strategy for solving the problem after it has been posed.

2.3.1 Modeling of an Energy System

The first step in the modelization of an engineering system is the selection of a number of degrees of freedom represented by parameters which can be varied at will, within acceptable limits. These independent parameters, called variables, represented by a vector $\overrightarrow{x}$, are used to create two systems of equations to represent the overall system to be studied:

$$\overrightarrow{H} = \left\{ \begin{matrix} \overrightarrow{h_1}(\overrightarrow{x}) \\ \overrightarrow{h_2}(\overrightarrow{x}) \\ \overrightarrow{h_3}(\overrightarrow{x}) \\ \ldots \\ \overrightarrow{h_n}(\overrightarrow{x}) \end{matrix} \right\} = \overrightarrow{0} \tag{2.1}$$

$$\overrightarrow{G} = \left\{ \begin{matrix} \overrightarrow{g_1}(\overrightarrow{x}) \\ \overrightarrow{g_2}(\overrightarrow{x}) \\ \overrightarrow{g_3}(\overrightarrow{x}) \\ \ldots \\ \overrightarrow{g_n}(\overrightarrow{x}) \end{matrix} \right\} \leq \overrightarrow{0} \tag{2.2}$$

The vector of equality constraints $\overrightarrow{H}$ is composed of sub-vectors $\overrightarrow{h_i}$ each of which mathematically describes a phenomenon usually within the realm of a particular discipline. The elements of the sub-vectors $\overrightarrow{h_i}$ are known as the state equations. For energy systems, a number of different disciplines may be represented by $\overrightarrow{H}$, the most common being the thermal sciences, controls and economics. The vector $\overrightarrow{G}$ of inequality constraints represents natural or artificial constraints imposed upon the system.

An arbitrary vector $\overrightarrow{x}$ which satisfies all the constraints imposed by eqs. 2.1 and 2.2 is called feasible solution. Vectors $\overrightarrow{H}$ and $\overrightarrow{G}$ are in general highly non-linear and so the iterative process which leads to identifying a feasible solution could be very iterative expensive.

The problem of DG energy system optimization has non-linear equality constraints defined by the power flow equations; hence, it is a non-convex optimization problem. The decision variables are either continuous or discrete and represent locations, sizes and types of components, and the topology of the network. As a result, DG energy system optimization planning is a non-convex combinatorial problem, with several local optima, and one global optimal solution. Non-convex, non-linear, combinatorial problems are usually difficult to solve using traditional mathematical methods, since these methods are designed to find local optima solutions.

The designer's task is to simplify the problem and find a solution which is very close to the reality, even if the problem has been simplified. In fact, the designer should know which simplifications can be made without affecting the final solutions. The complexity of this optimization task is dealt with assuming a simplified formulation of the problem (for example, linearization of the objective functions and constraints, relaxation of the constraints, reduction of the dimensions of the search space, assumption of the discrete nature of components as continuous and simplification of the time variability of loads). In this way, it is possible to solve the optimization problem using traditional mathematical programming methods, for which powerful programming methods are available (e.g. Mixed Integer Linear Programming). The application of this approach actually allows a reduction of the complexity of the problem but cannot assure that this method can be applied to overall problems. In fact, even applying these simplification techniques a complexity limit will be reached as well. So that it can be stated that this simplification approach only allows to optimize larger problems without giving a solution to all problems.

2.3.2 Multiobjective Optimization

The optimal design of DG energy systems must consider different targets. Normally, the first target of energy systems optimization was the economic performance of the system, and the systems were optimized minimizing the total annual costs or the total operating costs. The increasing need for more efficient systems that are both economically attractive and friendlier to the environment requests the development of new criteria and determine new design rules. Economic and environmental objectives are conflicting targets as it is often expensive to adopt environmentally friendly systems and the optimal solution is not trivial. When optimizing a system from the economic and environmental point of view, there does not necessarily exist a solution which is the best for all objectives, but it could be the best for one objective but the worst for the other.

A Multiobjective problem has no single solution, but a set of solutions. To determine if one solution is better than another, the concept of ”dominance” needs to be defined. A solution a dominates a solution b if the following conditions are verified at the same time:

- a is no worse than b wrt all objectives;
- a is better than b at least wrt one objective.

Therefore, b is ”dominated” by a, and a is ”non-dominated” if there is no other solutions which satisfy the two conditions with respect to a. All ”non-dominated” solutions form the Pareto Frontier as represented in 2.3, which is the solution of the Multiobjective problem. The Utopia point has the minimum of each objectives as coordinates and it corresponds to the optimal solution only if the objectives are not in competition. The final solution will be identified between the solutions forming the Pareto Front and it depends on secondary evaluations.

As stated by [5], finding a single solution of a Multiobjective problem involves two steps: optimization and decision-making. Two different approaches can be identified depending on the order in which the two steps are performed, as represented in Fig. 2.4. The approach on the left uses *a priori* consideration and single objective optimization. All objectives are included in one single objective function that is optimized (e.g weighted sum method), or alternatively, one objective is optimized and the other are constrained. In this case the decision-making step precedes the optimization step and only one solution can be obtained, without knowing the set of solutions which form the Pareto Front. This

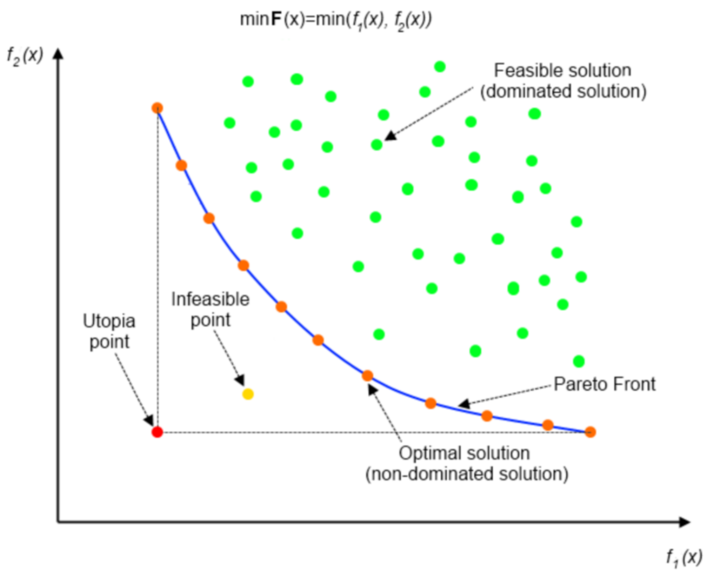


FIGURE 2.3 – Pareto Front for a two objectives problem

approach requires a deep knowledge of the problem to set adequately the weight or the constraints related to each objective, respectively.

If the information to set properly the weight or the constraint is not available, or if it is incomplete, obtaining as many solutions as possible is essential. These solutions form the Pareto Front and it is full of information which has to be considered in order to obtain a final solution. In this case the decision-making process takes place after the multi-objective optimization, as shown on the right of the Fig. 2.4.

The second approach has several points in favor:

- more methodical and less subjective wrt a priori approaches;
- provides various alternatives to choose from;
- permits a comparison between similar solutions.

On the other hand, the second approach is more computationally intensive and it is not possible to plot the Pareto front if there are more than three objectives.

Methods which allow to solve Multiobjective optimization problems can divided in two main groups:

- single objective techniques;
- techniques based on Evolutionary Algorithms.

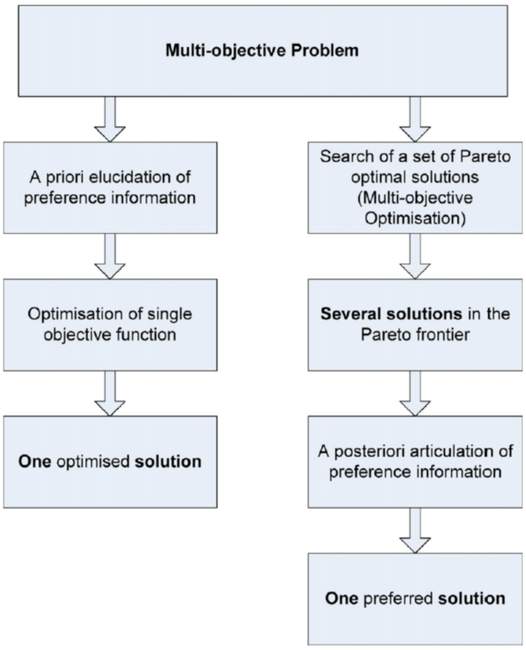


Figure 2.4 – Finding a single solution for a Multiobjective problem [5]

The single objective techniques are known as the classic approach to the Multiobjective optimization, as they treat a problem whit several objectives like a problem with a single objective. Two of the most common methods are the wighted sum method and the ϵ-constrained method. The weighted sum method is a weighted sum of each objective and it requires that all objectives are comparable as they are summed to each other. Moreover, it cannot deal with problem which comport a non-convex Pareto Front, as it cannot find any solution in the non-convex region [54]. The ϵ-constrained method overcome to this problem as it optimizes with respect to only one objective, while constraining the other objectives. Another method of single objective technique is the compromise programming, which minimizes the distance between the Pareto solution and the Utopia point, but is not often used in energy system optimizations [50]. All these techniques can guarantee the optimality of the solutions.

The techniques based on Evolutionary Algorithms can handle sets of possible solutions at the same time and, as a result, permit identification of several solutions of the Pareto front at once. Hence, Evolutionary Algorithm are recognized as a natural way of solving multi-objective problems efficiently, even if they have been applied only recently [55, 56, 47].

In the field of DG energy system optimization there are problem solved using either the first or the second method. In general it can be said that normally the Evolutionary Algorithm are used to solve highly non-linear problems, while the single objective techniques are used to solve intrinsically linear problems, so that direct technique can be applied, e.g. Mixed Integer Linear Programming (MILP) algorithms [43].

The problem handled in this PhD thesis concerns the optimization of a DG energy system, and the MILP optimization technique has been applied to solve the problem, using the ϵ-constrained method. The design task was posed as a bi-criteria programming problem, which could be mathematically expressed as $Minf(x) = \{f_1, f_2\}$. The solution to this problem was given by analyzing Pareto optimal points representing alternative process designs, each achieving a unique combination of the objectives. This method, as previously described, minimizes one objective and constraints the other. The problem can be mathematically express as:

$$\text{Min} \quad f_1(x) \tag{2.3}$$

Subject to

$$f_2(x) \leq \epsilon \qquad \text{with} \qquad \text{Lim}_{\text{inf}} \leq \epsilon \leq \text{Lim}_{\text{sup}} \tag{2.4}$$

$$\overrightarrow{H} = \overrightarrow{0} \tag{2.5}$$

$$\overrightarrow{G} \leq \overrightarrow{0} \tag{2.6}$$

where $\overrightarrow{H}$ and $\overrightarrow{G}$ are the equality and inequality constraint vectors defined previously (eqs. 2.1, 2.2). The problem has been optimized for different values of ϵ to obtain the Pareto front within two limits $[\text{Lim}_{\text{inf}}; \text{Lim}_{\text{sup}}]$ evaluated solving the problem with respect to $f_2(x)$ and $f_1(x)$, respectively. After the optimizations have been done and the Pareto front is available, one solution is identified evaluating all "non-dominated" solutions based on secondary criteria. This method is relatively simple, but very computationally intensive, so that decomposition techniques could help to reduce the complexity of the optimization, or alternatively, to allow optimization o more complex systems.

2.3.3 Problem decomposition

The problem decomposition can make an intractable, highly complex, highly dynamic problem with a large number of degrees of freedom tractable by breaking the original optimization problem into a set of smaller problems, the solution to which closely approximates the solution of the former. As stated by Tsatsaronis et al. [34] the decomposition of a problem can be done in three different ways, that can be simultaneously applied:

- *conceptual decomposition*: takes into account the conceptual aspects of the optimization problem, i.e. synthesis, design, and operation, into three levels of optimization. The first optimization is done at the synthesis level, and it corresponds to a definition of a set of possible configurations which respect the constraints of the problem, minimizing the system's objective function. The results of this optimization are then passed to the design level where for a fixed configuration the system's objective function is minimized (or maximized) with respect to a set of design variables. At the operational level, the system is optimized with respect to a set of operational/control variables for a fixed structure (synthesis and design defined at the upper level) across an entire load/environmental profile in order to determine optimal system behavior under any (design and off-design) conditions. An iterative procedure is then set up which moves back and forth between the three levels of optimization, terminating once the global optimum for the objective function has been found. This type of decomposition results in a set of nested optimization problems simpler than the original but much more computationally intensive [57–60].

- *time decomposition*: decomposes the continuous operational optimization problem into a series of quasi-stationary sub-problems each of which correspond to a given time interval. These can be optimized individually with respect to a set of unique operational/control variables and the results summed over all intervals. This form of decomposition complements the others because it can be applied only at the operation level [61–63].
- *physical decomposition*: decomposes the problem breaking it into a set of units (sub-systems, components, or sub-components), each of which forms a sub-problem within the context of the overall system optimization problem. The problems are though simpler than the whole problem and are optimized separately. They are connected to each other through coupling functions which have to be identified in the proper manner in order to guarantee the convergence of the iterative process [57]. This type of decomposition has many advantages such as the possibility of using different optimization algorithms for the sub-problem optimizations, different targets for the sub-problems, etc. but it works properly, giving the optimal solution of the whole problem, only if there are few discrete variables in each sub-problem. Otherwise, the marginal costs related to the coupling functions are not continuous and not convex preventing the convergence to the optimal solution [59, 64, 65].

Going from operation optimization to design and synthesis optimization of energy systems, the problem becomes much more difficult not only from a computational but also from a methodological point of view, especially if optimizing with respect to more objectives. Several methods have been developed, which have been shown to be successful at least for particular classes of problems, even when the number of degrees of freedom is large and the models involved highly nonlinear and complex. However, a method applicable to the problem of Multiobjective Optimization of Distributed Energy Systems has not been found yet. Reini and Buoro proposed a decomposition method suitable to this system called MILE, but it requires to properly define a set of optimization parameters, and this set can be actually find only for simple systems [66].

2.4 Conclusions

This chapter clears up the need of the adoption of optimal Distributed Generation systems. In fact, the benefits cannot be achieved if the system has not been optimized in order to define the optimal synthesis, design and its operation. A brief review of the State of the Art of the Distributed Generation Energy System Optimization field has been presented, introducing the underlying considerations which have been made in this research thesis. The problem formulation and the Multiobjective optimization has been presented identifying which strategies has been adopted.

The proposed approach has a limits which consists in the dimension of the problem that can be optimized. The approach works satisfactorily considering a small set of users (less then 10), because for larger problems the optimization time rises in an excessive way and a result cannot be obtained. For this reason a brief introduction to decomposition method has been reported, suggesting which the way is to overcome to this relevant problem.

3

Economic and Environmental MILP Model for Distributed Energy Systems

Chapter 3 introduces the MILP optimization model proposed to optimize a DG energy system for residential/tertiary users and it explains the method proposed to obtain the final solution of a specific problem. As a complex decision making problem, the optimal synthesis, design and operational plan of such systems inherently involves multiple conflicting objectives. In the specific case the objectives to be put in competition are the total annual cost (considered as the economic objective function) and the total annual operation emissions (considered as the environmental objective function), of which we will discuss later on in the specific sections 3.2.4 and 3.2.5.

Fig. 3.1 shows the flow chart of the multi-objective optimization procedure. When a designer has to define an optimal energy system first needs to define the problem to be solved. This step requires to collects as much as possible information about the specific problem. Secondly it has to define an optimization model which describes the system from technical, economic, environmental point of views and afterwards he can begin with the optimizations. Finally, he need to identify a final solution which will be the answer to the investor, that in few words is:

> Which is the best energy system configuration with respect to economical and environmental aspects?

The proposed procedure can be followed for different problems changing only the input data which characterize the specific case study, while the model and the optimization procedure are not related to a specific problem but are rather general and adoptable for various purpose whit the same superstructure.

3.1 Problem Definition

The problem definition is the first step when studying the optimal energy system for a specified area. In fact in this step all information related to users, technical information

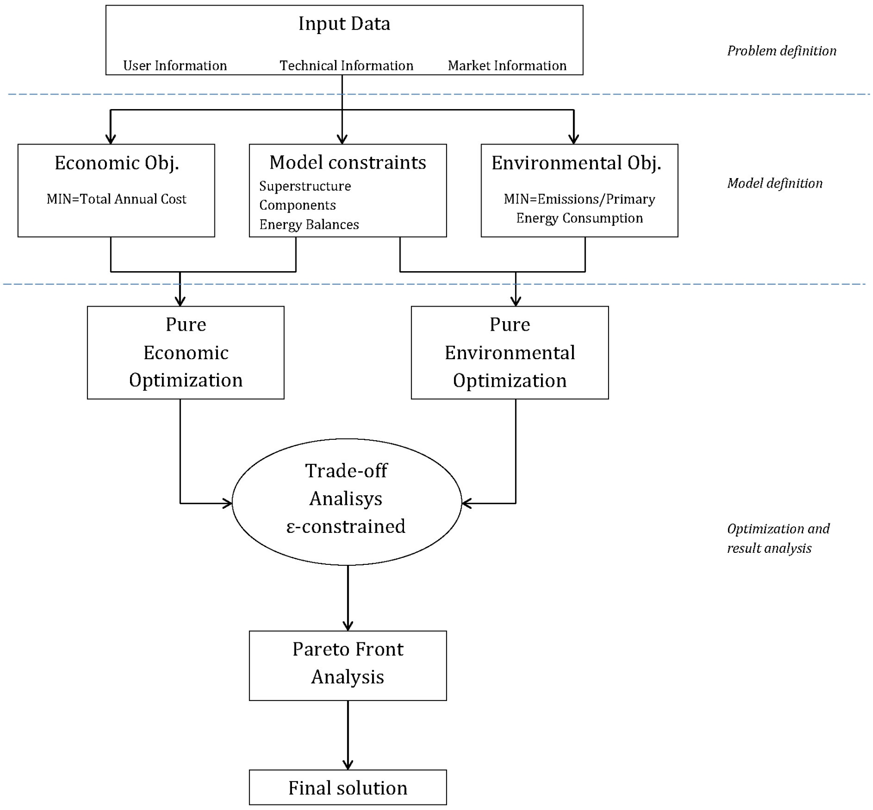


FIGURE 3.1 – Flow chart of the Multi Optimization procedure

related to the components that wants to be adopted, and market information which determines the market scenario, needs to be collected.

As the energy system will be adopted in the future, all information should refer to the future, but this inevitably brings to consideration about the future trends of energy demands, market scenario and component costs. In any case, it is recommended that all input data are referred to the same year (energy demands, costs, etc.).

In energy system synthesis/design and operation/control optimizations, system/ component models are typically treated deterministically, even though input values, which include the specific load profile for which the system or subsystem is developed, can have significant uncertainties that inevitably propagate through the system to the outputs. This deficiency can be overcome by treating the inputs and outputs with a probabilistic approach, considering that uncertainties affect either input values or constraints. Optimization results conducted under uncertainty shows that there is only little effect on the objectives and on final solution [60, 67]. In the specific problem of DG energy system optimization the uncertainties affect mainly the inputs values and not the constraints as could happen for the optimization of specific components. For this reason the uncertainties can be considered without affecting the model, optimizing the same problem for different values of energy demands and market prices. This allows to use the same deterministic model to explore possible future scenarios and to see how the solutions are affected by these variations. The designer will define the final solution based on secondary considerations and on his knowledge.

3.1.1 Users Information

The users information refers to all information related to the users, which characterizes them within the optimization problem. They can be defined as:

- geographic location. The geographic location is important when the DHN is considered. It is necessary to calculate the distances between the users and to define the possible path of the DHN branches.

- energy demands. The energy demands (electricity, thermal and cooling demands) are needed to define the energy requirements of the users. Due to the high temporal variability of energy demands in the residential and tertiary sectors, hourly demand data is needed in order to accurately analyze and optimize energy supply systems. Energy demands of each single user can be obtained directly from an energy audit if the building is occupied, otherwise they have to be obtained through softwares which simulate the building considering its specific end-use. However sometimes, even if the building is occupied, demand data is available only on a monthly basis. In this case, demand energy trends can be estimated knowing the specific use of the building to which the energy is supplied. The United States Department of Energy (DOE) [68] collected a large amount of data related to various commercial buildings (hospitals, swimming pools, banks, municipal buildings, etc.) and defined a model to obtain hourly demand profiles, based on power installed or monthly consumption.

- temperature and humidity. These values are required if the efficiencies of the components selected in the superstructure are affected by temperature and humidity.

- current cost of energy. This parameter, available only if the building is occupied, is necessary to compare the conventional cost obtained with the optimization, and the real one. The optimization can be performed for various type of possible configurations of the energy system and, among them, also for the conventional configuration. It refers to the actual energy system configuration and normally it is composed by a boiler for the production of thermal energy, by a compression chiller for the production of cooling energy, while the electric energy is bought from the electricity network. The final cost obtained gives an idea of how well the model approximates the reality. If there is a big difference between the real and calculated values it is necessary to adjust the input data through the typical days, but if the difference is small it is not necessary because the optimization procedure compares all possible configurations to each other on the basis of the same data and thus the error affects all configurations in the same way.

Due to the high variability of the energy demands, hourly based optimization is needed to accurately analyze and simulate energy supply systems, but a very high number of hours leads to a very high or unfeasible computational time expenses. To overcome this problem, the most common practice is to reduce the number of days used in the optimization procedure working only with *typical days* citeMitchell2005, Dominguez-Munoz2011a, Ortiga2011. The selection and the number of typical days depends on the energy demand variation and which determines monthly and weekly discretization. The months can be expressed through 3 typical days to represent winter, summer and mid-season, 4 days can represent the seasons, one each, while 12 days represent exactly the months. The weeks can be represented by 2 days, one to represent peak days (typically working days) and one to represent off-peak days (typically holidays), by 3 days for including also a non working day and by 7 days, without any approximation. The multiplication between the days which represent the months and the weeks gives the total number of typical days. Ortiga et al. [63] and Dominguez-Munoz et al. [62] presented procedures to reduce a full year of demand data to a few representative days that adequately preserve significant characteristics such as the peak demands, the demand duration curves, and the temporal inter-relationship between the different types of demands (electric, thermal and cooling). 24 typical days has been adopted in the specific application presented in this research: one week per month (12 typical weeks) and one working day and one non-working day for each week.

The number and the kind of typical days, therefore, determine how the user information needs to be collected. Fig. 3.2 shows the energy demand profiles of an hospital in a typical working winter day.

3.1.2 Technical Information

Technical information refers to the components which could potentially be part of the final optimal energy system. The set of information required are:

- relation between fuel and product. The relation could be represented by a single number, if it does not depend on the component load (constant efficiency), or could be represented by a curve. This relation could be also dependent on the ambient temperature and humidity.
- relation between product and sub-products. As the previous relation, it could be represented by a single number or by a curve and it is the relation between the main product and the sub-products, which normally are products of second relevance. For example, for the cogenerators the main product is the electricity while the thermal energy is considered as a sub-product.
- maintenance costs. Maintenance costs can be either fixed (cost for annual maintenance of the component) or variable depending on the product.

- technical limits. The load limits account the possibility of the components to operate at full or partial load while the size limits limit the size of the component which can be adopted within the superstructure.
- technical constraints. They are considered as all the constraints which each component could have and that have to be taken into consideration when the model is defined. Absorption chillers, for example, has a lower limit of the activation temperature, thermal storage and DHN have intrinsic thermal losses, etc.
- investment cost. The investment cost is dependent, as obvious, on the size of the component. If the component is considered of fixed size inside the superstructure, the investment cost is a single number, while, if the component is considered of variable size, the investment cost has to be related to the component size.
- life span. It is considered as the total life of the component, after that the component needs to be substituted by a new one. Sometimes, the life span is substituted by the amortization time if the economic influence on the final result wants to be taken into consideration.

3.1.3 Boundary Information

Boundary information is considered as all information not covered by the other two points:

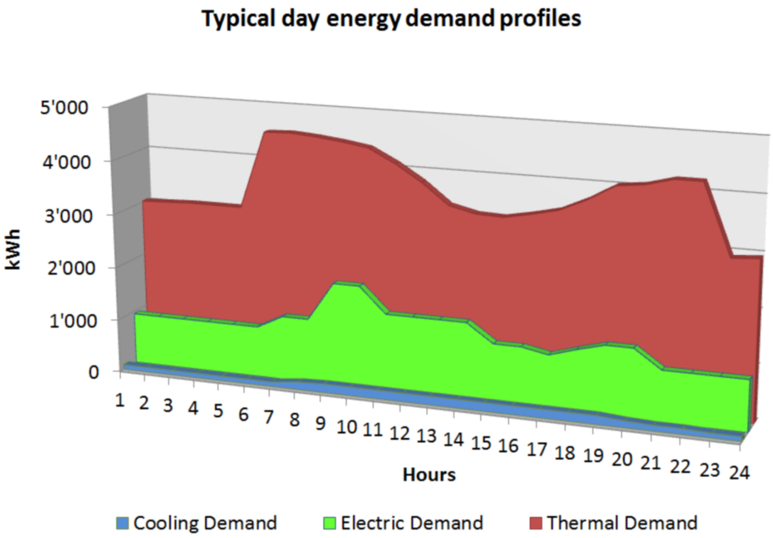


FIGURE 3.2 – Energy demand profile of the hospital used for the optimizations in a typical winter working day

- market energy prices. These are the costs of the electricity (bought and sold) and of the fuels used to supply the components (natural gas, biomass, etc.).
- incentives. The incentives could be either fixed or depending on the product. Fixed incentives are generally released when the component is installed for the first time and they affect the investment cost. Other incentives can be related to the products (e.g energy produced with photovoltaic panels) or to the fuels (e.g. fuel used to supply cogenerators) and affect the operating annual cost.
- greenhouse emissions. They comprehend the emission related to the electricity bought from the grid (through the electricity greenhouse emission coefficient which depends on the national electricity system) and the emission due to the combustion of fuels, which depends on the type of fuels and on where the fuels come from.
- interest rate. The interest rate is composed by two rates, one related to the current cost of money, while the other accounts for the investment risk. In this thesis the interest rate has been assumed equal to 6%.
- typical day weights. The weights depend on which kind of strategy has been adopted to determine the typical days and they represent the weight of each typical day in the objective functions.

3.2 Model Definition

The mathematical problem of optimizing the synthesis, design and operation of a DG energy system has to be generally regarded as a variational calculus problem because several decision variables related to the components are time dependent. However, a realistic description of the system may be represented by a MILP formulation by properly discretizing all dynamic variables in quasi-stationary variables and approximating all non-linear relations in a set of linear functions [69–71, 40, 72].

3.2.1 Superstructure

To solve the issue of synthesizing the configuration of the energy system, a reducible structure (known also as superstructure) which embeds several possible configurations and interconnections is defined. The superstructure should include as much as possible components and interconnections, because the more options are included, the more likely the absolute optimal configuration is obtained. On the other hand, if a lot of components are included in the superstructure and they are accurately described, the resulting optimization model will be extremely large and the optimization problem becomes difficult to solve. For this reason, the design engineer has to previously identify the more likely configurations based on his past experiences and they have to include only them into the optimal superstructure. This operation involves a preliminary analysis of the energy demands, the knowledge of the available technologies and of the process integrations, and a comprehensive view of the whole system.

The superstructure proposed in this research is shown in Fig. 3.3. The superstructure can be divided into two different parts: the superstructure related to each *site*; the superstructure related to the *central unit*. The green, red and blue lines represent the physical distributions of electric, thermal and cooling energy respectively, while the orange arrows represent the fuel inputs. Following each distribution line inside the site k, the electricity can be produced by ICEs, by MGTs and by the PV panels, can be bought from or sold to the electricity grid, used by CCs and by the HPs, while the rest is send to the user k. The thermal energy can be produced by ICEs, by MGTs, by ST panels, by BOIs and by HPs, can be stored in the TS, can be used by ABSs, can be send to the user k or to the DHN. The cooling energy can be produced by CCs, by ABSs and by HPs, can by stored in the Cooling Storage (CS), can be send to the user k or to the DCN. The central unit can produce electricity by the centralized ICE can produce thermal energy by the central ICE, by the central BOI and by the Solar thermal field (ST field). The thermal energy produced in the central unit can be send directly to the DHN and then to the users, or can be stored in a centralized TS and used in a second time. The electricity produced in the central unit by the centralized ICE can only be sold to the electricity grid [70].

The superstructure shown in 3.3 has been created specifically for the problem involved in the study, but it is general and can be integrated with other components. It can be modified with different connections of the components or it can be reduced eliminating some components considered superfluous. The number of users is not defined a priori by the superstructure as the proposed methodology is modular and can be applied to various context with different number of users. However the maximum number of users which can be considered is limited by the computational effort which is quadratic whit the overall number of decision variables.

3.2.2 Decision Variables

In the aforementioned problem the optimization variables to be considered in order to determine the optimal energy system can be divided in two main group:

- binary variables: they represent the existence/absence of each component and the operation status (on/off) of each component in each time interval. There are other additional binary variables which do not represent any physical quantity, added to linearize some relations;
- continuous variables: they represent the size of components, the size of pipelines, the load of components in each time interval, the energy stored in the storages and the connection flows.

In the following equations the decision variables are bold, while the remaining acronyms are fixed coefficients and quantity which can be evaluated by fixing the decision variables. The acronyms are formed by three parts, the former express the acronym, the second one represent the component/flow to which it is related, while the latter are general indexes. Fig. 3.4 reports an example of an acronym and it reports also which is the meaning of all the possible "sub-acronyms". Referring to the acronym reported in Fig. 3.4 it expresses

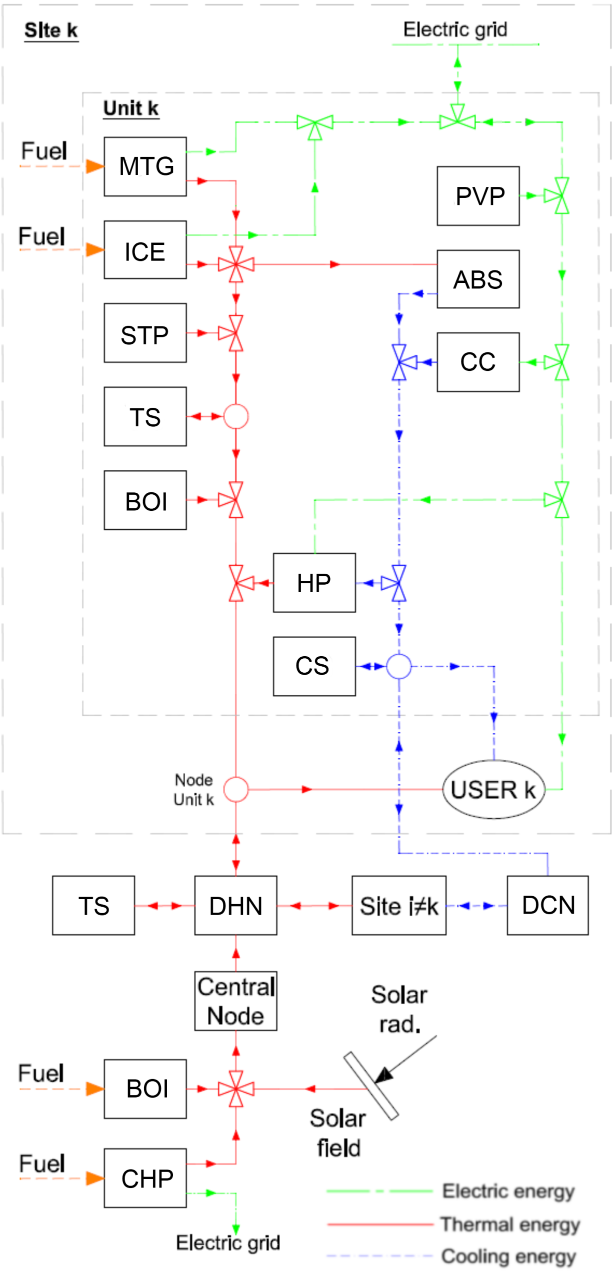
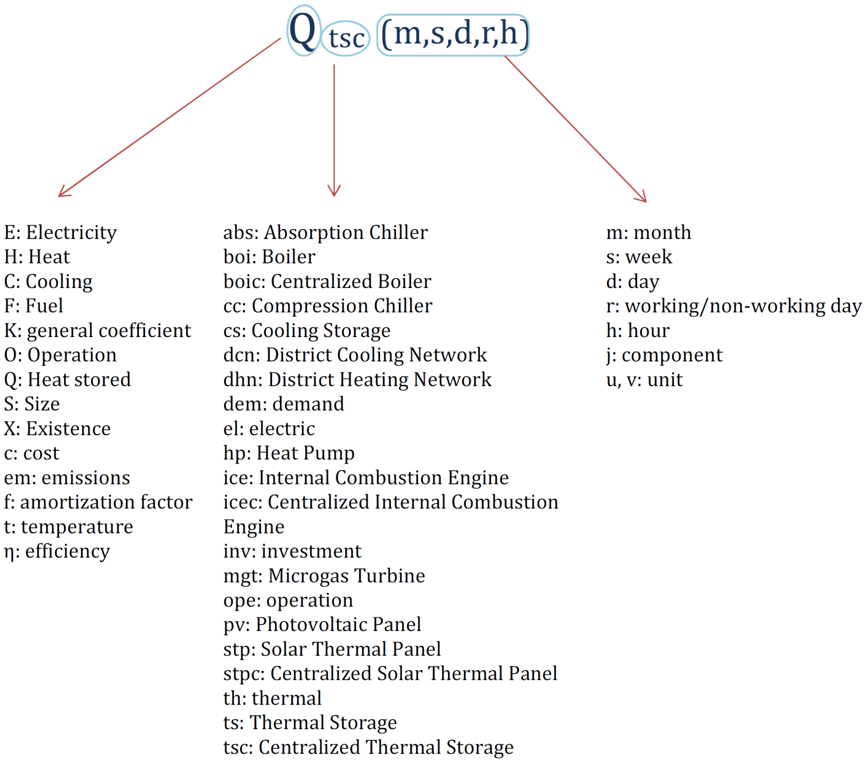


FIGURE 3.3 – Superstructure of the DG energy system

the heat (Q) stored in the centralized thermal storage (tsc) in the month m, week s, day d, day type r and hour h.



