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ENERGY SUPPLY OPTIMIZATION IN INDUSTRIAL AREAS

THE CASE STUDY OF THE PONTE ROSSO INDUSTRIAL AREA IN SAN VITO AL TAGLIAMENTO (ITALY)

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Abstract

Secure, reliable and affordable energy supplies are fundamental to economic stability and development. However, the current trend of rising energy demand and CO_2 emissions collides to the pollution reductions that are required to prevent dangerous climate change.

The industrial sector currently accounts for more than one third of the global energy consumptions and the quota is assumed to increase in the next future. However, the reduction of CO_2 emissions is an achievable target, but it requires the development of a wide range of energy efficiency measures and low-carbon technologies. Almost the half of the final energy savings from energy efficiency improvements expected by 2035 comes from the manufacturing sector.

The thesis presents the optimization of industrial energy supply systems, designed to provide heat and electricity to a set of users. The evaluation is performed with reference to an energy system made of nine factories belonging to the Ponte Rosso Industrial Area of San Vito al Tagliamento (Italy), but it can be applied, with appropriate modifications, to other real case studies.

According to industrial stakeholders, the objective is the minimization of the total annual cost for owning, operating and maintaining the energy supply system, which is represented through a mixed integer linear programming model, specifically developed to determine the best configuration and operation of the whole structure.

Although the minimum cost is the objective of the research, environmental issues, like pollutant emissions and availability of energy resources, need to be considered too. That is reason because various low impact alternatives and renewable energies technologies are included in the problem and their benefits are evaluated: distributed generation, combine heat and power modules, photovoltaic collectors and solar district heating system.

Contents

Acronyms

BAT	Best available technology
BOI	Boiler
CCS	Carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
CS	Conventional system
DDHNS	Distributed system with district heating network
DHN	District heating network
DSDHS	Distributed solar district heating system
DS	Decentralized system
EJ	Exajoules
FiP	Feed in Premium
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne
GW	Gigawatt
h	Hour
HS	Heat storage
ICE	Internal combustion engine
IEA	International Energy Agency
K	Kelvin
kg	Kilograms
kJ	Kilojoule
kW	Kilowatt
kWh	Kilowatt hour
k€	Kilo Euro
m^2	Square meter
mbd	Million barrels a day
MILP	Mixed integer linear programming
mm	millimetre
Mt	Megatonne

Mtoe	Million tonnes of oil equivalent
MW	Megawatt
MWh	Megawatt hour
OECD	Organisation for Economic Co-operation and Development
PES	Primary energy saving
ppm	Parts per million
PB	Payback period
PV	Photovoltaic
s	second
SDH	Solar district heating
ST	Solar thermal
TOE	Tonne of oil equivalent
Ton	Tonne
TWh	Terawatt hour
Wh	Watt hour
WP	White Papers
y	Year
°C	Degree Celsius
$	Dollar
€	Euro

Nomenclature

c_inv	Investment cost [€]
c_man	Maintenance cost [€]
c_net	Cost of DHN (datum) [€]
c_ope	Operating cost [€]
c_pv	Cost coefficient of PV (datum) [€/m^2]
c_st	Cost coefficient of ST (datum) [€/m^2]
c_sto	Cost coefficient of HS (datum) [€/m^3]
c_tot	Total cost [€]
cf_boi	Fixed cost coefficient of BOI (datum) [€]
cf_cog	Fixed cost coefficient of CHP (datum) [€]
cv_boi	Variable cost coefficient of BOI (datum) [€/kWh]
cv_cog	Variable cost coefficient of CHP (datum) [€/kWh]
E_buy	Electricity purchased by user (real variable) [kWh]
E_buy_tot	Total purchased electricity [kWh]
E_cog	Electricity produced by CHP (real variable) [kWh]
E_cog_cu	Electricity produced by central unit CHP (real variable) [kWh]
E_cog_tot	Total electricity cogenerated by CHP [kWh]
E_dem	Electricity user demand (datum) [kWh]
E_pv	Electricity produced by PV field (real variable) [kWh]
E_pv_u	Electricity self-consumed from PV field (real variable) [kWh]
E_sel	Electricity sold by user (real variable) [kWh]
E_sel_cu	Electricity sold by central unit (real variable) [kWh]
E_sel_pv	Electricity sold by PV field (real variable) [kWh]
E_sel_tot	Total sold electricity [kWh]
ex_boi	Existence of BOI (binary variable)
ex_cog	Existence of CHP (binary variable)
ex_boi_cu	Existence of central unit BOI (binary variable)
ex_cog_cu	Existence of central unit CHP (binary variable)
ex_net	Existence of DHN (binary variable)
f	Amortization cost factor (datum)
f_boi	Amortization cost factor of BOI (datum)

f_cog	Amortization cost factor of CHP (datum)
f_net	Amortization cost factor of DHN (datum)
f_pv	Amortization cost factor of PV (datum)
f_st	Amortization cost factor of ST (datum)
f_sto	Amortization cost factor of HS (datum)
f_1	Coefficient of fuel consumed by CHP (variable part)
f_2	Coefficient of fuel consumed by CHP (fixed part)
F_boi	Fuel consumed by BOI (real variable) [kWh]
F_cog	Fuel consumed by CHP (real variable) [kWh]
h	Time interval
h_1	Coefficient of heat produced by CHP (variable part)
h_2	Coefficient of heat produced by CHP (fixed part)
H_boi	Heat produced by BOI (real variable) [kWh]
H_boi_cu	Heat produced by central unit BOI (real variable) [kWh]
H_boi_tot	Total heat produced by BOI [kWh]
H_cog	Heat produced by CHP (real variable) [kWh]
H_cog_cu	Heat produced by central unit CHP (real variable) [kWh]
H_dem	Heat user demand (datum) [kWh]
H_dis	Heat dissipated by user (real variable) [kWh]
H_in	Heat from DHN to user (real variable) [kWh]
H_in_sto	Heat from DHN to HS (real variable) [kWh]
H_net	Heat flow in the DHN (real variable) [kWh]
H_out	Heat from user to DHN (real variable) [kWh]
H_out_cu	Heat from central unit to DHN [kWh]
H_out_sto	Heat from HS to DHN (real variable) [kWh]
H_st	Heat produced by ST field (real variable) [kWh]
H_sto	Heat stored in the HS (real variable) [kWh]
i	Interest rate of capital (datum) [%]
I	Incentive (datum) [€/x]
k_net	Heat loss coefficient of the DHN (datum) [%]
k_sto	Heat loss coefficient of the HS (datum) [%]
m_boi	Maintenance cost coefficient of BOI (datum) [€/kWh]
m_cog	Maintenance cost coefficient of CHP (datum) [€/kWh]
n	Life span of component (datum) [year]
op_cog	Operation of CHP (binary variable)
out_cog_lim	Lower partial load limit of CHP (datum) [%]
p_buy	Price of purchased electricity (datum) [€/kWh]
p_gas_boi	Price of natural gas for BOI (datum) [€/kWh]
p_gas_cog	Price of natural gas for CHP (datum) [€/kWh]
p_sel	Price of sold electricity (datum) [€/kWh]
PB	Payback period [y]
pv	PV hourly unitary production (datum) [kWh/m^2]
S_boi	Size of BOI (integer variable) [kW]
S_boi_cu	Size of central unit BOI (integer variable) [kW]
S_cog	Size of CHP (integer variable) [kW]

S_cog_cu	Size of central unit CHP (integer variable) [kW]
S_cog_max	Upper size limit of CHP (datum) [kW]
S_pv	Size of PV field (integer variable) [kW]
S_st	Size of ST field (integer variable) [kW]
S_sto	Size of HS (integer variable) [kW]
SP	Support policy [€]
st	ST hourly unitary production (datum) [kWh/m^2]
TL	Thermal Limit [%]
u	User
η_boi	Thermal efficiency of BOI (datum)
η_{el_ref}	Electrical reference efficiency [%]
η_{th_ref}	Thermal reference efficiency [%]

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Preface

Although future energy trends are difficult to predict accurately, global energy demand is assumed to progressively increase according to expected economic and world population growth.

Over one billion people are still estimated to be without electricity in 2030, while energy availability is undoubtedly a critical factor for the development of a country.

Despite the gradual growth in low carbon sources of energy, fossil fuels, supported by six time higher subsidies than the ones to renewables, remain dominant even in the future global energy mix. Actual emissions trend corresponds to a dangerous long-term average global temperature increase of 3.6°C.

Renewable energy technologies, energy efficiency and energy supply optimization are recognised as effective ways to face those problems, matching users' needs, reducing production costs, improving energy distribution and decreasing significantly pollutant emissions at the same time.

1

Introduction

Secure, reliable and affordable energy supplies are fundamental to economic stability and development. The erosion of energy security, the threat of disruptive climate change and the growing energy needs of the developing world all pose major challenges to energy decision makers.

In recent years fossil fuel prices have been very volatile. They look set to remain at high levels compared to the past. A number of factors contribute to this trend, including rising energy demand, particularly in the developing world, and concerns over the security and availability of oil and gas supplies. Reducing fossil fuel dependency is an important energy policy target in many countries.

These energy security concerns are compounded by the increasingly urgent need to mitigate greenhouse-gas emissions, including those relating to energy production and consumption.

The current trend of rising energy demand and rising emissions runs directly counter to the major emissions reductions that are required to prevent dangerous climate change [1].

The International Energy Agency (IEA) predicts in the *World Energy Outlook 2010* [2] that the relationship between incomes and energy use will remain strong, at least for the next quarter of a century, unless the introduction of substantial technological advances or unless governments intervene to change it, through measures that lead to a shift in behaviour or in the way in which energy needs are met. For as long as the global economy and population continue to expand, then the world's overall energy needs will undoubtedly rise, in the longer term and in the absence of a catastrophic event.

Without the heat and electricity from fuel combustion, economic activity would be limited and restrained. Modern society uses more and more energy for industry, services, homes and transport. This is particularly true for oil, which has become the most traded commodity, and part of economic growth is linked to its price.

However, neither oil nor any of the other fossil fuels, such as coal and natural gas, are unlimited resources. The combined effect of growing demand and depleting resources calls for a close monitoring of the energy situation.

Other reasons for needing a profound knowledge of energy supply and demand include energy dependency, security and efficiency, as well as environmental concerns. It is precisely at a time when more and more energy is produced, traded, transformed and consumed, when energy dependency is increasing and when greenhouse gas emissions are high on the international agenda, that it becomes more and more difficult to provide a timely and reliable picture of the worldwide energy situation [3].

What matters to users of energy, whether they be businesses or individuals, is the ultimate energy-related services that they receive: mobility, heating, cooling or a mechanical process. Today, these services are often provided in ways that involve unnecessarily large amounts of energy, much of it derived from fossil fuels. The technology exists today to increase greatly the efficiency with which those services are provided and that technology, including renewable resources systems, will surely continue to improve in the future. The commercial incentives for manufacturers to make available more efficient equipment and to develop environmental friendly appliances that use renewable resources too, and the incentives for consumers to buy them, are set to increase with rising energy costs. But commercial factors alone will be not sufficient. Governments need to act to reinforce those incentives so as to encourage even faster improvements in energy efficiency, to discourage energy waste, and in renewable systems, confident in the environmental, energy-security and broader economic benefits that would follow.

Besides this technological progress, it is also fundamental that suppliers and final users develop a proper approach to the energy management, with the aim to identify the most suitable solutions, considering all aspects of the problem, from supply/purchase to disposal passing through operation and maintenance. A possible way to meet this goal is presented in the dissertation and consists in adopting an optimization of the energy system analysed. The first positive consequence is a minimum total cost of the system and the second benefit is a reduction in pollutant emissions.

1.1 Global energy trends

That energy use typically rises with incomes is incontrovertible and widely understood. As economies grow, they require more energy to fuel factories and trucks, to heat and cool buildings and to meet growing personal demand for mobility, equipment and electrical appliances. Over the last several decades, energy use has tended to rise proportionately with gross domestic product (GDP) at the global level, though the relationship is usually less than one to one: in other words, energy needs usually grow somewhat less rapidly in percentage terms than the size of the economy, because of changes in economic structure towards less energy-intensive activities and because of technological change that gradually improves the efficiency of providing energy-related services.

Figure 1.1 presents the shares of different sectors in total world consumption of energy in 2010. Data are taken from the *Energy Balances of Non-OECD Countries*, published by the IEA in 2012 [4]. Manufacturing industry is the end-use sector that globally consumed the most energy, with a 37% share. It is followed by transport (27%), residential (24%) and services (8%). Other includes the net consumption for the transformation sectors, plus energy use in agriculture, forestry and fishing.