E: Electricity
H: Heat
C: Cooling
F: Fuel
K: general coefficient
O: Operation
Q: Heat stored
S: Size
X: Existence
c: cost
em: emissions
f: amortization factor
t: temperature
η: efficiency

abs: Absorption Chiller
boi: Boiler
boic: Centralized Boiler
cc: Compression Chiller
cs: Cooling Storage
dcn: District Cooling Network
dhn: District Heating Network
dem: demand
el: electric
hp: Heat Pump
ice: Internal Combustion Engine
icec: Centralized Internal Combustion Engine
inv: investment
mgt: Microgas Turbine
ope: operation
pv: Photovoltaic Panel
stp: Solar Thermal Panel
stpc: Centralized Solar Thermal Panel
th: thermal
ts: Thermal Storage
tsc: Centralized Thermal Storage

m: month
s: week
d: day
r: working/non-working day
h: hour
j: component
u, v: unit

FIGURE 3.4 – Acronym description

3.2.3 Problem Constraints

The constraints describe the energy system. As fundamental constraints, the performance characteristics of equipment and energy balance relationships are considered. If necessary, other constraints, such as relationships between maximum contract demands and consumptions of energy purchased and operational restrictions, are considered. There are equality constraints, forming the $\overrightarrow{H}$ matrix reported in eq. 2.1, which express fix relations and balances, while there are inequality constraints, forming the $\overrightarrow{G}$ matrix reported in eq. 2.2, which express limits and feasibility conditions. The constraints can be grouped in four categories which describe:

- components;
- district heating and cooling network;

- thermal storage;
- energy balances.

Components

The components are described relating the products to the fuels and introducing the size and load limits. Additional constraints are required to describe the superstructure, energy flows and operation conditions. All cogenerators, heat pumps and absorption chillers included in the superstructure are of fixed size, while boilers, compression chillers, solar and photovoltaic panels are of variable size. A fixed size components can be adopted several times within the optimal site configuration (up to j components). The components of the central unit are all of variable size.

The following constraints (eqs. 3.1, 3.5) describe the ICE which can be installed in each production site. The constraints which describe the MGT can be easily inferred changing in each variable or coefficient the subscript "ice" with the subscript "mgt".

The first set of constraints ensures that a consistent set of binary variables ($\boldsymbol{X_{ice}}$, $\boldsymbol{O_{ice}}$) is taken into account in each time interval and all the year long: the component j can be installed only if the component $j-1$ has been already adopted (eq. 3.1), and the component j can never be in operation if it has not been adopted (eq. 3.2).

$$\boldsymbol{X_{ice}}(j,u) \leq \boldsymbol{X_{ice}}(j-1,u) \tag{3.1}$$

$$\boldsymbol{O_{ice}}(m,d,h,j,u) \leq \boldsymbol{X_{ice}}(j,u) \tag{3.2}$$

The second group describes the partial load performance of energy conversion devices by means of linear relations:

$$H_{ice}(m,d,h,j,u) = Kh_{ice}(m,d,h,1) \cdot \boldsymbol{E_{ice}}(m,d,h,j,u) + Kh_{ice}(m,d,h,2) \cdot \boldsymbol{O_{ice}}(m,d,h,j,u) \tag{3.3}$$

$$F_{ice}(m,d,h,j,u) = Kf_{ice}(m,d,h,1) \cdot \boldsymbol{E_{ice}}(m,d,h,j,u) + Kf_{ice}(m,d,h,2) \cdot \boldsymbol{O_{ice}}(m,d,h,j,u) \tag{3.4}$$

$$E_{ice,lim}(m,d,h,u,1) \cdot \boldsymbol{O_{ice}}(m,d,h,j,u) \leq \boldsymbol{E_{ice}}(m,d,h,j,u) \leq E_{ice,lim}(m,d,h,u,2) \cdot \boldsymbol{O_{ice}}(m,d,h,j,u) \tag{3.5}$$

The coefficients Kh_{ice} and Kf_{ice} can be obtained through a linear regression of the load curves.

A variable size ICE can be installed in the central unit. As well as for the production site ICE it can work at partial load. The constraints which describe this component (eqs. 3.6, 3.11) are different from the previous constraints, because it is necessary to introduce additional constraints and decision variables in order to maintain the linearity of the problem.

The first set of constraints limits the size of the ICE which can be adopted and relate the operation to its existence:

$$S_{ice,lim,c}(1) \cdot \boldsymbol{X_{ice,c}} \leq \boldsymbol{S_{ice,c}} \leq S_{ice,lim,c}(2) \cdot \boldsymbol{X_{ice,c}} \tag{3.6}$$

$$\boldsymbol{O_{ice,c}}(m,d,h) \leq \boldsymbol{X_{ice,c}} \tag{3.7}$$

The second set of constraints relates the main product ($\boldsymbol{E_{ice,c}}$) to the sub-product ($H_{ice,c}$) and to the fuel ($F_{ice,c}$).

$$\begin{split} H_{ice,c}(m,d,h) = Kh_{ice,c}(m,d,h,1) \cdot \boldsymbol{E_{ice,c}} + \\ Kh_{ice,c}(m,d,h,2) \cdot \boldsymbol{O_{ice,c}}(m,d,h) + Kh_{ice,c}(m,d,h,3) \cdot \boldsymbol{\xi}_{ice,c}(m,d,h) \end{split} \tag{3.8}$$

$$\begin{split} F_{ice,c}(m,d,h) = Kf_{ice,c}(m,d,h,1) \cdot \boldsymbol{E_{ice,c}} + \\ Kf_{ice,c}(m,d,h,2) \cdot \boldsymbol{O_{ice,c}}(m,d,h) + Kf_{ice,c}(m,d,h,3) \cdot \boldsymbol{\xi}_{ice,c}(m,d,h) \end{split} \tag{3.9}$$

The last set of equations does not have any physical meaning, and they are required to constrain the additional variable $\boldsymbol{\xi}_{ice,c}$.

$$\boldsymbol{S_{ice,c}} + S_{ice,lim,c}(2) \cdot (\boldsymbol{O_{ice,c}}(m,d,h) - 1) \leq \boldsymbol{\xi}_{ice,c}(m,d,h) \leq \boldsymbol{S_{ice,c}} \tag{3.10}$$

$$S_{ice,lim,c}(1) \cdot \boldsymbol{O_{ice,c}}(m,d,h) \leq \boldsymbol{\xi}_{ice,c}(m,d,h) \leq S_{ice,lim,c}(2) \cdot \boldsymbol{O_{ice,c}}(m,d,h) \tag{3.11}$$

Boilers which can be installed in each production site are of variable size. For sick of simplicity it has been considered that they have no minimum load limit. This means that if in a time interval a boiler should operate below its load limit, in reality it will operate for a period shorter than the time interval at a load greater than the limit:

$$F_{boi}(m,d,h,u) = \frac{\boldsymbol{H_{boi}}(m,d,h,u)}{\eta_{boi}(m,d,h)} \tag{3.12}$$

$$\boldsymbol{H_{boi}}(m,d,h,u) \leq \boldsymbol{S_{boi}}(u) \tag{3.13}$$

Differently, the boiler which can be installed in the central unit has a minimum load limit and it is described by the following equations (eqs. 3.14, 3.17):

$$F_{boi,c}(m,d,h) = \frac{\boldsymbol{H_{boi,c}}(m,d,h)}{\eta_{boi,c}(m,d,h)} \tag{3.14}$$

$$H_{boi,lim,c} \cdot \boldsymbol{\psi_{boi,c}}(m,d,h) \leq \boldsymbol{H_{boi,c}}(m,d,h) \leq \boldsymbol{\psi_{boi,c}}(m,d,h) \tag{3.15}$$

$$\boldsymbol{S_{boi,c}} + S_{boi,lim,c}(2) \cdot (\boldsymbol{O_{boi,c}}(m,d,h) - 1) \leq \boldsymbol{\psi_{boi,c}}(m,d,h) \leq \boldsymbol{S_{boi,c}} \tag{3.16}$$

$$S_{boi,lim,c}(1) \cdot \boldsymbol{X_{boi,c}} \leq \boldsymbol{S_{boi,c}} \leq S_{ice,lim,c}(2) \cdot \boldsymbol{X_{boi,c}} \tag{3.17}$$

The solar thermal panels are modeled considering a production proportional to the size of the plant. The unitary production (K_{stp}) is evaluated a priori considering inclination and orientation angle of installation, and hourly solar radiation. The following equation 3.18 is written for the solar panel equipment which can be installed in each production site:

$$H_{stp}(m,d,h,u) = K_{stp}(m,d,h,u) \cdot \boldsymbol{S_{stp}}(u) \tag{3.18}$$

The equations related to photovoltaic panels and centralized solar field can be obtained changing the subscript *stp* with *pv* and *stp, c* respectively.

Absorption chillers are modeled by the following equations 3.19, 3.22:

$$\boldsymbol{X_{abs}}(j,u) \leq \boldsymbol{X_{abs}}(j-1,u) \tag{3.19}$$

$$\boldsymbol{O_{abs}}(m,d,h,j,u) \leq \boldsymbol{X_{abs}}(j,u) \tag{3.20}$$

$$H_{abs}(m,d,h,j,u) = Kc_{abs}(m,d,h,1) \cdot \boldsymbol{C_{abs}}(m,d,h,j,u) + Kc_{abs}(m,d,h,2) \cdot \boldsymbol{O_{abs}}(m,d,h,j,u) \tag{3.21}$$

$$C_{abs,lim}(m,d,h,u,1) \cdot \boldsymbol{O_{abs}}(m,d,h,j,u) \leq \boldsymbol{C_{abs}}(m,d,h,j,u) \leq C_{abs,lim}(m,d,h,u,2) \cdot \boldsymbol{O_{abs}}(m,d,h,j,u) \tag{3.22}$$

Compression chillers which can be installed in each production site are of variable size. For sick of simplicity it has been considered that they have no minimum load limit, as for boilers:

$$E_{cc}(m,d,h,u) = \frac{\boldsymbol{C_{cc}}(m,d,h,u)}{COP_{cc}(m,d,h,u)} \tag{3.23}$$

$$\boldsymbol{C_{cc}}(m,d,h,u) \leq \boldsymbol{S_{cc}}(u) \tag{3.24}$$

The heat pump is modeled considering it as an ideal machine that can produce either heat or cold, but not simultaneously:

$$\boldsymbol{X_{hp}}(j,u) \leq \boldsymbol{X_{hp}}(j-1,u) \tag{3.25}$$

$$\boldsymbol{O_{hp,h}}(m,d,h,j,u) \leq \boldsymbol{X_{hp}}(j,u) \tag{3.26}$$

$$\boldsymbol{O_{hp,c}}(m,d,h,j,u) \leq \boldsymbol{X_{hp}}(j,u) \tag{3.27}$$

$$\boldsymbol{O_{hp,h}}(m,d,h,j,u) + \boldsymbol{O_{hp,c}}(m,d,h,j,u) \leq 1 \tag{3.28}$$

$$H_{hp}(m,d,h,j,u) = K_{hp}(m,d,h,u,1) \cdot \boldsymbol{E_{hp,h}}(m,d,h,j,u) + K_{hp}(m,d,h,u,2) \cdot \boldsymbol{O_{hp,h}}(m,d,h,j,u) \tag{3.29}$$

$$C_{hp}(m,d,h,j,u) = K_{hp}(m,d,h,u,3) \cdot \boldsymbol{E_{hp,c}}(m,d,h,j,u) + K_{hp}(m,d,h,u,4) \cdot \boldsymbol{O_{hp,c}}(m,d,h,j,u) \tag{3.30}$$

$$S_{hp,lim}(m,d,h,u,1) \cdot \boldsymbol{O_{hp,h}}(m,d,h,j,u) \leq \boldsymbol{E_{hp,h}}(m,d,h,j,u) \leq S_{hp,lim}(m,d,h,u,2) \cdot \boldsymbol{O_{hp,h}}(m,d,h,j,u) \tag{3.31}$$

$$S_{hp,lim}(m,d,h,u,1) \cdot \boldsymbol{O_{hp,c}}(m,d,h,j,u) \leq \boldsymbol{E_{hp,c}}(m,d,h,j,u) \leq S_{hp,lim}(m,d,h,u,2) \cdot \boldsymbol{O_{hp,c}}(m,d,h,j,u) \tag{3.32}$$

$$E_{hp}(m,d,h,j,u) = \boldsymbol{E_{hp,h}}(m,d,h,c,u) + \boldsymbol{E_{hp,c}}(m,d,h,j,u) \tag{3.33}$$

There are few other constraints which determine the conditions for the operation of the ABS, which depends on the operations of other components, such as ICE, MGT. Equation 3.34 allows the ABS operation only if the heat produced by ICE and MGT is grater than the heat required by the ABS, while equation 3.35 relates the ABS existence to the ICE and MGT existence:

$$\boldsymbol{C_{abs}}(m,d,h,j,u) \leq H_{ice}(m,d,h,j,u) + H_{mgt}(m,d,h,j,u) \tag{3.34}$$

$$\boldsymbol{X_{abs}}(j,u) \leq \boldsymbol{X_{ice}}(j,u) + \boldsymbol{X_{mgt}}(j,u) \tag{3.35}$$

District Heating and Cooling Network

The modelization of the DHCN is important for the optimization of the DG energy system, because it strongly affects the optimal solution [73–75].

The aim of the DG energy system optimization, is to define the lay-out of the DHCN and the diameter of each single pipeline, taking into account the operation of the whole system. The heat which can be transferred by a DHCN pipeline can be expressed by:

$$\dot{Q}_p = A_p \cdot v_p \cdot \rho_p \cdot c_p \cdot \Delta t \tag{3.36}$$

Assuming that the velocity v_p is fixed, the transferred heat $\dot{Q}_p$ reported in equation 3.36 depends on two variables, which are the area of the pipeline A_p and the temperature difference between inlet and outlet pipelines Δt [76]. This determines two ways of accounting the network in the model:

- assuming a fixed temperature of the network and a fixed temperature difference between the inlet and outlet temperatures. This modelization let the size and the layout of the network be variable;
- assuming a fixed lay-out and size of the network and let the temperature of the network be variable. In this case, the thermal inertia of the network can be considered.

If the network temperature is considered constant, the constraints which model the DHCN represent the pipelines structure and the flow rate limits of each pipe. The first set of equations 3.37, 3.45 describe the existence conditions of thermal and cooling pipelines:

$$\boldsymbol{X_{tp}}(u,v) + \boldsymbol{X_{tp}}(v,u) \leq 1 \tag{3.37}$$

$$\boldsymbol{X_{cp}}(u,v) + \boldsymbol{X_{cp}}(v,u) \leq 1 \tag{3.38}$$

$$\boldsymbol{X_{net}}(u,v) \leq \boldsymbol{X_{tp}}(u,v) + \boldsymbol{X_{cp}}(u,v) \tag{3.39}$$

$$\boldsymbol{X_{net}}(u,v) \geq \boldsymbol{X_{tp}}(u,v) \tag{3.40}$$

$$\boldsymbol{X_{net}}(u,v) \geq \boldsymbol{X_{cp}}(u,v) \tag{3.41}$$

$$\boldsymbol{S_{H,net}}(u,v) \geq H_{net,lim}(1) \cdot \boldsymbol{X_{tp}}(u,v) \tag{3.42}$$

$$\boldsymbol{S_{C,net}}(u,v) \geq H_{net,lim}(1) \cdot \boldsymbol{X_{cp}}(u,v) \tag{3.43}$$

$$\boldsymbol{S_{H,net}}(u,v) \leq H_{net,lim}(2) \cdot \boldsymbol{X_{tp}}(u,v) \tag{3.44}$$

$$\boldsymbol{S_{C,net}}(u,v) \leq H_{net,lim}(2) \cdot \boldsymbol{X_{cp}}(u,v) \tag{3.45}$$

The second set of equations limits the energy flow through each pipeline based on its size:

$$\boldsymbol{H_{net}}(m,d,h,u,v) \leq \boldsymbol{S_{H,net}}(u,v) \tag{3.46}$$

$$\boldsymbol{C_{net}}(m,d,h,u,v) \leq \boldsymbol{S_{C,net}}(u,v) \tag{3.47}$$

In this case, there is a constant relation between the size of the pipeline and the maximum flow which can be transferred, which can be evaluated thorough equation 3.36. The Δt adopted normally ranges between $15 \div 25K$ depending on the application, while the medium velocity v_p ranges between $1.5 \div 2.5\frac{m}{s}$. The thermal losses are considered proportional to the length of each pipeline through the coefficients:

$$p_t(u,v) = \delta_t \cdot l_p(u,v) \tag{3.48}$$

$$p_c(u,v) = \delta_c \cdot l_p(u,v) \tag{3.49}$$

In the case where the temperature of the network is considered variable and consequently the lay-out and the size of the network is considered fixed and known in advance, there is a relation between the temperature of the medium inside each pipeline and the heat stored in the pipeline:

$$\begin{split} Q_{net}(m,d,h,u,v) = A_p(u,v) \cdot l_p(u,v) \cdot v_p \cdot \rho_p \cdot c_p \cdot \\ \big(\boldsymbol{t_{pip}}(m,d,h,u,v) - \boldsymbol{t_{pip}}(m,d,h-1,u,v)\big) \end{split} \tag{3.50}$$

The outlet temperature is considered fixed too, while the thermal losses are proportional to the medium temperature and can be evaluated through:

$$H_{los}(m,d,h,u,v) = K_{los,net} \cdot (\boldsymbol{t_{pip}}(m,d,h,u,v) - t_{env}(m,d,h)) \tag{3.51}$$

The energy balance of each pipeline is expressed by:

$$\begin{split} \boldsymbol{H_{net}}(m,d,h,u,v) - Q_{net}(m,d,h,u,v) - \\ H_{los}(m,d,h,u,v) - \boldsymbol{H_{ric}}(m,d,h,u,v) = 0 \end{split} \tag{3.52}$$

Considering the temperature of the network as a design variable, other constraints express the possibility for a user to get energy form the grid only if the temperature is greater than a proper limit:

$$\boldsymbol{H_{ric}}(m,d,h,u,v) \leq H_{net,lim}(2) \cdot \boldsymbol{\tau}(m,d,h,u,v) \tag{3.53}$$

$$\boldsymbol{t_{pip}} \geq t_{lim} \cdot \boldsymbol{\tau}(m,d,h,u,v) \tag{3.54}$$

The same modelization can be obtained for the district cooling network, properly changing the subscripts.

This kind of modelization of the DHCN can be used when the network is already existent, or when the distances between users is large. In fact, this kind of approach, differently from the first one, accounts also for the thermal inertia of the DHCN. The model considering a fixed layout of the DHCN has been applied to a large industrial area by Reini et al. [77] and it resulted that the thermal inertia did not affect significantly the overall optimal structure. However, it affected the optimal operation making the annual cost increasing by about 2%.

The model which has been applied in the application case, reported in the part II, uses the first approach described by equations 3.37÷3.47.

Thermal Storage

Thermal energy storages comprise several technologies which allows to store thermal energy for a later use. They can be employed either to decouple electric and thermal demands or to balance the intermittent production of thermal energy typical of solar energy systems. Therefore, they can be useful either for CHP production unit or solar systems.

Heat storage in a combined heat and power CHP system is a very important measure that is applied in large-scale DHN systems with CHP to enhance flexibility. In a system with CHP production units, there is one general problem that makes the use of thermal storage important. This problem is the fact that heat and power production are connected to each other but the demand for these are independent of each other, meaning that the production has to follow one of the demands. In a DHN system, the heat demand normally determines the production for an economic management of the system. Fluctuating heat load and electricity price at different time periods of the day of the year has a significant impact on the operation of CHP. The situation where heat load and electricity price do not coincide in time on diurnal basis makes the use of short-term thermal storage attractive [78]. When the electricity price is high and the momentarily heat demand is low, the storage can be charged with excess heat from the CHP and this heat can be used later on. During summer time, two conditions can appear: very low heat demand and high electricity price. In this situation, it may be worth to generate electricity through CHP plants and dump the heat generated simultaneously. With seasonal heat storage it could be possible to run the CHP during summer where the heat instead of dumping can be stored for a later use to replace peak load units and the electricity can generate revenues. Moreover, during summer time, for instance, the heat demand can be so low that the CHP plant must be shut down. In such situation, a heat-only boiler, which is often expensive in operational cost, must be taken into operation. A long-term thermal storage in this case might be able to extend the operation time of the CHP unit. By using thermal storage, power generation can be increased and the use of fossil fuels can be reduced [79]. In any case, all this general consideration are very difficult to be evaluated at the same time during the design phase and therefore an optimization can be very helpful for the designer to determine the optimal size, configuration and operation of the integrated system.

If renewable energy sources are considered, solar energy is an important alternative that will more likely be utilized in the future, and the TS will play an important role in its development, because one main factor that limits its application is that the solar energy is a cyclic, unpredictable, time-dependent energy resource . The problem of intermittent energy sources is especially severe for solar energy, because thermal energy is usually needed most when solar availability is lowest, namely, in winter. Small TS operates over short periods and can cover periods of inadequate sunshine, while large TS operates over long period and can partially cover the lower winter solar thermal production [80]. Also in this case, the design of the integrated system is very difficult and normally several rules of thumb are used to define the system. An optimization procedure also in this case is very helpful to determine the optimal system.

For residential space heating application the water is the medium of choice, due to the temperature application in the range 20÷80 ℃ and its high thermal capacity ($\approx$ 4.2 kj/kg). Moreover it is close to the upper temperature limit of the fluid exiting typical solar collectors. The possibility to obtain high convective heat transfer rates from water is both an advantage, as it allows high heat injection and extraction rates, and an inconvenience, as it makes stratification more difficult [81].

There are mainly four types of technologies employed worldwide as TS [82]:

- tank thermal storage: water tanks can be either artificial constructs made of steel and/or concrete or geological cavities. Heat is transported to or from the tank by a flow of water in and out of the tank, or by a fluid circulated in a heat exchanger inserted in the tank.

- aquifer thermal storage: an aquifer is a water reservoir and the amount of energy that can be stored depends on the allowable temperature change between hot and cold reservoir, the thermal conductivity, and the natural ground water flow.

- pit thermal storage: similar to tank thermal storage. Pit thermal energy storage is a technology for storing thermal energy seasonally in a large water-filled pit. The pits are usually dug into the ground, lined with an impermeable plastic barrier, filled in with water and covered by an insulating roof.

- borehole thermal energy storage: is a technology for storing thermal energy in underground geological formations. Hot or cold water is circulated in pipes set into boreholes.

For what concern this optimization model, the thermal and cooling storages which can be installed to each production unit or to the central unit can be modeled in the same way, accepting the approximations of perfect stratification of medium (water) inside the thermal storage. This approximation correspond to the hypothesis that if the storage is not completely empty (in energy meaning) the residual energy is stored at the same temperature required by the DHN. In other words, the different technologies of thermal storages do not affect their modelization in the optimization model.

The energy stored in the thermal energy storage, can be evaluated through:

$$\boldsymbol{Q_{ts}} = \boldsymbol{V_{ts}} \cdot \rho_p \cdot c_p \cdot \Delta t \tag{3.55}$$

As well as for the DHCN, the temperature difference Δt between inlet and oulet temperature is considered constant. Therefore, the thermal energy stored in the thermal storage is proportional to the volume of the medium inside the storage and it is considered as decision variable.

A set of equations is required to describe the energy balance of the thermal storage. In oder to allow for the seasonal charging/discharging cycle, the thermal storage has to be modeled throughout the whole year, without any time decomposition as it can be done for the other components, representing some similar days by one typical day. Applying the time decomposition to all operation variables, except for the variables which represent the energy stored in the thermal storages, allows to reduce the overall number of variables, because a reduced number of typical days is selected, and furthermore allows to represent the thermal storages all year long.

In the proposed model, the year is decomposed in 24 typical days of 24 hours, one typical working day and one typical non-working day each month. Therefore, each single month is composed by similar 4 weeks, in turn composed by 5 similar working days and 2 similar non-working days. In this way, the optimal operation of the system is similar in each working or non working day of the month and each month of the year is composed by 28 days. This approximation can be accepted selecting particular typical days which describe the whole year producing the same total consumption. Specific procedure for the identification of the proper typical days can be found in [63, 62].

The energy balance of the thermal storage is approximated considering that the energy contained in the storage in a general time interval t is equal to the energy stored in the time interval *t-1* multiplied by a thermal loss coefficient plus the input energy in the time interval t:

$$\boldsymbol{Q_{ts}}(m,s,d,r,h,u) - K_{los,ts}(u) \cdot \boldsymbol{Q_{ts}}(m,s,d,r,h-1,u) = \boldsymbol{H_{ts}}(m,d,h,u) \tag{3.56}$$

Additional constraints have to be added to connect the working days with non-working ones, weeks, months, etc. For example, eq. 3.57 connects two days of the same kind:

$$\boldsymbol{Q_{ts}}(m,s,d,r,h,u) - K_{los,ts}(u) \cdot \boldsymbol{Q_{ts}}(m,s,d,r-1,24,u) = \boldsymbol{H_{ts}}(m,d,h,u) \tag{3.57}$$

Finally, the heat stored inside the storage $\boldsymbol{Q_{ts}}$, has to be lower than the size of the storage $\boldsymbol{S_{ts}}$:

$$\boldsymbol{Q_{ts}}(m,d,h,u) \leq \boldsymbol{S_{ts}}(u) \tag{3.58}$$

Energy Balances

Energy balances are a set of constraints which ensures that in each node and in each time interval the input energy is equal to the output energy. With reference to the superstructure represented in fig. 3.3, the nodes are three for each site (electric, thermal and cooling) plus the two nodes of the central site (electric and thermal). The energy balance of the network is included in the node energy balance. In the following the electric balance for a site u is described in detail, while the thermal and cooling balances are reported with no description.

The electricity produced by the ICE ($\boldsymbol{E_{ice}}$), plus the electricity produced by the MGT ($\boldsymbol{E_{mgt}}$), plus the electricity produced by the PV panels (E_{pvp}), plus the electricity bought form the grid ($\boldsymbol{E_{bgt}}$), has to be equal to the electricity required by the CC (E_{cc}), plus the electricity required by the HP (E_{hp}), plus the electric demand of the user (E_{dem}), plus the sold electricity ($\boldsymbol{E_{sol}}$):

$$\begin{aligned}\boldsymbol{E_{ice}}(m,d,h,u) + \boldsymbol{E_{mgt}}(m,d,h,u) + E_{pvp}(m,d,h,u) + \boldsymbol{E_{bgt}}(m,d,h,u) = \\ E_{cc}(m,d,h,u) + E_{hp}(m,d,h,u) + E_{dem}(m,d,h,u) + \boldsymbol{E_{sol}}(m,d,h,u)\end{aligned} \tag{3.59}$$

The thermal balance of a site is expressed by:

$$\begin{aligned}&H_{mgt}(m,d,h,u) + H_{ice}(m,d,h,u) + \\ &\quad H_{stp}(m,d,h,u) + \boldsymbol{H_{boi}}(m,d,h,u) + H_{hp}(m,d,h,u) + \\ &\quad\quad \boldsymbol{H_{net}}(m,d,h,v,u) \cdot (1 - p_t(v,u)) = \boldsymbol{H_{ts}}(m,d,h,u) + \\ &\quad\quad\quad H_{abs}(m,d,h,u) + H_{dem}(m,d,h,u) + \boldsymbol{H_{net}}(m,d,h,u,v)\end{aligned} \tag{3.60}$$

The thermal energy to be stored can be produced only by ICE, MGT and ST panels:

$$H_{mgt}(m,d,h,u) + H_{ice}(m,d,h,u) + H_{stp}(m,d,h,u) - \boldsymbol{H_{ts}}(m,d,h,u) \geq 0 \tag{3.61}$$

The cooling balance of a site is expressed by:

$$\begin{aligned}\boldsymbol{C_{abs}}(m,d,h,u) + \boldsymbol{C_{cc}}(m,d,h,u) + C_{hp}(m,d,h,u) = \\ C_{dem}(m,d,h,u) + \boldsymbol{C_{ts}}(m,d,h,u)\end{aligned} \tag{3.62}$$

The cooling energy to be stored can be produced only by CC, ABS and HP:

$$\boldsymbol{C_{abs}}(m,d,h,u) + \boldsymbol{C_{cc}}(m,d,h,u) + C_{hp}(m,d,h,u) - \boldsymbol{C_{ts}}(m,d,h,u) \geq 0 \tag{3.63}$$

For what concern the central unit, the electric balance is very simple, because the electricity produced by the central CHP can only be sold, while the thermal balance is expressed by:

$$\begin{aligned}H_{ice,c}(m,d,h) + \boldsymbol{H_{boi,c}}(m,d,h) + H_{stp,c}(m,d,h) = \\ \boldsymbol{H_{net,c}}(m,d,h) + \boldsymbol{H_{ts,c}}(m,d,h)\end{aligned} \tag{3.64}$$

The thermal production of the central unit can connects to the other sites in the node of a site u. The thermal balance related to that site (eq. 3.60) changes therefore in:

$$\begin{aligned} & H_{mgt}(m,d,h,u) + H_{ice}(m,d,h,u) + \\ & \quad H_{stp}(m,d,h,u) + \boldsymbol{H_{boi}}(m,d,h,u) + H_{hp}(m,d,h,u) + \\ & \quad\quad \boldsymbol{H_{net}}(m,d,h,v,u) \cdot (1 - p_t\,(v,u)) + \boldsymbol{H_{net,c}}(m,d,h) \cdot (1 - p_{t,c}) = \\ & \boldsymbol{H_{ts}}(m,d,h,u) + H_{abs}(m,d,h,u) + H_{dem}(m,d,h,u) + \boldsymbol{H_{net}}(m,d,h,u,v) \end{aligned} \tag{3.65}$$

All continuous variables have to be greater than zero, except the variables related to the thermal storage input/output heat flow ($\boldsymbol{H_{ts,c}}$, $\boldsymbol{H_{ts}}$, $\boldsymbol{C_{ts}}$) which are free. Positive values represent input flows, while negative values means an energy extraction from the thermal storage.

The temperature of the thermal flows are not taken into account because it would have compromised the linearity of the problem. However, this is not a strong approximation considering that the thermal energy required by the users is normally supplied at a temperature of 50÷55 °and all components are able to produce the thermal energy at greater temperatures. Some restrictions due to the coupling of components related to the operating temperatures (ICE, MGT together with ABS) have been considered through a particular conformation of the superstructure and with additional constraints which consider this matter (e.g. eqs. 3.34, 3.35).

3.2.4 Economic Objective Function

The economic objective function to be minimized is the total annual cost for owning, operating and maintaining the whole system:

$$Min \quad c_{tot} = c_{inv} + c_{man} + c_{ope} \tag{3.66}$$

The annual cost for the investment (c_{inv}) is the sum of the investment cost of the sites, of the central unit, and of the network (eq. 3.71). The investment cost of a site can be evaluated through:

$$\begin{aligned} c_{inv,u}(u) = & \sum_j \Big(f_{mgt} \cdot \boldsymbol{X_{mgt}}(j,u) \cdot c_{mgt}(j,u) + f_{ice} \cdot \boldsymbol{X_{ice}}(j,u) \cdot c_{ice}(j,u) + \\ & \quad f_{hp} \cdot \boldsymbol{X_{hp}}(j,u) \cdot c_{hp}(j,u) + f_{abs} \cdot \boldsymbol{X_{abs}}(j,u) \cdot c_{abs}(j,u) \Big) + \\ & \quad\quad f_{boi} \cdot \boldsymbol{S_{boi}}(u) \cdot c_{boi} + f_{cc} \cdot \boldsymbol{S_{cc}}(u) \cdot c_{cc} + f_{pvp} \cdot S_{pvp}(u) \cdot c_{pvp} + \\ & \quad\quad\quad f_{stp} \cdot \boldsymbol{S_{stp}}(u) \cdot c_{stp} + f_{ts} \cdot \boldsymbol{S_{ts}}(u) \cdot c_{ts} + f_{ts} \cdot \boldsymbol{S_{cs}}(u) \cdot c_{ts} \end{aligned} \tag{3.67}$$

The investment cost of the central unit is:

$$\begin{aligned} c_{inv,c} = & f_{ice}\,(\boldsymbol{S_{ice,c}} \cdot c_{ice,v} + \boldsymbol{X_{ice,c}} \cdot c_{ice,f}) + \\ & \quad f_{boi} \cdot (\boldsymbol{S_{boi,c}} \cdot c_{boi,v} + \boldsymbol{X_{boi,c}} \cdot c_{boi,f}) + f_{stp} \cdot \boldsymbol{S_{stp,c}} \cdot c_{stp,c} + \\ & \quad\quad f_{ts} \cdot \boldsymbol{S_{ts,c}} \cdot c_{ts,c} + f_{net} \cdot (c_{net,f,c} \cdot \boldsymbol{X_{net,c}} + c_{net,v,c} \cdot \boldsymbol{S_{H,net,c}}) \end{aligned} \tag{3.68}$$

The investment cost of the network is:

$$c_{net} = f_{net} \cdot \sum_{u,v} (c_{net,f,c}(1) \cdot (\boldsymbol{X_{tp}}(u,v) + \boldsymbol{X_{cp}}(u,v)) + \\ c_{net,f,c}(1) \cdot \boldsymbol{X_{net}}(u,v) + c_{net,v} \cdot (\boldsymbol{S_{H,net,c}}(u,v) + \boldsymbol{S_{C,net}}(u,v))) \quad (3.69)$$

The amortization factor f are calculated through:

$$f_x = \frac{i \cdot (1+i)^{n_x}}{(1+i)^{n_x} - 1} \quad (3.70)$$

where i is the interest rate and n_x is the life span of the generic component x.

The annual investment cost is therefore:

$$c_{inv} = \sum_u (c_{inv,u}) + c_{inv,c} + c_{net} \quad (3.71)$$

Maintenance costs related to the components are considered proportional to the products, while the operation costs comprehend the costs for fuel, electricity bought from the grid and the eventual income from the sale of electricity. For each sit u the annual operation cost is evaluated as:

$$c_{ope,u}(u) = \sum_{m,d,h} (c_{fue,chp}(m) \cdot (F_{ice}(m,d,h,u) + F_{mgt}(m,d,h,u)) + \\ c_{fue,boi}(m) \cdot F_{boi}(m,d,h,u) + c_{el,bgt}(m,d,h) \cdot \boldsymbol{E_{bgt}}(m,d,h,u) - \\ c_{el,inc} \cdot E_{pvp}(m,d,h,u) - c_{el,sol}(m,d,h) \cdot \boldsymbol{E_{sol}}(m,d,h,u)) \cdot wgt(m,d,h) \quad (3.72)$$

For the central site the annual operation cost is:

$$c_{ope,c} = \sum_{m,d,h} (c_{fue,ice,c} \cdot F_{ice,c}(m,d,h) + \\ c_{fue,boi}(m) \cdot F_{boi,c}(m,d,h) - c_{el,sol}(m,d,h) \cdot \boldsymbol{E_{ice,c}}(m,d,h)) \cdot wgt(m,d,h) \quad (3.73)$$

The total annual operation cost is:

$$c_{ope} = \sum_u c_{ope,u}(u) + c_{ope,c} \quad (3.74)$$

3.2.5 Environmental Objective Function

The other objective function to be minimized is the annual operation greenhouse emissions ($\mathrm{CO_2}$ emissions). From the environmental point of view more than one aspect should be considered, for example taking into account other pollutant emissions (SO_2, CO and NO_x emissions), total life cycle emissions, etc. However, the minimization of these types of pollutant emissions can be obtained only optimizing each single component and not through the simple optimization of the configuration. For what concern the life cycle analysis, Charvalho [51] demonstrated that the impact of the pollutant emissions due to the technology in the equivalent total annual emissions is negligible, considering also different indicators (Eco-indicator 99 and total CO_2 emissions). For these reasons only CO_2 emissions are taken into consideration as environmental objective function, and furthermore the minimization of the greenhouse emissions correspond to the minimization of the primary energy consumption, which is one of the most important target of the 20-20-20.

The total annual emissions are related to the:

- consumption of electricity from the electricity network;
- introduction of electricity in the electricity network;
- consumption of fuels (fuels for boilers or CHP).

The total annual emissions can be evaluated through:

$$
\begin{aligned}
em_{tot} = em_{el} \cdot \sum_{m,d,h,u} (\boldsymbol{E_{bgt}}(m,d,h,u) - \boldsymbol{E_{sol}}(m,d,h,u) - \boldsymbol{E_{ice,c}}(m,d,h)) \cdot wgt(m,d,h) + \\
em_{f,chp} \cdot \sum_{m,d,h,u} (F_{ice}(m,d,h,u) + F_{mgt}(m,d,h,u)) \cdot wgt(m,d,h) + \\
em_{f,boi} \cdot \sum_{m,d,h,u} (F_{boi}(m,d,h,u) + F_{boi,c}(m,d,h)) \cdot wgt(m,d,h) + \\
em_{f,cen} \cdot \sum_{m,d,h} F_{ice,c}(m,d,h) \cdot wgt(m,d,h) \quad (3.75)
\end{aligned}
$$

The greenhouse emissions due to the consumption of fuel (natural gas, petrol, biomass, etc.) is related to the fuel kind itself and the conversion factor can be obtained from the literature [16]. The electricity carbon intensity heavily depend on the electricity mix of each country. For example, countries where coal is used diffusely for the production of electricity, the electricity carbon intensity is higher than in countries where the electricity is produced by nuclear power plants.

3.3 Optimizations and Result Analysis

As introduced previously, the results are obtained through a Multiobjective optimization of the problem, where the objectives to be optimized are presented in details in paragraph 3.2.4. These two are conflicting objectives because the adoption of environmental efficient energy systems are costly. Likewise, the solution which allows the minimum annual cost does not permit a minimum total annual operation emissions.

The ϵ-constrained method has been adopted to obtain the Pareto Front solutions. The first step is obtaining the two extremes of the Pareto Frontier by means of the separate minimization of the two objectives (economic and environmental), subjected to the same constraints. Referring to Fig. 3.5 the point A can be obtained minimizing

em_{tot}, while the point B can obtained minimizing c_{tot}. Each point is characterized by two coordinates, which are the total annual emissions and the total annual cost respectively. Hence, the point A is characterized by the lowest CO_2 emission limit and the greatest annual cost, while the point B is characterized by the lowest annual cost and the greatest CO_2 emissions, among the Pareto Solutions. Fig. 3.5 reports also a fictitious Pareto Front.

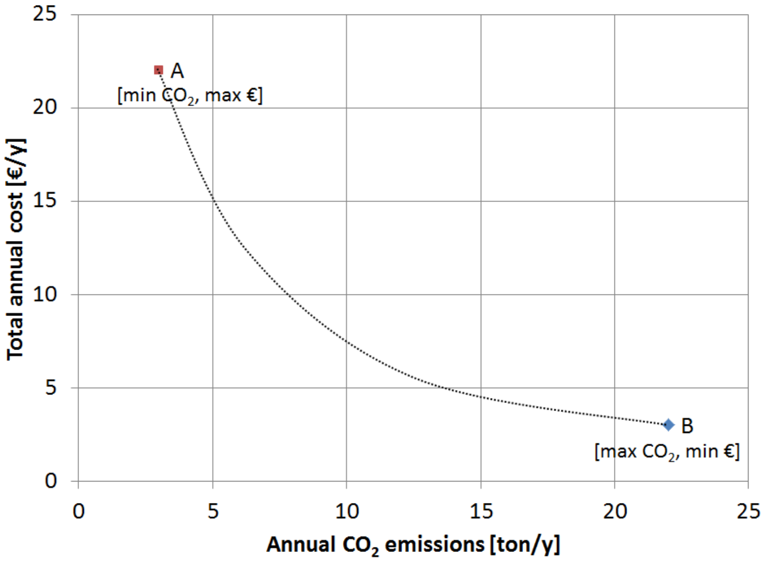


FIGURE 3.5 – Extreme Pareto Front Solutions

The other points forming the Pareto Front are obtained minimizing c_{tot} and including a new constraint:

$$em_{tot} \leq em_{lim}(i) \tag{3.76}$$

Whit

$$em_{lim}(i) = min\ CO_2 + \frac{(max\ CO_2 - min\ CO_2) \cdot i}{i_{max}}, \qquad con\ 1 \leq i \leq\ i_{max} \tag{3.77}$$

and i_{max} equal to the number of points forming the resultant Pareto Front.

All solutions forming the Pareto Front are optimal solutions. Among these solution one has to be chosen as the best one based on secondary consideration of the designer.

3.4 Conclusions

This chapter presents in detail the optimization model proposed in this research work. The model describes a DG energy system made up of several users with electric, thermal and cooling energy needs. Each user can remain isolated from the others satisfying its needs by means of an autonomous production unit. Alternatively it can be connected to the others through the DHCN. In this case it can produce its needs and feed other users, or can only receive energy from the network without any ”internal” production, or both. Moreover the model embeds a central unit which can feed all users through the DHCN.

The concept which is at the base of the model is that each unit, including the central one, can contain all possible technologies which can compete to achieving the optimal solution. The model includes several typical components (boilers, compression chillers, cogenerators, heat pumps, absorption machines, photovoltaic panels and solar thermal panels) showing how they can be represented inside the model and covering different components kind: one product, one product and one sub-product, two products, etc. Furthermore the superstructure includes also thermal storages. However the model can be integrated with other components (e.g. fuel cells, biomass boilers, biomass CHP etc.) incrementing the model complexity and the time required for each optimization.

The objective is the minimization of the total annual cost and of the total annual operation emissions thorough optimizing the configuration, design, and operation of the whole DG energy system. The optimization has to be performed all in one because it is not possible to optimize each single unit separately, because the actual energy requirements of each user cannot be known in advance without knowing the configuration of the DHCN.

II

Model application

4

Case study

Chapter 4 defines the scenario which will be considered in the following chapters as case study of the optimizations. The design of a DG energy systems for tertiary sector/residential users requires to collect sufficient information about the case study including users information (locations, energy demands, special constraints, etc.), technical information related to the components which should be included in the superstructure and market information, which determines the market scenario.

The first section introduces the users identified for the optimizations, reporting the energy demand profiles and the plan of the area with the possible path of the DHCN pipelines. The second section reports the technical data of the machines which constitute the energy system superstructure, while the third section reports the market prices of electricity and fuels, and possible incentive policies.

In summary, chapter 4 establishes the framework which will be utilized in the optimization procedure, where a DG energy system will be synthesized on the basis of economical and environmental aspects.

4.1 Energy demands and user locations

A systematic approach for the selection of an appropriate DG energy supply system requires a detailed knowledge of heat, cooling, and electricity user demands. The detail level affects the model complexity and one of the factors which plays against the model compactness is the number of time intervals considered. These periods are defined by the number of different energy demands that have to be covered, and the periodicity considered in the model (hourly, weekly, monthly). Long time periods such as weeks or months can be considered for industrial applications, characterized by quite constant energy demands that are fairly independent of ambient conditions. Hourly energy demand data is very important when tertiary sector/residential energy systems are analyzed, where the influence of ambient conditions is quite important. In this last case, one solution to contain the model complexity is to represent the whole year through some typical days [63]. In the current optimization case study, the whole year has been subdivided into 24 typical days composed by 24 hours each. 12 typical days refer to working days, while the remaining 12 refer to non-working days, so that each month is represented by one working and one non-working day. All values related to each single time interval are weighted through the parameter wgt, which consider their weights in the overall year. The grouping through typical days can be done for all variables, with the exception of the variables related to the thermal storages (either thermal or cooling) for which the whole year has to be considered (detailed explanation can be found in par. 3.2.3).

This case study is constituted by nine tertiary sector users located closely to each other in the center of a small city (60,000 inhabitants) in the North-East of Italy. The user considered are all owned by the public service and this gave us the possibility to access at the energy demand data. The users considered are:

1. Town hall;
2. Theater;
3. Library;
4. Primary school;
5. Retirement home;
6. Archive;
7. Hospital;
8. Secondary school;
9. Swimming pool;

The heterogeneous choice of the considered buildings, characterized by different kinds of energy demands, allows to consider the achieved results not affected by a specific user profile. Furthermore, a similar mix of users is expected to be easily recognized in a lot of other small and medium size town in Europe. Fig. 4.1 shows the location of the nine buildings involved in the study and of the central unit together with solar field. In addition, the possible path of the DHCN is outlined in red.

Fig. 4.2 reports a schematic lay-out of the DHCN together with the length of each pipeline. The determination of the possible paths is the result of a preliminary study which considers:

- conformation of the roads which connect the buildings;
- position of the underground utilities (waterworks, sanitation, gas network, etc.);
- location of thermal halls of the buildings.

The users are close to each other and the maximum distance, between user 1 and the central unit, is about 2.5 kms. The model gives the possibility to connect through the DHCN all users to each other, but for example, it is not reasonable connecting user 1 to user 4, without connecting 2 and 3. In the case of a direct connection between user 1 and 4, the cost for the DHCN would be almost the same even if also users 2 and 3 were connected, but there would be no possibility to exchange energy with them. Therefore, in order to sensibly reduce the computational effort and the time required for

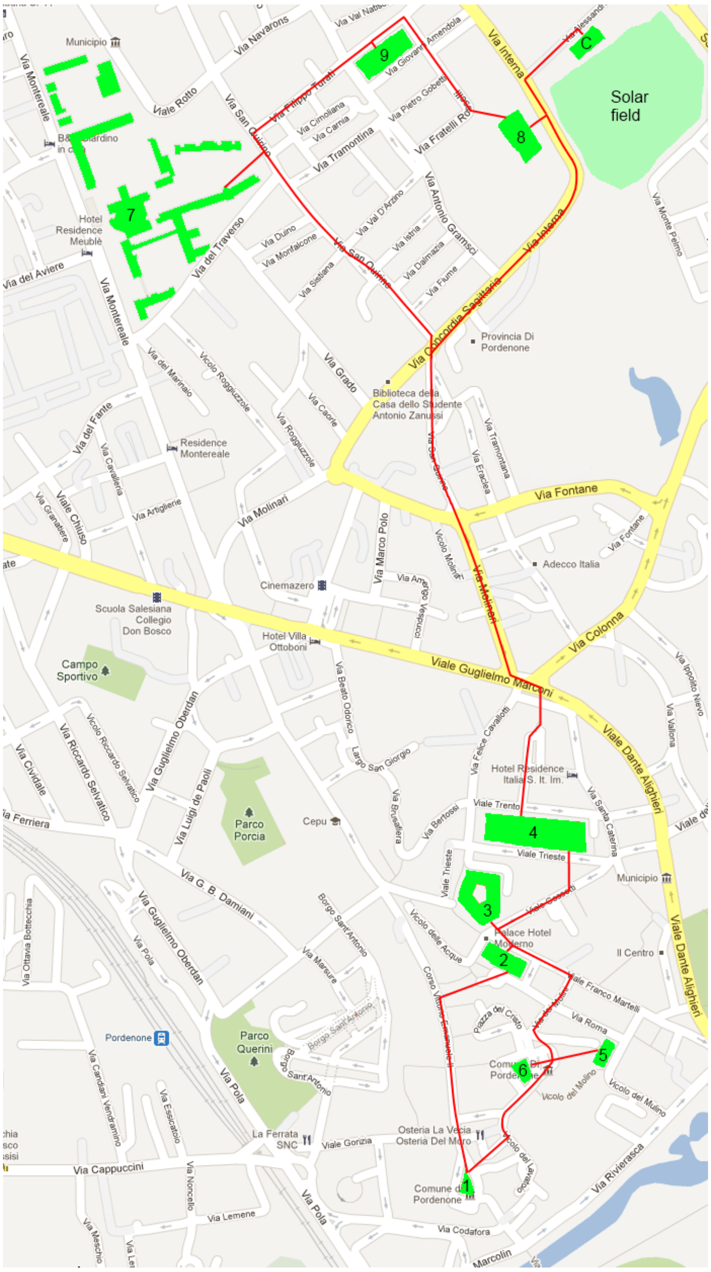


FIGURE 4.1 – Plan of the users locations and the possible path of the DHCN. 1-Town Hall; 2-Theatre; 3-Library; 4-Primary School; 5-Retirement Home; 6-Archive; 7-Hospital; 8-Secondary School; 9-Swimming Pool.

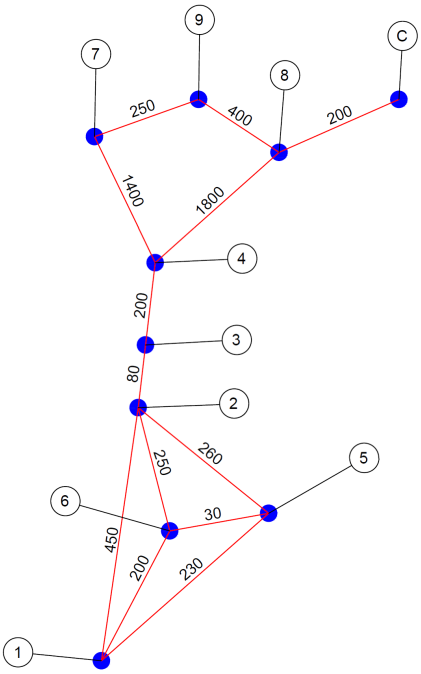


FIGURE 4.2 – Schematic lay-out of the DHCN with the length of each possible connection [m]. 1-Town Hall; 2-Theatre; 3-Library; 4-Primary School; 5-Retirement Home; 6-Archive; 7-Hospital; 8-Secondary School; 9-Swimming Pool.

the optimizations, some pipeline of the DHCN have been excluded a priori, keeping only those reported in Fig. 4.1 and 4.2.

All considered buildings are already occupied and the energy demand data are available on a monthly basis, with the exception of the hospital where the demands are available on hourly basis. However, the demand trends can be estimated knowing the specific use of the building and applying the reference curves which can be found in a study performed by the The United States Department of Energy (DOE) [68]. They collected a large amount of data related to various commercial buildings and defined a model for the definition of typical demand profiles, depending on power installed and/or monthly consumption.

The users considered requires thermal energy for space heating and for sanitary hot water, which at the current time is produced by boilers. The thermal energy required is fed at a temperature greater than 65÷70°C . The cooling energy is required only for space cooling typically during the summer season and it is produced by compression chillers. The electric energy is bought from the grid and covers either the electricity demands or the electricity required to power the mechanical chillers.

Table 4.1 reports the annual energy consumptions and peak power of the nine users. Fig. 4.3 shows the percentage split of the electric energy demand and as it can be noted,

Table 4.1 – User's energy demand data

USERS	ELECTRIC		HEATING		COOLING	
	Year dem. [MWh]	Peak power [kW$_e$]	Year dem. [MWh]	Peak power [kW$_t$]	Year dem. [MWh]	Peak power [kW$_c$]
Town Hall	346,640	189	692,720	410	148,712	150
Theatre	852,208	270	908,648	655	457,688	458
Library	492,240	110	587,608	296	112,364	115
Primary School	73,808	54	979,468	591	0	0
Retirement Home	489,048	101	739,956	246	207,568	138
Archive	82,516	36	429,604	238	78,652	91
Hospital	3,284,416	628	7,884,141	1,847	1,445,612	2,087
Secondary School	303,668	148	2,301,980	2,084	0	0
Swimming Pool	1,043,572	315	2,794,580	1,425	297,416	435
Total	6,968,116	1,717	17,318,705	7,017	2,748,012	3,048
User Peak Power sum		1,851		7,792		3,474

the hospital requires about the 50% of the electric energy consumption, the second energy consumer is the swimming pool while the other users require less than the 7% each. Similar diagrams can be found for thermal and cooling demand (4.4, 4.5), whit the exception that cooling energy is not required by the schools, as in summer there are no students and the cooling plants have not been provided. The last row of Table 4.1 reports the sum of all power peaks and it is, as can be expected, greater than the total power peak by about 10%. The electric demand reported in the table does not account for the energy required by the compression chillers for the production of cooling energy. The real electric energy demand obtained from the energy audit have been adjusted removing the electricity consumed by the compression chillers currently installed, considering the acutual Coefficient Of Performance (COP).

Fig. 4.6 shows the trend of electric, thermal and energy demands for all buildings. It shows clearly that the trends are characteristic of tertiary sector users and characteristic of typical continental Europe climate, where during winter the thermal demand is higher than in summer period because of the needing of space heating. During summer the thermal demand is only due to hot sanitary water demand, while there is a requirement of cold for space cooling. The electric energy is a little bit higher during winter and lower in summer. This trend is related to the daylight hours, as during the summer there is a lower need of lighting.

The energy demand patterns of the Hospital in winter and summer are reported in Fig. 4.7, for representative working days. The winter trend shows greater electric energy demand during the daylight hours due to an higher occupancy factor, a heating demand higher in the morning and in the evening and a very low cooling demand, which is required by the air conditioning system. In summer, the cooling demand is higher with respect to the winter season and it reaches the top at about 15pm, the electric demand is similar to the winter one, while the thermal demand employed as sanitary water is higher during daylight hours and lower during the night. Each building has different energy patterns which depend on the occupancy factor, thermal insulation, night lighting, etc.

4.2 Superstructure components

The type and the size of the equipment which is part of the system superstructure must be appropriate to allow their integration, and proportionate to the user energy demands. All components considered in the optimization are commercially available and the prices have been obtained through a market survey. Two different kind of components have been considered: fixed size components and variable size components. The optimal size/configuration of the energy system is obtained by defining the number of fixed size equipment installed and the size of variable size components (boilers, compression chillers, thermal storages).

Table 4.2 shows the sizes of the fixed size components (the main product is used as size reference). Up to 6 components of the same kind can be adopted in each unit.

TABLE 4.2 – Component sizes [kW]

Equipment	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9
MGT	65	100	30	30	30	30	200	65	100
ICE	70	140	50	50	50	50	200	70	140
ABS	70	105	35	35	35	35	105	70	105
HP	70	105	35	35	35	35	105	70	105

4.2.1 Microgas Turbines

Capstone C30, C65, C200 and Turbec T100 have been selected as Microgas Turbine. The most important parameters are reporter in table 4.3, including also the investment costs. Maintenance costs have been assumed equal for all MGTs and equal to 0.005€/kWh. Fig. 4.8 shows the effect of the ambient temperature on the electric, thermal and global efficiencies and the partial load effiency related to Capstone C65. Similar trends can be found for each one of the machines identified. The parameters related to the MGTs have been evaluated for each time interval through a linear regression of the performance curves, considering also the effect of the ambient temperature. Each MGT is equipped with a heat exchanger to produce thermal energy at 85°C.

4.2.2 Internal Combustion Engines

Viessmann Vitobloc 200 EM 50/81, EM 70/115, EM 140/207 and EM 200/264 have been selected as internal combustion engines. Table 4.4 reports the most important data related to the ICEs. In this case the influence of the ambient temperature is negligible

TABLE 4.3 – Microgas Turbine Technical data [6–9]

	Capstone C30	Capstone C65	Turbec T100	Capstone C200
Electric output [kW]	30	65	100	200
Thermal output @90°C[kW]	58	119	167	315
Electric efficiency at full load	26%	29%	30%	30.2%
Thermal efficiency at full load	50%	53%	50%	52%
Cost [k€]	50	100	140	230

so that it has not been taken into account. The thermal energy is recovered at a temperature of 85°C through a heat exchanger from exhaust gases and engine cooling circuit. 0.02€/kWh has been considered as maintenance cost.

TABLE 4.4 – Internal Combustion Engine data [10]

	EM 50	EM 70/115	EM 140/207	EM 200/264
Electric output [kW]	50	70	140	200
Thermal output @90°C[kW]	81	115	207	264
Electric efficiency at full load	34.5%	34.3%	36%	37%
Thermal efficiency at full load	55.9%	56.4%	54%	48.9%
Cost [k€]	60	70	125	165

4.2.3 Absorption Chillers

Maya Yazaky WFC-SC 10, 20 and 30 has been selected as absorption chillers. Each one of them can be installed only if at least one cogenerator is installed, and they can operate only if the related cogenerator is operating. They are connected at the cogenerators through direct water circuits in order to reduce thermal losses. Table 4.5 reports the technical data of the absorption machines considered. 0.001€/kWh has been considered as maintenance cost.

TABLE 4.5 – Absorption chillers data [11]

	WFC-SC10	WFC-SC20	WFC-SC30
Cooling capacity [kW]	35	70	105
COP	0.7	0.7	0.7
Cost [k€]	21	40.6	60

4.2.4 Heat Pumps

Daikin air source heat pumps have been selected for this study. They can produce hot water at a temperature of 65°C. The table 4.6 reports the main important data related to the heat pumps. The technical parameters are evaluated at ISO conditions. 0.001€/kWh has been considered as maintenance cost.

TABLE 4.6 – Heat pumps data [12]

	EWYQ 35	EWYQ 70	EWYQ 105
Total power input [kW]	35	70	105
EER	3.1	3.1	3.1
COP	3.4	3.4	3.4
Cost [k€]	20.5	36	52.5

4.2.5 Boilers

The boilers which can be installed either inside the production units or in the central unit are described through a single parameter which is the boiler efficiency. It is reported in table 4.7 together with the variable and fixed investment costs. 0.001€/kWh has been considered as maintenance cost. The cost of boilers which can be installed to the production unit is proportional with respect to its size (so that the fixed cost is null), while the cost of the central unit boiler is linear with respect to the size.

TABLE 4.7 – Boilers data [13]

	Production unit boilers	Central unit boiler
Efficiency	92%	95,5%
Variable Cost [€/kW]	c_{boi}= 70	$c_{boi,v}$= 30
Fixed Cost [k€]		$c_{boi,f}$=195

4.2.6 Compression Chillers

Compression chillers are described through a single parameter which is the COP. It is reported in table 4.8 together with the variable investment costs. 0.002€/kWh has been considered the maintenance cost.

TABLE 4.8 – Compression Chillers data

Coefficient of Performance COP	3
Variable Cost [€/kW]	230

4.2.7 Solar Thermal and Photovoltaic Panels

The hourly production per surface unit of solar thermal and photovoltaic panels is the input parameter considered in the optimization model. Hourly solar radiation of a south oriented and 30°inclined surface, is obtained through a certified model called SOLTERM® distributed by ENEA [83]. Average daily solar radiation obtained for the considered site is reported in Fig. 4.9, while table 4.9 reports the average annual production and the cost of a square meter of panel. Flat plate collectors have been chosen as solar thermal panels, while polycrystalline silicon panels as photovoltaic panels. Table 4.9 reports the solar thermal panels which can be installed to the the unit and in the solar field. The different costs are related to scale economies.

Table 4.9 – Solar Thermal and Photovoltaic Panels data

	Solar thermal panels	Solar field panels	Photovoltaic panels
Average Annual production [kWh]	800	800	1,150
Cost [€/m^2]	350	180	250

In the case study, 200 m^2 per unit has been considered as a maximum surface available for the installation of ST panels or PV panels.

4.2.8 District Heating and Cooling network

The technical parameter which describes the pipelines of the DHCN is the thermal loss coefficient per unit length. This parameter is reported in table 4.10 together with the cost proportional only to the length and the cost proportional to the size and to the length of the pipeline. The costs of the central pipeline different as they have been linearized for larger sizes, as the central pipe can be larger than the others.

Table 4.10 – District heating and cooling network data [14]

	Cooling pipeline	Thermal pipeline	Central pipeline
Percentage loss per unit length (%/km)	5%	8%	8%
Fixed cost $c_{net,f,c}$, $c_{net,f,c}$€/m	215	215	470
Variable cost $c_{net,f,c}$, $c_{net,f,c}$€/kW m	0.17	0.17	0.03

4.2.9 Thermal/cooling storages

The characteristic parameters of the thermal/cooling storages considered in the optimization model are the thermal loss percentage ($K_{los,ts}$) and the cost per cubic meter (see table 4.11). Table 4.11 reports also the real thermal loss coefficient which have been used to calculate the thermal loss percentage. The $K_{los,ts}$represent the percentage of thermal energy lost in a time interval (1 hour). The thermal losses in the central storages which can be installed in the production units are greater due to the different technologies adopted.

TABLE 4.11 – Thermal storage data [15]

	Thermal storage	Cooling storage	Central storage
Themal losses ($K_{los,ts}$)	0.1%	0.2%	0.001%
Real Thermal losses $[kj/h \cdot m^2 \cdot K]$	1,6	1,6	0,5
Cost [€/m^3]	300	300	80

4.3 Boundary Information

All other information required to complete the economic/environmental scenario is reported in this section.

4.3.1 Economic data

The economic data considered for the study can be subdivided in:

- investment costs and amortization time;
- maintenance costs;
- operation costs.

The investment costs of each piece of equipment, reported in the previous section 4.2, have been obtained by a market survey and incorporate also transportation, installation, connection, engineering costs, etc.

The amortization factors which multiply the investment costs are function of the interest rate and of the life span of each component. The interest rate is assumed equal to 6% and it is a sum of the real economic interest rate (4%) and a risk rate, assumed in this case equal to 2%. The life span of the components is reported in table 4.12

TABLE 4.12 – Component life span [years]

ICE	MGT	BOI	ABS	CC	HP	PV panels	ST panels	TS	DHCN
15	15	10	15	10	15	20	20	20	30

Maintenance costs are reported in the previous section 4.2 and they are proportional to the energy produced by each component.

Operation costs are related to the costs of fuels and electricity. The Italian gas and electricity market has been liberalized since 2007, after a process which began in the 1999 with the "Bersani Decree" [84] and last 8 years. Since 2007 all consumers can freely choose a supplier and leave the regulated-rate system or can remain connected to the old regulated market. Herein, the regulated-rate system has been considered as reference for the electricity and gas prices. The natural gas cost has been considered constant all year long, as well as the price of the bought electricity, while the price of the sold electricity has been assumed variable in each time interval, based on the hourly market prices (see table 4.13. The prices reported embed the pure cost of energy (about 40%) and taxes (about 60%).

TABLE 4.13 – Energy prices [€/kWh]

Electricity bought price	0.17
Electricity sold price	0.05÷0.12
Natural gas price	0.06

4.3.2 Environmental data

The CO_2 emissions related to the consumption of electricity and natural gas have been assumed from literature [16]. The natural gas CO_2 emissions depend on the chemical composition of the gas and then from its provenience. However, the slightly difference can be neglected considering the same value for the natural gas CO_2 emissions. The same approximation cannot be made for electricity. In fact, electricity carbon intensity heavily depends on the national electricity system. The reference case study has been optimized assuming the average electricity carbon intensity of the European Union in 2007-2009, while a second set of optimizations has been performed assuming the average electricity carbon intensity of the OECD Americas (Canada, United States, Mexico, Chile) in 2007-2009. The considered values has been reported in table 4.14.

TABLE 4.14 – CO_2 emissions [kg_{CO_2}/kWh] [16]

Electricity carbon intensity (EU)	0.356
Electricity carbon intensity (OECD Americas)	0.485
Natural gas carbon intensity	0.202

4.3.3 Incentives

In the last decade several incentives have been created to stimulate the development of new energy technologies. The main target of the incentives is the achievement of the 20-20-20 targets and they have been developed together with advertisement campaigns to sensitize people to use environmentally friendly energy systems. The incentive policies should stimulate the market in the first phase of a technology life, when the investment cost are high and the technology itself is not profitable, so that it would not be adopted. After this period, the technology should be profitable as it has been developed at the market level and can compete with other technologies. The incentives can be subdivided in two main type:

- incentives on the investment;
- incentives on the product.

The first kind of incentive is used for technologies which does not imply operation costs (such as solar thermal collectors), while the second kind of incentive is used for the components which involve operation costs. In this way the legislator assures the profitability of the incentives, which are always paid by the energy consumers.

Two different incentives have been considered for the reference case study:

1. natural gas detaxation for cogeneration use;
2. photovoltaic production incentives.

Cogeneration systems operate in Italy with natural gas detaxation, if complying with particular restrictions. The Dlgs 20/07 [85] explains precisely when the detaxation can be applied, but in general the cogeneration plant is classified as "*High Efficiency Cogeneration System*" and get the incentives if:

- the Primary Energy Saving (PES) is greater than 0 (for systems $< 1MW_{el}$);
- the Thermal Limit (TL) is greater than 30%.

The parameter PES expresses the actual saving of primary energy with respect to the conventional production, while the TL assures that the system operates in cogeneration mode and not only for the production of electricity. Equation 4.1 is used for the determination of the PES index for an internal combustion engine. $\eta_{el,ref}$ and $\eta_{th,ref}$ are electric and thermal efficiencies of reference which depend on the size of the cogeneration system and are defined year per year by the legislator. Equation 4.2 is used for the determination of the TL index.

$$PES = 1 - \frac{F_{ice}}{\frac{\boldsymbol{E_{ice}}}{\eta_{el,ref}} + \frac{H_{ice}}{\eta_{th,ref}}} > 0 \tag{4.1}$$

$$TL = \frac{H_{ice}}{\boldsymbol{E_{ice}} + H_{ice}} > 30\% \tag{4.2}$$

If the cogeneration system respects these restrictions the detaxation of the natural gas price can be applied. The cost of the natural gas for cogeneration use in the case study has been considered equal to 0.045 €/kWh (25% less with respect to conventional natural gas). Additional incentives could be recognized to cogeneration systems (such as White Certificates), but have not been taken into account for the specific application as they barely affect the final result.

The second incentive considered in the case study is applied to the electricity produced by photovoltaic panels. The Italian energy system has been stimulating the installation of photovoltaic systems since 2005 with the first incentive policy called "Primo Conto Energia". In 2012 the fifth incentive policy is in force ("Quinto Conto Energia" [17]) and considers:

- a global comprehensive price for the electricity produced by PV panels and put into the grid;

- a special rate for the electricity produced by PV panels and directly used by the users.

The different rates depend on the size of the system and on the connection time of the system to grid: the later the system is connected, the lower the prices are. The rates considered in the case study are reported in table 4.15.

TABLE 4.15 – Photovoltaic electrcicity rates [€/kWh] [17]

Electricity put into the grid	0.199
Electricity directly used by the user	0.111

4.4 Conclusions

Chapter 4 reports briefly all required input information for the application of the optimization model to a real case study.

The following step have to be performed to establish the base scenario of the case study:

- the annual energy services demands have been obtained and expressed on an hourly basis by two representative days per month;
- the geographic location of the users has been obtained to identify the possible path of the DHCN;
- the size and kind of some components have been previously selected to match energy demands of the users. Common components (boilers and compression chillers) are considered of variable size;
- performance curves have been obtained for each component, based on supplier data;
- investment and maintenance costs have been estimated based on a market survey;
- energy prices and incentives have been determined based on market information.

Once all information is collected, it has to be properly prepared in the input format accepted by the optimization model. The model described in capter 3 can now be optmized for the specific case study. Sensitivity analysis can be performed changing specific input information and verifying which is the impact on the optimal results.