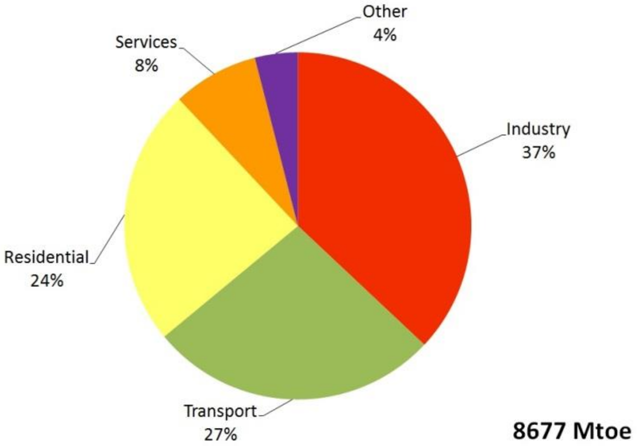


Figure 1.1 - Total energy consumption by sector in 2010

Looking at energy trends, a set of important factors need to be considered in order to evaluate future scenarios: government policies, level of economic activity, energy prices, demographic change, energy efficiency improvements and new technologies.

According to the IEA *Energy Technology Perspective 2010* [1], energy use increases in all sectors in the Baseline scenario, roughly doubles in power generation, industry, transport and buildings (Figure 1.2). The Baseline scenario follows the reference scenario to 2035 presented in [2] and assumes that: no new policies are introduced, global CO_2 emissions grow rapidly, oil and gas prices are high and energy security concerns increase as imports rise.

In this background, transportation demand increases on average by 1.6% a year between 2007 and 2050, mainly driven by continued strong population and income growth in developing countries. Energy consumption in the industrial sector grows at an average of 1.3% a year. Nearly all the growth in industrial energy consumption occurs outside the Organisation for Economic Co-operation and Development (OECD).

Energy use in the buildings sector also grows by 1.1% a year, with around 64% of this growth coming from developing countries.

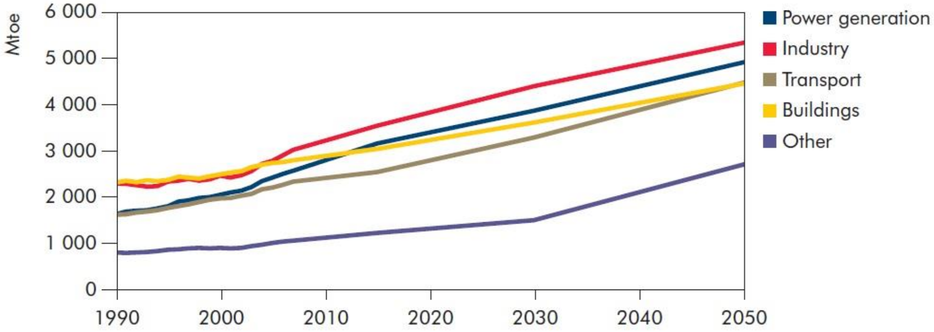


Figure 1.2 - Energy use trends by sector in the Baseline scenario [1]

Figure 1.3 presents a comparison of future energy use by sector between the following cases: 2007 values, 2030 Baseline scenario, 2050 Baseline scenario and 2050 BLUE Map scenario. The BLUE Map scenario assumes that global energy-related CO_2 emissions are reduced to 450ppm (half their 2005 levels) by 2050 and is broadly optimistic for all technologies. The scenario is consistent with a long-term global rise in temperatures limited to 2°C.

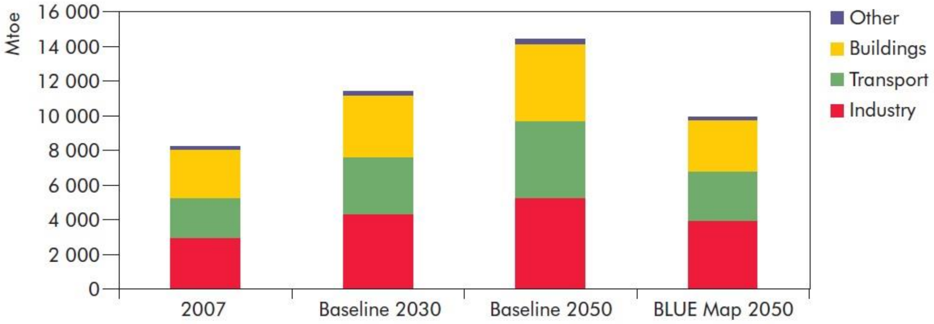


Figure 1.3 - Final energy use by sector [1]

The figure shows that, despite the savings achieved in the BLUE Map scenario, energy demand continues to grow in all end-use sectors between 2007 and 2050. The highest growth rate is in industry, followed by transport and buildings. Final energy consumption in the industry, buildings and transport sectors grows on average by 0.4% a year in the BLUE Map scenario.

Energy savings are achieved in all end-use sectors in the BLUE Map scenario compared to the Baseline scenario. As a consequence, total final energy demand is 31% lower in the BLUE Map scenario in 2050 than in the Baseline scenario.

The largest absolute reductions in energy use occur in the buildings and transport sectors. In buildings, savings of 1509Mtoe in 2050 reflect the significant technical potential to reduce space heating and cooling needs in both existing and new buildings, as well as to improve the energy efficiency of lighting, electric appliances and equipment. OECD countries account for a little less than the half of the total energy savings in buildings.

In transport, savings of 1631Mtoe in 2050 come from significant fuel efficiency improvements in conventional engines, together with a move to hybrid and then fully electric vehicles. Slightly larger savings come from developing countries than from OECD countries.

Industry contributes relatively smaller savings (1350Mtoe), reflecting the high efficiencies already achieved in a number of energy-intensive sectors and the intrinsic need for energy in many industrial processes. Around one-third of this is in OECD countries and two-thirds is in non-OECD countries.

Considering the demand by fuel source over the outlook period (Figure 1.4), fossil fuels (oil, coal and natural gas) continue to supply the bulk of global energy consumption.

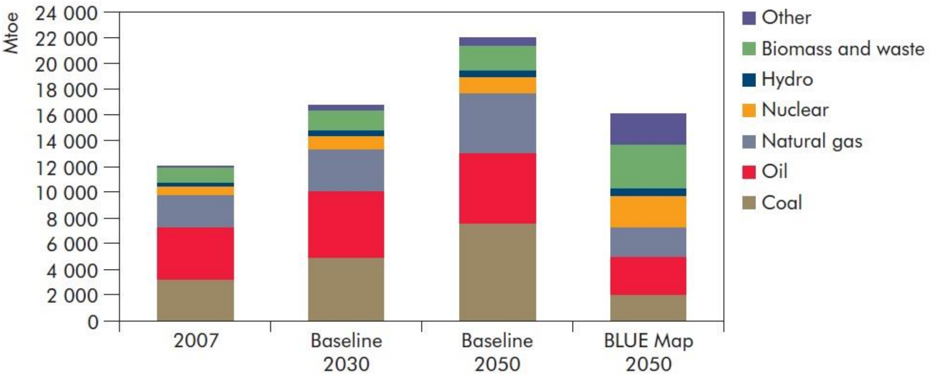


Figure 1.4 - Total primary energy supply by fuel source [1]

In the Baseline scenario, total primary energy supply grows by 1.4% on average per year, from 12020Mtoe in 2007 to 22078Mtoe in 2050. This rate of growth is less than the 2.2% a year that occurred between 1971 and 2007, but it still represents an increase of 84% in primary energy demand between 2007 and 2050. The share of fossil fuels in total demand remains fairly constant between 2007 and 2050, despite strong growth in nuclear and renewable energy in absolute terms. By 2050, coal becomes the predominant fuel and accounts for 34% of primary energy use. Oil's share declines from 34% in 2007 to 25% in 2050. The share of natural gas stays constant at 21%. Of the non-fossil fuels, nuclear share remains at 6% in 2050, while the share of renewables increases to 14%. The use of fossil fuels in 2050 is 59% lower in the BLUE Map scenario than in the Baseline scenario. In absolute terms, total demand for fossil fuels in the BLUE Map scenario in 2050 is 26% below the level of 2007. But even in the BLUE Map scenario, fossil fuels are an important contributor to the energy system. The reduction in fossil-fuel use can be attributed to energy efficiency gains and fuel switching. The use of carbon-free fuels increases much faster than total primary energy supply. The growth in biofuels, to a point where their use in 2050 in the BLUE Map scenario is similar to the level of coal use today, demonstrates just how significant a change is needed to deliver the outcomes implicit in the BLUE Map scenario.

The primary energy demand by fuel and by scenario is clearer shown in Figure 1.5. The next lines focus on the four main future fuel sources: coal, liquid fuel, natural gas and biomass.

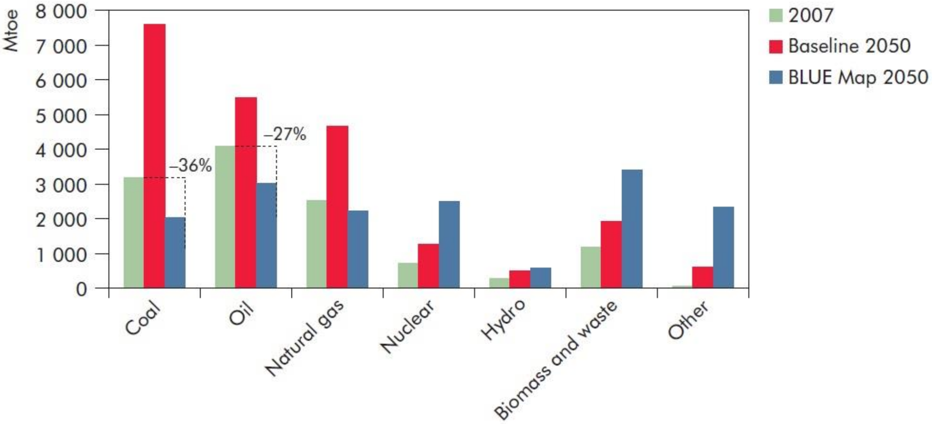


Figure 1.5 - Primary energy demand by fuel and by scenario [1]

In the Baseline scenario, coal demand in 2050 is 138% higher than in 2007. Coal's share of total demand grows from 27% in 2007 to 34% in 2050. Between 2030 and 2050, coal eclipses oil as the single most important fuel. Coal's strong growth in the Baseline scenario is driven by three factors. First, high oil prices make coal-to-liquid technologies more economical and the production of synfuels from coal increases significantly after 2030. In 2050, around 2000Mtoe of coal is being consumed by coal-to-liquid plants. Second, high gas prices result in more new coal-fired electricity generating plants being built. Third, energy-intensive industrial production grows rapidly in developing countries, especially China and India, which have large coal reserves, but limited reserves of other energy resources. In the BLUE Map scenario, coal demand in 2050 is 36% below the 2007 level, a reduction of over 70% compared to the Baseline scenario. This very significant reduction comes as a result of many sectors switching out of coal in favour of lower carbon energy sources, even with the prospect of carbon capture and storage (CCS). In percentage terms, coal use declines most in OECD countries. In non-OECD countries, coal use in the BLUE Map scenario in 2050 is 22% less than today's consumption.

Liquid fuel demand in the Baseline scenario increases by 58% between 2007 and 2050, from 4208Mtoe to 6633Mtoe. This is an increase from 85 million barrels a day (mbd) to 134mbd. Such growth is unlikely to be met by conventional oil. In the Baseline scenario there is significant growth in the production of non-conventional oil from heavy oil, oil sands, shale oil and arctic oil, to about 29mbd. These sources account for about 20% of total supply in 2050. A rising share of demand is also met by synfuels produced from coal and gas, which increase from very low levels today to 17mbd in 2050, comprising 12% of total supply. Biofuels play a limited role in the Baseline scenario, with a 5% share. Liquid fuel demand grows most rapidly in the transport sector, at 1.6% on average a year. In the buildings sector it grows by 0.4% a year and in the industrial sector by 1.0% a year. In the BLUE Map scenario, the increased use of biofuels and improvements in the average fuel efficiency of transportation vehicles mean that total liquid fuel demand is only 4045Mtoe in 2050, 39% lower than in the Baseline scenario. Oil demand in 2050 is about 23% below the 2007 level. This will make a potentially significant contribution to security of supply, although substantial oil import dependence will remain for many countries. The significant demand reductions in the BLUE Map scenario imply that there would be much less need for non-conventional oil and synfuels. Biofuels would account for 23% of supply. This has important CO_2 benefits. The reduction in oil demand in the BLUE Map scenario can be largely attributed to the transport sector. This reflects the fact that oil demand for transport rises rapidly in the Baseline scenario. The reduction in primary oil demand is less than the reduction in the demand for oil products as synfuel production is phased out in the BLUE Map scenario. In the Baseline scenario, non-OECD countries' share of primary oil demand rises from 47% in 2007 to 71% in 2050. This share only drops slightly in the BLUE Map scenario.