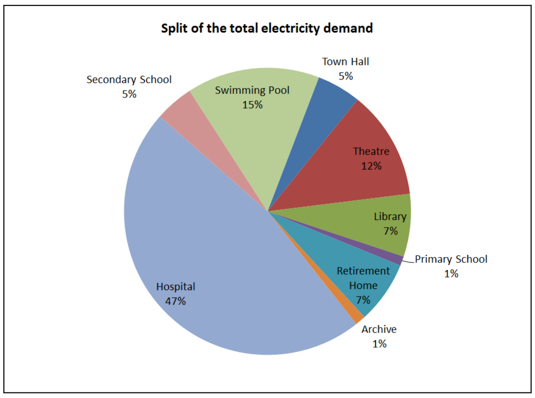


FIGURE 4.3 – Split of the total electric demand

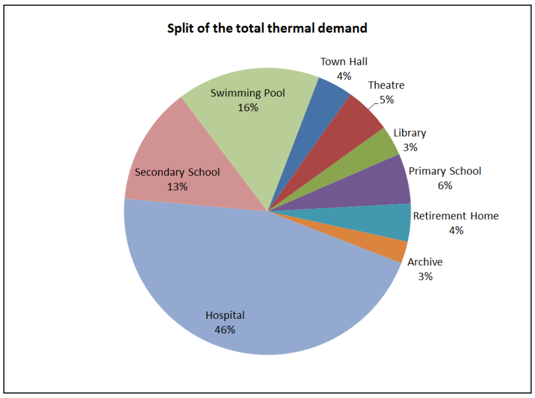


FIGURE 4.4 – Split of the total thermal demand

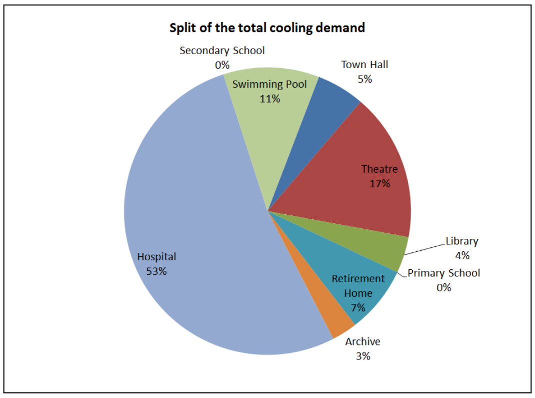


FIGURE 4.5 – Split of the total cooling demand

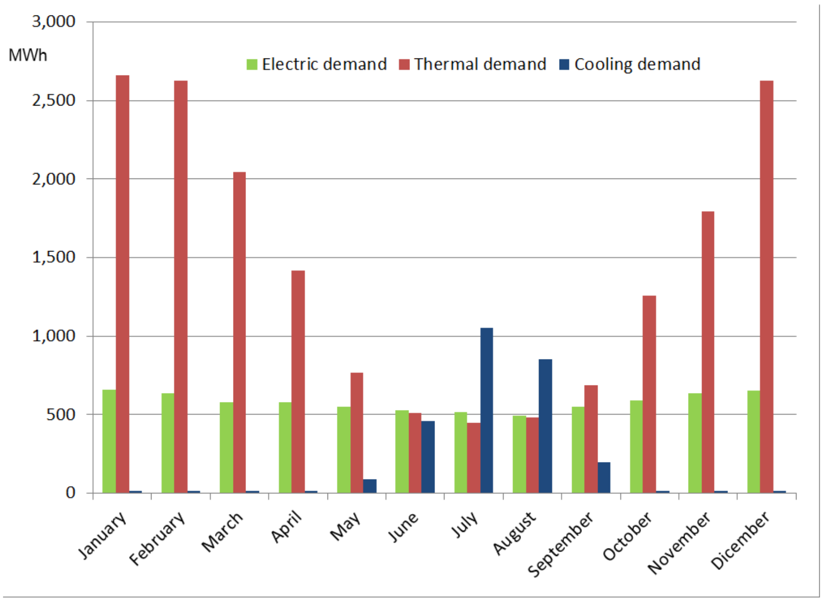
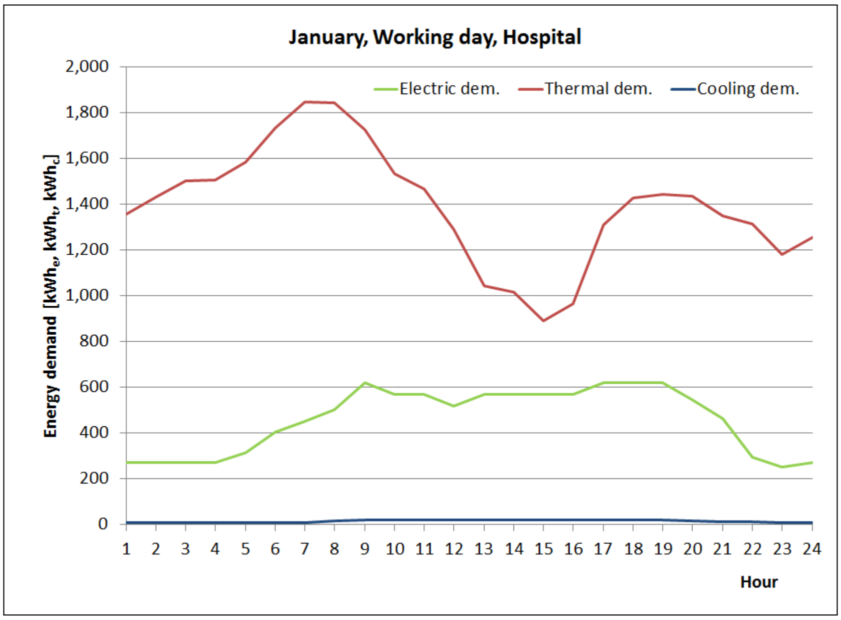
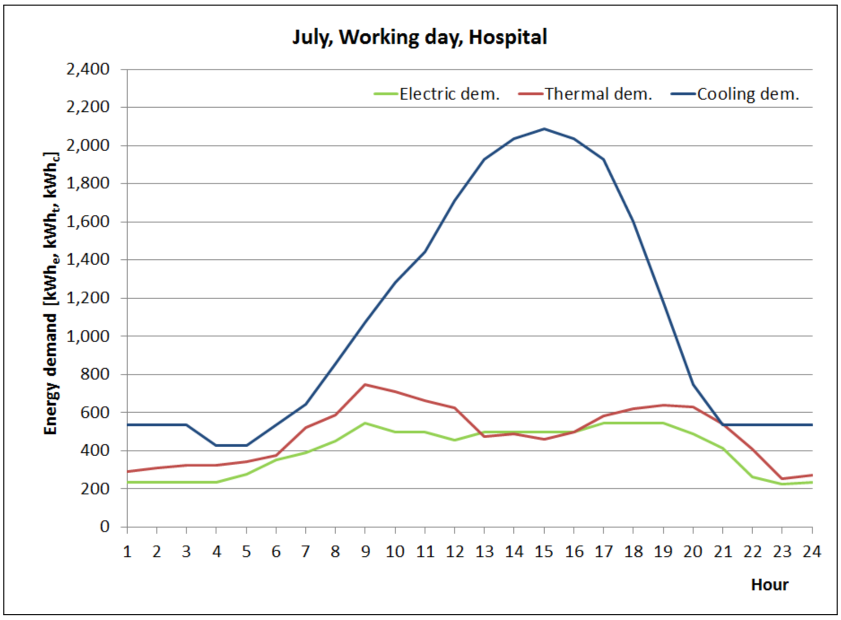


FIGURE 4.6 – Trends of electric, thermal and cooling energy demands

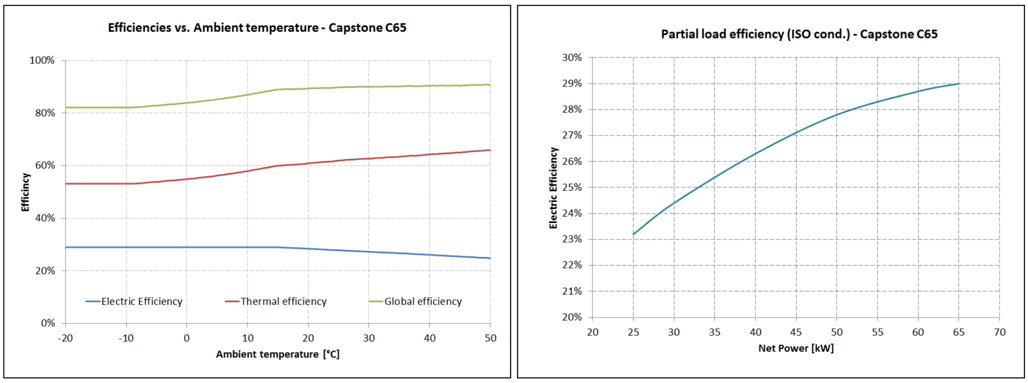


(A)



(B)

FIGURE 4.7 – Hospital hourly energy demand patterns for a typical working day in winter (A) and summer (B)



(A) (B)

FIGURE 4.8 – Capstone C65 performance curves [6]

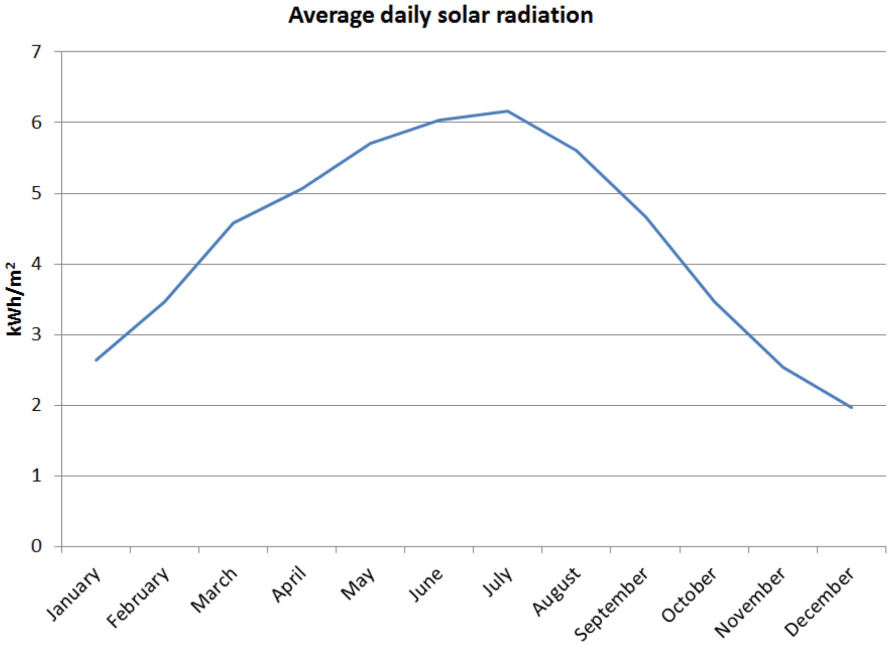


FIGURE 4.9 – Average daily solar radiation obtained for the considered site

5

Multiobjective Optimization of a Distributed Energy System

The current chapter presents the results deriving from the optimization of the case study presented in chapter 4, using the MILP model introduced in chapter 3. The aim of the optimization is to determine the optimal configuration of a complex DG energy system together with the optimal operational strategy on an hourly basis throughout one year.

The optimization procedure reduces the superstructure defined in chapter 3 to the optimal DG energy system, considering specific demands of the case study consisting of nine users located in a city centre of a small town of the North-East of Italy. The objective functions of the optimizations are the total annual cost for owing, operating and maintaining the whole system and the total annual operation CO_2 emissions. Using the ϵ-constrained method the Pareto fronts have been obtained for different plant configurations.

The superstructure proposed in chapter 3 embeds all possible components which can be adopted in the optimal solution for the minimization of the objective functions. However, additional constraints can be added to reduce the complete superstructure to a restricted superstructure by limiting the existence of some components. The model has been optimized to obtain the optimal solution in different cases:

1. conventional solution;
2. isolated solution;
3. distributed generation solution without central unit and district cooling network;
4. distributed generation solution with central unit but without cooling network;
5. complete distributed generation solution.

As can be noted, the last configuration includes all the other configurations, while the conventional solution is a subset of all the other configurations. In this way it is possible to understand which is the influence of the different configurations and how the different configurations contribute to the achievement of the minimization of the objective functions.

The MILP model has been implemented in the X-press® Optimization Suite. X-press® is a commercial software produced by FICO® for solving large optimization problems by means of the application of integrated algorithms. The mathematical model has been implemented through Mosel, a modeling and programming language that allows users to formulate problems, solve them using the solver engines, and analyze the solutions.

5.1 Model Application

The mathematical model presented in chapter 3 has been implemented through the Mosel language in the X-press Optimization Suite. The users' data has to be properly prepared in separated text files which are called from the main program. After a careful preparation of the model and of the users' data, the optimization procedure can start. When the optimization is finished the solution is stored in an external text file which contains the values of all decision variables. This data is then elaborated to obtain the information required by the designer.

The Optimization toolbox uses evolutionary algorithms, cut generations and heuristic algorithms, together with the Branch and Bound technique and revised Simplex techniques. The Simplex method can be used only if all variable are continuous. In a generic MILP problem, there is at least one decision variable which is non continuous (binary or discrete) and thus the Simplex method cannot be applied directly. In this case, the Simplex method can be applied only if this variable is relaxed by removing the discrete constraint. The optimal solution of the relaxed problem is considered the best achievable solution, because with the introduction of a discrete constraint, the objective function will worsen or at least will remain the same, but cannot improve. This is due to the fact that the introduction of a generic constraint cannot affect the objective function in positive, but only in negative.

The Branch and Bound method starts with the optimization of the relaxed MILP problem, and step by step fix one discrete decision variable at a time. So that, the more decision variables are fixed, the worse the best achievable objective function is. When all discrete decision variables are fixed, the optimization is concluded and the objective function of the relaxed problem correspond to the objective function of the real problem. The percentage difference between the objective function of the relaxed problem and of the current problem is called GAP(eq. 5.1). Fig. 5.1 shows a graph with the values of the obj_{currl}, $obj_{relaxed}$, and GAP.

$$GAP = \frac{obj_{currl} - obj_{relaxed}}{obj_{currl}} \cdot 100 \tag{5.1}$$

The identification of the absolute objective function requires to examine all nodes of the Branch and Bound tree and, if the number of discrete variables is very high, a long optimization time is required. If the absolute objective function is not a priority and a near optimal solution can be accepted, the optimization can be stopped when a determined GAP is reached. The Optimization problem presented in chapter 3 applied

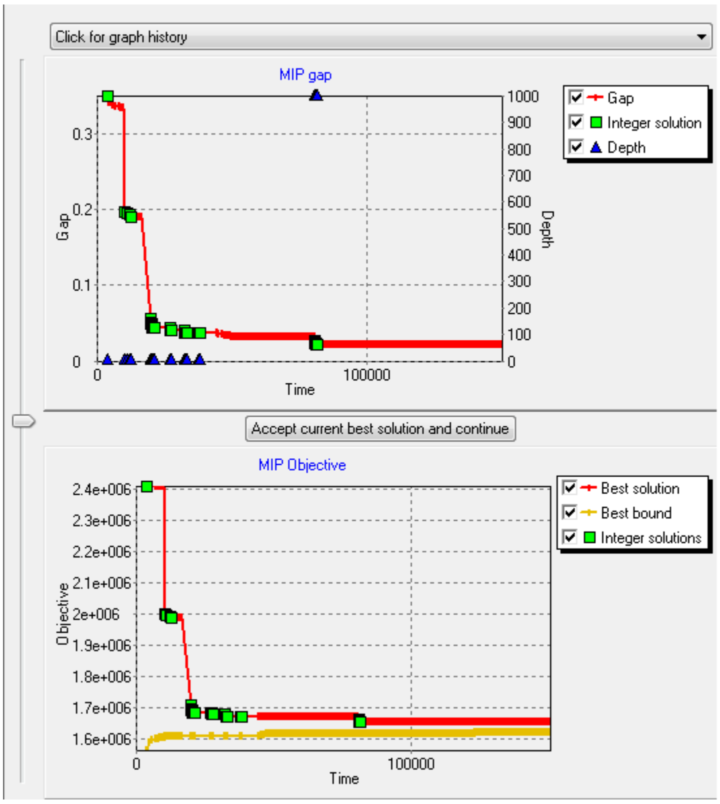


FIGURE 5.1 – Screen shot of the MILP objectives and GAP graph, obtained during an optimization

to a case study can be considered a very large problem as the decision variables are about 600,000 and the constraints 950,000. The determination of the absolute optimal solution would require a time too long (several weeks) and for this reason the optimization procedure is stopped when a GAP lower than 1% is reached.

The optimizations has been performed with a PC equipped with a processor Intel® Core$^{\text{TM}}$ i7CPU 920@2.67GHz , 6.00GB RAM and a 64bit operating system. An optimization of the overall problem, accepting a GAP of 1%, lasts about 100 hours.

5.2 Conventional Solution

The Conventional Solution is considered as the reference solution, assuming that all thermal energy is produced by BOI, all cooling energy is produced by electric CC and all electricity is bought from the grid. Furthermore, the thermal and colling energy can be stored in separated energy storages. The optimization is performed adopting a reduced superstructure where only BOI and CC can be installed (Fig. 5.2).

In the following optimizations, the investment costs of the conventional systems have

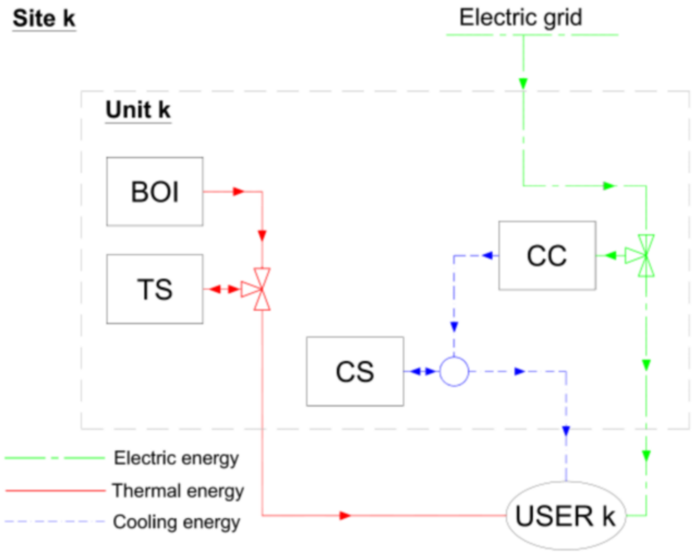


FIGURE 5.2 – Superstructure of the conventional solution

been always considered. For existing plants based on a traditional configuration of the energy system, if the intention is to evaluate a feasible and profitable alternative compared to this conventional system, the investment costs of the conventional system shall not be taken into account. On the contrary, in a case of the realization a completely new energy system, such as this case study, the investment costs of the conventional system must be considered because also the conventional components have to be compared to the others.

Table 5.1 reports the optimal configuration of the conventional solution, obtained minimizing the total annual cost. The table reports also the energy peaks of each single user. It can be noted that the boilers installed in each unit are of smaller sizes with respect to the thermal peaks, as all units are provided with a proper sized thermal storage. On the contrary, the sizes of the compression chillers correspond to the cooling peaks as the cooling storages are not included in the optimal solution.

Table 5.2 reports the economic and environmental results of the optimization performed for the conventional solution. The total annual cost of the conventional solution is 2,622 k€ per year, and it is constituted by about 93% of operation costs (costs for thermal energy and electricity), 6% of investment costs and 1% of maintenance costs. The results shows also that the hospital contributes to the total annual cost for about 50%, as it is the largest energy consumer. The table shows also the environmental results and they depend basically on the energy consumption of each user.

The energy balances are reported in table 5.3 and for the conventional solution they collapse to simple balances where the electricity bought is equal to electricity user demand plus the electricity required by CC, the thermal energy is produced by BOI and the

TABLE 5.1 – Optimal configuration of the conventional solution

User	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Electric peak [kW]	189	270	110	54	101	36	628	148	315
Thermal peak [kW]	410	655	296	591	246	238	1,847	2,084	1,425
Cooling peak [kW]	150	458	115	0	138	91	2,087	0	435
Boiler [kW]	294	479	217	418	205	179	1,623	1,673	1,153
Compression chiller [kW]	150	458	115	0	138	91	2,087	0	435
Thermal storage [kWh]	544	375	312	766	173	298	690	2,251	1,564

TABLE 5.2 – Economic and environmental results of the optimization - Conventional solution

User	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
Natural gas cost [k€/y]	44	58	37	62	47	27	498	146	177	1,096
Electricity cost [k€/y]	67	171	90	13	95	18	640	52	194	1,340
Operating cost [k€/y]	111	228	127	75	142	46	1,138	198	371	2,437
Maintenance cost [k€/y]	1	2	1	1	1	1	11	2	3	23
Total investment cost [k€]	58	141	43	33	47	35	597	127	188	1,267
Annual investment cost [k€/y]	7	18	6	4	6	4	77	16	24	163
Total annual cost [k€/y]	**120**	**248**	**134**	**80**	**149**	**51**	**1,226**	**216**	**399**	**2,622**
Electricity emissions [ton/y]	141	358	189	26	199	39	1,341	108	407	2,807
Natural gas emissions [ton/y]	148	194	125	209	158	92	1,677	492	596	3,691
Total annual emissions [ton/y]	**289**	**551**	**314**	**236**	**356**	**130**	**3,018**	**600**	**1,003**	**6,497**

TABLE 5.3 – Optimal annual energy magnitudes [MWh] - Conventional solution

User	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
Bought electricity [MWh]	396	1,005	530	74	558	109	3,766	304	1,143	7,884
Electric user demand [MWh]	347	852	492	74	489	83	3,284	304	1,044	6,968
Electricity required by CC [MWh]	50	153	37	0	69	26	482	0	99	916
Heat produced by BOI [MWh]	696	911	590	984	741	432	7,888	2,312	2,802	17,357
Thermal user demand [MWh]	693	909	588	979	740	430	7,884	2,302	2,795	17,319
Wasted heat [MWh]	0	0	0	0	0	0	0	0	0	0
Cooling energy prod. by CC [MWh]	149	458	112	0	208	79	1,446	0	297	2,748
Cooling energy user demand [MWh]	149	458	112	0	208	79	1,446	0	297	2,748
Wasted cooling energy [MWh]	0	0	0	0	0	0	0	0	0	0

cooling energy by CC. The thermal energy produced by BOI is slightly higher than the thermal energy required by the users, because of the heat losses in the TS. It could also be noticed that, as can be expected, the thermal and cooling energies produced by the components are all used by the users without any wasting.

The results presented in this section, obtained minimizing the economic objective function of the conventional solution, will be used as reference for the forthcoming optimizations. The environmental optimization would have produced different results, but in general the conventional solutions do not focus at the environmental result, but only at the minimum operation cost.

5.3 Isolated Solution

Two different superstructures have been considered for the optimization of the isolated solution: one superstructure including all components considered in the model (see Fig. 5.3), and one superstructure including all components with the exception of the local thermal storages (either heating or cooling). These two different optimizations allows to understand which the influence of the thermal storages in the optimal solution is. Pure Economic and Environmental optimizations have been conduced for the isolated solutions.

The optimal configurations of the isolated solutions are compared to each other and to the conventional solution in table 5.4. For matters of clarity, only the total power installed, related to each component, has been reported, without explicitly specifying the optimal configuration of each production unit. Focusing on the economic optimizations,

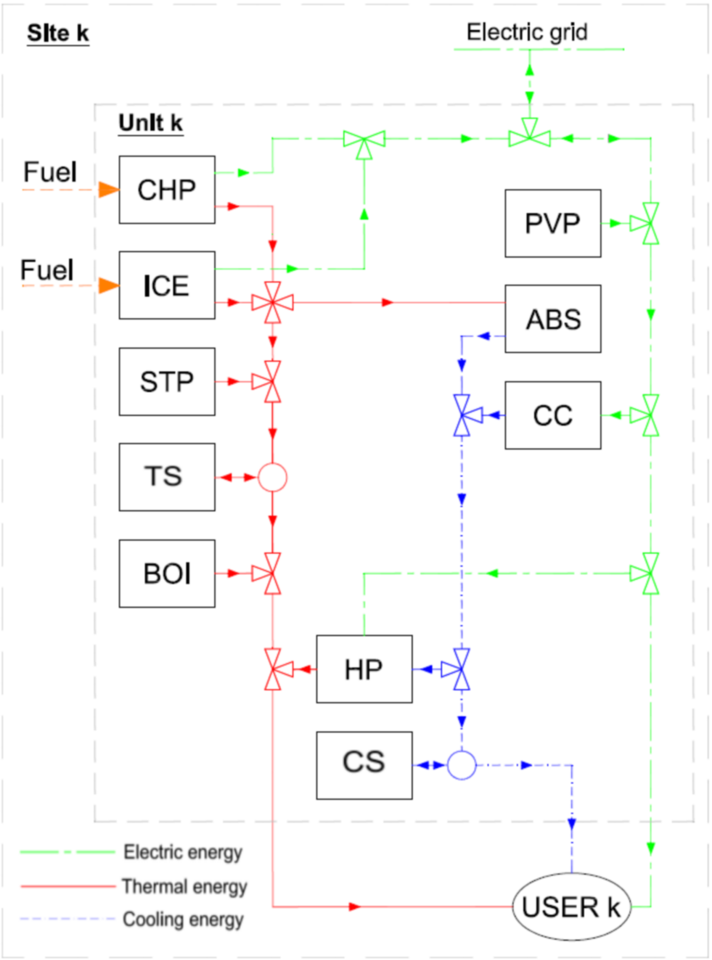


FIGURE 5.3 – Superstructure of the Isolated Solution with TSs

different types of component have been adopted in the optimal solution. The ICEs have been adopted as cogenerators, while the MGTs are never installed. The ST panels are never adopted as well, because having a limited space to install panels, PV panels are more convenient. The introduction of the TS allows a sensible reduction of the sizes of BOI and HP, while the ICEs size slightly increases. The CS are not adopted in the optimal solution but, due to the arrangement of the optimal operation caused by the introduction of the TS, the CCs size increases while the ABSs size decreases. Focusing on the environmental optimization, it should be observed that the component sizes do not follow a specific criteria, as the adoption of larger component does not affect the environmental objective function. However, it can be outlined that the ST panels replace the PV panels adopted in the economic optimization.

Table 5.4 – Optimal configurations of the Isolated Solutions compared to the Conventional Solution - Whole system

	Economic Optimization			**Environmental Optimization**	
	Conventional solution	**Isolated solution - no TS**	**Isolated solution**	**Isolated solution - no TS**	**Isolated solution**
ICE [kW]	0	2,820	2,840	4,920	4,920
MGT [kW]	0	0	0	3,900	3,900
BOI [kW]	6,241	2,145	984	609	431
ABS [kW]	0	840	735	3,570	3,570
HP [kW]	0	1,750	980	3,570	3,570
CC [kW]	3,474	1,274	1,763	1,948	2,008
PV panels [kW_p]	0	225	225	45	0
ST panels [m^2]	0	0	0	1,438	1,800
TS [kWh]	6,973	0	15,016	0	36,000
CS [kWh]	0	0	0	0	36,000

Table 5.5 shows the results of the optimizations performed for the isolated solutions. Comparing the economic optimizations to the conventional solution, the cost for natural gas used by BOIs significantly decreases, as well as the bought electricity. The cost for natural gas used by CHP did not exist for the conventional solution. However, the operating cost in the optimal isolated solutions is halved with respect to the conventional one. The optimal isolated solutions, without and with the TS and CS, obtained minimizing the economic objective functions allow to reduce the total annual cost of 37.6% and 38.8%, and the total annual emissions of 15.9% and 16.5%, respectively. Therefore, the adoption of TSs allows to reduce either the total annual cost or the total annual emissions.

The environmental optimizations shows an increment of the operation costs of about 60% with respect to the economic optimizations, while allows a reduction of about 25% of the total annual emissions with respect to the conventional solution. It can be also noted that the amount of emissions due to the electricity significantly increases, while the saved emissions due to the electricity sold to the grid and the emissions of the usage of natural gas significantly decrease.

The energy balances of the optimizations performed for the isolated solutions are reported in table 5.6. It can be observed that in the economic optimizations, the bought electricity is negligible, while a significant amount of electricity is sold to the grid. The amount of electricity sold to the grid is higher when the TSs are adopted, as they allow to decouple the thermal demand to the electric demand, and operate with ICE when it is more convenient. Almost all thermal demand is satisfied by the ICEs, while the cooling demand is covered by all three kinds of components which can be adopted (CC, ABS, HP). In the environmental optimizations, the electricity produced by CHPs and sold to the grid decreases noticeably, while the electricity bought from the grid increases. The

Table 5.5 – Total economic and environmental results of the optimizations - Isolated solutions

	Economic Optimization			**Environmental Optimization**	
	Conventional solution	**Isolated solution - no TS**	**Isolated solution**	**Isolated solution - no TS**	**Isolated solution**
CHP natural gas cost [k€/y]	0	1,458	1,561	624	600
BOI natural gas cost [k€/y]	1,096	67	50	13	2
Bought electricity cost [k€/y]	1,340	29	28	1,216	1,257
Sold electricity income [k€/y]	0	365	490	138	140
Photovoltaic incentive [k€/y]	0	68	68	16	0
Operating cost [k€/y]	2,437	1,121	1,081	1,699	1,720
Maintenance cost [k€/y]	23	120	128	53	52
Total investment cost [k€]	1,267	4,288	4,021	12,138	12,518
Annual investment cost [k€/y]	163	421	395	1,175	1,206
Total annual cost [k€/y]	**2,622**	**1,661**	**1,604**	**2,927**	**2,977**
Reduction wrt conv. solution		36.7%	38.8%	-11.6%	-13.5%
Electricity emissions [ton/y]	2,807	61	59	2,545	2,633
Sold electricity emissions [ton/y]	0	1,363	1,806	508	499
Natural gas emissions [ton/y]	3,691	6,769	7,173	2,844	2,701
Total annual emissions [ton/y]	**6,497**	**5,467**	**5,427**	**4,882**	**4,836**
Reduction wrt conv. solution		15.9%	16.5%	24.9%	25.6%

Table 5.6 – Total optimal annual energy magnitudes [MWh] - Isolated solutions

	Economic Optimization			**Environmental Optimization**	
	Conventional solution	**Isolated solution - no TS**	**Isolated solution**	**Isolated solution - no TS**	**Isolated solution**
ICE electricity	0	11,563	12,455	4,599	4,591
MGT electricity	0	0	0	331	175
PV panels electricity	0	239	239	48	0
Bought electricity	7,884	173	166	7,150	7,395
Electric user demand	6,968	6,968	6,968	6,968	6,968
CC electricity	916	137	191	398	394
HP electricity	0	1,042	628	3,337	3,399
Sold electricity	0	3,828	5,073	1,426	1,401
ICE thermal energy	0	16,906	18,133	6,603	6,628
MGT thermal energy	0	0	0	566	299
BOI thermal energy	17,357	1,064	787	205	36
HP thermal energy	0	2,103	946	9,279	9,419
ST panels thermal energy	0	0	0	1,108	1,387
Thermal user demand	17,319	17,319	17,319	17,319	17,319
ABS thermal energy	0	1,733	1,604	290	131
Wasted thermal energy	0	1,022	399	152	92
CC cooling energy	2,748	410	574	1,194	1,182
ABS cooling energy	0	1,127	1,055	163	79
HP cooling energy	0	1,213	1,121	1,392	1,488
Cooling user demand	2,748	2,748	2,748	2,748	2,748
Wasted cooling energy	0	2	1	0	0

heat produced by the HPs increases significantly, while the cooling energy required by the users is produced by CCs and HPs.

The Isolated Solutions obtained minimizing the total annual cost permit a consistent reduction of the total cost with respect to the conventional solution (37%), together with a reduction of the CO_2 emissions (16%). The adoption of local thermal storages is convenient either from the economic of environmental point of view.

5.4 Distributed Generation Solution

The Distributed Generation Solution includes the DHN to the Isolated solution (Fig. 5.4). The thermal energy produced in a production unit can be used directly either from the user of the site, or from other users, exchanging the heat through the DHN. This solution gives the possibility to create a central production unit where all energy is produced and sent to the users through the DHN. The electric energy, if not used directly to the user has to be sent to the electric network. However, the Isolated Solution can still be adopted if more convenient, based on economic and environmental evaluations.

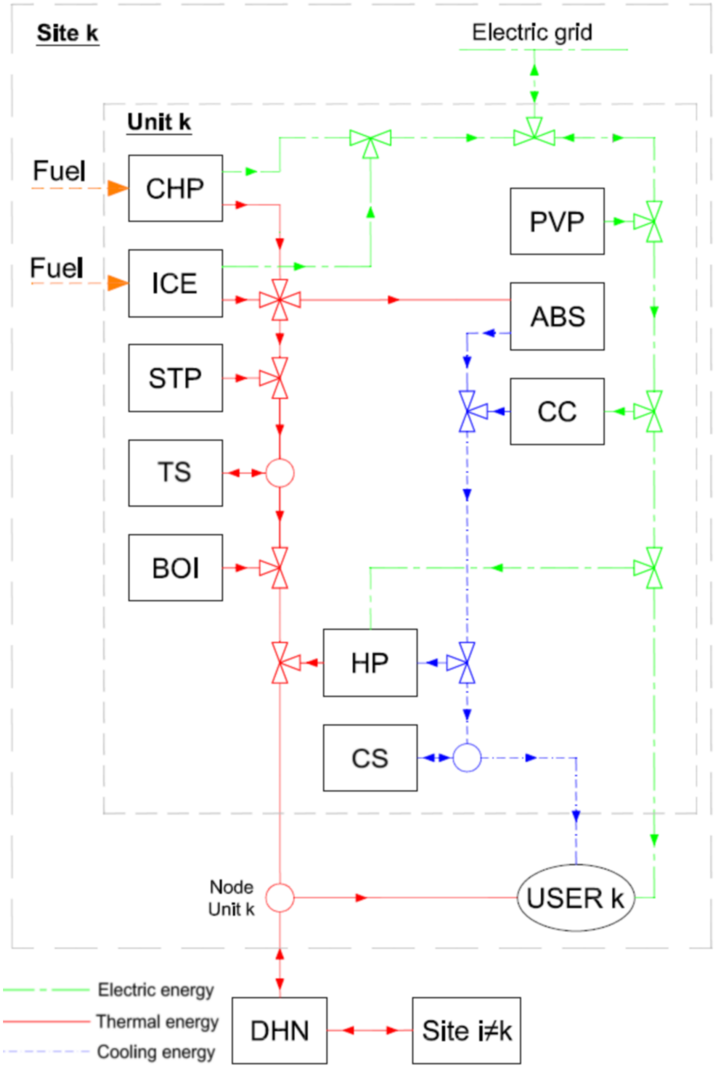


FIGURE 5.4 – Superstructure of the Distributed Generation Solution

Table 5.7 shows the optimal configurations obtained for the Distributed Cogeneration Solution. First, the economic and environmental optimal solutions are obtained. Secondly, the difference between the environmental objective functions is calculated. Thirdly, the interval between these objective functions was portioned in 4 parts, and the intermediate optimal solutions have been obtained using the ϵ-constrained method (see eqs 3.76, 3.77). 30%, 60% and 90% refer to a percentage calculated as reported in eq.

5.2:

$$\epsilon = \frac{em_{tot-cur,sol} - em_{tot-eco,sol}}{em_{tot-env,sol} - em_{tot-eco,sol}} \tag{5.2}$$

where $em_{tot-cur,sol}$ is the total CO_2 emissions of the current optimization, $em_{tot-eco,sol}$ is the total CO_2 emissions of the economic optimization and $em_{tot-env,sol}$ is the total CO_2 emissions of the environmental optimization.

From a general overview of table 5.7 it can be noted that the DHN is convenient either from an economic or environmental point of view, while the MGTs , the CSs and the BOIs are actually never adopted, with the exception of the Environmental Solution. Moving from the economic towards the environmental optimal solution, the number of the DHN pipelines increase, as well as the size of the HPs and the ST panels installed. The size of the CCs remains quite constant while the size of ICEs, of ABSs, of PV panels and of TSs adopted decreases. The sizes of the components related to the environmental optimal solution do not follow a logic trend. This is due to the fact that in the environmental optimum the costs of the investment do not affect the Environmental objective function and thus, adopting a component of a proper size or a component of a larger size result equivalent for the optimization procedure, even if it is never used at full load.

Table 5.7 – Optimal configurations of the Distributed Generation Solution

	Environmental Opt.	**90% Env. Opt.**	**60% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
DHN pipes [n°]	18	13	9	7	7
ICE [kW]	4,920	2,190	2,290	2,590	2,840
MGT [kW]	3,900	0	0	0	0
BOI [kW]	502	0	0	2	13
ABS [kW]	3,570	0	0	595	770
HP [kW]	3,570	2,590	2,380	1,715	1,050
CC [kW]	1,593	1,682	1,759	1,620	1,656
PV panels [kW$_p$]	0	0	134	225	225
ST panels [m^2]	1,800	1,800	734	0	0
TS [kWh]	36,000	6,316	8,553	12,337	15,017
CS [kWh]	36,000	0	0	0	0

Table 5.8 reports the economic and environmental results of the optimizations. Moving from the economic to the environmental optimum the operation cost increase by about 80%, resulting from a significant increment of the bought electricity cost and a decrement of the natural gas cost and sold electricity income. The maintenance cost decreases sensibly, while the investment cost increases significantly. The total annual cost increase as a compromise of the reduction of the total annual CO_2 emissions. The CO_2 emissions due to the usage of electricity from the grid increases significantly, while

the emissions due to the usage of natural gas and the saved emissions due the electricity sold to the electricity grid decrease. The environmental optimal solutions are characterized by a sensible reduction of the Total annual emissions, but a raising in Total annual cost.