Primary demand for natural gas in the Baseline scenario grows by 85% between 2007 and 2050, rising from 2520Mtoe to 4653Mtoe. Global gas use by the electricity generation sector increases from 992Mtoe in 2007 to 2174Mtoe in 2050. Natural gas used in other transformation activities grows from 254Mtoe in 2007 to 432Mtoe in 2050. Most of this increase is for gas-to-liquid plants and refinery hydrogen production. Demand for natural gas in the final consumption sectors grows at 1.2% a year, with little difference between the growth in industry and that in buildings at the global level. Primary demand for natural gas in non-OECD countries increases in the Baseline scenario from 1261Mtoe in 2007 to 3071Mtoe in 2050. Non-OECD countries' share of world gas demand rises from 50% in 2007 to 66% in 2050. It rises further to 76% in the BLUE Map scenario. Almost half the growth in demand in non-OECD countries in the BLUE scenario comes from electricity generation and the remainder from end-use sectors and fuel transformation. Demand for gas in OECD countries falls from 1259Mtoe in 2007 to 526Mtoe in 2050 in the BLUE Map scenario.

Biomass is by far the most important source of renewable energy today, accounting for about 10% of total primary energy use and 78% of total renewable energy. Most biomass is currently used for traditional small-scale domestic heating and cooking. Only about 10% of biomass is used on an industrial scale for the production of electricity or fuels. The role of biomass almost triples in the BLUE Map scenario. In this scenario, bioenergy use in 2050 is slightly higher than the level of coal consumption today. This would require fundamental improvements in agriculture and forestry. About half of the primary bioenergy in the BLUE Map scenario would be used for the production of liquid biofuels. The other half would be used for power generation, heating and industrial feedstocks. In the buildings sector, the use of biomass increases by 4% in the Baseline scenario. Biomass use declines in the BLUE

Map scenario but, as it is used much more efficiently, the share of biomass in delivered energy services increases. Solar water-heating and space-heating systems increase fourfold between the Baseline and BLUE Map scenarios. In the BLUE Map scenario, the share of biomass and waste in industry increases from 6% in 2007 to 14% in 2050. Part of this is biomass for steam and process heat. Biomass feedstocks also play an increasing role.

1.2 Global CO_2 trends

Figure 1.6 shows the global CO_2 emissions by sector in 2007 and in the two future scenarios (Baseline and BLUE Map).

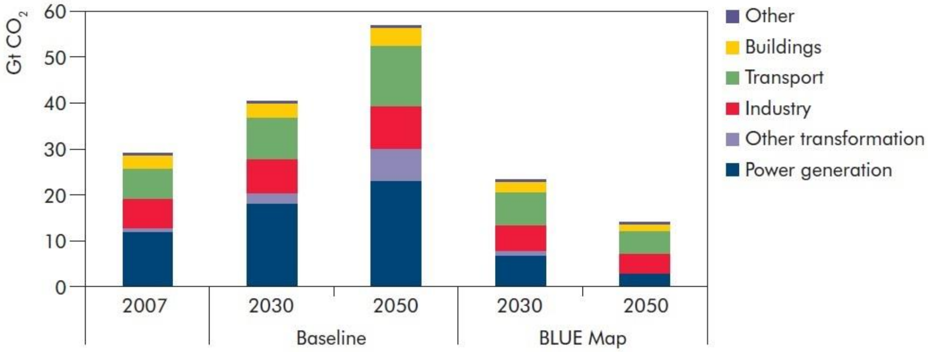


Figure 1.6 - Global CO_2 emissions by sector [1]

CO_2 emissions continue to grow in the Baseline scenario projections of the IEA, reaching 57Gt in 2050 (i.e. almost double that in 2007), an average increase of 1.6% a year for the period 2007 to 2050. Nearly all the growth in global CO_2 emissions in the Baseline scenario comes from outside the OECD. Emissions from non-OECD countries grow from 15Gt CO_2 in 2007 to 42Gt CO_2 in 2050 while OECD emissions grow only from 14Gt CO_2 to 15Gt CO_2 over the same period. In the BLUE Map scenario, CO_2 emissions in 2050 are reduced to 14Gt, around half the level emitted in 2005. This means emissions are 43Gt lower in 2050 than projected in the Baseline scenario. Achieving these CO_2 emissions reductions will require the development and deployment of a wide range of energy-efficient and low-carbon technologies across every sector of the economy. OECD countries account for just over 30% of the total global emissions reduction in 2050 in the BLUE Map scenario as compared to the Baseline scenario. The least-cost approach of the BLUE Map scenario leads to OECD countries reducing their emissions by 77% compared to 2005 levels. Non-OECD countries reduce their emissions by 24% over the period, although their emissions continue to grow up to 2020, reducing significantly only after 2030.

In the next 20 years, the power sector and all end-use sectors together need to play an equal part in the emissions reduction effort. Within the end-use sectors, energy efficiency measures need to play the biggest role in the next twenty years. Beyond 2030, the transport sector has an increasingly important role to play in reducing emissions. In the BLUE Map scenario, end-use efficiency accounts for 38% of the CO_2 emissions reduction in 2050. CCS in power generation, fuel transformation and industry accounts for 19% of the total emissions reduction. The increased use of renewable energy accounts for 17% of the total emissions reduction, while nuclear energy accounts for 6%.

The outcomes projected in the Baseline scenario are not inevitable. The BLUE scenarios show that it is possible to completely transform the energy system over the next half century using a combination of existing and new technologies, if the right decisions are taken early enough. This would enable a more secure and sustainable energy future, but would require significant investments to achieve substantial changes in both energy supply and energy demand infrastructure. Such investments would also generate significant fuel savings in buildings, transport and industry over the longer term.

1.3 Objectives of the thesis

The thesis presents the optimization of industrial energy supply systems, designed to provide heat and electricity to a set of users. The generic energy generation system is represented through a mixed integer linear programming (MILP) model, specifically developed to determine the best configuration and operation of the whole structure.

The evaluation is performed with reference to an energy system made of nine factories that belong to the Ponte Rosso Industrial Area of San Vito al Tagliamento - Italy.

According to industrial stakeholders, who make their decisions looking for the minimum cost solution, the objective of the model is the minimization of the total annual cost for owning, operating and maintaining the whole energy system.

The optimization model elaborated in the thesis can be applied to other real case studies and the obtained results are supposed to be used by energy suppliers and end-users in order to help making economic decisions and implementing proper operation control strategies.

The model is optimized considering different cases: from a traditional supply structure to a complete system that includes various non-conventional equipment and renewable energy technologies, adding one or more components at each step. This procedure makes possible to evaluate the influence of the components and machines to the optimal design and operation of the system, and to assess how the different configurations contribute to achieve the minimization of the objective function and the reduction of pollutant emissions. The model is also optimized introducing two real support schemes; the purpose is to compare the energy and cost savings achieved by implementing these incentives with the economic cost for society.

Although the minimum cost is the objective of the research, environmental issues, like greenhouse gas (GHG) effects and availability of energy resources, need to be considered too. That is reason because various low impact alternatives and renewable energies technologies are included in the problem and their benefits are evaluated: distributed generation, combine heat and power (CHP) modules, photovoltaic (PV) collectors and solar district heating (SDH) system.

Furthermore, a chapter of the thesis is dedicated to the potential benefits of energy efficiency, considering, besides other advantages, its importance as CO_2 abatement option.

1.4 Structure of the thesis

After a brief presentation of the global current and future energy and CO_2 emissions trends (chapter 1), chapter 2 describes the potential of the energy efficiency to reduce energy consumptions and to mitigate pollutions, focusing the attention on the industrial sector.

Chapter 3 introduces a methodological approach to the definition, representation and resolution of MILP optimization problems.

Chapter 4 presents in detail the optimization model of the energy supply system developed in the thesis, defining all information of the investigated problem.

Chapter 5 defines the analysed case study, specifying technical characteristics of components, users’ requirements and economic data.

Chapter 6 illustrates the results of the optimized cases, presenting the obtained system designs, the operation strategies and the economic and environmental performances.

2

Energy efficiency

Energy efficiency is widely recognised as a key opportunity to reduce energy demand, to gain economic growth and to mitigate pollution. Considering the existing policies and prudently assuming that those recently announced commitments are implemented by governments (New Policies Scenario), the IEA identifies in the *World Energy Outlook 2012* [5] the following potential benefits on global economy and climate trends coming from the adoption of energy efficiency actions:

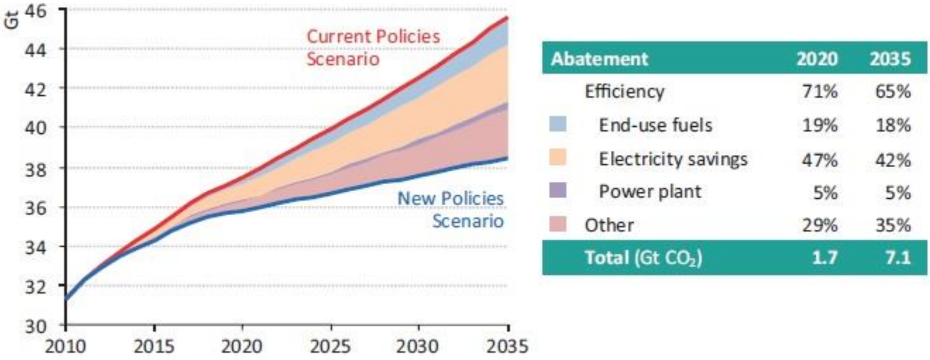
- the growth in global primary energy demand to 2035 would be halved;
- oil demand would be almost 13 million barrel/day lower by 2035, reducing import needs of energy-importing countries;
- reduced fuel expenditures would ease new discoveries and additional investments in energy-efficient technologies;
- the accrued resources would increase competitiveness, facilitate a gradual reorientation of the global economy and create million new jobs;
- universal access to modern energy would be easier to achieve and air quality improved, as emissions of local pollutants fall sharply.

Energy efficiency delivers the single largest share of energy savings in achieving the New Policies Scenario and in moving beyond it, reflecting the large amount of cost-effective potential that exists. Efficiency accounts for about 70% (1060Mtoe) of the reduction in projected global energy demand in 2035, compared with the Current Policies Scenario of the IEA. Energy demand in the New Policies Scenario still grows by

35% in the period 2010-2035, but without the implementation of the assumed efficiency measures the growth would be 43%. As a result, global energy intensity (i.e. the amount of energy used to produce a unit of GDP) declines at 1.9% per year on average over the outlined period.

In the hypothesis of the New Policies Scenario, energy efficiency represents also the largest share in CO_2 savings compared with the Current Policy Scenario: 65% of total savings and 4.6Gt reduction in 2035. The share of energy efficiency in total savings declines over time, as energy efficiency is cheaper than other abatement options and is among the first options used. Lower electricity demand from more efficient appliances, industrial motors and buildings reduces fuel input to the power sector and is the largest factor in CO_2 reduction through efficiency measures (2.9Gt of savings in 2035). Fuel savings achieved through more efficient vehicles, industrial processes and heating applications save an additional 1.3Gt of CO_2. Higher power generation efficiency accounts for an additional 0.3Gt of savings, less significant than the contribution from increased renewables (1.6Gt) or nuclear (0.4Gt).

The energy efficiency contribution in reduction of CO_2 emissions is represented in Figure 2.1.