Fig. 5.5 shows the Pareto Frontiers of the Distributed Generation Solutions, and they are compared with the Isolated Solutions and Conventional Solution. In can be clearly seen that the Distributed Generation Solution Pareto Front dominate the Isolated Solutions and the Conventional Solution. However, the Distributed Generation Solution does not lead to a significant improvement of the objective functions with respect to the Isolated Solutions (less than 1%). With the exception of the environmental optimal solutions, all the other optimal solutions dominate the Conventional Solution and allow to improve the objective functions.

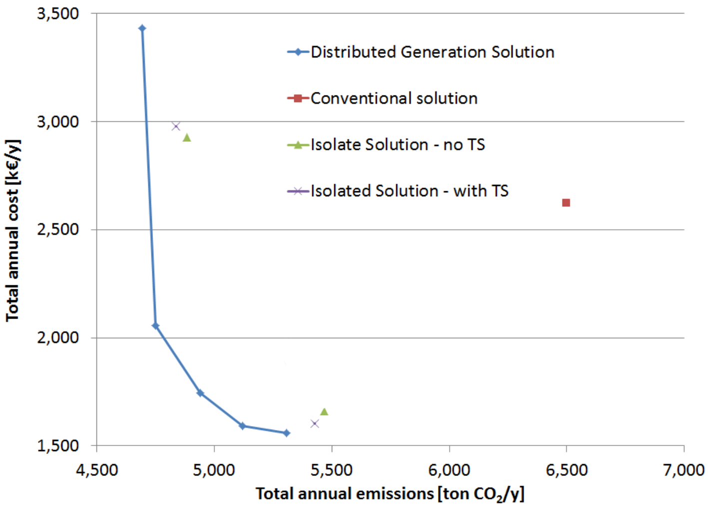


FIGURE 5.5 – Pareto Front of the optimal Distributed Generation Solutions, including Isolated Solutions and Conventional Solution

Table 5.9 reports the total optimal annual energy magnitudes of the different solutions. Moving from the economic optimal solution towards the environmental optimal solution, it can be noted that the electricity produced by the ICEs decreases significantly while on the other hand the electricity bought from the grid increases, feeding electric components such as CCs and HPs. In the economic optimal solution almost all thermal energy is produced by ICEs, while in the environmental optimal solution it decreases significantly and it is substituted by HPs and ST panels. For what concern the cooling energy balance, the cooling energy produced by the CCs is quite constant, while ABSs and HPs have opposite trends moving from economic towards environmental optimum. The HPs is more convenient in the environmental optimal solution. In all optimal solutions, the thermal and cooling energy wasted is negligible.

Analyzing all parameters of the optimal solutions, a final configuration can be chosen.

Table 5.8 – Total economic and environmental results of the optimizations - Distributed Generation Solutions

	Environmental Opt.	**90% Env. Opt.**	**60% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
CHP natural gas cost [k€/y]	389	643	994	1,296	1,614
BOI natural gas cost [k€/y]	0	0	0	0	0
Bought electricity cost [k€/y]	1,603	1,030	446	130	21
Sold electricity income [k€/y]	76	82	126	264	539
Photovoltaic incentive [k€/y]	0	0	30	58	67
Operating cost [k€/y]	1,917	1,591	1,284	1,105	1,028
Maintenance cost [k€/y]	37	57	84	107	132
Annual investment cost [k€/y]	1,519	410	378	381	397
Total investment cost [k€]	17,422	4,403	3,968	4,050	4,178
Total annual cost [k€/y]	**3,472**	**2,058**	**1,746**	**1,593**	**1,558**
Reduction wrt conv. solution	-32.44%	21.52%	33.42%	39.23%	40.59%
Electricity emissions [ton/y]	3,358	2,157	934	273	44
Sold electricity emissions [ton/y]	269	292	456	972	1,981
Natural gas emissions [ton/y]	1,710	2,885	4,461	5,818	7,244
Total annual emissions [ton/y]	**4,699**	**4,750**	**4,940**	**5,120**	**5,307**
Reduction wrt conv. solution	27.68%	26.89%	23.97%	21.20%	18.33%

Table 5.9 – Total optimal annual energy magnitudes [MWh] - Distributed Generation Solutions [MWh]

	Environmental Opt.	**90% Env. Opt.**	**60% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
ICE electricity	3,131	5,190	8,014	10,431	12,933
MGT electricity	0	0	0	0	0
PV panels electricity	0	0	141	239	239
Bought electricity	9,431	6,060	2,625	767	123
Electric user demand	6,968	6,968	6,968	6,968	6,968
CC electricity	217	230	266	180	231
HP electricity	4,617	3,232	2,266	1,560	532
Sold electricity	760	820	1,281	2,729	5,565
ICE thermal energy	4,619	7,468	11,510	15,022	18,742
MGT thermal energy	0	0	0	0	0
BOI thermal energy	0	0	0	0	3
HP thermal energy	11,581	8,663	5,406	3,450	834
ST panels thermal energy	1,387	1,387	566	0	0
Thermal user demand	17,319	17,319	17,319	17,319	17,319
ABS thermal energy	0	0	0	809	1,704
Wasted thermal energy	0	0	0	0	9
CC cooling energy	652	689	797	540	692
ABS cooling energy	0	0	0	523	1,140
HP cooling energy	2,096	2,059	1,951	1,686	917
Cooling user demand	2,748	2,748	2,748	2,748	2,748
Wasted cooling energy	0	0	0	0	1

It can be based on further technical evaluation of the designer and on economic evaluation of the stakeholders. For example, if the only aim to achieve is the lowest total annual cost, the economic optimal solution will be adopted, but in an other situation where the sensibility to environmental problem is more important the environmental solution 90% could be adopted. The pure Environmental solution does not have to be considered as a reasonable solution, as it does not consider costs at all. 90% Environmental solution allows to significantly reduce the Total annual emissions, controlling also the Total annual cost.

In this specific case study, the environmental optimal solution 60% has been identified as the best compromise. Fig. 5.6 reports the optimal configuration and the lay out of the network in this best case. It can be noted that the best compromise solution provides a subdivision of the sites in two different subsystems: the first one is made up of sites 1 to 6, the second one is made of the sites 7 to 9. In the first subsystem the site 2 can be identified as a central node where the greatest part of the thermal energy is produced and sent to the other sites through the DHN. In the second subsystem the sites are integrated to each other and a main site cannot be identified.

Distributed Generation Solutions permit to slightly improve the economic objective function (less than 1%) with respect to the Isolated Solutions, and by about 2% the environmental objective function.

5.5 Distributed Generation Solution integrated with Central Solar System

The following results consider a superstructure which embeds all components included in the previous superstructure (5.4) and also a central system constituted by a ICE, a BOI, the central storage and the solar field (Fig. 5.7).

Table 5.10 reports the optimal configurations resulting from the optimization procedure applied to the Distributed Generation Solution integrated with the Central Solar System. Four optimizations have been performed: one economic optimization, one environmental optimization and 2 intermediate optimizations obtained constraining the environmental objective function. Looking at the optimal configurations it can be noted that in all optimizations the solar field is adopted together with the central thermal storage, while the central BOI and ICE are never adopted. The BOI is not adopted because it is not convenient to produce energy in the central unit and to transfer it to the sites, loosing thermal energy through the DHN. The ICE is not adopted because when the electricity is sold to the grid, the marginal cost of the heat is much higher than when the electricity is directly used to the users. Therefore, as the electric energy produced by the central ICE cannot be sent directly to the users, but can only be sold to the grid, the adoption of the central ICE is not convenient. The central pipe is the pipe which connect the central unit to the site 8.

Two differences have to be highlighted comparing the results with the ones observed in the section 5.4: the first difference is the presence of the boilers to cover the thermal peaks, the which size increases moving towards the environmental solution. The second

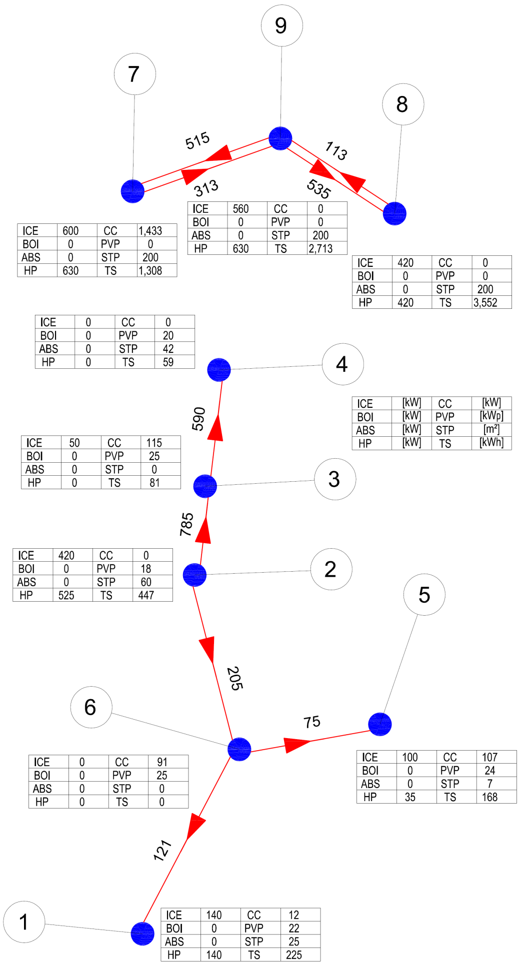


FIGURE 5.6 – Superstructure of the 60% Environmental Optimum - Distributed Generation Solution. In red the DHN pipes have been reported together with their size [kW]. The table reports the size of the components installed.

difference is the presence of thermal storages in the production units only in two optimizations: in the first two optimizations (economic optimization and 30% optimization) there is still a separation between the sites forming two separated subsystems: site 1 to 6, and site 7 to 9 connected to the central unit. Starting from the 70% optimization, all users are connected to each other and the storages installed in the production units disappear. Moreover, starting from the 70% optimization, a larger central thermal storage has been adopted. The size of ABSs increases, while the ST panels are never adopted. In the first two optimizations the PV panels are more convenient wrt the ST panels while in the last two optimizations the ST panels are installed in the central unit, leaving available the space to the sites for PV panels. The other components show a trend similar to the one observed in the previous optimizations.

TABLE 5.10 – Optimal configurations of the Distributed Generation Solutions Integrated with Central Solar System

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
DHN pipes [n°]	14	8	7	7
Central pipe size [kW]	7,500	6,323	3,579	1,907
ICE [kW]	4,920	1,840	2,380	2,500
MGT [kW]	0	0	0	0
BOI [kW]	3,480	3,408	2,730	2,023
ABS [kW]	3,570	1,260	1,155	1,085
HP [kW]	3,570	1,120	1,225	1,155
CC [kW]	1,584	1,056	1,053	1,233
PV panels [kW$_p$]	225	225	225	225
ST panels [m^2]	0	0	0	0
TS [kWh]	0	0	2,315	5,134
CS [kWh]	0	0	0	0
Central ICE [kW]	0	0	0	0
Central BOI [kW]	0	0	0	0
ST field [m^2]	27,736	23,585	19,013	8,035
Central TS [kWh]	400,000	173,935	41,855	19,025

Table 5.11 reports the economic and environmental results of the optimizations. The trends of the costs and of the emissions are similar to the one observed in the optimizations performed in section 5.4. Comparing table 5.8 with table 5.10 it can be observed that the operating cost of the solutions integrated with the Central Solar Unit is lower (-6%), while they are characterized by higher investment costs (+30%). Looking at Fig. 5.8 it can be noted that the Pareto Front obtained with integrating the Central Solar Unit dominates the other Pareto Frontiers, as all the solutions obtained allow to achieve lower total annual costs together with lower total annual emission. As the superstructure reported in Fig. 5.7 includes the one reported in Fig. 5.4, it could not have happened that the Pareto Front obtained integrating the Central Unit was dominated by the Pareto Front of the simple Distribute Generation Solution. If the Central Unit had not been convenient, the optimal solutions would have been the same of the one obtained for the Distribute Generation Solution and then the Pareto Front would have been the same.

Table 5.12 reports the total annual energy magnitudes obtained for the optimizations of the Distributed Generation Solution integrated with the Central Solar Unit. The

Table 5.11 – Total economic and environmental results of the optimizations - Distributed Generation Solutions integrated with Central Solar System

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
CHP natural gas cost [k€/y]	86	741	1,059	1,339
BOI natural gas cost [k€/y]	1	10	9	33
Bought electricity cost [k€/y]	1,482	451	221	32
Sold electricity income [k€/y]	30	125	234	373
Photovoltaic incentive [k€/y]	75	53	55	66
Operating cost [k€/y]	1,464	1,025	1,000	965
Maintenance cost [k€/y]	10	63	88	113
Total investment cost [k€]	22,314	8,248	6,368	5,359
Annual investment cost [k€/y]	1,760	705	569	453
Total annual cost [k€/y]	**3,233**	**1,792**	**1,657**	**1,531**
Reduction wrt conv. solution	-23.32%	31.64%	36.80%	41.61%
Electricity emissions [ton/y]	3,104	945	463	67
Sold electricity emissions [ton/y]	190	461	856	1,385
Natural gas emissions [ton/y]	388	3,362	4,784	6,268
Total annual emissions [ton/y]	**3,301**	**3,846**	**4,392**	**4,950**
Reduction wrt conv. solution	49.20%	40.80%	32.41%	23.81%

trends of each item are similar to the ones observed in table 5.9. The most important differences which have to be outlined are the thermal production of the ST panels, which increases noticeably due to the presence of the ST field, and the amount of wasted thermal energy. The latter directly depend on the size of the solar thermal field and of the thermal storage, as well as from the optimal operation. In the pure and 30% economic optimizations, the solar field covers around about 50% of the thermal demand and a small central thermal storage is adopted. It is operated with a daily/weekly charging/discharging cycles. During the summer, when the solar field is producing a lot of thermal energy, the thermal storage is full and the user do not require thermal energy, the heat produced by the solar field is wasted. The adoption of a larger thermal storage would involve to an investment cost sensibly greater which would not be paid back by the related savings, thus making the total annual cost increases. Therefore, exceeded a certain dimension of the thermal storage, the investment marginal cost related to a kWh results to be greater than the marginal cost of the heat produced by boilers and/or cogenerators. Hence, it is more convenient to waste the exceeding heat (instead of storing it) and produce it by boilers and/or cogenerators when necessary.

In the pure environmental and 70% optimizations, the solar field as much as the thermal demand of the users and the thermal storage is larger with respect to the other optimizations. In this case, the thermal storage is operated with a seasonal charging/discharging cycle.

Figure 5.9 refers to the economic optimization and reports the trends of the thermal energy demand of sites 7, 8 and 9, the central storage level and the in/out storage thermal flow in a typical week. The other sites are not included in the sum of the thermal demand as the central storage is not connected to them. In can be noted that during week-end the thermal demand is lower than during the working days, and consequently the heat produced by the solar field is stored in the thermal storage. This heat is then used in the first hours of the following working days when the operation of the ICE is not convenient. A similar trend can be noted in each week of the year and thus it can be stated that, in this application case, the storage has weekly charging/discharging cycles.

A different operation of the thermal storage can be identified for the optimizations which adopt a larger thermal storage (70% and pure environmental optimizations). In these cases the thermal storage is operated as a seasonal thermal storage: from April to August, part of the heat produced by the solar field is stored in the thermal storage, and is used from September to November. In the other months the storage is operated with weekly charging/discharging cycles (see Fig. 5.10). A larger thermal storage and a larger solar field had probably allowed a real seasonal operation of the storage: the heat stored from April to August is used from September to March, thus the storage is empty at the end of Mach and full at the end of August. However, this solution would have lead to higher investment costs which would not have been paid back by a real reduction of the operation costs. When the thermal storage is operated with a seasonal strategy, the marginal investment cost of the "last" kWh of capacity can be completely charged to the "last" kWh of the thermal energy stored in August. The "last" kWh of capacity will be adopted only if the production cost of the kWh stored, with alternative technologies, is higher.

In Figure 5.10 the yearly discretization, intrinsic to the model, can be noted. In fact,

TABLE 5.12 – Total optimal annual energy magnitudes [MWh] - Distributed Generation Solutions integrated with the Central Solar Unit

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
ICE electricity	693	5,957	8,482	10,956
MGT electricity	0	0	0	0
PV panels electricity	239	239	239	239
Bought electricity	8,718	2,656	1,302	188
Electric user demand	6,968	6,968	6,968	6,968
CC electricity	209	137	121	162
HP electricity	1,938	453	529	363
Sold electricity	534	1,294	2,404	3,889
ICE thermal energy	1,024	8,547	12,284	15,979
MGT thermal energy	0	0	0	0
BOI thermal energy	11	161	146	529
HP thermal energy	3,991	675	866	497
ST panels thermal energy	20,931	17,880	14,651	6,191
Thermal user demand	17,319	17,319	17,319	17,319
ABS thermal energy	0	2,316	2,336	2,341
Wasted thermal energy	7,850	6,918	8,018	2,571
CC cooling energy	626	410	364	487
ABS cooling energy	0	1,521	1,522	1,549
HP cooling energy	2,122	820	872	717
Cooling user demand	2,748	2,748	2,748	2,748
Wasted cooling energy	0	3	10	4

the year is constituted by 48 weeks (instead of 54) grouped by 4, representing the 12 months. Each single week is constituted by 5 working days plus two non-working days. This leads to the fact that the charging/discharging cycles can be only: daily, weekly or yearly. Intermediate cycles or monthly cycles cannot obtained from the optimizations. For example, a monthly cycle where in the first two weeks the thermal energy is stored and in the last two weeks is used, cannot be obtained form the optimizations, as all weeks of the same month are characterized by the same operation. Even so, cycles which comprehend two months where the heat is stored in the first month and used in the second one, can be obtained. This behavior which result from the optimizations is in accordance with the natural operation logics of the seasonal thermal storages. Fig. 5.10 shows clearly the fact that each month is characterized by weeks with the same operation.

As per the Distributed Generation Solutions, a best solution has been identified even for this set of optimizations. It represents a compromise between the best economic result and the most environmentally friendly solution. In this case, the environmental optimal solution 70% has been taken as the best compromise solution, it allows a 32% reduction of the total cost and a 41% reduction of the total annual emissions, with respect to the conventional solution. Fig. 5.11 reports the optimal configuration and the lay out of the network. It can be noted that the DHN connects the users to each other differently from the optimal solution reported in Fig. 5.6 where the users were subdivided in two sub networks. In this case the thermal energy produced in the central unit can be send to all the users through the DHN. The dimension of the pipes decreases moving towards sites 1 and 7.

The introduction of the central unit which include a central solar field and a large thermal storage allow a significant reduction of the CO_2 emissions (-30%).

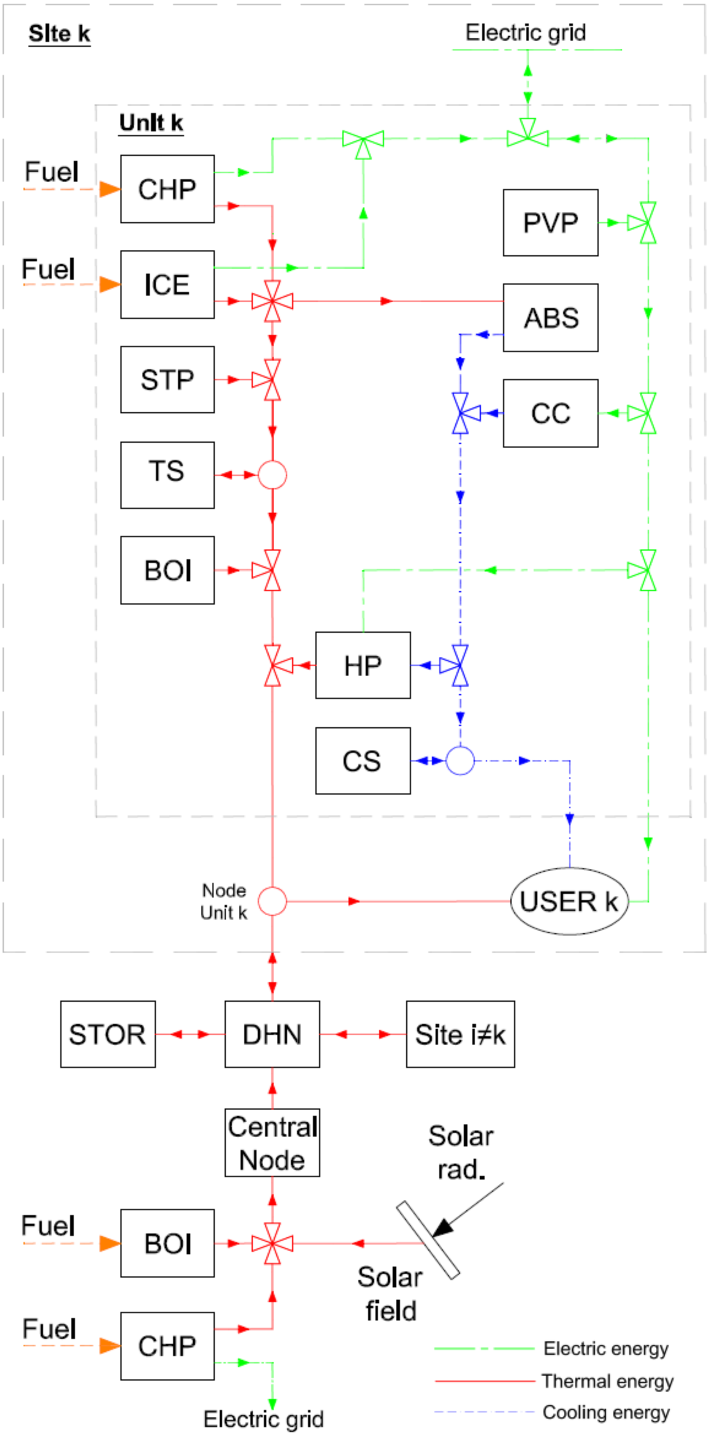


FIGURE 5.7 – Superstructure of the Distributed Generation Solution integrated with Central Solar System

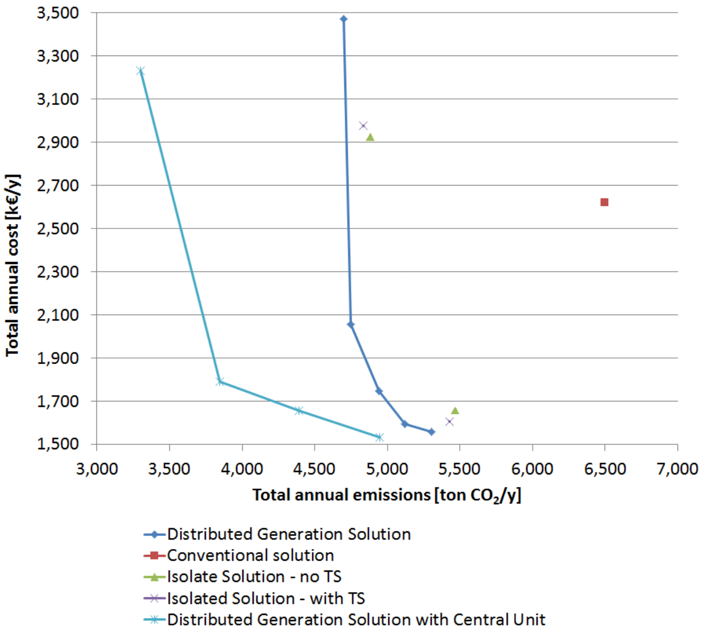


Figure 5.8 – Pareto Front of the optimal Distributed Generation Solutions integrated with Central Solar Unit

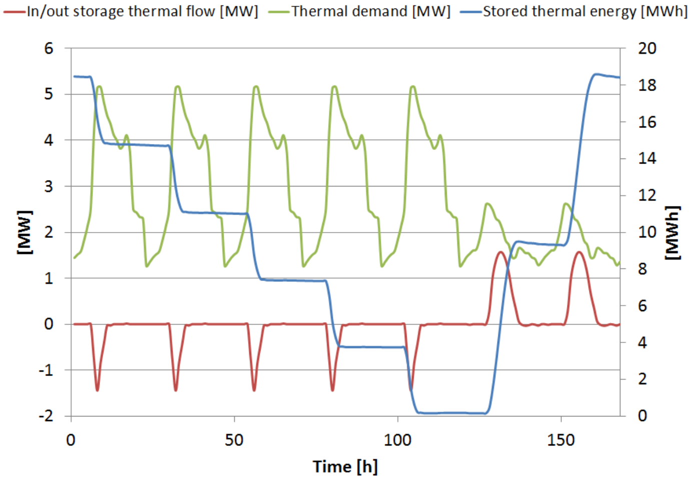


Figure 5.9 – Optimal operation of the storage in a typical week-Economic optimization fo the Distributed Generation Solutions integrated with the Central Solar Unit

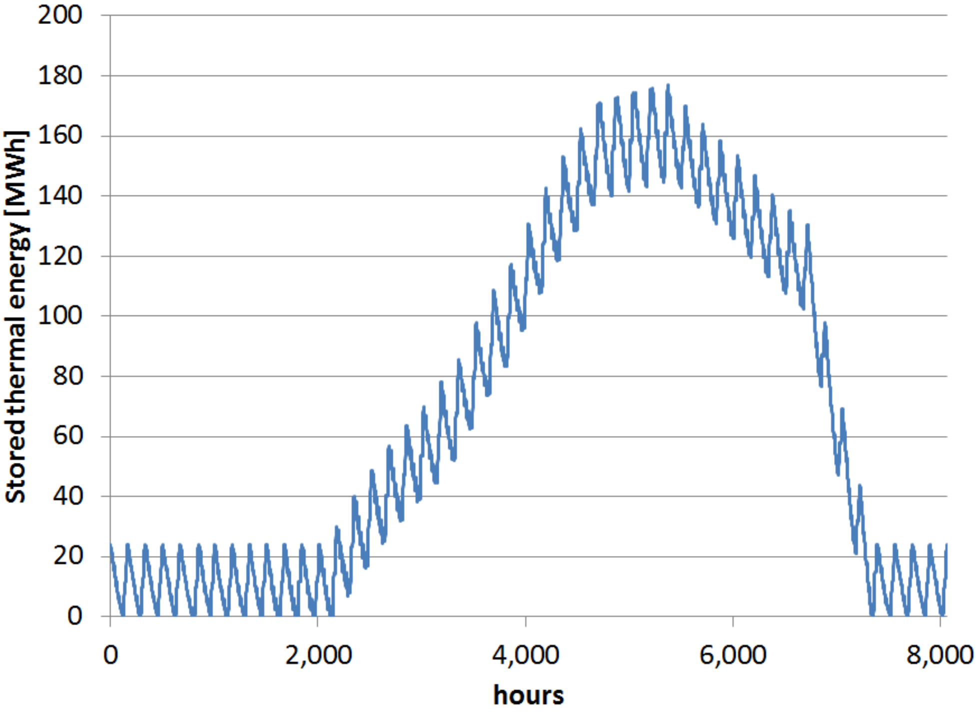


Figure 5.10 – Yearly optimal operation of the storage-70% environmental optimization of the Distributed Generation Solutions integrated with the Central Solar Unit

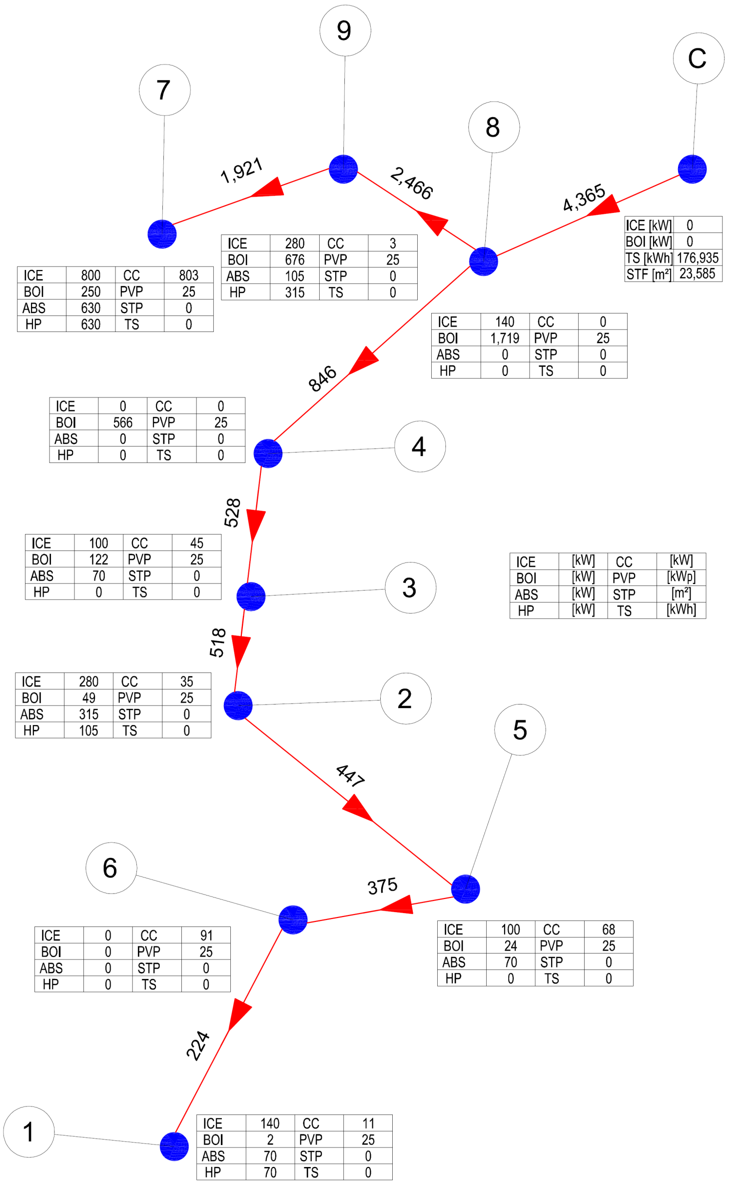


FIGURE 5.11 – Superstructure of the 70% Environmental Optimum - Distributed Generation Solution integrated with Central Solar System. In red the DHN pipes have been reported together with their size [kW]. The tables report the size of the components installed.

5.6 Complete Distributed Generation Solution

The Complete Distributed Generation Solution include also the DCN to the superstructure and it refers to the most general superstructure presented in chapter 3 (see Fig. 3.3).

Table 5.13 shows the optimal configuration of the optimizations performed. Also in this case, four optimizations have been performed: one economic optimization, one environmental optimization and 2 intermediate optimizations obtained constraining the environmental objective function. The optimal configurations and the trends are very similar to the ones obtained in the previous paragraph 5.5, where the DCN was not included in the superstructure. Also in this case, the first two optimizations (economic and 30% optimizations) subdivide the the whole system in two sub DHN: sites 1 to 6, and sites 7 to 9 connected to the central unit. The last two optimizations (pure environmental and 70% optimizations) provide a DHN which connects all sites to each other. The DCN is adopted and it connects always site 2 to sites 5 and 6, and site 9 to 7. Starting from 70% environmental optimization, also site 1 is connected to site 6. With respect to the previous optimizations (see Fig. 5.10) the size of the CC decreases sensibly, because of the presence of the DCN.

Table 5.13 – Optimal configurations of the Complete Distributed Generation Solutions

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
DHN pipes [n°]	14	8	7	7
DCN pipes [n°]	7	4	3	3
Central pipe size [kW]	7,500	4,980	4,118	1,922
ICE [kW]	4,920	1,840	2,270	2,380
MGT [kW]	0	0	0	0
BOI [kW]	12	1,954	1,406	1,252
ABS [kW]	3,570	1,435	1,190	1,120
HP [kW]	3,570	1,890	1,680	1,680
CC [kW]	778	250	174	306
PV panels [kW$_p$]	225	225	225	225
ST panels [m^2]	0	0	0	0
TS [kWh]	0	0	2,176	4,939
CS [kWh]	0	0	0	0
Central ICE	0	0	0	0
Central BOI	0	0	0	0
ST field [m^2]	22,736	21,764	17,664	8,710
Central TS [kWh]	400,000	169,926	30,980	20,366

The introduction of DCN do not change significantly the arrangement of the economic and environmental results. In fact, the total annual cost and the total annual emissions improve only by few percentage points (see table 5.14). Focusing on the economic optimization, the operation costs decrease by about 60 k€ with respect to the optimal solution obtained for the Distributed Generation Solution Integrated with the Central Solar Unit. The annual investment cost increases by 10 k€, due to the adoption of 3 pipes of the DCN. Thus, the total annual cost decrease by about 50 k€.

The environmental optimization leads to a slight improvement of the total annual emissions (10 tons): lower emissions due to the bought of electricity, higher emissions due to the usage of natural gas and higher saved emissions due to the input of the electricity in the electricity network.

As can be note in Fig. 5.12 the Complete Distributed Generation Solutions dominates all the other solutions analyzed for this case study. The economic optimal solution allows a reduction of 41% of the total annual cost and of 23% of the total annual emissions (see table 5.14), with respect to the conventional solution. The environmental optimal solution allows a reduction of about 50% wrt the Conventional solution, while the total annual cost increases. The 70% environmental solution which has been identified as the best compromise of the Complete Distributed Solutions, allows a 31% reduction of the total annual cost and a 41% reduction of the total annual emissions.

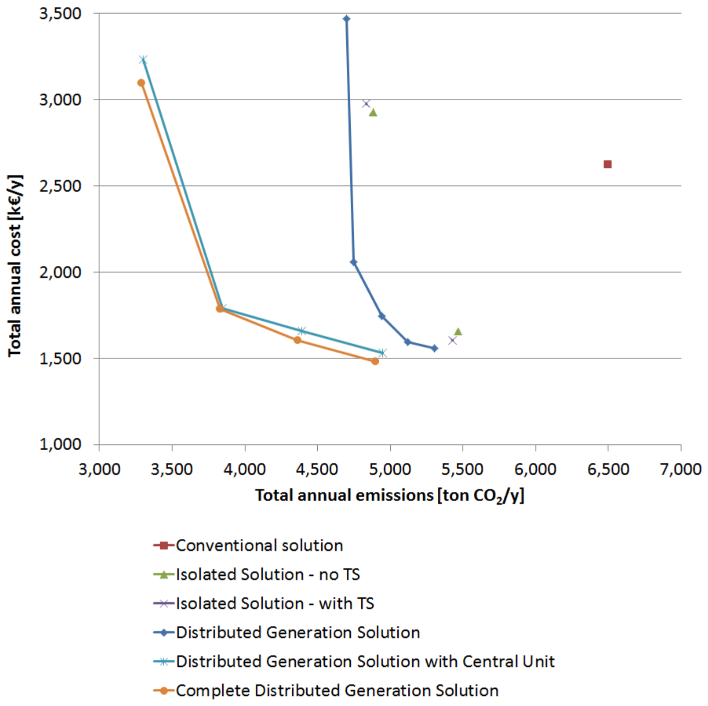


FIGURE 5.12 – Pareto Front of the optimal Complete Distributed Generation Solutions

Table 5.14 – Total economic and environmental results of the optimizations - Complete Distributed Generation Solution

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
CHP natural gas cost [k€/y]	202	757	1,026	1,242
BOI natural gas cost [k€/y]	0	7	4	33
Bought electricity cost [k€/y]	1,474	486	218	38
Sold electricity income [k€/y]	126	153	266	340
Photovoltaic incentive [k€/y]	75	53	56	66
Operating cost [k€/y]	1,475	1,045	926	908
Maintenance cost [k€/y]	10	60	88	107
Total investment cost [k€]	24,806	8,114	6,909	5,219
Annual investment cost [k€/y]	1,611	680	592	466
Total annual cost [k€/y]	**3,095**	**1,785**	**1,606**	**1,481**
Reduction wrt conv. solution	-18.05%	31.93%	38.75%	43.50%
Electricity emissions [ton/y]	3,087	1,018	457	80
Sold electricity emissions [ton/y]	197	453	864	1,157
Natural gas emissions [ton/y]	403	3,262	4,769	5,974
Total annual emissions [ton/y]	**3,292**	**3,827**	**4,362**	**4,897**
Reduction wrt conv. solution	49.33%	41.10%	32.87%	24.63%

A comparison between the annual energy magnitudes of the Complete Distributed Generation Optimization and of the Distributed Generation Optimization integrated with the Central Solar Unit (table 5.15 and table 5.12) shows only few arrangements. In the Complete Distribute Generation Optimization the electricity used by HPs and the cooling energy produced by ABSs is higher (+67% and +8%, respectively), while the sold electricity and is decreased (-17%) . All the other energy amounts do not show a significant change.

As introduced before, the 70% environmental optimization has been identified as the best compromise between the minimum total annual cost and minimum total annual emissions. Fig. 5.13 reports the optimal configuration: the layout of the DHCN has been reported together with the size of the components installed in each site. The DCN connects sites 2, 5, 6 and 1, and a single pipe connects site 7 to 9. The layout of the DHN is very similar to the one reported in Fig. 5.11 for the Distributed Generation Solution integrated with the Central Solar Unit, while the component sizes installed in each production unit are slightly changed. This difference can be due either to internal arrangement due to the introduction of the DCN or to the moment when the optimization has been stopped. In fact, each optimization has been stopped when a GAP lower that 1% is achieved (see paragraph 5.1). This means that the same result in terms of economic and environmental benefits could be achieved with other similar solutions, which are catheterized by the same GAP. So that, when the DHN is included in the superstructure the number of similar solutions increases exponentially, and two solutions which are apparently different because the location of the components is completely different, are actually similar, as they lead to the same result of the minimized objective function.

TABLE 5.15 – Total optimal annual energy magnitudes [MWh] - Complete Distributed Generation Solutions

	Environmental Opt.	**70% Env. Opt.**	**30% Env. Opt.**	**Economic Opt.**
ICE electricity	726	5,807	8,510	10,412
MGT electricity	0	0	0	0
PV panels electricity	239	239	239	239
Bought electricity	8,671	2,858	1,283	226
Electric user demand	6,968	6,968	6,968	6,968
CC electricity	78	54	34	51
HP electricity	2,035	610	604	607
Sold electricity	501	1,257	2,411	3,234
ICE thermal energy	1,057	8,313	12,241	15,187
MGT thermal energy	0	0	0	0
BOI thermal energy	0	112	63	527
HP thermal energy	3,974	820	916	1,054
ST panels thermal energy	17,520	16,771	13,612	6,711
Thermal user demand	17,319	17,319	17,319	17,319
ABS thermal energy	0	2,077	2,431	2,560
Wasted thermal energy	4,436	5,930	6,753	3,439
CC cooling energy	234	162	101	153
ABS cooling energy	0	1,377	1,594	1,676
HP cooling energy	2,537	1,227	1,074	933
Cooling user demand	2,748	2,748	2,748	2,748
Wasted cooling energy	0	4	8	5

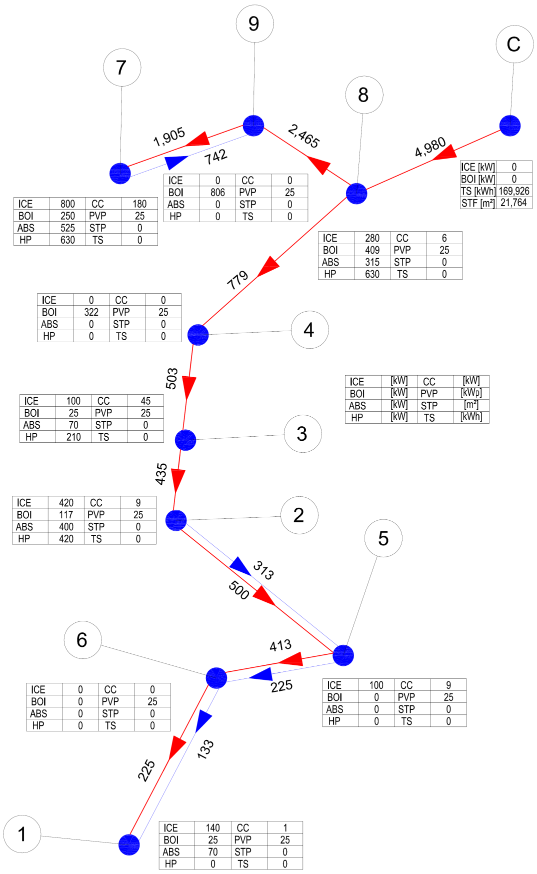


Figure 5.13 – Superstructure of the 70% Environmental Optimum - Complete Distributed Generation Solution. In red the DHN pipes and in blue the DCN pipes have been reported together with their size [kW]. The tables report the size of the components installed.

5.7 Operation Optimization

The optimization model proposed in this research Thesis allows the simultaneous optimization of the configuration and of the operation of a Distributed Generation Energy System. Furthermore, if the DHCN is included in the superstructure, these two optimizations must be performed simultaneously because they are strictly related to each other: the preliminary energy loads of each production unit cannot be known without knowing the related operation, and vice versa.

The previous paragraphs of this chapter introduced the optimal configurations resulting from the optimization of different different solutions of the same problem. As all optimal operation results, of each site and of each optimization cannot be reported for matter of space, an example of the optimal hourly energy balances in a typical winter and summer day are reported in the following. The results refers to the optimal operation of the site 2 (Theatre), obtained optimizing the Distributed Generation Solution - 60% Environmental Optimization.

Figures 5.14 and 5.15 report the electric balances in a summer and winter typical day. The two trends are very different, due to different electric and thermal demands. Focusing on the summer typical day (Fig. 5.14), it can be noted that the electricity is required mainly for the internal consumption of the user and for feeding the heat pumps. The electricity is mainly bought from the grid and only in few hours (6th, 22nd, 23rd) the ICEs are in operation. In the winter typical day (Fig. 5.15) the electricity required by the user and by the HPs is produced entirely by the ICEs. The exceeding amount of electricity is sold to the grid. This difference is due to the fact that the ICE operates conveniently only if the heat produced can be actually used.

Figures 5.16 and 5.17 show the thermal balances. Focusing at the summer typical day, a certain amount of heat is required by the DHN and it is mainly covered by HPs and using the heat stored in the TS. The heat produced by ST panels during the daylight hours is stored in the TS, as the thermal demand is null in these hours. In the evening the thermal energy required by the user and by the DHN is produced by the HPs and by ICEs. The exceeding amount is stored in the TS. In the winter typical day the ICEs are in operation at full load for the greatest part of the day, as well as the HPs. The heat produced is send to the user and to the DHN.

Figure 5.18 report the cooling energy balance in a summer typical day. The cooling energy required by the user it totally produced by the HPs.

The graphics reported in Fig. 5.14-5.18 can be obtained for each optimization performed, for each site, and for each typical day considered in the optimization model.

The optimal configurations obtained by means of the optimizations, must be adopted entirely to achieve the economical and environmental targets, together with the optimal operation. The optimization model is based on a preliminary knowledge of the energy user demands, but in reality only forecast can be made and the future energy consumption are not known in advance. So that, the optimal operation cannot be adopted as a result to be applied to the system, but can only be used to define the logics which control the operation of the system.

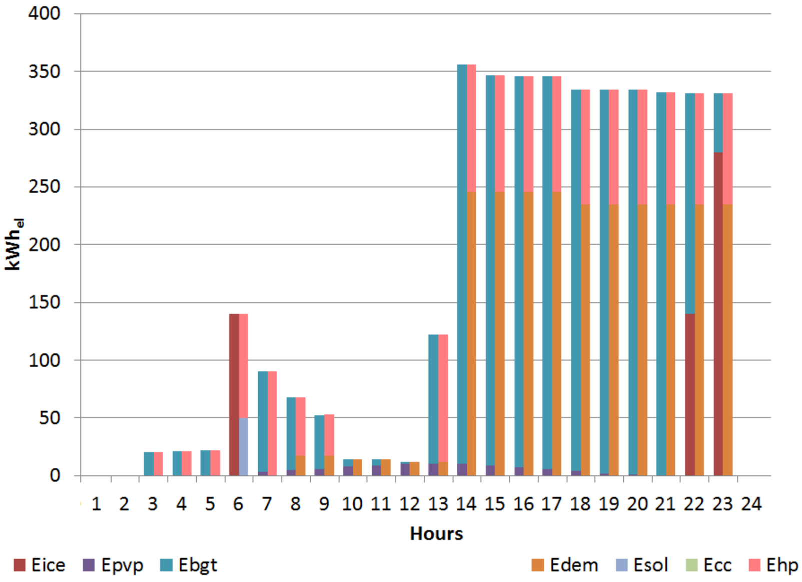


FIGURE 5.14 – Optimal Electric Balance - Summer Typical Day, Site 2

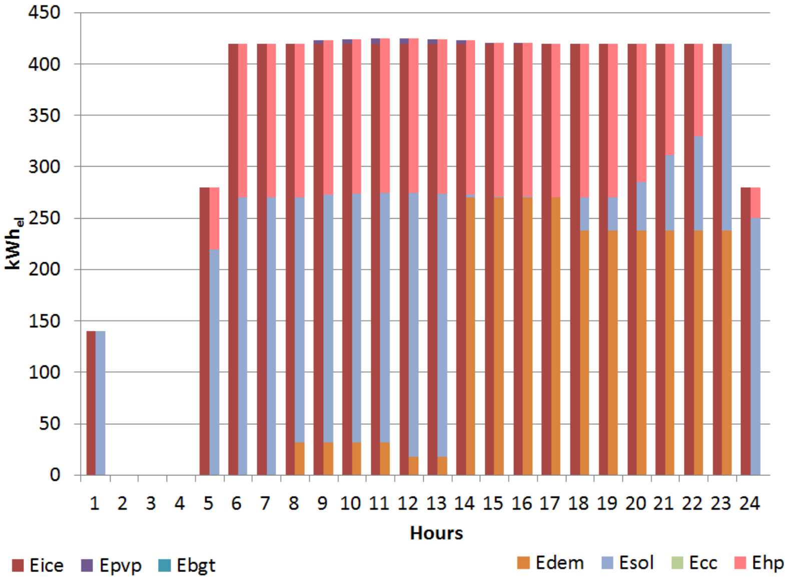


FIGURE 5.15 – Optimal Electric Balance - Winter Typical Day, Site 2

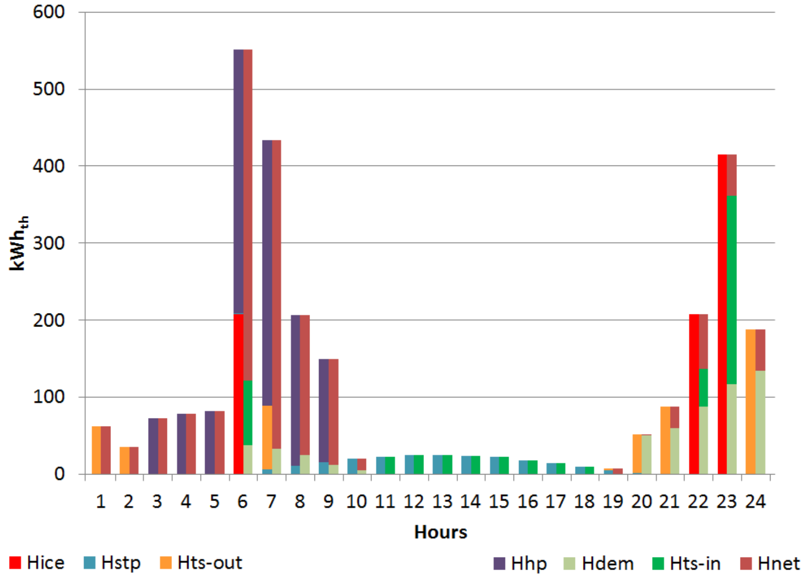


FIGURE 5.16 – Optimal Thermal Balance - Summer Typical Day, Site 2

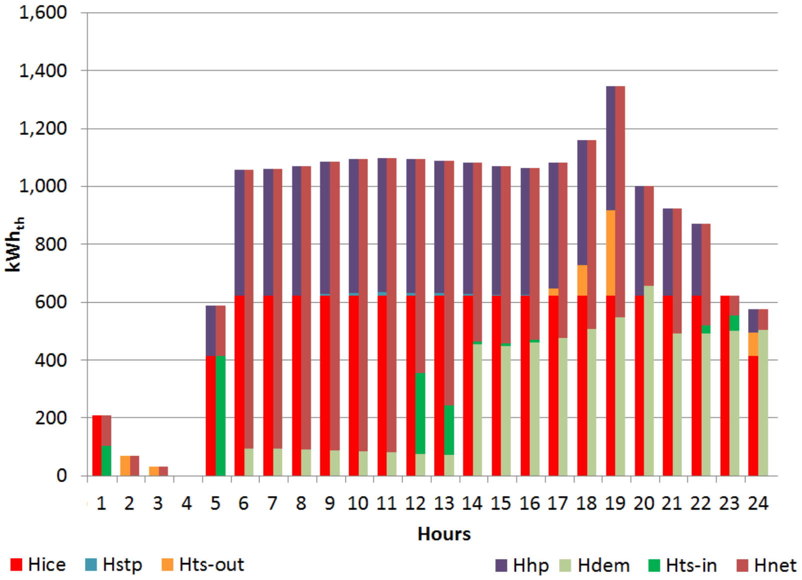


FIGURE 5.17 – Optimal Thermal Balance - Winter Typical Day, Site 2

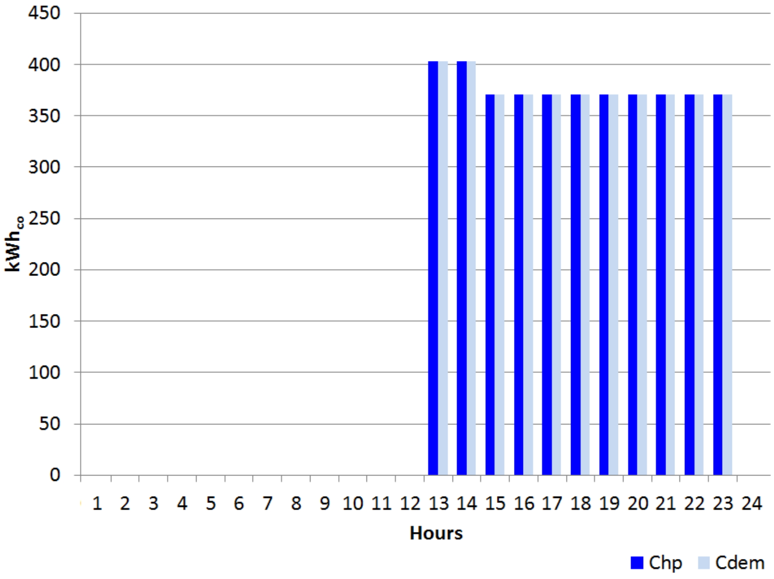


FIGURE 5.18 – Optimal Cooling Balance - Summer Typical Day, Site 2

5.8 Influence of greenhouse emission cost on the economic objective function

One of the "*Kyoto Protocol*" targets is the global reduction of the greenhouse emissions [20]. The achievement of this goal is very challenging as it is directly related to the energy sources usage and to the global energy consumption. The "*Kyoto Protocol*" fixed a 20% reduction of the global greenhouse emissions by the 2020, with respect to 1990 greenhouse emissions. The European Union proposed a strategy based on the Emission Trading and it represents a cornerstone in the fight against climate change. It is the first international trading system for CO_2 emissions in the world. It covers over 11,500 energy-intensive installations across the EU, which represent close to half of Europe's emissions of CO_2 . These installations include combustion plants, oil refineries, coke ovens, iron and steel plants, and factories making cement, glass, lime, brick, ceramics, pulp and paper.

The aim of the EU Emission Trading Scheme (ETS) is to help EU Member States achieve compliance with their commitments under the *Kyoto Protocol*. Emissions trading does not imply new environmental targets, but allows for cheaper compliance with existing targets under the *Kyoto Protocol*. Letting participating companies buy or sell emission allowances means that the targets can be achieved at least cost. The emissions exchange price is then fixed by the trading mechanism. The emission trading begun in 2008 and since this year the price of the emissions has been very volatile [86], varying from 10 €/ton to 40 €/ton.

The optimization model described in chapter 3 does not take into account for the price of the greenhouse emissions and optimizes with respect to the economic and environmental objective functions separately. The environmental objective function correspond to the greenhouse emissions (sec 3.2.5) and they can be added to the economic objective function by simply adding a term which consider the emission costs. However, as the optimizations have been performed considering the objective functions not linked to one another, it is possible to use the results obtained in the previous sections to understand how the emission costs affect the economic objective functions and the best economic solution. A new Pareto Front can be obtained for different costs of the greenhouse emissions, adding to the total annual cost, the related cost of the CO_2 emissions.

The Optimal solutions of the Complete Distributed Generation Solution have been evaluated for different values of the emissions prices. The expectation is that for a certain value of the emission costs, the environmental solutions became more convenient than the "economic" solution, due to the fact that the economic solution is characterized by greater greenhouse emissions. The results are reported in figure 5.19 and several Pareto Fronts have been obtained for different emission prices. It can be noted that, for prices of the greenhouse emissions in line with the current trading prices (0÷50 €/ton) the economic optimal solution remains the best solution from the economic point of view. The environmental solutions became more convenient than the economic solution only if the price raises up to 300 €/ton.

From the pure economic point of view, in the specific case study, the emission trading system does not affect the optimal economic solution if the emission cost is lower than about 300 €/ton. This means that there are other activities or systems where the investment in more environmentally friendly technologies is more convenient.

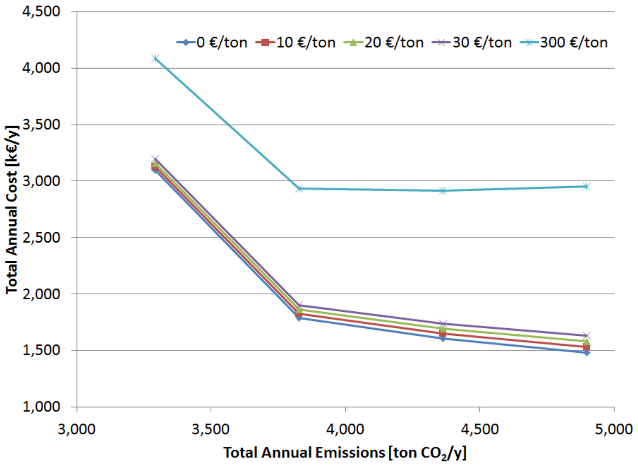


FIGURE 5.19 – Pareto Fronts of the Complete Distributed Generation Solution evaluated for different prices of the greenhouse emissions

5.9 Conclusions

The MILP model presented in Chapter 3 has been used to optimize the optimal configuration and operation of a real case study presented in Chapter 4. The aim was to obtain the optimal configuration of the Distributed Energy Generation System to satisfy the energy requirements of the users minimizing the Total Annual Cost and the Total Operation CO_2 Emissions. The model has been optimized for different cases:

- conventional solution;
- isolated solution;
- distributed generation solution without central unit and district cooling network;
- distributed generation solution with central unit but without cooling network;
- complete distributed generation solution;

in order to understand how the different components added step by step affect the final configuration of the system. The optimizations started from the simpler solution towards the most complete one representable by the model. Pareto Frontiers of the last three solutions analyzed have been obtained in order to identify the best compromise between the best economic solution and the most environmentally friendly.

The best solution either from economic or environmental point of view can be achieved with the Complete Distributed Generation Solution which includes various kind of energy components, DHCN , a solar field and a seasonal thermal storage. The best economic solution allows a 43% reduction of the total annual cost wrt the conventional solution, while the best environmental solution allows about a 50% reduction of the total annual emissions. This result can be achieved only with the optimal adoption of the components and the optimal operation of the energy system.

A total annual cost similar to the one obtained for the Complete Distributed Generation Solution can be obtained also with the Isolated Solution. It allows a 37% reduction of the total annual cost wrt to the conventional solution, with an investment cost which is a sixth wrt to the investment cost of the Complete Distributed Generation Solution. In a long time view (over 20 years) the Complete Distributed Generation Solution is more convenient and allows also a greater reduction of the total annual emissions, but from a pure economic point of view, the Isolated Solution is more attractive, as the financial exposure is dramatically lower and consequently the risk.

If from the economical point of view good results can be obtained also with the Isolated Solutions, important reductions of the total annual emissions can be obtained only with the adoption of the solar field, of the seasonal storage and of the district heating network.

Table 5.16 summarizes the compromise solutions obtained for the different optimization performed. The final best solution should be taken among them, based on further evaluation together with the stakeholders.

The optimal operations reported in paragraph 5.7 show that the central thermal storage is operated with seasonal charging/discharging cycles only when the environmental objective function is considered in the optimizations. The heat produced by the solar field during wormer months is used during the first colder months. Pure economic optimizations provides a weekly operation of the central thermal storage: the heat produced by the solar field during week-end when the energy demand is lower, is used during the following working days.

Multiobjective optimization technique allows the determination of the best solutions for single objective energy system analysis and gives the possibility to obtain also compromise solutions which try to minimize at the same time different objective functions. In this case study, the economic and environmental objective functions were considered as single objective functions, and a single solution which minimized both of them could not be identified. The analysis of the Pareto Frontiers obtained using the ϵ-constrained method allowed the identification of the best compromise solutions, in the different cases analyzed.

The influence of the greenhouse emission cost has been also investigated and it results that, from the pure economic point of view, the emission trading system does not affect the optimal economic solution, if the emission cost is lower than about 300 €/ton. This means that there are other activities or systems where the investment in more environmentally friendly technologies is more convenient.

Table 5.16 – Summary of the different compromise solutions obtained for the different configurations considered

	Convent. Solution	**Isolated Solution**	**Distributed Generation Solution**	**Distributed Generation Solution with Central Solar Unit**	**Complete Distributed Generation Solution**
DHN pipes [n°]	-	-	9	8	8
DCN pipes [n°]	-	-	-	-	4
Central pipe size [kW]	-	-	-	6,323	4,980
ICE [kW]	-	1,840	2,290	1,840	1,840
MGT [kW]	-	0	0	0	0
BOI [kW]	6,241	984	0	3,408	1,954
ABS [kW]	-	735	0	1,620	1,435
HP [kW]	-	980	2,380	1,120	1,890
CC [kW]	3,474	1,763	1,759	1,056	250
PV panels [kW$_p$]	-	225	134	225	225
ST panels [m^2]	-	0	734	0	0
TS [kWh]	6,973	15,016	8,553	0	0
CS [kWh]	0	0	0	0	0
Central ICE	-	-	-	0	0
Central BOI	-	-	-	0	0
ST field [m^2]	-	-	-	23,585	21,764
Central TS [kWh]	-	-	-	173,935	169,926
Operating cost [k€/y]	2,473	1,080	1,284	1,025	1,045
Total investment cost [k€]	1,267	4,020	3,968	8,248	8,114
Total annual cost [k€/y]	**2,622**	**1,604**	**1,746**	**1,792**	**1,785**
Reduction wrt conv. solution	-	38.8%	33.4%	31.7%	31.9%
Total annual emissions [ton/y]	**6,497**	**5,427**	**4,940**	**3,846**	**3,827**
Reduction wrt conv. solution	-	16.2%	24.0%	40.8%	41.1%

Conclusions

The aim of the research Thesis was to develop a reliable tool for the synthesis, design and operation optimization of a Distributed Generation Energy System, focusing on environmental and economic results. This tool can be very helpful to attain the environmental targets defined by the most important world authorities, in fact allows to contain the costs of the energy systems, either in terms of investment or operation. A MILP model has been proposed for the Multiobjective optimization of a Distributed Generation Energy System which provides electricity, thermal and cooling energy to a set of users.

After a brief introduction where the current economic, political and technical context is presented, the Thesis is divided in two parts: the first parts introduces the procedure proposed for the optimization of an Energy System, together with the definition of the MILP optimization model. The second part focus on a specific application case, showing the preliminary operations required for the application of the model and the results obtained from the optimizations performed. The results have been interpreted trying to reach a more general conclusion which is not related only to the specific case study.

The Distributed Generation Energy System considered for the definition of the optimization procedure includes several production units located close to the users, a central unit and the District Heating and Cooling Network which can connect all the users to each other and to the central unit. Thus, each user can remain isolated from the others satisfying its needs by means of an autonomous production unit. Alternatively it can be connected to the others through the District Heating and Cooling network. In this case, it can produce its needs and feed other users, or can only receive energy from the network without any "internal" production, or both. When the District Heating and Cooling Network is included in the superstructure (a theoretical structure which embeds all possible components and interconnections of the optimal system), the synthesis-design and operation problems cannot be solved separately. For isolated systems, where the energy required by the user is produced locally, the design of the energy system can be obtained considering the maximum energy required and eventually, the average load required, without the needing of defining the optimal operation. As Distributed Generation Energy Systems embed the district heating and cooling network, the optimal synthesis-design and operation cannot be obtained separately because the energy to be produced by each production site is not known in advance, as the flows through the District Heating and Cooling Network are not defined. So that, a model for the simultaneous definition of the optimal synthesis, design and operation definition has been proposed. Various tools and methodologies can be found in literature for the optimization of energy systems located close to the users or for the optimization of District Heating Network, but a tool which allows the integrated optimization of Distributed Generation Energy System, similar to the one proposed in this Thesis, has not been developed yet.

The concept at the base of the model is that each production unit, including the central one, can contain all possible technologies which can compete to achieving the optimal solution. The model includes several typical components (boilers, compression chillers, cogenerators, heat pumps, absorption machines, photovoltaic panels and solar thermal panels) showing how they can be represented inside the model. Furthermore the superstructure includes also thermal storages. However, the model can be integrated with other components (e.g. fuel cells, biomass boilers, biomass cogenerators, etc.) incrementing the model complexity and the time required for each optimization.

From the economic side, the total annual cost for owning, operating and maintaining the whole system has been used as objective function. From the environmental side, the total annual CO_2 emissions has been used as objective function. From the environmental point of view more than one aspect should be considered, for example other pollutant emissions could have been taken into account: SO_2, CO and NO_x emissions, total life cycle emissions, etc. However, the minimization of these types of pollutant emissions can be obtained only optimizing each single component and not through the simple optimization of the energy system configuration. For what concern the life cycle analysis, the impact of the pollutant emissions due to the realization of physical components in the equivalent total annual emissions is negligible. For these reasons only CO_2 emissions are taken into consideration as environmental objective function, furthermore the minimization of the greenhouse emissions correspond to the minimization of the primary energy consumption, which is one of the most important goals of the 20-20-20 targets.

The case study refers to a set of tertiary sector users located in the North-east of Italy. The heterogeneous choice of users (hospital, schools, theater, town hall, swimming pool, etc.) with different kinds of energy demand patterns allows to consider the achieved results not affected by a specific user profile, so that the results are not valid only for the specific case study, but can be extended to other similar cases, which can be easily recognized in other small-medium towns of Europe. The whole year has been subdivided into 24 typical days composed by 24 hours each. 12 typical days refer to working days, while the remaining 12 refer to non-working days, so that each month is represented by one working and one non-working day. The components adopted in the case study are all commercially available. Their prices and performances have been obtained through a market survey. The prices and greenhouse electricity carbon intensity in Italy in 2010 have been considered for the electricity and natural gas.

The model has been optimized starting from different superstructures: from the most simple superstructure where only the traditional components were included, to the most complex superstructure where all components where included. This allows to understand how the different components added step by step affect the optimal solution. For the cases where the District Heating and Cooling network were included, the Pareto Frontier has been obtained in order to identify the best compromise between the best economic solution and the most environmentally friendly.

The first optimization has been conduced for the conventional case, where the electricity is bought from the grid, the thermal energy required is produced by boilers and the cooling energy by electrical driven compression chillers. The total annual cost turned out to be 2,622 k€/y while the total annual emissions resulted 6,497 tons/y. The results of this optimization have been taken as reference for the results obtained in the other optimizations.

The best solution either from economic or environmental point of view can be achieved with the Complete Distributed Generation Solution which includes various kind of energy components, the District Heating and Cooling network, a solar field and a seasonal thermal storage. The best economic solution allows a 43% reduction of the total annual cost with respect to the conventional solution, while the best environmental solution allows about a 50% reduction of the total annual emissions. This result can be achieved only with the optimal adoption of the components and the optimal operation of the energy system.

A total annual cost similar to the one obtained for the Complete Distributed Generation Solution can be obtained also with the Isolated Solution, where the District Heating and Cooling Network is not included. It allows a 37% reduction of the total annual cost with respect to the conventional solution, with an investment cost which is a sixth compared to the investment cost of the Complete Distributed Generation Solution. In a long time view (over 20 years) the Complete Distributed Generation Solution is more convenient and allows also a greater reduction of the total annual emissions, but from a pure economic point of view, the Isolated Solution is more attractive, as the financial exposure is dramatically lower and consequently leads to a lower risk.

Even if from the economical point of view good results can be obtained also with the Isolated Solutions, important reductions of the total annual emissions can be obtained only with the adoption of the solar field, of the seasonal storage and of the district heating network.

Further optimizations have been performed without the District Cooling network and it turns out that the it does not affect the total annual annual cost of the optimal solution, as the Pareto Fronts are almost overlapped. The adoption of the solar field together with the seasonal storage allows a significant improvement of the total annual emissions, while they do not affect the total annual cost as the grater investment costs are compensated by a reduction of the operation costs.

The optimal operations show that the central thermal storage is operated with seasonal charging/discharging cycles only when the environmental objective function is considered in the optimizations. The heat produced by the solar field during wormer months is used during the first colder months. Pure economic optimizations provides a weekly operation of the central thermal storage: the heat produced by the solar field during week-end when the energy demand is lower, is used during the following working days.

The influence of the greenhouse emission cost has been also investigated and it results that, from the pure economic point of view, the emission trading system does not affect the optimal economic solution, if the emission cost is lower than about 300 €/ton. This means that there are other activities or systems where the investment in more environmentally friendly technologies is more convenient.

Multiobjective optimization technique allows the determination of the pure economic and environmental solutions and in addition gives the possibility to obtain also compromise solutions which try to minimize at the same time the different objective functions.

Distributed Generation Energy System are increasing in importance as permit substantial reduction of energy bills, primary energy consumption and greenhouse emissions, especially in domestic energy systems. However, good results can be obtained only if an optimal system is adopted and this is possible only optimizing simultaneously the synthesis, design and operation of the whole system. The proposed methodology is very flexible, and besides allowing the optimization of the systems, can be also used to perform sensitivity analysis varying investment and energy costs, greenhouse emissions and to see the effect of different incentive policies on the optimal solution.

The proposed methodology and model, despite being reliable and flexible, have some limitations which should be solved for helping its large scale application. The main limit is the number of sites/users which can be dealt with by the model. In fact, as the number of users increases, the number of decision variables increases as well and long computational times are required for the optimization. This limits the number of users which can be considered in the optimization.

Even if the computing resources are getting more available and powerful, accordin to the Moore's law [87] which claims that the processor performances double each 18 months, there will be always a limit. Another possible solution to overcome this issue is the problem decomposition. Further research is required for the development and application of decomposition methodology to the specific case.

When the issue of the maximum number of users which can be considered in the optimization is solved, the model will be able to define energy policies and strategies of small and large town, regions and even whole countries.