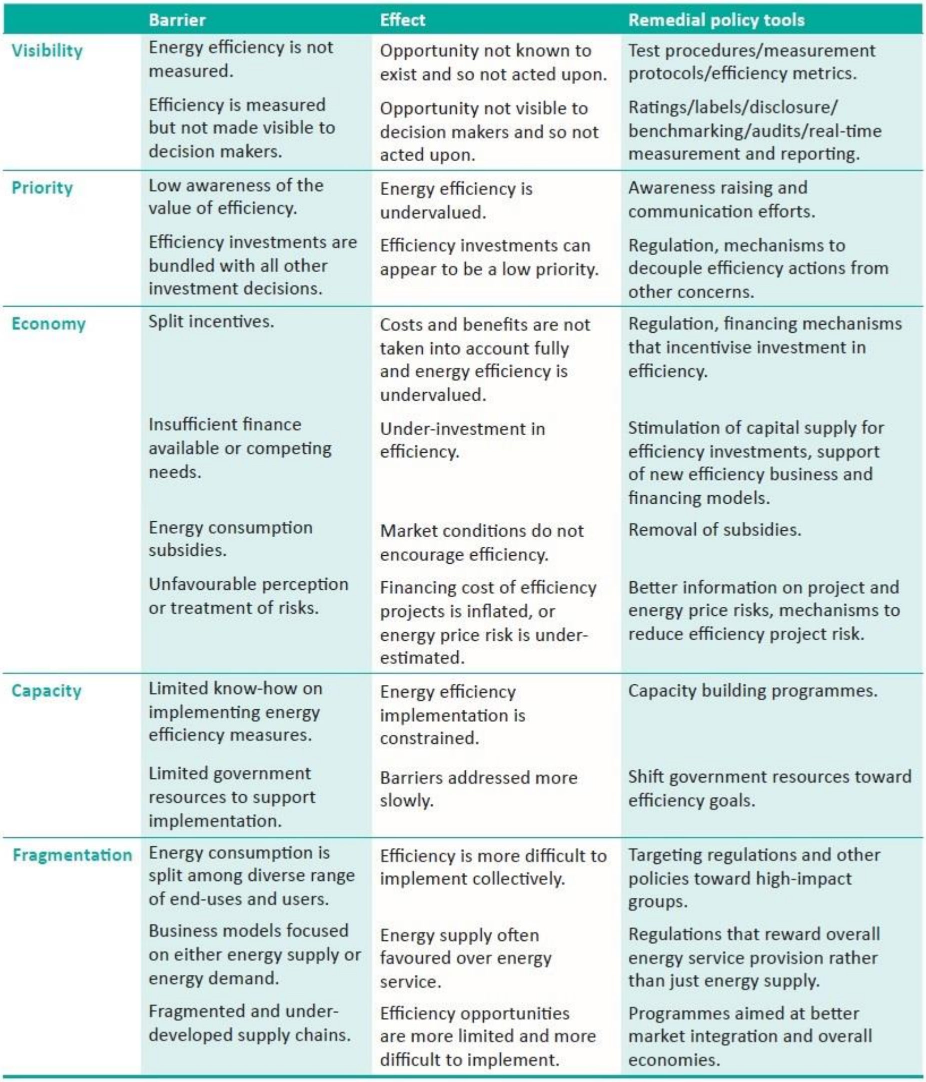
Abatement	2020	2035
Efficiency	71%	65%
🟦 End-use fuels	19%	18%
🟧 Electricity savings	47%	42%
🟪 Power plant	5%	5%
🟥 Other	29%	35%
Total (Gt CO_2)	**1.7**	**7.1**

Figure 2.1 - Energy efficiency contribution in CO_2 emissions [5]

While investment in many energy-efficient technologies and practices appear to make good economic sense, the level of their deployment is often much lower than expected. This is due to the existence of a number of barriers that discourage decision makers, such as households and firms, from making the best economic choices.

In addition, despite the key role that energy efficiency plays in cutting energy demand and CO_2 emissions, only a small part of its economic potential is exploited. Over the projection period ending in 2035, it is in fact estimated that four-fifths of the potential in the buildings sector and more than half in industry still remain untapped. Much stronger policies could realise the full potential of energy efficiency and deliver significant economic, environmental and energy security gains.

Table 2.1 summarizes the most evident barriers that slow the implementation of energy efficiency actions and for each issue suggests one or more remedial tools that parties or governments may adopt to unlock the situation.



	Barrier	Effect	Remedial policy tools
Visibility	Energy efficiency is not measured.	Opportunity not known to exist and so not acted upon.	Test procedures/measurement protocols/efficiency metrics.
	Efficiency is measured but not made visible to decision makers.	Opportunity not visible to decision makers and so not acted upon.	Ratings/labels/disclosure/ benchmarking/audits/real-time measurement and reporting.
Priority	Low awareness of the value of efficiency.	Energy efficiency is undervalued.	Awareness raising and communication efforts.
	Efficiency investments are bundled with all other investment decisions.	Efficiency investments can appear to be a low priority.	Regulation, mechanisms to decouple efficiency actions from other concerns.
Economy	Split incentives.	Costs and benefits are not taken into account fully and energy efficiency is undervalued.	Regulation, financing mechanisms that incentivise investment in efficiency.
	Insufficient finance available or competing needs.	Under-investment in efficiency.	Stimulation of capital supply for efficiency investments, support of new efficiency business and financing models.
	Energy consumption subsidies.	Market conditions do not encourage efficiency.	Removal of subsidies.
	Unfavourable perception or treatment of risks.	Financing cost of efficiency projects is inflated, or energy price risk is under-estimated.	Better information on project and energy price risks, mechanisms to reduce efficiency project risk.
Capacity	Limited know-how on implementing energy efficiency measures.	Energy efficiency implementation is constrained.	Capacity building programmes.
	Limited government resources to support implementation.	Barriers addressed more slowly.	Shift government resources toward efficiency goals.
Fragmentation	Energy consumption is split among diverse range of end-uses and users.	Efficiency is more difficult to implement collectively.	Targeting regulations and other policies toward high-impact groups.
	Business models focused on either energy supply or energy demand.	Energy supply often favoured over energy service.	Regulations that reward overall energy service provision rather than just energy supply.
	Fragmented and under-developed supply chains.	Efficiency opportunities are more limited and more difficult to implement.	Programmes aimed at better market integration and overall economies.

Table 2.1 - Key barriers to energy efficiency and remedial tools [5]

2.1 Energy efficiency in the industrial sector

Energy-efficient components in industrial systems, while important, will not yield the expected energy savings if the entire system is not properly designed and operated. Energy systems need to be optimized in tandem with production processes, as well as across equipment components.

Energy efficiency improvements in the industrial sector can be classified into three main categories:

- Better equipment and technology. It is estimated that the accelerated adoption of best available technology (BAT) could cut global industrial energy use by almost a third [6]. Replacing technologies such as inefficient compressors, which often lose up to 80% of input energy as heat, could contribute to radical energy cuts. Various non-conventional technologies are introduced in the energy system analysed in the dissertation. These alternatives include low-impact and cost-effective appliances, such as CHP units and hot water storage (HS), and renewable energy technologies, like solar thermal (ST) modules and PV collectors.
- Managing energy and optimizing operations. Efficiency improvements through systems optimization can, in some cases, achieve additional savings, up to 20% [7]. Systems optimization means going beyond component replacement towards integrated system design and operation. Optimization of electric motor systems, such as fans, pumps, compressors and drives, has potential for particularly large and profitable savings in all industry sectors [8]. The main originality of the thesis is the development of an optimization model, representing the energy supply system under analysis, used to identify the best system configuration and operation.
- Transforming production systems. More radical reductions in industrial energy use require an integrated approach to the management of resources and waste over the whole industrial process and consumption chain. Strategies for transforming production systems include increased use of recycled or waste materials and energy, sharing resources among industries and dematerialisation. Although process integration is not an objective of the dissertation, the installation of a district heating network (DHN), connecting all the users of the energy system together, is an example of energy management integration.

There are significant barriers to the implementation of energy efficiency measures in industry and these are often hard to overcome. They include the requirement for short payback periods, in some cases lack of awareness and know-how, and concern that time spent on efficiency improvement is a distraction from core business and that change could interrupt production or affect reliability. Government intervention can address these barriers, creating incentives for companies and ensuring that enabling and supporting systems are in place.

Since the 1970s, countries have introduced numerous policies and measures to promote energy efficiency in the industry sector. The most common measures include incentives in the form of subsidies or energy taxes, emissions trading schemes, equipment performance standards, energy management programmes and funding of research and technology development. In addition, a variety of supporting measures, such as capacity building, provision of training, facilitating access to energy efficiency service providers and sources of finance are used to promote the uptake of energy efficient technologies and practices [9].

In OECD countries, policy measures are taken to increase the rate of energy efficiency refurbishment and systems optimisation in existing facilities. In emerging and developing economies, greater emphasis is placed on establishing an efficient industrial base by ensuring that the most efficient technologies are used when designing and commissioning new facilities, and that there is an acceleration in the closure, or comprehensive retrofit of facilities with obsolete technology. Technology and knowledge transfer to developing countries is increased together with experience exchange on effective policy making.

Comparing the New Policies Scenario of the IEA with the Current Scenario, 44% of the final energy savings that result from efficiency improvements come from the industry sector (Table 2.2). An increasing share of industrial output comes from emerging economies, where most of the new capacity is added. The uptake of more efficient technologies is strong in OECD countries and China, because of increased energy prices and energy efficiency investments in energy-intensive industries, due to the introduction of CO_2 prices and minimum energy performance standards.

	Energy demand in the New Policies Scenario			Cumulative energy savings due to energy efficiency
	2010	2020	2035	2011-2035
Industry	2 421	3 035	3 497	3 221
Transport	2 377	2 778	3 272	2 510
Buildings	2 910	3 302	3 748	1 138
Other	970	1 107	1 232	465
Total	8 678	10 223	11 750	7 334

Table 2.2 - Energy savings due to energy efficiency by sector [Mtoe] [5]

The potential for energy efficiency improvements in industry varies across sub-sectors. Energy-intensive industries, such as iron and steel, cement, chemicals, and pulp and paper, currently account for roughly half of total final industrial energy consumption.

While in many OECD countries large energy-intensive industries already use efficient technologies, further improvements can be realised by replacing older facilities, optimizing processes or through enhanced energy management practices. Untapped potential also remains in the non-energy-intensive industry sector.

In non-OECD countries, where most of the increase in industrial production to 2035 occurs, new manufacturing facilities in energy-intensive industries are often equipped with the latest efficient technologies. These new plants are often large scale and therefore more energy efficient, since production size has a strong influence on specific energy consumption (energy consumption per unit of output). However, older infrastructure in non-OECD regions is in most cases less efficient and accelerating the closure of plants with outdated technology can produce significant energy savings. Pure technological changes can achieve only a part of the energy savings while the rest requires systems optimization and wider process changes.

To achieve the projected gains, investment in energy efficiency needs to increase steadily. In the New Policies Scenario, additional investment in improving energy efficiency in industry amounts to $450 billion between 2011 and 2035, compared with the Current Policies Scenario. Average annual investment increases over time as cheaper options are tapped in the early years and the number of projects undertaken to raise efficiency increases. About two-thirds of the additional investment in industry is in improving the efficiency of heat systems, where much unrealised potential exists [10]. The remainder of the investment is in electrical equipment, mostly industrial motors. Improved motor systems have been available on the market for some years, but their uptake has been slow, especially in developing countries.

The payback period (PB) of the energy efficiency actions that are assumed to be adopted is short. Energy efficiency measures in industry in OECD countries have a payback of less than five years (two-and-a-half years for motors), while the payback period for investment in industry in non-OECD countries is below two years (Figure 2.2). Including transaction costs averaging 20% of the investment cost does not greatly change the payback period.

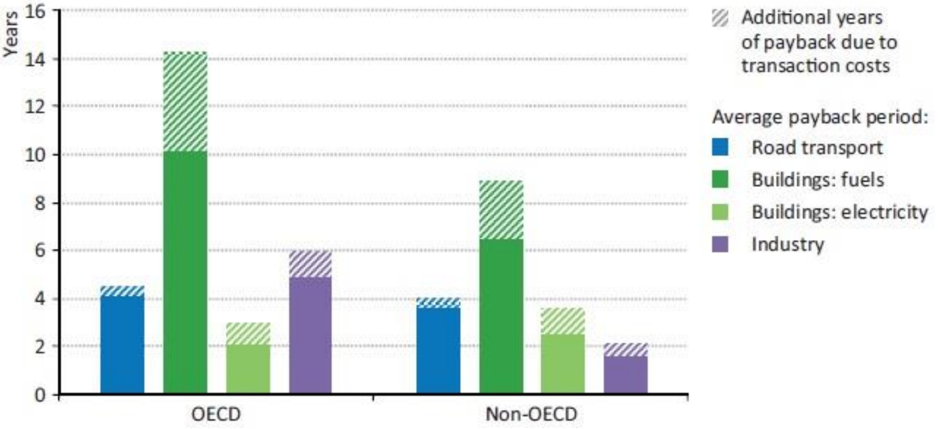


Figure 2.2 - Payback period of energy efficiency actions by sector [5]

2.1.1 Energy efficiency management system

All industrial companies can save energy by applying the same management principles and techniques they use elsewhere in the business for key resources, such as finance, raw material and labour, as well as for environment, health and safety. These management practices consider techniques to achieve energy efficiency at an installation level and include full managerial accountability for energy use. The management of energy consumption and costs eliminates waste and brings cumulative savings over time.

An energy efficiency management system is a tool that operators can use to design, construction, maintenance, operation and decommissioning issues in a systematic and demonstrable way. The method includes the organisational structure, responsibilities, practices, procedures, processes and resources for developing, implementing, maintaining, reviewing and monitoring the energy efficiency policy.

Management to achieve energy efficiency requires structured attention to energy with the objective of continuously reducing energy consumption and improving efficiency in production and utilities, and sustaining the achieved improvements at both company and site level. It provides a structure and a basis for the determination of the current energy efficiency, defining possibilities for progress and ensuring continuous improvement, meaning that energy management is a process, not a project which eventually comes to an end.

There are various process designs, but most management systems are based on the plan-do-check-act approach, which is widely used in other company management contexts. The cycle is a reiterative dynamic model, where the completion of one cycle flows into the beginning of the next (Figure 2.3).

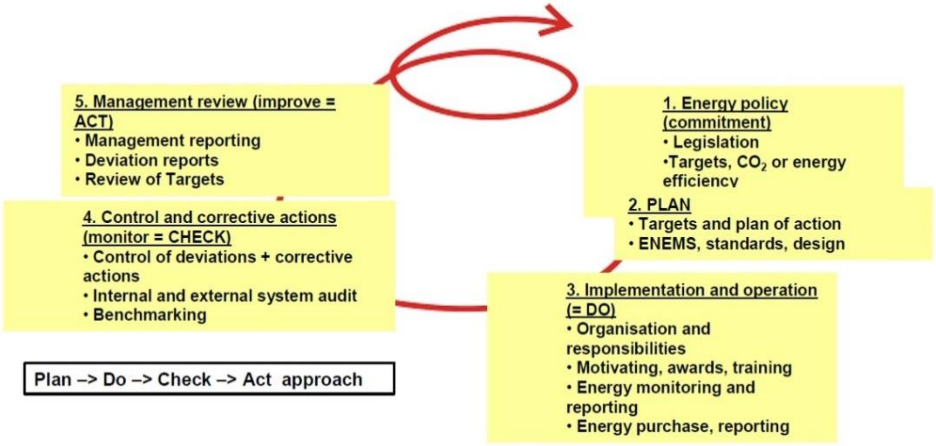


Figure 2.3 - Energy efficiency management system [11]

The best performance of an energy efficiency management system incorporates the following features [12]:

- Commitment of top management.
- Definition of an energy efficiency policy.
- Planning and establishing objectives and targets.
- Implementation and operation of procedures:
    - structure and responsibilities;
    - training, awareness and competence;
    - communication;
    - employee involvement;

  - documentation;
  - effective control of processes;
  - maintenance;
  - emergency preparedness and response.
- Benchmarking.
- Checking and corrective action:
  - monitoring and measurement;
  - corrective and preventive action;
  - records and reporting;
  - energy audit and energy diagnosis;
  - periodic evaluation of compliance with legislation and agreements.
- Management review.
- Preparation of a regular energy efficiency statement.
- Validation by certification body or external verifier.
- Design considerations for end-of-life plant decommissioning.
- Development of energy efficient technologies.

2.1.2 Best available technology

Best available technology is the most energy-efficient way of producing goods and services that is commercially viable and in use. It refers to the most advanced usable technologies and methods of operation, the way installations that deploy them are built and operated, and the economic feasibility of the technologies. Normally the newest technologies in an industry, BATs are always changing due to continuous radical and incremental innovation.

Most industrial plants and much energy-intensive capital stock have long technical life spans, slowing the diffusion of best available technology. A plant built today could remain in service for decades, retrofitted and refurbished several times. In many developing countries, equipment stays in service even longer because capital costs are so much higher than energy costs. Continuously upgrading to BAT entails retiring equipment earlier or retrofitting it sooner, although premature replacement might not be economical.

Over time, global average industrial energy efficiency and BAT in specific sectors both improve, sometimes in parallel and sometimes converging, implying that innovation and BAT uptake must go together.

In 2010 industry spent around $1 trillion on energy, 55% of it in developing countries. Energy cost savings from adopting best practice techniques in industrial energy-efficiency projects could reach \$65 billion in developed countries and \$165 billion in developing countries, 23% of total energy costs. Investing between 2010 and 2030 to achieve current levels of BAT would improve energy efficiency 1.2% a year and save \$365 billion in costs by 2030, excluding investment costs [13].

The environmental benefits of best available investments are also substantial. Investing in BAT could yield savings of around 30 exajoules (EJ) a year, some 27% of total energy use by industry (60% of it in developing countries) and 6% of global energy use. Achieving BAT would reduce carbon dioxide emissions by as much as 1.3Gt, a reduction of 12% in total industry emissions and 4% in global emissions from 2006 levels [14].

Besides the extent of the topic, a specific presentation of existing best available technologies is not an objective of the dissertation. Detailed descriptions of BAT by sector, installation and activity can be found for example in the reference documents on best available techniques of the European Commission.

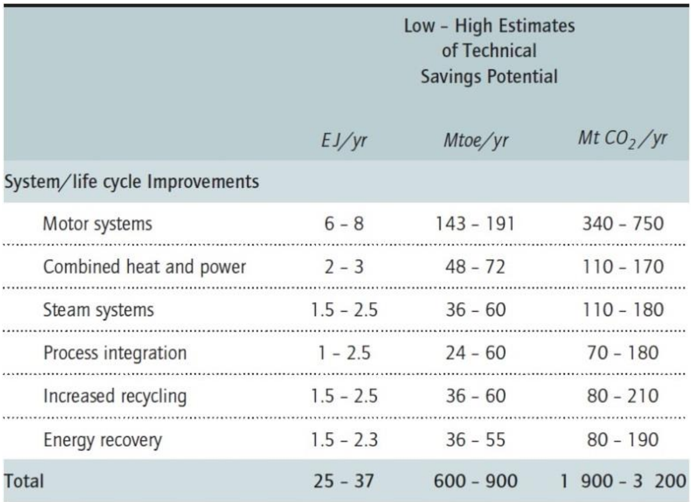
2.1.3 Common energy efficiency interventions

Globally, the energy-consuming systems with the highest potential energy savings in the industrial sector are motors and steam systems. These represent together 41% of total industrial energy use.

Manufacturing industry can improve its energy efficiency by 18 to 26% (5 to 8% of the global energy use), while reducing the sector's CO_2 emissions by 19 to 32%, based on proven technology. Identified improvement options can contribute 7 to 12% reduction in global energy and process-related CO_2 emissions. The estimated savings do not consider new technologies that are not yet widely applied and other options such as CCS systems. Therefore, these should be considered lower range estimates of the technical potential for energy savings and CO_2 emissions reductions in the manufacturing industry sector [15].

The energy and CO_2 savings by consuming system on a primary energy basis are shown in Table 2.3.

Motor-driven equipment is spread worldwide: it accounts for about 60% of total manufacturing electricity use and for 15% of global final industry energy consumption. Motor systems, consisting of drives, pumps and fans, are a largely untapped, cost-effective source of industrial energy-efficiency savings that could be realized with existing technologies. Some 55% of the electricity used by motor systems (16% of total industrial energy consumption) is lost before the motor systems do any work. Losses can be reduced by using more efficient motors and variable speed drives, sizing motors appropriately and optimizing motor-driven systems, such as pumps and conveyors. The more efficient motors are generally profitable where energy prices are high. Large savings can often be achieved by analysing and then optimising the complete motor system. It is estimated that industries can cost-effectively reduce the electricity use of motor systems by 20-25%, although the potential will vary from plant to plant. Initial capital costs are typically 5-20% of lifecycle cost, and efficient motors cost only 10-25% more than less efficient motors. High efficiency motors allow to decrease losses by 20-30% compared to standard motors. Their additional cost can be recovered in less than three years, but the uptake has been slow, suggesting an opportunity for policy intervention to expedite uptake of best available technology. IE3 motors (i.e. the highest international efficiency standard for electric motors) have been around since before 1995, but the market sales share in 2010 was still less than 20% (Figure 2.4).



	Low - High Estimates of Technical Savings Potential		
	EJ/yr	*Mtoe/yr*	*Mt CO_2/yr*
System/life cycle Improvements			
Motor systems	6 - 8	143 - 191	340 - 750
Combined heat and power	2 - 3	48 - 72	110 - 170
Steam systems	1.5 - 2.5	36 - 60	110 - 180
Process integration	1 - 2.5	24 - 60	70 - 180
Increased recycling	1.5 - 2.5	36 - 60	80 - 210
Energy recovery	1.5 - 2.3	36 - 55	80 - 190
Total	25 - 37	600 - 900	1 900 - 3 200

Table 2.3 - Energy and CO_2 savings by consuming system [15]

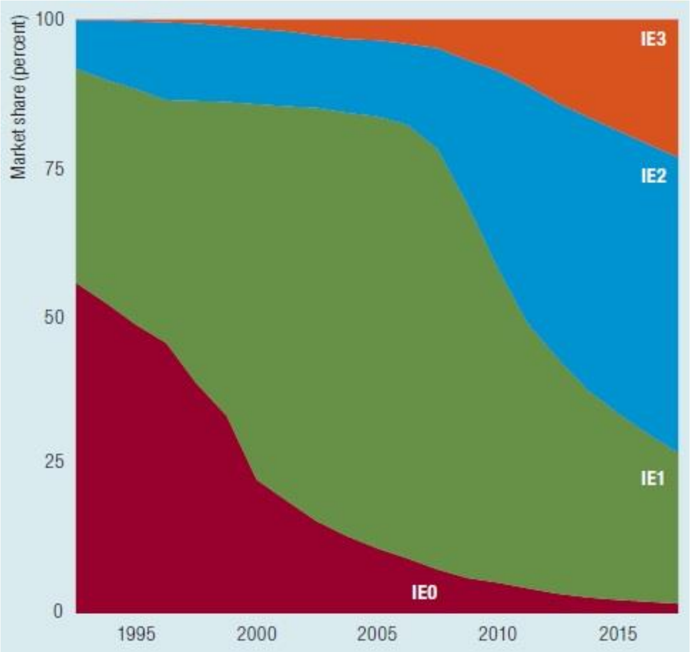
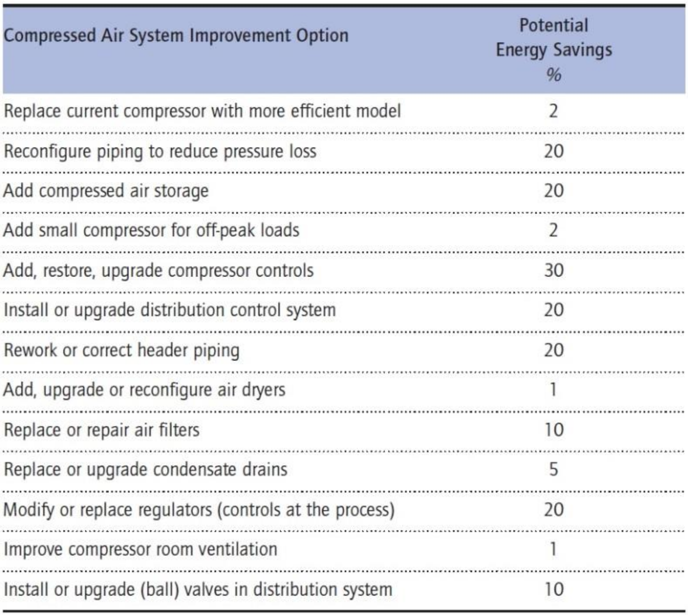


Figure 2.4 - Market sales share of electric motors by efficiency [7]

Compressors, drives, air treatment, compressed gas network and the end-use devices driven by compressed air account for 10% of industrial consumption of electricity. Compressors lose 80% of the mechanical work done by the motor, while up to half of the remaining energy is often lost to leaks and inappropriate end uses, resulting in a net system efficiency of 10-15%. Case studies show that savings of up to 50% are possible, but these are not being realized under current market and decision mechanisms [16]. Table 2.4 lists the energy saving potential in a compressed air system.