A

Optimization model

```
model phd_model
uses "mmxprs"; !gain access to the Xpress-Optimizer solver

!optional parameters section
parameters
intro="econ_rete_caldo"! solo pompa di calore, utenze isolate")
!parametri accumulo
!dispersioni
disp=0.98
disp_c=0.995
!dimensione massima
Sst_max=4000
Sst_c_max=400000

!parametri rete
Smin=40
Smax=2100

!parametri rete centralizzata
Smin_c=1000
Smax_c=7500

!lunghezza ramo rete centralizzata
l_c=300

!rendimento boiler e chiller meccanico
etaboi=0.95
COPcc=3

!costi energetici
cgas_chp=0.045
cgas_boi=0.06
```

```
cfue_ice=0.045
cfue_boi=0.06
cel_bgt=0.17
rel_sel=0.1
romn=0.199
rout=0.117

!costi di manutenzione
mmgt=0.002
mice=0.01
mice_c=0.01
mboi=0.001
mboi_c=0.001
mhp=0.001
mcc=0.002
mabs=0.001
mpv=0
mst=0

!costi di investimento
!Costi investimento ICE centralizzato
Cice_v=670
Cice_f=230000
!costi di investimento ICE
Cice200=165000
Cice140=125000
Cice70=70000
Cice50=60000
!costi di investimento MGT
Cmgt200=230000
Cmgt100=140000
Cmgt65=100000
Cmgt30=50000
!costi di investimento HP
Chp35=20500
Chp70=36000
Chp105=52500
!costi di investimento ABS
Cabs35=21000
Cabs70=40600
Cabs105=60000
!Costi investimento BOI centralizzato
Cboi_v=110
Cboi_f=195000
!altri costi di investimento
```

```
Ci_boi=70
Ci_cc=230
Ci_st=4.5
Ci_st_c=1.75
Ci_pv=2000
Ci_stp=400
Ci_stp_c=100
!Costi rete
Cvar=0.1676
Cnet=215.38
Cfix=110
Cvar_c=0.03
Cfix_c=470

!anni di ammortamento
n_mgt=15
n_ice=15
n_boi=10
n_cc=10
n_hp=15
n_abs=15
n_stp=20
n_pv=20
n_st=20
n_net=30
!indice di interesse
int=0.05

!emissioni di CO2
ci_el=0.356
ci_gas=0.202
ci_ice=0.202
ci_boi=0.202

!parametri cogeneratore centralizzato
kh_c = 1.175
kf_c = 2.646
Eice_c_lim = 0.2

!parametri boiler centralizzato
Fb_c = 0.955
Fboi_c_lim = 0.1

end-parameters
```

```
!declarations section
declarations

!index
mont=1..12 !mesi
sett=1..4     !settimane
days=1..2   !giorni
hour=1..24 !ore
comp=1..6   !components
unit=1..9   !units
ripe=range

!decision variables
Xice_c,Xboi_c: mpvar
Xmgt,Xice:    array(comp,unit) of mpvar
Xabs,Xhp:     array(comp,unit) of mpvar
Sice_c,Sboi_c: mpvar
Sstp_c:     mpvar
Sstp,Spv:     array(unit) of mpvar
Shst_c:      mpvar
Shst,Scst:    array(unit) of mpvar
Sboi,Scc:      array(unit) of mpvar
Oboi_c:      array(mont,days,hour) of mpvar
Omgt,Oice:    array(mont,days,hour,comp,unit) of mpvar
Oabs,Ohhp,Ochp: array(mont,days,hour,comp,unit) of mpvar
Eice_c:      array(mont,days,hour) of mpvar
Emgt,Eice:     array(mont,days,hour,comp,unit) of mpvar
Esel,Espv:    array(mont,days,hour,unit) of mpvar
Hboi_c:      array(mont,days,hour) of mpvar
Hboi:       array(mont,days,hour,unit) of mpvar
Ebgt:       array(mont,days,hour,unit) of mpvar
Hsto_c:      array(mont,days,hour) of mpvar
Hsto,Csto:     array(mont,days,hour,unit) of mpvar
Qhst_c:      array(mont,sett,days,range,hour) of mpvar
Qhst,Qcst:    array(mont,sett,days,range,hour,unit) of mpvar
Cabs:           array(mont,days,hour,comp,unit) of mpvar
Ehhp,Echp:    array(mont,days,hour,comp,unit) of mpvar
Ccc:        array(mont,days,hour,unit) of mpvar
cal_c:      array(mont,days,hour) of mpvar
prov:        dynamic array(real) of mpvar
rc_c:        mpvar
rc,rt,rn:      array(unit,unit) of mpvar
Qt,Qc:      array(mont,days,hour,unit,unit) of mpvar
Sn:        mpvar
St,Sc:      array(unit,unit) of mpvar
```

```
!variabili note
Edem,Hdem,Cdem:    array(mont,days,hour,unit) of real
ST,PV:        array(mont,days,hour) of real
Sp_lim:        array(unit) of real
S_ice,S_mgt:       array(unit) of real
S_abs:         array(unit) of real
S_hp:          array(unit) of real
Kf_mgt,Kh_mgt,MGTlim: array(mont,days,hour,unit,1..2) of real
Khp:          array(mont,days,hour,unit,1..4) of real
HPlim:        array(mont,days,hour,unit,1..2) of real
Ha,ABSlim:      array(mont,days,hour,unit,1..2) of real
Kpv,Kst:        array(mont,days,hour) of real
Ci_mgt,Ci_ice:    array(unit) of real
Ci_abs,Ci_hp:      array(unit) of real
Ci_inst:       array(comp) of real
Kh_ice,Kf_ice:     array(unit,1..2) of real
ICElim:        array(unit,1..2) of real
rep:          array(days) of integer
l,Be:          array(unit,unit) of real
Sice_c_lim,Sboi_c_lim:  array(1..2) of real

end-declarations

setparam('XPRS_MIPRELSTOP',0.002)

!richiamo file esterni
initializations from "Edem.dat"
Edem
end-initializations

initializations from "Hdem.dat"
Hdem
end-initializations

initializations from "Cdem.dat"
Cdem
end-initializations

initializations from "MGT.dat"
Kf_mgt Kh_mgt MGTlim
end-initializations

initializations from "ICE.dat"
Kf_ice Kh_ice ICElim
```

```
end-initializations

initializations from "HP.dat"
Khp HPlim
end-initializations

initializations from "ABS.dat"
Ha ABSlim
end-initializations

initializations from "PAN.dat"
Kpv Kst
end-initializations

!Taglie massime componenti]
Sice_c_lim::[1000, 6500]
Sboi_c_lim::[1000, 7500]
Sp_lim::[200,200,200,200,200,200,200,200,200]
S_mgt::[65,100,30,30,30,30,200,65,100]
S_ice::[70,140,50,50,50,50,200,70,140]
S_abs::[70,105,35,35,35,35,105,70,105]
S_hp::[70,105,35,35,35,35,105,70,105]

!Costi di investimento per unit
Ci_inst::[1, 0.8, 0.75, 0.7, 0.7, 0.7]
Ci_ice::[Cice70, Cice140, Cice50, Cice50, Cice50,
Cice50, Cice200, Cice70, Cice140]
Ci_mgt::[Cmgt65, Cmgt100, Cmgt30, Cmgt30, Cmgt30,
Cmgt30, Cmgt200, Cmgt65, Cmgt100]
Ci_abs::[Cabs70, Cabs105, Cabs35, Cabs35, Cabs35,
Cabs35, Cabs105, Cabs70, Cabs105]
Ci_hp::[Chp70, Chp105, Chp35, Chp35, Chp35, Chp35,
Chp105, Chp70, Chp105]

!ripetizione giorni
rep::[5,2]

l::[   0, 450,   0,   0, 230, 200,   0,   0,   0,
 450,   0,  80,   0, 250, 260,   0,   0,   0,
   0,  80,   0, 200,   0,   0,   0,   0,   0,
   0,   0, 200,   0,   0,   0,1400,1400,   0,
     230, 250,   0,   0,   0,  30,   0,   0,   0,
 200, 260,   0,   0,  30,   0,   0,   0,   0,
   0,   0,   0,1400,   0,   0,   0,   0, 250,
   0,   0,   0,1800,   0,   0,   0,   0, 400,
```

```
   0,   0,   0,   0,   0,   0, 250, 400,   0]

Be::[   0,   1,   0,   0,   1,   1,   0,   0,   0,
    1,   0,   1,   0,   1,   1,   0,   0,   0,
    0,   1,   0,   1,   0,   0,   0,   0,   0,
    0,   0,   1,   0,   0,   0,   1,   1,   0,
        1,   1,   0,   0,   0,   1,   0,   0,   0,
    1,   1,   0,   0,   1,   0,   0,   0,   0,
    0,   0,   0,   1,   0,   0,   0,   0,   1,
    0,   0,   0,   1,   0,   0,   0,   0,   1,
    0,   0,   0,   0,   0,   0,   1,   1,   0]


!Eliminare pompa di calore
!Xice_c=0
!Xboi_c=0
!Sn=0
!Sstp_c=0
!Shst_c=0

forall(c in comp,u in unit) do
!Xhp(c,u)=0
!Xabs(c,u)=0
Xmgt(c,u)=0
!Xice(c,u)=0
end-do

forall(m in mont, d in days, h in hour, c in comp, u in unit) do
Omgt(m,d,h,c,u)=0
!Oice(m,d,h,c,u)=0
!Oabs(m,d,h,c,u)=0
!Ochp(m,d,h,c,u)=0
!Ohhp(m,d,h,c,u)=0
end-do

!forall(u in unit)do
!Sstp(u)=0
!Spv(u)=0
!end-do

forall(u in unit) do
Shst(u)=0
Scst(u)=0
end-do
```

```
!assenza rete
(!forall(j,k in unit)do
rc(j,k)=0
rt(j,k)=0
rn(j,k)=0
end-do!)

!definizione variabili binarie
Xice_c is_binary
Xboi_c is_binary
rc_c is_binary
forall (m in mont, d in days, h in hour) Oboi_c(m,d,h) is_binary
forall (c in comp, u in unit) Xmgt(c,u) is_binary
forall (c in comp, u in unit) Xice(c,u) is_binary
forall (c in comp, u in unit) Xabs(c,u) is_binary
forall (c in comp, u in unit) Xhp(c,u) is_binary
forall (m in mont, d in days, h in hour, c in comp, u in unit)
Omgt(m,d,h,c,u) is_binary
forall (m in mont, d in days, h in hour, c in comp, u in unit)
Oice(m,d,h,c,u) is_binary
forall (m in mont, d in days, h in hour, c in comp, u in unit)
Oabs(m,d,h,c,u) is_binary
forall (m in mont, d in days, h in hour, c in comp, u in unit)
Ohhp(m,d,h,c,u) is_binary
forall (m in mont, d in days, h in hour, c in comp, u in unit)
Ochp(m,d,h,c,u) is_binary
forall (m in mont, d in days, h in hour, u in unit) Hsto(m,d,h,u)
is_free
forall (m in mont, d in days, h in hour) Hsto_c(m,d,h) is_free
forall (j,k in unit) rc(j,k) is_binary
forall (j,k in unit) rt(j,k) is_binary
forall (j,k in unit) rn(j,k) is_binary



!cogeneratore centralizzato
forall (m in mont, d in days, h in hour) do

!carico termico in funzione del carico elettrico
Hice_c(m,d,h):=kh_c*Eice_c(m,d,h)
!Fuel consumato in funzione del carico elettrico
Fice_c(m,d,h):=kf_c*Eice_c(m,d,h)
!carico limitato dalla taglia
Eice_c_lim*Sice_c<=Eice_c(m,d,h)
Eice_c(m,d,h)<=Sice_c
```

```
end-do

!limite della taglia
Sice_c_lim(1)*Xice_c<=Sice_c
Sice_c<=Sice_c_lim(2)*Xice_c

!caldaia centralizzata
forall (m in mont, d in days, h in hour) do

!fuel consumato
Fboi_c(m,d,h):=Hboi_c(m,d,h)/Fb_c
!limiti di funzionamento
Fboi_c_lim*cal_c(m,d,h)<=Hboi_c(m,d,h)
Hboi_c(m,d,h)<=cal_c(m,d,h)
Sboi_c+Sboi_c_lim(2)*(Oboi_c(m,d,h)-1)<=cal_c(m,d,h)
cal_c(m,d,h)<=Sboi_c

end-do

!limiti di taglia
Sboi_c_lim(1)*Xboi_c<=Sboi_c
Sboi_c<=Sboi_c_lim(2)*Xboi_c

!produzione campo solare
forall (m in mont, d in days, h in hour) do
Hstp_c(m,d,h):=Kst(m,d,h)*Sstp_c/300
end-do

!accumulo stagionale centralizzato
forall(m in mont) do
forall(s in sett) do
forall(d in days) do
forall(r in 1..rep(d)) do
forall(h in hour) do
create(Qhst_c(m,s,d,r,h))
if(m=1 and s=1 and d=1 and r=1 and h=1)then
!prima ora dell'anno uguale ultima
Qhst_c(1,1,1,1,1)-disp_c*Qhst_c(12,4,2,2,24)=
Hsto_c(m,d,h)
elif(m>1 and s=1 and d=1 and r=1 and h=1)then
!passaggio mese
Qhst_c(m,s,d,r,h)-disp_c*Qhst_c(m-1,4,2,2,24)=
Hsto_c(m,d,h)
elif(s>1 and d=1 and r=1 and h=1)then
```

```
!passaggio settimana
Qhst_c(m,s,d,r,h)-disp_c*Qhst_c(m,s-1,2,2,24)=
Hsto_c(m,d,h)
elif(d>1 and r=1 and h=1)then
!passaggio tipo di giorno
Qhst_c(m,s,d,r,h)-disp_c*Qhst_c(m,s,d-1,rep(d-1),24)=
Hsto_c(m,d,h)
elif(r>1 and h=1)then
!passattio giorno
Qhst_c(m,s,d,r,h)-disp_c*Qhst_c(m,s,d,r-1,24)=
Hsto_c(m,d,h)
else
!ore rimanenti
Qhst_c(m,s,d,r,h)-disp_c*Qhst_c(m,s,d,r,h-1)=
Hsto_c(m,d,h)
end-if
!massima energia accumulata
Qhst_c(m,s,d,r,h)<=Shst_c
end-do
end-do
end-do
end-do
end-do

!Limite taglia accumulo
Shst_c<=Sst_c_max

!bilancio termico centrale
forall(m in mont, d in days, h in hour) do
Hnet(m,d,h):=Hice_c(m,d,h)+Hboi_c(m,d,h)+Hstp_c(m,d,h)-Hsto_c(m,d,h)
Hnet(m,d,h)<=Sn
Hnet(m,d,h)>=0
end-do

!esistenza ramo rete centralizzato
Smin_c*rc_c<=Sn
Sn<=Smax_c*rc_c

!modello MGT
forall(c in comp, u in unit|c>=2) do
!criterio assunzione turbina a gas
Xmgt(c,u)<=Xmgt(c-1,u)
end-do

forall(m in mont, d in days, h in hour, c in comp, u in unit) do
```

```
!accensione solo se esiste
Omgt(m,d,h,c,u)<=Xmgt(c,u)

!relazione calore cogenerato, energia elettrica prodotta
Hmgt(m,d,h,c,u):=Kh_mgt(m,d,h,u,1)*Emgt(m,d,h,c,u)+Kh_mgt(m,d,h,u,2)
*Omgt(m,d,h,c,u)
!relazione fuel consumato, energia elettrica prodotta
Fmgt(m,d,h,c,u):=Kf_mgt(m,d,h,u,1)*Emgt(m,d,h,c,u)+Kf_mgt(m,d,h,u,2)
*Omgt(m,d,h,c,u)

!limiti energia elettrica prodotta
Emgt(m,d,h,c,u)>=MGTlim(m,d,h,u,2)*Omgt(m,d,h,c,u)
Emgt(m,d,h,c,u)<=MGTlim(m,d,h,u,1)*Omgt(m,d,h,c,u)

end-do

!modello ICE
forall(c in comp, u in unit|c>=2) do
!criterio assunzione ICE
Xice(c,u)<=Xice(c-1,u)
end-do

forall(m in mont, d in days, h in hour, c in comp, u in unit) do
!accensione solo se esiste
Oice(m,d,h,c,u)<=Xice(c,u)

!relazione calore cogenerato, energia elettrica prodotta
Hice(m,d,h,c,u):=Kh_ice(u,1)*Eice(m,d,h,c,u)+Kh_ice(u,2)*Oice(m,d,h,c,u)
!relazione fuel consumato, energia elettrica prodotta
Fice(m,d,h,c,u):=Kf_ice(u,1)*Eice(m,d,h,c,u)+Kf_ice(u,2)*Oice(m,d,h,c,u)

!limiti energia elettrica prodotta
Eice(m,d,h,c,u)>=ICElim(u,1)*Oice(m,d,h,c,u)
Eice(m,d,h,c,u)<=ICElim(u,2)*Oice(m,d,h,c,u)

end-do

!modello STP
forall(m in mont, d in days, h in hour, u in unit) do

!calore prodotto dall'impianto
Hstp(m,d,h,u):=Kst(m,d,h)*Sstp(u)/300

end-do
```

```
!modello PV
forall(m in mont, d in days, h in hour, u in unit) do

!calore prodotto dall'impianto
Epv(m,d,h,u):=Kpv(m,d,h)*Spv(u)/300

end-do

!limite pannelli
forall(u in unit) do

8*Spv(u)+Sstp(u)<=Sp_lim(u)

end-do

!primo bilancio termico
forall(m in mont, d in days, h in hour, u in unit) do
Hext(m,d,h,u):=sum(c in comp) (Hmgt(m,d,h,c,u)+Hice(m,d,h,c,u))
+ Hboi(m,d,h,u) + Hstp(m,d,h,u) - Hsto(m,d,h,u)
Hext(m,d,h,u)>=0
end-do

!bilancio termico accumulo
forall(m in mont) do
forall(s in sett) do
forall(d in days) do
forall(r in 1..rep(d)) do
forall(h in hour, u in unit) do
create(Qhst(m,s,d,r,h,u))
if(m=1 and s=1 and d=1 and r=1 and h=1)then
!prima ora dell'anno uguale ultima
Qhst(1,1,1,1,1,u)-disp*Qhst(12,4,2,2,24,u)=Hsto(m,d,h,u)
elif(m>1 and s=1 and d=1 and r=1 and h=1)then
!passaggio mese
Qhst(m,s,d,r,h,u)-disp*Qhst(m-1,4,2,2,24,u)=Hsto(m,d,h,u)
elif(s>1 and d=1 and r=1 and h=1)then
!passaggio settimana
Qhst(m,s,d,r,h,u)-disp*Qhst(m,s-1,2,2,24,u)=Hsto(m,d,h,u)
elif(d>1 and r=1 and h=1)then
!passaggio tipo di giorno
Qhst(m,s,d,r,h,u)-disp*Qhst(m,s,d-1,rep(d-1),24,u)=Hsto(m,d,h,u)
elif(r>1 and h=1)then
!passattio giorno
Qhst(m,s,d,r,h,u)-disp*Qhst(m,s,d,r-1,24,u)=Hsto(m,d,h,u)
else
```

```
!ore rimanenti
Qhst(m,s,d,r,h,u)-disp*Qhst(m,s,d,r,h-1,u)=Hsto(m,d,h,u)
end-if
!massima energia accumulata
Qhst(m,s,d,r,h,u)<=Shst(u)
end-do
end-do
end-do
end-do
end-do

!Limite taglia accumulo
forall(u in unit) do
Shst(u)<=Sst_max
end-do

!modello boiler
forall(m in mont, d in days, h in hour, u in unit) do
Fboi(m,d,h,u):=Hboi(m,d,h,u)/etaboi
Hboi(m,d,h,u)<=Sboi(u)
end-do

!modello ABS
forall(c in comp, u in unit|c>=2) do
!criterio assunzione ABS
Xabs(c,u)<=Xabs(c-1,u)
end-do

forall(m in mont, d in days, h in hour, c in comp, u in unit) do
!funziona solo se esiste
Oabs(m,d,h,c,u)<=Xabs(c,u)
!relazione calore richiesto, energia frigo prodotta
Habs(m,d,h,c,u):=Ha(m,d,h,u,1)*Cabs(m,d,h,c,u)+Ha(m,d,h,u,2)
*Oabs(m,d,h,c,u)

!limiti energia frigorifera prodotta
Cabs(m,d,h,c,u)>=ABSlim(m,d,h,u,1)*Oabs(m,d,h,c,u)
Cabs(m,d,h,c,u)<=ABSlim(m,d,h,u,2)*Oabs(m,d,h,c,u)

end-do

forall(m in mont, d in days, h in hour, u in unit) do
!ABS funziona solo se l'energia proviene da ICE, MGT, BOI o STO
Vabs(m,d,h,u):=Hext(m,d,h,u) + Hboi(m,d,h,u) - sum(c in comp)
Habs(m,d,h,c,u)>=0
```

```
end-do

!modello HP
forall(c in comp, u in unit|c>=2) do
!criterio assunzione HP
Xhp(c,u)<=Xhp(c-1,u)
end-do

forall(m in mont, d in days, h in hour, c in comp, u in unit) do
!funziona solo se esiste
Ohhp(m,d,h,c,u)<=Xhp(c,u)
Ochp(m,d,h,c,u)<=Xhp(c,u)
!o fa caldo o fa freddo
Ohhp(m,d,h,c,u)+Ochp(m,d,h,c,u)<=1

!relazione calore, energia elettrica
Hhp(m,d,h,c,u):=Khp(m,d,h,u,1)*Ehhp(m,d,h,c,u)+Khp(m,d,h,u,2)
*Ohhp(m,d,h,c,u)
!relazione energia frigorifera, energia elettrica
Chp(m,d,h,c,u):=Khp(m,d,h,u,3)*Echp(m,d,h,c,u)+Khp(m,d,h,u,4)
*Ochp(m,d,h,c,u)

!limiti di funzionamento
Ehhp(m,d,h,c,u)>=HPlim(m,d,h,u,1)*Ohhp(m,d,h,c,u)
Ehhp(m,d,h,c,u)<=HPlim(m,d,h,u,2)*Ohhp(m,d,h,c,u)
Echp(m,d,h,c,u)>=HPlim(m,d,h,u,1)*Ochp(m,d,h,c,u)
Echp(m,d,h,c,u)<=HPlim(m,d,h,u,2)*Ochp(m,d,h,c,u)

Ehp(m,d,h,c,u):=Ehhp(m,d,h,c,u)+Echp(m,d,h,c,u)

end-do

!modello chiller
forall(m in mont, d in days, h in hour, u in unit) do
Ecc(m,d,h,u):=Ccc(m,d,h,u)/COPcc
Ccc(m,d,h,u)<=Scc(u)
end-do

!vincoli della rete
forall(j in unit, k in unit) do
!assegnazione parametri di perdita della RETE
pc(j,k):=0.08*(l(j,k)/1000)
pt(j,k):=0.05*(l(j,k)/1000)

!il ramo di RETE tra nodo j e k esiste una sola volta
```

```
rc(j,k)+rc(k,j)<=1
rc(j,k)+rt(k,j)<=1

!calcolo del parametro per il costo fisso della rete
rn(j,k)<=rc(j,k)+rt(j,k)
rn(j,k)>=rc(j,k)
rn(j,k)>=rt(j,k)

!diametro tubazione compreso entro un certo valore
Sc(j,k)>=Smin*rc(j,k)
Sc(j,k)<=Smax*rc(j,k)
St(j,k)>=Smin*rt(j,k)
St(j,k)<=Smax*rt(j,k)


end-do

!Fissare rami di rete che non possono esistere
forall(j in unit, k in unit|Be(j,k)=0) do

rc(j,k)=0
rt(j,k)=0
rn(j,k)=0

end-do

!Fissare rami di rete che non possono esistere
forall(j in unit, k in unit|Be(j,k)=2) do

rt(j,k)=1
rn(j,k)=1

end-do


forall (m in mont, d in days, h in hour, j in unit, k in unit) do

!portata massima nei rami della RETE
Qc(m,d,h,j,k) <= Sc(j,k)
Qt(m,d,h,j,k) <= St(j,k)

end-do

!bilancio termico
forall(m in mont, d in days, h in hour, u in unit|u<>8) do
```

```
Hwas(m,d,h,u):=Hext(m,d,h,u)+sum(c in comp)(Hhp(m,d,h,c,u))-
sum(c in comp)(Habs(m,d,h,c,u))-Hdem(m,d,h,u)+ sum(k in unit)
(Qt(m,d,h,k,u)*(1-pt(u,k))-Qt(m,d,h,u,k))
Hwas(m,d,h,u)>=0

end-do

forall(m in mont, d in days, h in hour, u in unit|u=8) do

Hwas(m,d,h,u):=Hext(m,d,h,u)+sum(c in comp)(Hhp(m,d,h,c,u))-
sum(c in comp)(Habs(m,d,h,c,u))-Hdem(m,d,h,u)+ sum(k in unit)
(Qt(m,d,h,k,u)*(1-pt(u,k))-Qt(m,d,h,u,k))+Hnet(m,d,h)
Hwas(m,d,h,u)>=0

end-do

!bilancio frigo
forall(m in mont, d in days, h in hour, u in unit) do

Cwas(m,d,h,u):=sum(c in comp) (Cabs(m,d,h,c,u))+Ccc(m,d,h,u) +
sum(c in comp) (Chp(m,d,h,c,u)) - Cdem(m,d,h,u) - Csto(m,d,h,u) +
sum(k in unit) (Qc(m,d,h,k,u)*(1-pc(u,k))-Qc(m,d,h,u,k))
Cwas(m,d,h,u)>=0

end-do

!bilancio frigo accumulo
forall(m in mont) do
forall(s in sett) do
forall(d in days) do
forall(r in 1..rep(d)) do
forall(h in hour, u in unit) do
create(Qcst(m,s,d,r,h,u))
if(m=1 and s=1 and d=1 and r=1 and h=1)then
!prima ora dell'anno uguale ultima
Qcst(1,1,1,1,1,u)-disp*Qcst(12,4,2,2,24,u)=Csto(m,d,h,u)
elif(s>1 and d=1 and r=1 and h=1)then
!passaggio settimana
Qcst(m,s,d,r,h,u)-disp*Qcst(m,s-1,2,2,24,u)=Csto(m,d,h,u)
elif(d>1 and r=1 and h=1)then
!passaggio tipo di giorno
Qcst(m,s,d,r,h,u)-disp*Qcst(m,s,d-1,rep(d-1),24,u)
=Csto(m,d,h,u)
elif(r>1 and h=1)then
```

```
!passattio giorno
Qcst(m,s,d,r,h,u)-disp*Qcst(m,s,d,r-1,24,u)
=Csto(m,d,h,u)
elif(h>1)then
!ore rimanenti
Qcst(m,s,d,r,h,u)-disp*Qcst(m,s,d,r,h-1,u)
=Csto(m,d,h,u)
end-if
!massima energia accumulata
Qcst(m,s,d,r,h,u)<=Scst(u)
end-do
end-do
end-do
end-do
end-do


!Limite taglia accumulo
forall(u in unit) do
Scst(u)<=Sst_max
end-do

!bilancio elettrico
forall(m in mont, d in days, h in hour, u in unit) do
!energia elettrica derivante dalla linea senza fotovoltaico
Eut(m,d,h,u):=sum(c in comp)(Emgt(m,d,h,c,u) + Eice(m,d,h,c,u))
+ Ebgt(m,d,h,u) - Esel(m,d,h,u)
Eut(m,d,h,u)>=0
!energia elettrica derivante dal fotovoltaico
Eupv(m,d,h,u):=Epv(m,d,h,u)-Espv(m,d,h,u)
Eupv(m,d,h,u)>=0
!bilancio conclusivo
Ecst(m,d,h,u):=Eut(m,d,h,u)+Eupv(m,d,h,u)-Edem(m,d,h,u)
- Ecc(m,d,h,u) - sum(c in comp)(Ehp(m,d,h,c,u)) =0

end-do

!calcolo quantit energetiche intervallo temporale
forall(m in mont, d in days, h in hour, u in unit)do
!quantit elettriche
Eice_tu(m,d,h,u):=sum(c in comp) (Eice(m,d,h,c,u))
Emgt_tu(m,d,h,u):=sum(c in comp) (Emgt(m,d,h,c,u))
Ehp_tu(m,d,h,u):=sum(c in comp) (Ehp(m,d,h,c,u))
!quantit termiche
Hice_tu(m,d,h,u):=sum(c in comp) (Hice(m,d,h,c,u))
```

```
Hmgt_tu(m,d,h,u):=sum(c in comp) (Hmgt(m,d,h,c,u))
Hhp_tu(m,d,h,u):=sum(c in comp) (Hhp(m,d,h,c,u))
Habs_tu(m,d,h,u):=sum(c in comp) (Habs(m,d,h,c,u))
!quantit frigorifere
Cabs_tu(m,d,h,u):=sum(c in comp) (Cabs(m,d,h,c,u))
Chp_tu(m,d,h,u):=sum(c in comp) (Chp(m,d,h,c,u))
!fuel
Fice_tu(m,d,h,u):=sum(c in comp) (Fice(m,d,h,c,u))
Fmgt_tu(m,d,h,u):=sum(c in comp) (Fmgt(m,d,h,c,u))
end-do

!calcolo quantita energetiche unit
forall(u in unit)do
!quantit elettriche
Eice_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Eice(m,d,h,c,u)*4*rep(d))
Emgt_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Emgt(m,d,h,c,u)*4*rep(d))
Epv_u(u):=sum(m in mont, d in days, h in hour)
(Epv(m,d,h,u)*4*rep(d))
Ebgt_u(u):=sum(m in mont, d in days, h in hour)
(Ebgt(m,d,h,u)*4*rep(d))
Esel_u(u):=sum(m in mont, d in days, h in hour)
(Esel(m,d,h,u)*4*rep(d))
Espv_u(u):=sum(m in mont, d in days, h in hour)
(Espv(m,d,h,u)*4*rep(d))
Ecc_u(u):=sum(m in mont, d in days, h in hour)
(Ecc(m,d,h,u)*4*rep(d))
Ehp_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Ehp(m,d,h,c,u)*4*rep(d))
Edem_u(u):=sum(m in mont, d in days, h in hour)
(Edem(m,d,h,u)*4*rep(d))
!quantit termiche
Hice_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Hice(m,d,h,c,u)*4*rep(d))
Hmgt_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Hmgt(m,d,h,c,u)*4*rep(d))
Hboi_u(u):=sum(m in mont, d in days, h in hour)
(Hboi(m,d,h,u)*4*rep(d))
Hhp_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Hhp(m,d,h,c,u)*4*rep(d))
Habs_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Habs(m,d,h,c,u)*4*rep(d))
Hwas_u(u):=sum(m in mont, d in days, h in hour)
(Hwas(m,d,h,u)*4*rep(d))
```

```
Hstp_u(u):=sum(m in mont, d in days, h in hour)
(Hstp(m,d,h,u)*4*rep(d))
Hdem_u(u):=sum(m in mont, d in days, h in hour)
(Hdem(m,d,h,u)*4*rep(d))
!quantit frigorifere
Cabs_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Cabs(m,d,h,c,u)*4*rep(d))
Chp_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Chp(m,d,h,c,u)*4*rep(d))
Ccc_u(u):=sum(m in mont, d in days, h in hour)
(Ccc(m,d,h,u)*4*rep(d))
Cdem_u(u):=sum(m in mont, d in days, h in hour)
(Cdem(m,d,h,u)*4*rep(d))
Cwas_u(u):=sum(m in mont, d in days, h in hour)
(Cwas(m,d,h,u)*4*rep(d))
!fuel
Fice_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Fice(m,d,h,c,u)*4*rep(d))
Fmgt_u(u):=sum(m in mont, d in days, h in hour, c in comp)
(Fmgt(m,d,h,c,u)*4*rep(d))
Fboi_u(u):=sum(m in mont, d in days, h in hour)
(Fboi(m,d,h,u)*4*rep(d))
end-do

!calcolo quantit energetiche intervallo temporale unit centralizzata

!quantit energetiche
Eice_c_t:=sum(m in mont, d in days, h in hour) (Eice_c(m,d,h)*4*rep(d))
!quantit termiche
Hice_c_t:=sum(m in mont, d in days, h in hour) (Hice_c(m,d,h)*4*rep(d))
Hboi_c_t:=sum(m in mont, d in days, h in hour) (Hboi_c(m,d,h)*4*rep(d))
Hstp_c_t:=sum(m in mont, d in days, h in hour) (Hstp_c(m,d,h)*4*rep(d))
Hnet_c_t:=sum(m in mont, d in days, h in hour) (Hnet(m,d,h)*4*rep(d))
!fuel
Fice_c_t:=sum(m in mont, d in days, h in hour) (Fice_c(m,d,h)*4*rep(d))
Fboi_c_t:=sum(m in mont, d in days, h in hour) (Fboi_c(m,d,h)*4*rep(d))


!calcolo costo orario operativo
forall(m in mont, d in days, h in hour, u in unit)do
!costi acquisto gas
cope_chp_tu(m,d,h,u):=cgas_chp*sum(c in comp)(Fice(m,d,h,c,u)
+Fmgt(m,d,h,c,u))
cope_boi_tu(m,d,h,u):=cgas_boi*Fboi(m,d,h,u)
!costo energia elettrica
```

```
cope_eb_tu(m,d,h,u):=cel_bgt*Ebgt(m,d,h,u)
!ricavo energia elettrica
rope_es_tu(m,d,h,u):=rel_sel*Esel(m,d,h,u)
!ricavo produzione fotovoltaico
romn_pv_tu(m,d,h,u):=romn*Epv(m,d,h,u)
!ricavo autoconsumo
rout_pv_tu(m,d,h,u):=rout*Espv(m,d,h,u)
!costi di manutenzione
cman_mgt_tu(m,d,h,u):=mmgt*sum(c in comp) Emgt(m,d,h,c,u)
cman_ice_tu(m,d,h,u):=mice*sum(c in comp) Eice(m,d,h,c,u)
cman_abs_tu(m,d,h,u):=mabs*sum(c in comp) Cabs(m,d,h,c,u)
cman_hp_tu(m,d,h,u):=mhp*sum(c in comp) Ehp(m,d,h,c,u)
cman_boi_tu(m,d,h,u):=mboi*Hboi(m,d,h,u)
cman_cc_tu(m,d,h,u):=mcc*Ccc(m,d,h,u)
cman_pv_tu(m,d,h,u):=mpv*Epv(m,d,h,u)
cman_st_tu(m,d,h,u):=mst*Hstp(m,d,h,u)

end-do

!calcolo costo orario operativo centrale
forall(m in mont, d in days, h in hour)do
!costi acquisto gas caldaia
cope_boi_c(m,d,h):=cfue_boi*Fboi_c(m,d,h)*4*rep(d)
!costi acquisto fuel ice
cope_ice_c(m,d,h):=cfue_ice*Fice_c(m,d,h)*4*rep(d)
!ricavo vendita energia elettrica
rope_es_c(m,d,h):=rel_sel*Eice_c(m,d,h)*4*rep(d)
end-do

!costi operativi per unit
forall(u in unit)do
!costi acquisto gas
cope_chp_u(u):=sum(m in mont, d in days, h in hour)
(cope_chp_tu(m,d,h,u)*4*rep(d))
cope_boi_u(u):=sum(m in mont, d in days, h in hour)
(cope_boi_tu(m,d,h,u)*4*rep(d))
!costo energia elettrica
cope_eb_u(u):=sum(m in mont, d in days, h in hour)
(cope_eb_tu(m,d,h,u)*4*rep(d))
!ricavo energia elettrica
rope_es_u(u):=sum(m in mont, d in days, h in hour)
(rope_es_tu(m,d,h,u)*4*rep(d))
!ricavo incentivo produzione fotovoltaico
romn_pv_u(u):=sum(m in mont, d in days, h in hour)
(romn_pv_tu(m,d,h,u)*4*rep(d))
```

```
rout_pv_u(u):=sum(m in mont, d in days, h in hour)
(rout_pv_tu(m,d,h,u)*4*rep(d))
!costo operativo unit
cope_u(u):=cope_chp_u(u)+cope_boi_u(u)+cope_eb_u(u)
-rope_es_u(u)-rout_pv_u(u)-romn_pv_u(u)
!costi di manutenzione
cman_mgt_u(u):=sum(m in mont, d in days, h in hour)
(cman_mgt_tu(m,d,h,u)*4*rep(d))
cman_ice_u(u):=sum(m in mont, d in days, h in hour)
(cman_ice_tu(m,d,h,u)*4*rep(d))
cman_abs_u(u):=sum(m in mont, d in days, h in hour)
(cman_abs_tu(m,d,h,u)*4*rep(d))
cman_hp_u(u):=sum(m in mont, d in days, h in hour)
(cman_hp_tu(m,d,h,u)*4*rep(d))
cman_boi_u(u):=sum(m in mont, d in days, h in hour)
(cman_boi_tu(m,d,h,u)*4*rep(d))
cman_cc_u(u):=sum(m in mont, d in days, h in hour)
(cman_cc_tu(m,d,h,u)*4*rep(d))
cman_pv_u(u):=sum(m in mont, d in days, h in hour)
(cman_pv_tu(m,d,h,u)*4*rep(d))
cman_st_u(u):=sum(m in mont, d in days, h in hour)
(cman_st_tu(m,d,h,u)*4*rep(d))
cman_u(u):=cman_mgt_u(u)+cman_ice_u(u)+cman_abs_u(u)
+cman_hp_u(u)+cman_boi_u(u)+cman_cc_u(u)+cman_pv_u(u)+cman_st_u(u)
!emissioni per unit
em_el_u(u):=ci_el*(Ebgt_u(u))
em_sel_u(u):=ci_el*(Esel_u(u)+Espv_u(u))
em_gas_u(u):=ci_gas*(Fice_u(u)+Fmgt_u(u)+Fboi_u(u))
em_u(u):=em_el_u(u)+em_gas_u(u)-em_sel_u(u)
end-do

!emissioni centrale
em_sel_c:=ci_el*Eice_c_t
em_ice_c:=ci_ice*Fice_c_t
em_boi_c:=ci_boi*Fboi_c_t
em_tot_c:=em_ice_c + em_boi_c - em_sel_c

!costi operativi centrale
cope_boi_c_t:=sum(m in mont, d in days, h in hour)
(cope_boi_c(m,d,h)*4*rep(d))
cope_ice_c_t:=sum(m in mont, d in days, h in hour)
(cope_ice_c(m,d,h)*4*rep(d))
rope_es_c_t:=sum(m in mont, d in days, h in hour)
(rope_es_c(m,d,h)*4*rep(d))
cope_c:=cope_boi_c_t+cope_ice_c_t-rope_es_c_t
```

```
cman_boi_c:=mboi_c*Hboi_c_t
cman_ice_c:=mice_c*Eice_c_t
cman_c:=cman_boi_c+cman_ice_c

!fattori di ammortamento
f_mgt:=(int*(1+int)^n_mgt)/((1+int)^(n_mgt)-1)
f_ice:=(int*(1+int)^n_ice)/((1+int)^(n_ice)-1)
f_abs:=(int*(1+int)^n_abs)/((1+int)^(n_abs)-1)
f_boi:=(int*(1+int)^n_boi)/((1+int)^(n_boi)-1)
f_cc:=(int*(1+int)^n_cc)/((1+int)^(n_cc)-1)
f_hp:=(int*(1+int)^n_hp)/((1+int)^(n_hp)-1)
f_pv:=(int*(1+int)^n_pv)/((1+int)^(n_pv)-1)
f_stp:=(int*(1+int)^n_stp)/((1+int)^(n_stp)-1)
f_st:=(int*(1+int)^n_st)/((1+int)^(n_st)-1)
f_net:=(int*(1+int)^n_net)/((1+int)^(n_net)-1)

!costi di investimento annuo unit
forall(u in unit)do
cinv_mgt_u(u):=f_mgt*sum(c in comp) (Xmgt(c,u)*Ci_mgt(u)*Ci_inst(c))
cinv_ice_u(u):=f_ice*sum(c in comp) (Xice(c,u)*Ci_ice(u)*Ci_inst(c))
cinv_abs_u(u):=f_abs*sum(c in comp) (Xabs(c,u)*Ci_abs(u)*Ci_inst(c))
cinv_boi_u(u):=f_boi*Sboi(u)*Ci_boi
cinv_cc_u(u):=f_cc*Scc(u)*Ci_cc
cinv_hp_u(u):=f_hp*sum(c in comp) (Xhp(c,u)*Ci_hp(u)*Ci_inst(c))
cinv_pv_u(u):=f_pv*Spv(u)*Ci_pv
cinv_stp_u(u):=f_stp*Sstp(u)*Ci_stp
cinv_shst_u(u):=f_st*Shst(u)*Ci_st
cinv_scst_u(u):=f_st*Scst(u)*Ci_st
!costo di investimento per unit
cinv_u(u):=cinv_scst_u(u)+cinv_shst_u(u)+cinv_stp_u(u)
+cinv_pv_u(u)+cinv_mgt_u(u)+cinv_ice_u(u)+cinv_abs_u(u)
+cinv_boi_u(u)+cinv_cc_u(u)+cinv_hp_u(u)
!costo annuo unit
cann_u(u):=cinv_u(u)+cope_u(u)+cman_u(u)
end-do

!costi di investimento centrale
inv_ice_c:=Cice_v*Sice_c+Cice_f*Xice_c
inv_boi_c:=Cboi_v*Sboi_c+Cboi_f*Xboi_c
inv_stp_c:=Ci_stp_c*Sstp_c
inv_sto_c:=Ci_st_c*Shst_c
inv_net_c:=l_c*(Sn*Cvar_c+rc_c*Cfix_c)

inv_c:=inv_ice_c+inv_boi_c+inv_stp_c+inv_sto_c
```

```
!costi di investmento annuo centrale
inv_ice_c_a:=inv_ice_c*f_ice
inv_boi_c_a:=inv_boi_c*f_boi
inv_stp_c_a:=inv_stp_c*f_stp
inv_sto_c_a:=inv_sto_c*f_net
inv_net_c_a:=inv_net_c*f_net

inv_c_a:=inv_ice_c_a+inv_boi_c_a+inv_stp_c_a+inv_sto_c_a

cann_c:=inv_c_a+cope_c+cman_c+inv_net_c_a

!costi di investimento totale
forall(u in unit)do
inv_mgt_u(u):=sum(c in comp) (Xmgt(c,u)*Ci_mgt(u)*Ci_inst(c))
inv_ice_u(u):=sum(c in comp) (Xice(c,u)*Ci_ice(u)*Ci_inst(c))
inv_abs_u(u):=sum(c in comp) (Xabs(c,u)*Ci_abs(u)*Ci_inst(c))
inv_boi_u(u):=Sboi(u)*Ci_boi
inv_cc_u(u):=Scc(u)*Ci_cc
inv_hp_u(u):=sum(c in comp) (Xhp(c,u)*Ci_hp(u)*Ci_inst(c))
inv_pv_u(u):=Spv(u)*Ci_pv
inv_stp_u(u):=Sstp(u)*Ci_stp
inv_shst_u(u):=Shst(u)*Ci_st
inv_scst_u(u):=Scst(u)*Ci_st
!costo di investimento per unit
inv_u(u):=inv_scst_u(u)+inv_shst_u(u)+inv_stp_u(u)+inv_pv_u(u)
+inv_mgt_u(u)+inv_ice_u(u)+inv_abs_u(u)+inv_boi_u(u)
+inv_cc_u(u)+inv_hp_u(u)
end-do

!quantit energetiche totali
!bilancio elettrico
Eice_tot:=sum(u in unit) Eice_u(u)+Eice_c_t
Emgt_tot:=sum(u in unit)Emgt_u(u)
Epv_tot:=sum(u in unit)Epv_u(u)
Ebgt_tot:=sum(u in unit)Ebgt_u(u)
Esel_tot:=sum(u in unit)Esel_u(u)
Espv_tot:=sum(u in unit)Espv_u(u)
Ecc_tot:=sum(u in unit)Ecc_u(u)
Ehp_tot:=sum(u in unit)Ehp_u(u)
Edem_tot:=sum(u in unit)Edem_u(u)
!bilancio termico
Hice_tot:=sum(u in unit)Hice_u(u)+Hice_c_t
Hmgt_tot:=sum(u in unit)Hmgt_u(u)
Hboi_tot:=sum(u in unit)Hboi_u(u)+Hboi_c_t
Hhp_tot:=sum(u in unit)Hhp_u(u)
```

```
Habs_tot:=sum(u in unit)Habs_u(u)
Hwas_tot:=sum(u in unit)Hwas_u(u)
Hstp_tot:=sum(u in unit)Hstp_u(u)+Hstp_c_t
Hdem_tot:=sum(u in unit)Hdem_u(u)
!bilancio frigorifero
Cabs_tot:=sum(u in unit)Cabs_u(u)
Chp_tot:=sum(u in unit)Chp_u(u)
Ccc_tot:=sum(u in unit)Ccc_u(u)
Cdem_tot:=sum(u in unit)Cdem_u(u)
Cwas_tot:=sum(u in unit)Cwas_u(u)
!fuel
Fice_tot:=sum(u in unit)Fice_u(u)
Fmgt_tot:=sum(u in unit)Fmgt_u(u)
Fboi_tot:=sum(u in unit)Fboi_u(u)

!costo della rete
net_cost:=sum(j, k in unit |j<>k)(l(j,k)*((Sc(j,k)+St(j,k))
*Cvar+(rc(j,k)+rt(j,k))*(Cnet-Cfix)+rn(j,k)*Cfix)) + inv_net_c

!costi operativi totali
cchp_tot:=sum(u in unit) cope_chp_u(u)+cope_ice_c_t
cboi_tot:=sum(u in unit) cope_boi_u(u)+cope_boi_c_t
cbgt_tot:=sum(u in unit) cope_eb_u(u)
rsel_tot:=sum(u in unit) rope_es_u(u)+rope_es_c_t
cope_tot:=sum(u in unit) cope_u(u)+cope_c
romn_tot:=sum(u in unit) romn_pv_u(u)
rout_tot:=sum(u in unit) rout_pv_u(u)
!costi di manutenzione totali
cman_tot:=sum(u in unit) cman_u(u)+cman_c
!costi di investimento totali
cinv_tot:=sum(u in unit) cinv_u(u) + net_cost*f_net + inv_c_a
!investimento iniziale totale
inv_tot:=sum(u in unit) inv_u(u) + inv_c

!calcolo emissioni CO2
em_el_tot:=sum(u in unit) em_el_u(u)
em_sel_tot:=sum(u in unit) em_sel_u(u)+em_sel_c
em_gas_tot:=sum(u in unit) em_gas_u(u)+em_ice_c+em_boi_c

em_tot:=em_el_tot+em_gas_tot-em_sel_tot

!em_tot<=4085000

!costo totale annuo
c_ann:=cope_tot+cman_tot+cinv_tot
```

```
minimize(c_ann)

!potenza installata componenti
forall(u in unit)do
Sice(u):=sum(c in comp) (S_ice(u)*Xice(c,u))
Smgt(u):=sum(c in comp) (S_mgt(u)*Xmgt(c,u))
Sabs(u):=sum(c in comp) (S_abs(u)*Xabs(c,u))
Shp(u):=sum(c in comp) (S_hp(u)*Xhp(c,u))
end-do

forall(m in mont, d in days, h in hour, u in unit|u<>8) do

Qrict(m,d,h,u):= sum(k in unit) (Qt(m,d,h,k,u)*(1-pt(u,k)))
Qcedt(m,d,h,u):= sum(k in unit) (-Qt(m,d,h,u,k))
Qricc(m,d,h,u):= sum(k in unit) (Qc(m,d,h,k,u)*(1-pc(u,k)))
Qcedc(m,d,h,u):= sum(k in unit) (-Qc(m,d,h,u,k))

end-do

forall(m in mont, d in days, h in hour, u in unit|u=8) do

Qrict(m,d,h,u):= sum(k in unit) (Qt(m,d,h,k,u)*(1-pt(u,k)))
+Hnet(m,d,h)
Qcedt(m,d,h,u):= sum(k in unit) (-Qt(m,d,h,u,k))
Qricc(m,d,h,u):= sum(k in unit) (Qc(m,d,h,k,u)*(1-pc(u,k)))
Qcedc(m,d,h,u):= sum(k in unit) (-Qc(m,d,h,u,k))

end-do


fopen("RISULTATI.txt",F_OUTPUT)

writeln(intro)
writeln
writeln("!parametri accumulo")
writeln("!dispersioni")
writeln("disp=",disp)
writeln("disp_c=",disp_c)
writeln("!dimensione massima")
writeln("Sst_max=",Sst_max)
writeln("Sst_c_max=",Sst_c_max)
writeln
writeln("!parametri rete")
writeln("Smin=",Smin)
```

```
writeln("Smax=",Smax)
writeln
writeln("!parametri rete centralizzata")
writeln("Smin_c=",Smin_c)
writeln("Smax_c=",Smax_c)
writeln
writeln("!rendimento boiler e chiller meccanico")
writeln("etaboi=",etaboi)
writeln("COPcc=",COPcc)
writeln
writeln("!costi energetici")
writeln("cgas_chp=",cgas_chp)
writeln("cgas_boi=",cgas_boi)
writeln("cfue_ice=",cfue_ice)
writeln("cfue_boi=",cfue_boi)
writeln("cel_bgt=",cel_bgt)
writeln("rel_sel=",rel_sel)
writeln("romn=",romn)
writeln("rout=",rout)
writeln
writeln("!costi di manutenzione")
writeln("mmgt=",mmgt)
writeln("mice=",mice)
writeln("mice_c=",mice_c)
writeln("mboi=",mboi)
writeln("mboi_c=",mboi_c)
writeln("mhp=",mhp)
writeln("mcc=",mcc)
writeln("mabs=",mabs)
writeln("mpv=",mpv)
writeln("mst=",mst)
writeln
writeln("!costi di investimento")
writeln("!costi di investimento ICE centalizzato")
writeln("Cice_v=",Cice_v)
writeln("Cice_f=",Cice_f)
writeln("!costi di investimento ICE")
writeln("Cice200=",Cice200)
writeln("Cice140=",Cice140)
writeln("Cice70=",Cice70)
writeln("Cice50=",Cice50)
writeln("!costi di investimento MGT")
writeln("Cmgt200=",Cmgt200)
writeln("Cmgt100=",Cmgt100)
writeln("Cmgt65=",Cmgt65)
```

```
writeln("Cmgt30=",Cmgt30)
writeln("!costi di investimento HP")
writeln("Chp35=",Chp35)
writeln("Chp70=",Chp70)
writeln("Chp105=",Chp105)
writeln("!costi di investimento ABS")
writeln("Cabs35=",Cabs35)
writeln("Cabs70=",Cabs70)
writeln("Cabs105=",Cabs105)
writeln("!costi di investimento BOI centalizzato")
writeln("Cboi_v=",Cboi_v)
writeln("Cboi_f=",Cboi_f)
writeln("!altri costi di investimento")
writeln("Ci_boi=",Ci_boi)
writeln("Ci_cc=",Ci_cc)
writeln("Ci_st=",Ci_st)
writeln("Ci_st_c=",Ci_st_c)
writeln("Ci_pv=",Ci_pv)
writeln("Ci_stp=",Ci_stp)
writeln("Ci_stp_c=",Ci_stp_c)
writeln("Cvar=",Cvar)
writeln("Cnet=",Cnet)
writeln("Cfix=",Cfix)
writeln("Cvar_c=",Cvar_c)
writeln("Cfix_c=",Cfix_c)
writeln
writeln("!anni di ammortamento")
writeln("n_mgt=",n_mgt)
writeln("n_ice=",n_ice)
writeln("n_boi=",n_boi)
writeln("n_cc=",n_cc)
writeln("n_hp=",n_hp)
writeln("n_abs=",n_abs)
writeln("n_stp=",n_stp)
writeln("n_pv=",n_pv)
writeln("n_st=",n_st)
writeln("n_net=",n_net)
writeln("!indice di interesse")
writeln("int=",int)
writeln
writeln("!emissioni di CO2")
writeln("ci_el=",ci_el)
writeln("ci_gas=",ci_gas)
writeln("ci_boi=",ci_boi)
writeln("ci_ice=",ci_ice)
```

```
writeln
writeln("!parametri cogeneratore centralizzato")
writeln("kh_c=",kh_c)
writeln("kf_c=",kf_c)
writeln("Eice_c_lim=",Eice_c_lim)
writeln
writeln("!parametri boiler centralizzato")
writeln("Fb_c=",Fb_c)
writeln("Fboi_c_lim=",Fboi_c_lim)
writeln
writeln("Configurazione ottima")
writeln
writeln("Rete caldo")
writeln("Rete caldo centrale:",strfmt(getsol(Sn),6,0))
writeln
writeln("Da/a  1    2    3    4    5    6    7    8    9")
forall(j in unit) do
writeln(" ",j,strfmt(getsol(St(j,1)),5,0),strfmt(getsol(St(j,2)),5,0)
,strfmt(getsol(St(j,3)),5,0),strfmt(getsol(St(j,4)),5,0),strfmt
(getsol(St(j,5)),5,0),strfmt(getsol(St(j,6)),5,0),strfmt(getsol
(St(j,7)),5,0),strfmt(getsol(St(j,8)),5,0),strfmt(getsol(St(j,9))
,5,0))
end-do
writeln
writeln("Rete freddo")
writeln
writeln("Da/a  1    2    3    4    5    6    7    8    9")
forall(j in unit) do
writeln(" ",j,strfmt(getsol(Sc(j,1)),5,0),strfmt(getsol(Sc(j,2)),5,0)
,strfmt(getsol(Sc(j,3)),5,0),strfmt(getsol(Sc(j,4)),5,0),strfmt
(getsol(Sc(j,5)),5,0),strfmt(getsol(Sc(j,6)),5,0),strfmt(getsol
(Sc(j,7)),5,0),strfmt(getsol(Sc(j,8)),5,0),strfmt(getsol(Sc(j,9))
,5,0))
end-do
writeln
writeln("Unit centrale")
writeln("    ICE       BOI        ST       HST")
writeln(strfmt(getsol(Sice_c),7,0),strfmt(getsol(Sboi_c),10,0),strfmt
(getsol(Sstp_c),10,0),strfmt(getsol(Shst_c),10,0))
writeln
writeln("Unit di produzione")
writeln
writeln("un  ICE  MGT  BOI  ABS   HP   CC   PV   ST  HST  CST")
forall(u in unit)do
writeln(strfmt(u,2,0),strfmt(getsol(Sice(u)),5,0),strfmt(getsol
```

```
(Smgt(u)),5,0)
,strfmt(getsol(Sboi(u)),5,0),strfmt(getsol(Sabs(u)),5,0),strfmt(getsol
(Shp(u)),5,0),strfmt(getsol(Scc(u)),5,0),strfmt(getsol(Spv(u)),5,0),
strfmt(getsol(Sstp(u)),5,0),strfmt(getsol(Shst(u)),5,0),strfmt(getsol
(Scst(u)),5,0))
end-do
writeln
writeln("------------------------Costi ed emissioni-------------")
writeln
writeln("----------------------------Generale-------------------")
writeln
writeln("Costo totale annuo                                ",
strfmt(getsol(c_ann),10,0))
writeln
writeln("Costo gas cogeneratori:                           ",
strfmt(getsol(cchp_tot),10,0))
writeln("Costo gas boiler:                                 ",
strfmt(getsol(cboi_tot),10,0))
writeln("Costo energia elettrica acquistata:               ",
strfmt(getsol(cbgt_tot),10,0))
writeln("Ricavo energia elettrica venduta:                 ",
strfmt(getsol(rsel_tot),10,0))
writeln("Ricavo PV omnicomprensivo:                        ",
strfmt(getsol(romn_tot),10,0))
writeln("Ricavo autoconsumo:                               ",
strfmt(getsol(rout_tot),10,0))
writeln("Costo operativo annuo:                            ",
strfmt(getsol(cope_tot),10,0))
writeln("Costo manutenzione annuo:                         ",
strfmt(getsol(cman_tot),10,0))
writeln("Costo investimento annuo:                         ",
strfmt(getsol(cinv_tot),10,0))
writeln("Costo investimento componenti:                    ",
strfmt(getsol(inv_tot),10,0))
writeln("Costo investimento rete:                          ",
strfmt(getsol(net_cost),10,0))
writeln
writeln("Emissioni dovute all’ energia elettrica:          ",
strfmt(getsol(em_el_tot),10,0))
writeln("Emissioni risparmiate x vendita energia elettrica: ",
strfmt(getsol(em_sel_tot),10,0))
writeln("Emissioni dovute alla combustione di gas:         ",
strfmt(getsol(em_gas_tot),10,0))
writeln("Emissioni totali:                                 ",
strfmt(getsol(em_tot),10,0))
```

```
writeln
writeln(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>Centrale<<<<<<<<<<<<<<")
writeln
writeln("Costo totale annuo:                                ",
strfmt(getsol(cann_c),10,0))
writeln
writeln("Costo gas cogeneratore:                            ",
strfmt(getsol(cope_ice_c_t),10,0))
writeln("Costo gas boiler:                                  ",
strfmt(getsol(cope_boi_c_t),10,0))
writeln("Ricavo energia elettrica venduta:                  ",
strfmt(getsol(rope_es_c_t),10,0))
writeln("Totale costi operativi:                            ",
strfmt(getsol(cope_c),10,0))
writeln("Costi di manutenzione:                             ",
strfmt(getsol(cman_c),10,0))
writeln("Costi di investimento annuo componenti:            ",
strfmt(getsol(inv_c_a),10,0))
writeln("Costo di investimento annuo rete centrale:         ",
strfmt(getsol(inv_net_c_a),10,0))
writeln("Costo totale investimento componenti:              ",
strfmt(getsol(inv_c),10,0))
writeln("Costo totale investimento rete centrale:           ",
strfmt(getsol(inv_net_c),10,0))
writeln
writeln("Emissioni risparmiate x vendita energia elettrica: ",
strfmt(getsol(em_sel_c),10,0))
writeln("Emissioni dovute alla combustione di gas ICE:      ",
strfmt(getsol(em_ice_c),10,0))
writeln("Emissioni dovute alla combustione di gas BOI:      ",
strfmt(getsol(em_boi_c),10,0))
writeln("Emissioni totali:                                  ",
strfmt(getsol(em_tot_c),10,0))
writeln
forall(u in unit)do
writeln
writeln(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>Utenza N ",u," <<<<")
writeln
writeln("Costo totale annuo:                                ",
strfmt(getsol(cann_u(u)),10,0))
writeln
writeln("Costo gas cogeneratore:                            ",
strfmt(getsol(cope_chp_u(u)),10,0))
writeln("Costo gas boiler:                                  ",
strfmt(getsol(cope_boi_u(u)),10,0))
```

```
writeln("Costo energia elettrica acquistata:                ",
strfmt(getsol(cope_eb_u(u)),10,0))
writeln("Ricavo energia elettrica venduta:                  ",
strfmt(getsol(rope_es_u(u)),10,0))
writeln("Ricavo PV omnicomprensivo:                         ",
strfmt(getsol(romn_pv_u(u)),10,0))
writeln("Ricavo PV autoconsumo:                             ",
strfmt(getsol(rout_pv_u(u)),10,0))
writeln("Totale costi operativi:                            ",
strfmt(getsol(cope_u(u)),10,0))
writeln("Costi di manutenzione:                             ",
strfmt(getsol(cman_u(u)),10,0))
writeln("Costi di investimento annuo:                       ",
strfmt(getsol(cinv_u(u)),10,0))
writeln("Costo totale investimento:                         ",
strfmt(getsol(inv_u(u)),10,0))
writeln
writeln("Emissioni dovute all’energia elettrica:            ",
strfmt(getsol(em_el_u(u)),10,0))
writeln("Emissioni risparmiate x vendita energia elettrica: ",
strfmt(getsol(em_sel_u(u)),10,0))
writeln("Emissioni dovute alla combustione di gas:          ",
strfmt(getsol(em_gas_u(u)),10,0))
writeln("Emissioni totali:                                  ",
strfmt(getsol(em_u(u)),10,0))
end-do
writeln
writeln("-------------------------Quantit energetiche--------
------")
writeln
writeln("-------------------------------Generale----------
-------------")
writeln
writeln("Energia elettrica prodotta ICE:                    ",
strfmt(getsol(Eice_tot),10,0))
writeln("Energia elettrica prodotta MGT:                    ",
strfmt(getsol(Emgt_tot),10,0))
writeln("Energia elettrica prodotta PV:                     ",
strfmt(getsol(Epv_tot),10,0))
writeln("Energia elettrica acquistata:                      ",
strfmt(getsol(Ebgt_tot),10,0))
writeln("Energia elettrica richiesta dalle utenze:          ",
strfmt(getsol(Edem_tot),10,0))
writeln("Energia elettrica richiesta CC:                    ",
strfmt(getsol(Ecc_tot),10,0))
```

```
writeln("Energia elettrica richiesta HP:                  ",
strfmt(getsol(Ehp_tot),10,0))
writeln("Energia elettrica venduta:                       ",
strfmt(getsol(Esel_tot),10,0))
writeln("Energia elettrica immessa PV:                    ",
strfmt(getsol(Espv_tot),10,0))
writeln
writeln("Calore prodotto ICE:                             ",
strfmt(getsol(Hice_tot),10,0))
writeln("Calore prodotto MGT:                             ",
strfmt(getsol(Hmgt_tot),10,0))
writeln("Calore prodotto BOI:                             ",
strfmt(getsol(Hboi_tot),10,0))
writeln("Calore prodotto HP:                              ",
strfmt(getsol(Hhp_tot),10,0))
writeln("Calore prodotto STP:                             ",
strfmt(getsol(Hstp_tot),10,0))
writeln("Calore richiesto dalle utenze:                   ",
strfmt(getsol(Hdem_tot),10,0))
writeln("Calore richiesto ABS:                            ",
strfmt(getsol(Habs_tot),10,0))
writeln("Calore dissipato:                                ",
strfmt(getsol(Hwas_tot),10,0))
writeln
writeln("Freddo prodotto dal CC:                          ",
strfmt(getsol(Ccc_tot),10,0))
writeln("Freddo prodotto dalle ABS:                       ",
strfmt(getsol(Cabs_tot),10,0))
writeln("Freddo prodotto dalle HP:                        ",
strfmt(getsol(Chp_tot),10,0))
writeln("Freddo richiesto dalle utenze:                   ",
strfmt(getsol(Cdem_tot),10,0))
writeln("Freddo dissipato:                                ",
strfmt(getsol(Cwas_tot),10,0))
writeln
writeln("Fuel richiesto ICE:                              ",
strfmt(getsol(Fice_tot),10,0))
writeln("Fuel richiesto MGT:                              ",
strfmt(getsol(Fmgt_tot),10,0))
writeln("Fuel richiesto BOI:                              ",
strfmt(getsol(Fboi_tot),10,0))
writeln
writeln(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>Centrale<<<<<<<<<<<<<<<<<<<<<
<<<<<<<<<<<<<<<<")
writeln
```

```
writeln
writeln("Energia elettrica prodotta ICE:                    ",
strfmt(getsol(Eice_c_t),10,0))
writeln("Energia elettrica venduta:                         ",
strfmt(getsol(Eice_c_t),10,0))
writeln
writeln("Calore prodotto ICE:                               ",
strfmt(getsol(Hice_c_t),10,0))
writeln("Calore prodotto BOI:                               ",
strfmt(getsol(Hboi_c_t),10,0))
writeln("Calore prodotto STP:
(getsol(Hstp_c_t),10,0))
writeln("Calore inviato alle utenze:                        ",
strfmt(getsol(Hnet_c_t),10,0))
writeln
writeln("Fuel richiesto ICE:                                ",
strfmt(getsol(Fice_c_t),10,0))
writeln("Fuel richiesto BOI:                                ",
strfmt(getsol(Fboi_c_t),10,0))
writeln
forall(u in unit)do
writeln
writeln(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>>Utenza N ",u,"<<<<<<<<<<")
writeln
writeln
writeln("Energia elettrica prodotta ICE:                    ",
strfmt(getsol(Eice_u(u)),10,0))
writeln("Energia elettrica prodotta MGT:                    ",
s
trfmt(getsol(Emgt_u(u)),10,0))
writeln("Energia elettrica prodotta PV:                     ",
strfmt(getsol(Epv_u(u)),10,0))
writeln("Energia elettrica acquistata:                      ",
strfmt(getsol(Ebgt_u(u)),10,0))
writeln("Energia elettrica richiesta dalle utenze:          ",
strfmt(getsol(Edem_u(u)),10,0))
writeln("Energia elettrica richiesta CC:                    ",
strfmt(getsol(Ecc_u(u)),10,0))
writeln("Energia elettrica richiesta HP:                    ",
strfmt(getsol(Ehp_u(u)),10,0))
writeln("Energia elettrica venduta:                         ",
strfmt(getsol(Esel_u(u)),10,0))
writeln("Energia elettrica immessa PV:                      ",
strfmt(getsol(Espv_u(u)),10,0))
writeln
```

```
writeln("Calore prodotto ICE:                               ",
strfmt(getsol(Hice_u(u)),10,0))
writeln("Calore prodotto MGT:                               ",
strfmt(getsol(Hmgt_u(u)),10,0))
writeln("Calore prodotto BOI:                               ",
strfmt(getsol(Hboi_u(u)),10,0))
writeln("Calore prodotto HP:                                ",
strfmt(getsol(Hhp_u(u)),10,0))
writeln("Calore prodotto STP:                               ",
strfmt(getsol(Hstp_u(u)),10,0))
writeln("Calore richiesto dalle utenze:                     ",
strfmt(getsol(Hdem_u(u)),10,0))
writeln("Calore richiesto ABS:                              ",
strfmt(getsol(Habs_u(u)),10,0))
writeln("Calore dissipato:                                  ",
strfmt(getsol(Hwas_u(u)),10,0))
writeln

writeln("Freddo prodotto dal CC:                            ",
strfmt(getsol(Ccc_u(u)),10,0))
writeln("Freddo prodotto dalle ABS:                         ",
strfmt(getsol(Cabs_u(u)),10,0))
writeln("Freddo prodotto dalle HP:                          ",
strfmt(getsol(Chp_u(u)),10,0))
writeln("Freddo richiesto dalle utenze:                     ",
strfmt(getsol(Cdem_u(u)),10,0))
writeln("Freddo dissipato:                                  ",
strfmt(getsol(Cwas_u(u)),10,0))
writeln
writeln("Fuel richiesto ICE:                                ",
strfmt(getsol(Fice_u(u)),10,0))
writeln("Fuel richiesto MGT:                                ",
strfmt(getsol(Fmgt_u(u)),10,0))
writeln("Fuel richiesto BOI:                                ",
strfmt(getsol(Fboi_u(u)),10,0))
writeln
writeln("---------------------------------------------------")
end-do
writeln
fclose(F_OUTPUT)

end-model
```