Compressed Air System Improvement Option	Potential Energy Savings %
Replace current compressor with more efficient model	2
Reconfigure piping to reduce pressure loss	20
Add compressed air storage	20
Add small compressor for off-peak loads	2
Add, restore, upgrade compressor controls	30
Install or upgrade distribution control system	20
Rework or correct header piping	20
Add, upgrade or reconfigure air dryers	1
Replace or repair air filters	10
Replace or upgrade condensate drains	5
Modify or replace regulators (controls at the process)	20
Improve compressor room ventilation	1
Install or upgrade (ball) valves in distribution system	10

Table 2.4 - Energy saving potential by compressed air improvement [17]

Steam systems account for 35% of global industrial energy consumption. These systems lose an average 45% of their input heat before reaching point of use (Figure 2.5). In many developing countries, the losses are substantially larger. For example, in the Russian Federation, most steam systems have no pipeline insulation. In China, many small-scale boilers operate with considerable excess air and incomplete coal combustion. Experience in well managed industrial facilities in OECD countries shows potential energy-efficiency gains of about 10% from system efficiency measures. Table 2.5 indicates the savings potentials for steam systems.

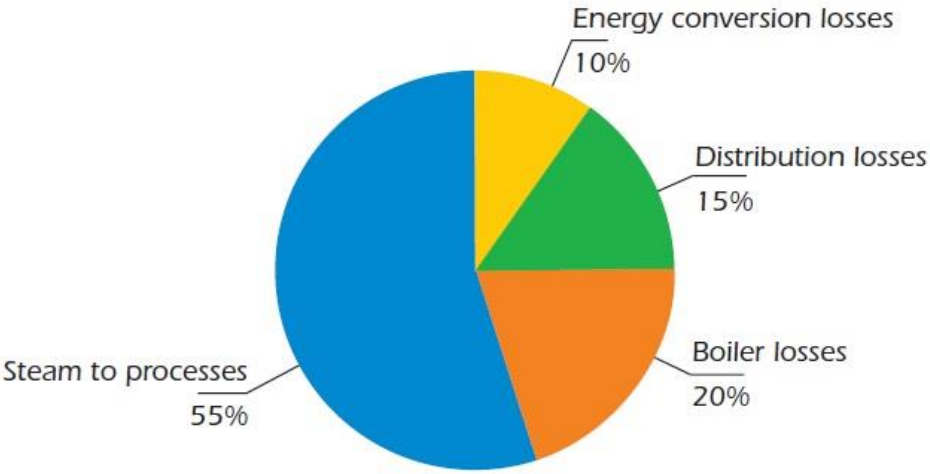
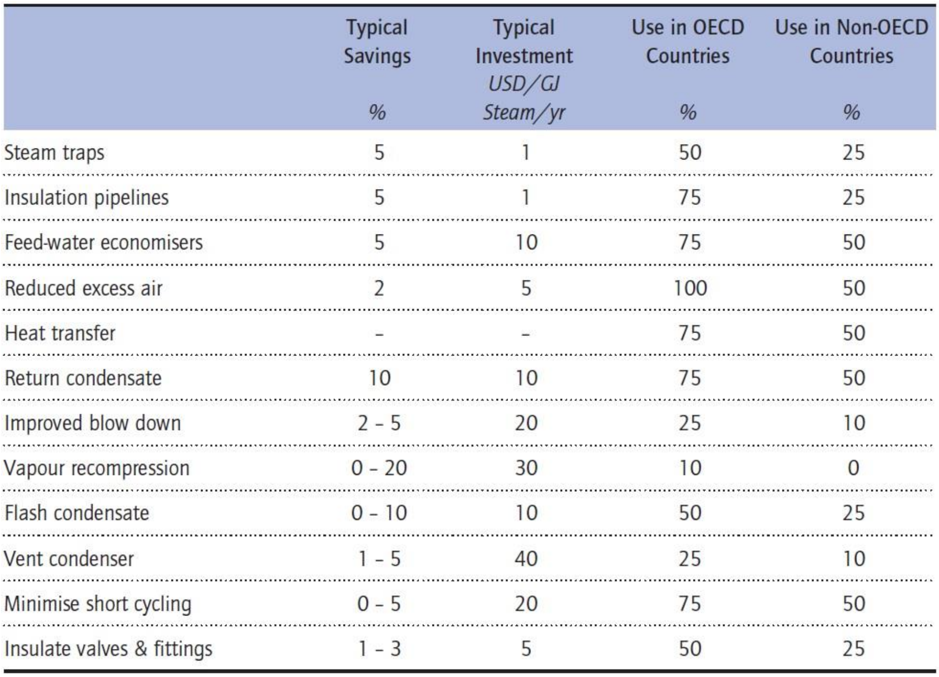


Figure 2.5 - Steam system balance [15]



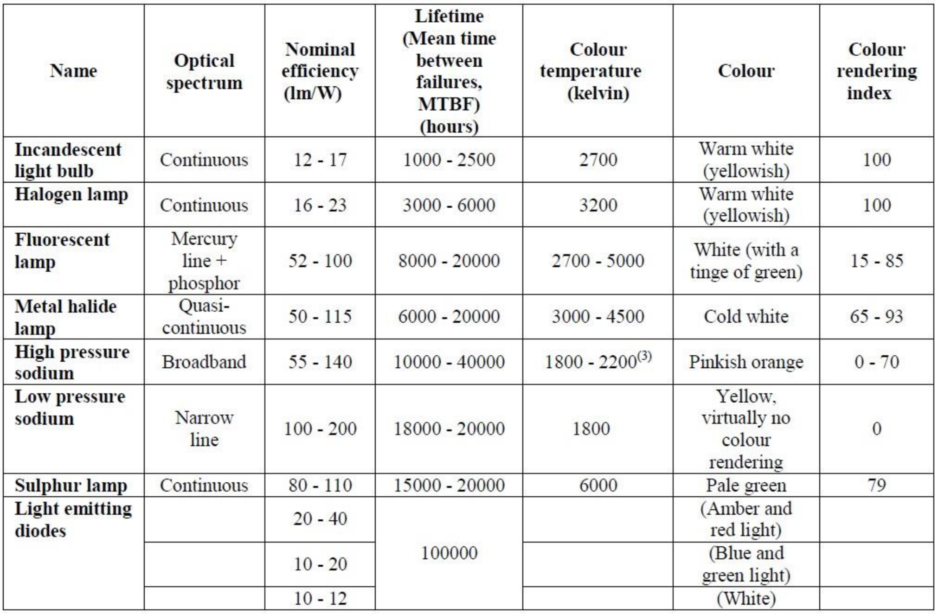
	Typical Savings %	Typical Investment *USD/GJ Steam/yr*	Use in OECD Countries %	Use in Non-OECD Countries %
Steam traps	5	1	50	25
Insulation pipelines	5	1	75	25
Feed-water economisers	5	10	75	50
Reduced excess air	2	5	100	50
Heat transfer	-	-	75	50
Return condensate	10	10	75	50
Improved blow down	2 - 5	20	25	10
Vapour recompression	0 - 20	30	10	0
Flash condensate	0 - 10	10	50	25
Vent condenser	1 - 5	40	25	10
Minimise short cycling	0 - 5	20	75	50
Insulate valves & fittings	1 - 3	5	50	25

Table 2.5 - Steam system efficiency improvements [15]

Apart from plugging leaks, installing cogeneration systems may be the best way to reduce energy loss in steam generation. A traditional system produces heat and power separately, with a typical combined efficiency of 45-60%. In a CHP unit fuel technologies generate power at the point of use, allowing recovery of the heat normally lost in power generation. Cogeneration systems can operate with a first-law energy efficiency of 75-90% and avoid electricity system distribution losses as well. Cogeneration is widely applied in the paper, pulp and printing, chemicals and petrochemicals, oil refining, food processing sectors, and its share is rising in others.

The most promising opportunities occur in non-stop operations (24 hours a day, seven days a week). Globally, CHP generates about 10% of all electricity and a few countries reach 20% share of their electricity from cogeneration. Installed capacity in OECD countries is 174 gigawatt (GW) (6% of total electricity generation). The amount of heat that is co-generated is not exactly known, but it is in the range of 5-15 EJ per year, which represents an important share of industrial heat supply. The estimated global potential for new industrial cogeneration is around 160GW, enough to generate 500 terawatt hours (TWh) of electricity a year, to reduce primary energy consumption by 4.5EJ and CO_2 emissions of 252 megatonne (Mt) per year [15].

An important opportunity for energy efficiency is the lighting improvement. Artificial lighting accounts in fact for a significant part of all electrical energy consumed worldwide: in offices, from 20 to 50% of the total energy consumed is due to lighting. Most importantly, for some buildings over 90% of lighting energy consumed can be an unnecessary expense through over-illumination. Thus, lighting represents a critical component of energy use today, especially in large office buildings and for other large scale uses where there are many alternatives for energy utilisation in lighting. However, besides the kind of technology used, the lighting requirement for each area of a building is a crucial factor to the selection of a type of lighting system: much less light is needed for illuminating a walkway compared to that required for a computer station. Due to the number of lighting technologies available in the market and due to the diversity of existing applications, it is difficult to make a precise evaluation of the potential of lighting improvements. Nevertheless, the Green Light Programme of the European Commission [18] evaluated that investing in proven energy efficient lighting systems can reduce lighting energy use between 30 and 50%, with earning rates of return from 20 to 50%. Table 2.6 reports characteristics and efficiency of different light types.



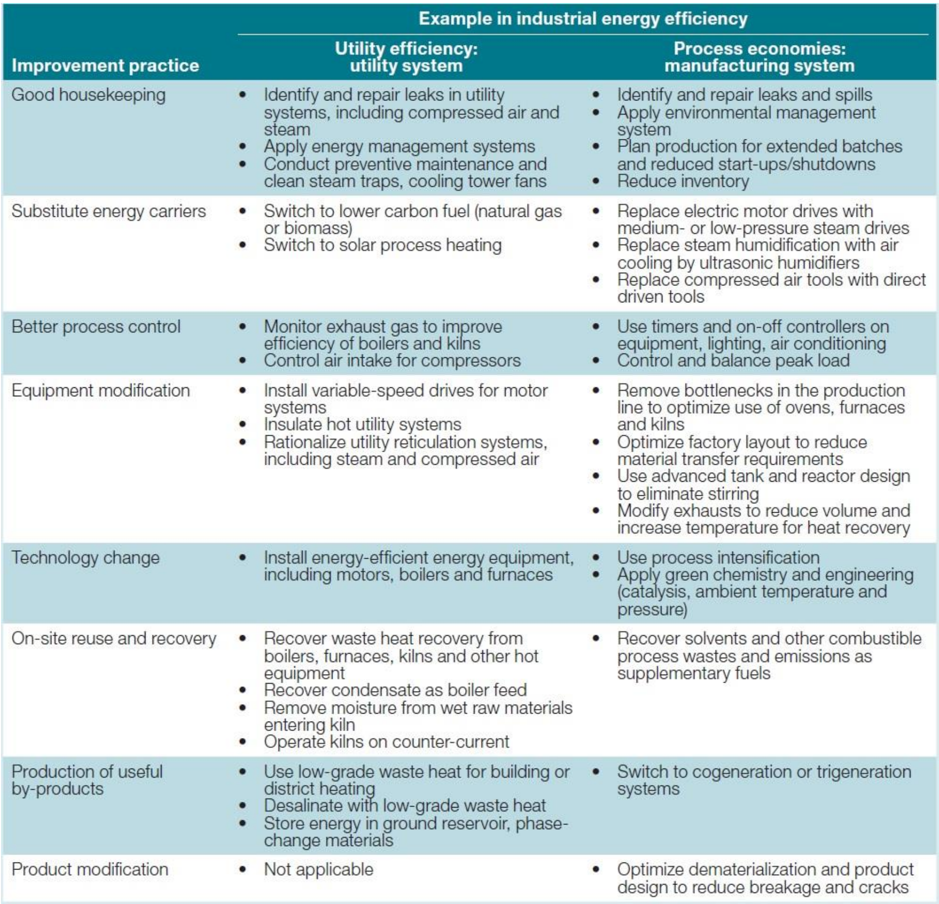
Name	Optical spectrum	Nominal efficiency (lm/W)	Lifetime (Mean time between failures, MTBF) (hours)	Colour temperature (kelvin)	Colour	Colour rendering index
Incandescent light bulb	Continuous	12 - 17	1000 - 2500	2700	Warm white (yellowish)	100
Halogen lamp	Continuous	16 - 23	3000 - 6000	3200	Warm white (yellowish)	100
Fluorescent lamp	Mercury line + phosphor	52 - 100	8000 - 20000	2700 - 5000	White (with a tinge of green)	15 - 85
Metal halide lamp	Quasi-continuous	50 - 115	6000 - 20000	3000 - 4500	Cold white	65 - 93
High pressure sodium	Broadband	55 - 140	10000 - 40000	1800 - 2200[3]	Pinkish orange	0 - 70
Low pressure sodium	Narrow line	100 - 200	18000 - 20000	1800	Yellow, virtually no colour rendering	0
Sulphur lamp	Continuous	80 - 110	15000 - 20000	6000	Pale green	79
Light emitting diodes		20 - 40	100000		(Amber and red light)	
		10 - 20			(Blue and green light)	
		10 - 12			(White)	