B

List of Publications

In the following the publications related to the present thesis are reported:

Journal articles

- D. Buoro, M. Casisi, A. De Nardi, P. Pinamonti, M. Reini, "Multicriteria optimization of a distributed energy supply system for an industrial area", Accepted for publication in *Energy*, 2013.
- D. Buoro, M. Casisi, P. Pinamonti, M. Reini, "Optimal synthesis and operation of advanced energy supply systems for standard and domotic home", *Energy Conversion and Management*, 60:96-105, 2012;
- D. Buoro, M. Casisi, P. Pinamonti, M. Reini, "Optimization of Distributed Trigeneration Systems Integrated with Heating and Cooling Micro-grids", *Distributed generation and alternative energy journal*, 26(2):7-34, 2010;

Conference Proceedings

- D. Buoro, M. Casisi, A. De Nardi, P. Pinamonti, M. Reini,, "Ottimizzazione di un sistema di cogenerazione distribuita integrato con pannelli solari e accumulo termico a servizio di un area industriale", *The 67th Congresso Nazionale ATI*, September 11-14, 2012, Trieste, Italy.
- R. Bellina, D. Buoro, M. Casisi, P. Pinamonti, M. Reini, "Progetto ottimo di un sistema integrato con impianto trigenerativo e rete di teleriscaldamento", *The 67th Congresso Nazionale ATI*, September 11-14, 2012, Trieste, Italy;
- D. Buoro, M. Casisi, P. Pinamonti, M. Reini, P. Sartori, "Multicriteria optimization of a distributed energy supply system for an industrial area", *The 25th Internation conference on Efficiency, Cost, Optimization, Simulation and Environmental impact of Energy Systems*, June 26-29, 2012, Perugia, Italy;
- D. Buoro, A. De Nardi, P. Pinamonti, M. Reini, "Optimization of an industrial area energy supply system with distribute cogeneration and solar district heating",

ASME TurboExpo 2012, Paper n. GT2012-68988, June 11-15, 2012, Copenhagen, Denmark;

- D. Buoro, M. Casisi, A. De Nardi, P. Pinamonti, M. Reini, "Ottimizzazione multiobiettivo di sistemi distribuiti di trigenerazione", *The 66th Congresso Nazionale ATI*, September 5-9, 2011, Cosenza, Italy;
- D. Buoro, M. Casisi, P. Pinamonti, M. Reini, P. Sartori, "Optimal Synthesis and Operation of Advanced Energy Supply Systems for Standard and Domotic Home", *The 24th Internation conference on Efficiency, Cost, Optimization, Simulation and Environmental impact of Energy Systems*, July 4-7, 2011, Novi Sad, Serbia;
- M. Reini, D. Buoro, C. Covassin, A. De Nardi, P. Pinamonti, , "Optimization of a distributed trigeneration system with heating micro-grids for an industrial area", *2nd European Conference on Polygeneration*, March 30-April 1, 2011, Tarragona, Spain;
- D. Buoro, M. Reini, "Mixed Integer Linearized Exergoeconomic (MILE) method for energy system synthesis and optimization", *The 23rd Internation conference on Efficiency, Cost, Optimization, Simulation and Environmental impact of Energy Systems*, June 14-17, 2010, Lausanne, Switzerland;
- D. Buoro, M. Casisi, P. Pinamonti, M. Reini, "Optimal lay-out and operation of district heating and cooling distributed trigeneration systems", *ASME TurboExpo 2010*, Paper n. GT2010-23416, June 14-18, 2010, Glasgow, United Kingdom;

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