Table 2.6 - Characteristics and efficiency of light types [12]

Another typical intervention is the power factor correction. Many electrical devices require both active and reactive electrical power, but, while the active part is converted into work, the reactive component is used to maintain the devices' magnetic field and is not useful. This means that electrical equipment must be sized for greater power ratings and that the utilities are faced with extra expenditure for additional power losses. External suppliers make additional charges for reactive power if this exceeds a certain threshold. A certain target power factor of cos φ between 0.9 and 1.0 is specified, at which point the reactive energy requirements is significantly reduced. The cost of power correction is low and some new equipment (e.g. high efficiency motors) self-addresses power correction. Power factor correction is most effective when it is physically near to the load, for example by installing a capacitor. In an installation, it is estimated that if an operator with a power correction factor of 0.73 corrected the cos φ to 0.95, he would save 0.6% of his power usage [12].

Other types of technical improvements combine energy-efficiency measures, such as cogeneration, with electricity delivery to the grid, district heating networks and heat cascading for large industrial sites. Rapidly growing global experience suggests important energy-saving opportunities from cooperation and energy systems integration among firms that need to be assessed case by case.

Table 2.7 presents a list of common improvement practices for industrial energy efficiency at the utility and manufacturing levels.



Improvement practice	Example in industrial energy efficiency: Utility efficiency: utility system	Example in industrial energy efficiency: Process economies: manufacturing system
Good housekeeping	• Identify and repair leaks in utility systems, including compressed air and steam • Apply energy management systems • Conduct preventive maintenance and clean steam traps, cooling tower fans	• Identify and repair leaks and spills • Apply environmental management system • Plan production for extended batches and reduced start-ups/shutdowns • Reduce inventory
Substitute energy carriers	• Switch to lower carbon fuel (natural gas or biomass) • Switch to solar process heating	• Replace electric motor drives with medium- or low-pressure steam drives • Replace steam humidification with air cooling by ultrasonic humidifiers • Replace compressed air tools with direct driven tools
Better process control	• Monitor exhaust gas to improve efficiency of boilers and kilns • Control air intake for compressors	• Use timers and on-off controllers on equipment, lighting, air conditioning • Control and balance peak load
Equipment modification	• Install variable-speed drives for motor systems • Insulate hot utility systems • Rationalize utility reticulation systems, including steam and compressed air	• Remove bottlenecks in the production line to optimize use of ovens, furnaces and kilns • Optimize factory layout to reduce material transfer requirements • Use advanced tank and reactor design to eliminate stirring • Modify exhausts to reduce volume and increase temperature for heat recovery
Technology change	• Install energy-efficient energy equipment, including motors, boilers and furnaces	• Use process intensification • Apply green chemistry and engineering (catalysis, ambient temperature and pressure)
On-site reuse and recovery	• Recover waste heat recovery from boilers, furnaces, kilns and other hot equipment • Recover condensate as boiler feed • Remove moisture from wet raw materials entering kiln • Operate kilns on counter-current	• Recover solvents and other combustible process wastes and emissions as supplementary fuels
Production of useful by-products	• Use low-grade waste heat for building or district heating • Desalinate with low-grade waste heat • Store energy in ground reservoir, phase-change materials	• Switch to cogeneration or trigeneration systems
Product modification	• Not applicable	• Optimize dematerialization and product design to reduce breakage and cracks

Table 2.7 - Common energy efficiency interventions [7]

3

Optimization of energy supply systems

The basic requirement for an energy system is the ability to generate enough power for everybody's needs at an affordable price and in a clean, safe and reliable way [19]. An energy system may potentially include an infinite number of components, committed to the transformation, distribution and storage of energy vectors. Therefore, it is clear that, due to the complexity of the problem, design and management optimization is fundamental to obtain the desired results with a rational use of both economic and natural resources.

The best system is the one that satisfies a criterion of optimality, i.e. the one that minimizes (or maximizes) an objective function. Three levels of optimization are identified [20]:

- Synthesis, implying the set of components appearing in a system and their interconnections;
- Design, implying the technical specifications of the components and the properties of substances flowing throughout the system at the nominal load;
- Operation, implying the operating properties of components and substances under specified conditions.

The algorithm developed in the dissertation allows optimizing all three levels of the supply system under examination:

- Synthesis, it determines the optimal configuration of the system (existence and location of all components);
- Design, it determines the size of all components of the system;
- Operation, it determines operation status (on/off) and load level of each component, and all the energy flows of the system.

3.1 State of the art

The importance of the energy system optimization is also underlined by the amount of research available in literature. Over the last decades an increasing number of papers have in fact been produced ([21] [22] [23] [24] [25] [26] [27] [28] [29]).

One of the first optimization model was developed by Henning in 1992 [30], and it consists on a linear programming model to minimize the operating cost of an energy supply system for local Swedish utilities. In 1997 Henning presented a linear programming model called MODEST [31], for the minimization of capital and operation costs of energy supply and demand side management. Curti et al. [32] 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 pumps. Yokoyama et al. [33] 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 [34] has recently presented the MIND method, a decision support for optimization of industrial energy systems.

The researches normally focus only on a specific target, such as operation or synthesis optimization, unit or DHN optimization etc. However, all the aspects of the problem must be considered at the same time, and not in successive steps, when the design and operation of complex energy systems, including also DHN and HS, are optimized. The reason is because the operation optimization heavily affects the configuration of the system. Some recent works seem to go in this direction. Chinese [35] proposed a MILP model for the optimization of a district heating and cooling network in a distributed generation context. Söderman and Petterson [36] presented a structural and operational optimization of an energy system. Carvalho [37] developed a model for the synthesis and operation optimization of residential units, considering environmental and economic aspects.

The energy supply model of the thesis includes various components: CHP units, boilers, DHN, HS, ST and PV collectors. Its optimization allows comparing different configuration options (i.e. centralize and decentralize generation), analysing the simultaneous operation of the selected equipment of the system and evaluating the competitiveness of non-conventional technologies and renewable energy sources. The tool is supposed to assist the stakeholders of the energy systems in making appropriate managerial decisions, based on objective criteria instead on personal experience, in a very complex environment.

3.1.1 Approaches to energy system optimization

The various methods that have appeared in the literature on the optimal synthesis of energy systems can be classified into three groups [20]:

(a) Methods based on heuristics and evolutionary search;

(b) Methods attempting to reach predetermined targets, which have been identified by the application of physical rules;

(c) Methods starting with a superstructure, which is reduced to the optimal configuration.

In class (a), rules based on engineering experience and on physical concepts (e.g. exergy) are applied to generate feasible configurations, which are subsequently improved by applying a set of evolutionary rules in a systematic way. These rules may come from special techniques, such as exergy analysis. Artificial Intelligence and Expert Systems have proven effective in generating appropriate configurations. For each acceptable configuration, a figure of merit or performance indicator is evaluated (e.g. efficiency, cost, etc.) and the system with the best performance is selected. The best of a certain set of configurations, however, does not guarantee that the optimal configuration has been revealed. In most cases, though, at least a near-optimal configuration has been obtained ([38] [39] [40]).

In class (b), principles from thermodynamics and other physical sciences are applied to obtain targets for the optimal system configuration. These targets can correspond to upper or lower bounds on the best possible configuration and provide vital information for improvement of existing configurations. In addition, many configurations are excluded from further investigation, thus reducing the search space for the best system. If the physical target is the optimization objective (e.g. minimization of energy utilization), these methods provide the solution to the optimization problem. However, if the optimization objective is economic, e.g. minimization of the total cost, then these methods are not very appropriate. Attempts have been made to introduce economics at a second level, but the whole approach is mathematically non-rigorous and, consequently, the configuration obtained may be non-optimal ([41] [42]).

In class (c), a superstructure is considered with all the possible (or necessary) components and interconnections. An objective function is specified and the optimization problem is formulated. The solution of the optimization problem gives the optimal system configuration, which, inevitably, depends on (and is restricted by) the initial superstructure. The main advantages of such an approach are that it can work with any objective function and that it automatically reveals the optimal system configuration. The difficulty with these methods is that the size of the optimization problem may be such that the available mathematical optimization algorithms may not be capable of a rigorous solution. Thus, the need arises for advances in optimization theory and algorithms. The methods of class (c) can obviously find the optimal configuration only out of those represented in the superstructure ([43] [44] [45] [46] [47] [48]).

The distinction among the three classes may not be so clear-cut. For example, the targets of class (b) can serve as heuristics or rules in class (a) and they can be embedded in the optimization procedures of class (c) to the benefit of the whole process. Moreover, up until now, there has been no single method that can tackle the synthesis optimization problem in all its generality and completeness. The field is thus still open to research [20].

The model of the energy system presented in the thesis is developed with the third approach: an initial superstructure, which includes all the equipment considered in the research, is then reduced by the optimization algorithm to obtain the best possible configuration of the system, according to the defined objective function.

3.1.2 Representation of energy optimization problems

Design and synthesis optimization problems can be solved by a series of representative methods, no matter the class they belong to [20]:

- Connectivity Matrix method;
- Simulated Annealing;
- Targeting methods;
- Intelligent Functional approach;
- Decomposition;
- Artificial Intelligence and Expert Systems techniques;
- Algorithmic approaches.

The Connectivity Matrix method is a direct application of Graph Theory to process design ([49] [50]) and consists of the following steps:

1. Create a logical process scheme. This is a very general task and does not imply the selection or placement of any component. It entails though the selection of the chemical/physical sub-processes that constitute the main process.
2. Construct the connectivity matrix for the logical process scheme. The rows of matrix represent fluxes of matter or of energy, while the columns represent operations to be performed on these fluxes. A "1" in position *ij* signifies that flux *i* undergoes transformation *j*; a "0" signals no interaction of flux *i* with sub-process *j*.
3. Translate each operation listed in the connectivity matrix into a series of physical transformations and devise one elementary sub-process scheme for each transformation. Introduce these sub-process schemes into each one of the applicable columns of the matrix: this corresponds to expanding the matrix by adding several additional columns.

4. Substitute into each transformation in every sub-process the component that performs it. Notice that at this point technical and operational constraints may come into play and limit or deny altogether the feasibility of a certain solution.
5. The resulting matrix is the connectivity matrix of the real process analysed. A proper quantitative simulation of the process must now be performed to obtain the optimal set of operational parameters.

It is apparent that this method is a direct translation of the mental scheme a process engineer applies to a design task, and it is entirely deterministic. Unfortunately, it is also clear that the method is strongly biased by the choices made in points 1 and 3. Choosing a process scheme in fact sets a major structural constraint on the resulting process configuration, and this step is entirely left to the experience of the designer. Similarly, splitting a process into sub-processes can be done in more than one way, and selecting the one or the other corresponds to biasing the entire procedure [20].

Simulated Annealing is a very smart variant of the Matrix method and, in spite of some limitations presented below, is a very reliable process synthesizer. Though originally conceived as a multi-variable optimization tool, it was later adapted to function as a structural optimizer [51]. The original idea for simulated Annealing was that of constructing an algorithm that could mimic this search for a global optimum by controlling the rate of decrease of a global energy parameter (which was called T, a fictitious temperature) and nesting a sub-optimization for each level of T. The procedure consists of the following steps:

1. Select a process superstructure, i.e. a fictitious process connectivity matrix in which all of the components that may be useful in any of the possible sub-processes that lead from input to output are represented. This particular matrix has a very high interconnectivity: most components are connected to most others by at least one of the possible fluxes of matter or energy.
2. Establish a global fictitious quantity T that, assuming to minimize the objective function, if the system is in state X, with a corresponding value $f(X)$, there is a small probability that, for a given T, a different configuration Y, with $f(Y) > f(X)$ is admissible, i.e. can be reached by the system.
3. Perform a simplified process simulation (if necessary introducing artificial constraints to force some of the most unlikely matches among components) and compute the objective function (usually consisting of a proper combination of performance and cost index).
4. Randomly modify the system interconnection, i.e. by inserting “0” in all entries in a randomly selected column *k*: this corresponds to eliminating component *K*. Not all moves are acceptable: some physical (mass and energy balances) and possibly some configuration constraints apply.

5. Perform a simplified process simulation again and compute the new value of the objective function. If $f(Y) < f(X)$, the new configuration is accepted. If $f(Y) > f(X)$, there is a probability that $f(Y)$ may still be an acceptable state.
6. Decrease T by a preassigned amount and repeat steps 4 and 5.
7. Repeat steps 3 to 6 n times: this corresponds in our example to subtracting n components from the initial super-configuration, but other norms for n are acceptable as well. Record the minimum (or maximum, depending on the case) value of the objective function reached in these n reduced configurations.
8. Take now as the new super-configuration the modified configuration that achieved the lowest (or highest) value of the objective function in the previous n trials.
9. Repeat steps 3 to 7 until the value of the objective function does not change much from one new super-configuration to the next. The last configuration (which is likely to consist of a much lower number of components than the original one) is the sought after optimal process structure.

The correct choice of the quantifier T is crucial in simulated Annealing. Unfortunately, its formulation is entirely heuristic, because the analogy between the numerical procedure and the physical annealing process is not perfect. Usually, a dimensionless T is defined, and its decrease from one level to the next is established a priori by a linear law of the type $T_{j+1} = T_j (1-\varepsilon)$ with $\varepsilon = 1 \div 3\%$. It is important to remark, though this is rarely mentioned, that the choice of the initial superstructure has a strong influence on the final outcome, simulated Annealing is in fact strongly biased according to its initial conditions [20].

The ideas behind the targeting methods originated in the attempt to optimize district heating network (DHN). One of the targets is the minimum utility cost target and the related problem can be stated as follows: given a heat recovery approach temperature, determine the minimum utility consumption (or utility cost) of a heat exchanger network without prior knowledge of the DHN configuration. This is a very important target since it corresponds to the maximum energy recovery that can be attained in a feasible DHN for a fixed heat recovery approach temperature. This target leads to near-optimal solutions as long as the energy is the dominant cost item as compared to the investment cost. The key concept that allows for a determination of the minimum utility cost prior to knowing the DHN structure is the pinch point. The related concepts and applications are presented in the literature ([42] [44] [45] [52]). The related methods have been extended in two ways: to include capital and operational expenses other than the cost of utilities, and to allow application to energy systems that include other components in addition to heat exchangers (e.g. power plants). The whole optimization problem is decomposed into two levels: synthesis of the system directed by thermodynamic targets and then cost minimization. However, this decomposition is not always mathematically correct, leading to inexact solutions of the optimization problem [20].

The Intelligent Functional Approach is a further development of the Functional Approach described in the literature ([45] [53] [54]). It operates on a superstructure, which is properly analysed to define the functions of the various components and the related Lagrange multipliers. The values of the Lagrange multipliers, as they are calculated in the procedure, are used to decide on the existence of certain components. Multilevel optimization for the synthesis, design and operation optimization problems is applied. Decomposition can also be applied with respect to subsystems and/or with respect to time, if conditions change with time. A combination of genetic algorithms, nonlinear programming algorithms, and the Intelligent Functional approach has been successful in reducing the time for solution of the optimization problem [20].

Three principal types of decomposition exist: conceptual, time, and physical.

The first of these decomposes the conceptual aspects of the optimization problem, i.e. synthesis, design, and operation, into two or three levels of optimization. At the operational level, the system is optimized with respect to a set of operational/control variables for a fixed structure (synthesis/design) across an entire load/environmental profile in order to determine optimal system behaviour under any (design and off-design) conditions. The results are then integrated over time and introduced at the synthesis level. At this level, a new choice of system configuration (synthesis) is made based on minimizing (or maximizing) the system's objective function with respect to a set of synthesis variables. 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) according to a set of design variables. 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 ([43] [45]). A variation on this type of decomposition, which avoids this sort of nesting, completely separates the synthesis/design level(s) from the operational level ([46] [47] [48]). In this approach, the system's synthesis/design is optimized for the most stringent of the load/environmental conditions and a set of optimum and near-optimum feasible solutions determined for the given synthesis/design point. These feasible solutions are then optimized at all off-design conditions in order to determine the overall optimal solution. This type of decomposition reduces the computational burden seen with the former approach by assuming that only a limited number of feasible solutions need be optimally evaluated at off-design.

The next type of decomposition is time decomposition, which decomposes the 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.

In contrast to the two previous types of decomposition, physical decomposition looks at the system itself and breaks it down 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. All such approaches within the literature ([46] [47] [48] [55]), can be classified either as a Local-Global Optimization or an Iterative Local-Global Optimization approach. In both, it is assumed that a number of disjoint sub-sets of the set of synthesis/design variables (one set for each unit and one, if needed, at the system level) can be established. Each set at the unit-level is used to optimize its respective sub-problem while the system-level set is used to optimize the overall problem at the system-level. In Local-Global Optimization, this results in a nested set of optimizations of unit-level problems within an overall system-level problem. Of course, as with the other decomposition approaches, the principle disadvantage of Local-Global Optimization is that it is very computationally intensive. To circumvent this, Iterative Local-Global Optimization instead of Local-Global Optimization may be applied since the former avoids the need for creating any of the optimum response surfaces and avoids as well the nesting inherent in the other decomposition approaches.

There are a number of reasons for using decomposition in its various forms to reformulate the optimization problem for energy system synthesis, design, and operation, which in its full complexity is defined as a dynamic, non-linear, mixed-integer programming problem. For example, 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. Decomposition may also be warranted when certain company and geographical boundaries (e.g., design teams located far from each other) do not permit solution of the original problem as a single problem [20].

Artificial Intelligence techniques allow the codification of procedures that somehow mimic the thinking patterns of the human mind aiming at automate the conceptual task of a process. Currently, only a subset of these techniques, called Expert Systems, have been successfully applied to energy systems. Expert Systems can be used to reproduce the engineer’s decisional path that proceeds from the design data and constraints to possible process configurations. Expert Systems are based on relational languages that use the symbolism of formal propositional logic. They draw inferences from a number of facts stored in a particular database, properly called a knowledge base. These facts can be design data, design rules, physical or logical constraints, etc. Each Expert System manipulates this knowledge in its own way, according to a logical procedure contained in its inference engine. More information can be found in the literature ([20] [40] [56] [57]).

The algorithmic approaches include mixed integer linear or nonlinear programming algorithms (depending on whether the objective function and the constraints functions are linear or nonlinear) and genetic algorithms ([44] [58] [59] [60]). They both operate on a specified superstructure. Usually, integer variables are used to describe the synthesis of the system (e.g. existence or non-existence of components), while real variables correspond to design and operational characteristics of components. Genetic algorithms have the advantage that they can reveal more than one near-optimal configuration, so the designer may apply additional criteria to select the preferable one. Computationally they are more intense and they can be, if not properly conditioned, rather sensitive to the choice of the initial superstructure. It is also possible to combine a genetic algorithm with a linear or nonlinear programming algorithm. The first one is used to effectively reach near-optimal solutions for configuration, design and operation and the second one to determine the exact values of the independent variables at the design and operation levels. Multilevel optimization and decomposition can be used to facilitate the solution [20].

The mathematical model of the energy supply system presented in the thesis is developed through the Mosel Language with the Xpress Optimization Suite and it is based on a mixed integer linear programming algorithm. The optimization toolbox uses Simplex and Newton-Barrier (interior point) algorithms, together with Branch-and-Bound, Heuristic and cut generation techniques.

3.2 Mathematical modelling of optimization problems

As presented in the previous section, various optimization techniques help the energy system designers to find out the best solutions to their problems, among a set of possible alternatives and considering different criteria. In the simplest case, an optimization problem consists of maximizing or minimizing an objective function, systematically choosing input values within an allowed set and computing the value of the function.

Operations research provides advanced analytical methods to help researchers making better decisions [61]. Based on mathematical sciences, such as mathematical modelling, statistical analysis and mathematical optimization, operations research allows defining optimal or near-optimal solutions to complex decision-making problems. Because of its focus on practical applications, it is applied to various disciplines, like industrial engineering, operations management, economy and organization science [62]. Among various specific applications, operations research is used in the field of energy systems too [63].

The optimization of a generation energy systems consists of two major elements: pose the problem as a set of mathematical statements amenable to solution and define a strategy to solve the problem after it is posed.

The objective function of a general optimization problem (i.e. synthesis, design, and operation) can be written in the following standard form [20]:

$minimize_{x,w,z}\, F(x,w,z)$ subject to the constraints:

$h_i(x) = 0, \qquad i = 1,2\ldots,I$

$g_j(x) \leq 0, \qquad j = 1,2\ldots,J$

Where:

- x represents the set of independent variables for operation optimization (load factors of components, mass flow rates, pressures and temperatures of streams, etc.);
- w represents the set of independent variables for design optimization (nominal capacities of components, geometry, mass flow rates, pressures and temperatures of streams, etc.);
- z represents the set of independent variables for synthesis optimization. There is only one variable of this type for each component, indicating whether the component exists in the optimal configuration or not; it may be a binary (0 or 1), an integer, or a continuous variable such as the rated power of a component, with a zero value indicating the non-existence of a component in the final configuration;
- $h_i(x)$ represents the equality constraint functions, which constitute the simulation model of the system and are derived by an analysis of the system (energetic, exergetic, economic, etc.);
- $g_j(x)$ represents the inequality constraint functions corresponding to design and operation limits, state regulations, safety requirements, etc.

Several objectives pertinent to energy systems can be written in the general form of the above equation. For example, F can be the fuel consumption, exergy destruction, annualized cost of owning and operating the system, life-cycle cost (including environmental considerations, if needed), etc. Multi-objective optimization can also be written in the same form, but only if the various objectives are combined into one objective function by means of weighting factors.

A set of x, w and z that satisfies all the constraints $h_i(x)$ and $g_j(x)$ represents a feasible solution for the problem. $h_i(x)$ and $g_j(x)$ are in general nonlinear and so the process that brings to identify a feasible solution could be computationally very onerous.

For a given synthesis (structure) of the system, i.e. for given z, the optimization problem becomes one of design and operation:

$$minimize_{X,W}\ F'(x,w)$$

Furthermore, if the system is completely specified (both z and w are given), then an operation optimization problem is indicated:

$$minimize_{X}\ F''(x)$$

The designers of energy systems are required to simplify complex tasks and to find a solution as close as possible to the reality, without affecting the boundary conditions of the analysis. The difficult part of the optimization is therefore related to simplify the formulation of the problem, implementing for example: a linearization of objective function and constraints, a relaxation of constraints, a reduction of the dimension of the search space, an assumption of continuous nature of components and a simplification of the time variability of loads. These approaches allow solving the optimization problems using traditional mathematical programming algorithms (e.g. MILP). Nevertheless, a complexity limit may be reached anyway and the techniques may not be applicable to any kind of problem [64].

3.3 Distributed energy systems

Designers of energy supply systems are confronted with a variety of options and the first issue is the choice between a centralized or decentralized system.

Conventionally, power plants have been large, centralized units. Opposite, decentralized energy generation means that single buildings can be completely self-supporting in terms of electricity, heat, and cooling energy. This latter principle has already been applied, for example, in hospitals that are very dependent on the reliability of electricity supply, e.g. [65]. It is hard to imagine a situation where the total electricity consumption of a country is covered by a single power plant and, on the other hand, the return to complete self-sufficiency in terms of energy seems to be improbable.

An energy system is thus unlikely going to be completely centralized or completely decentralized, but it is probably going to be somewhere in between, creating a system where centralized and decentralized sub-systems operate parallel to each other and where the attention increasingly focus on sustainability aspects of the system, such as energy efficiency, reliability and environmental impacts. The result is the distributed energy generation, a system that combines the advantages of the two configurations: energy conversion units are situated close to consumers, and large production plants continue to supply their services (energy vectors) through distribution lines [66].

A distributed generation system is also increasingly required to focus on sustainability aspects, such as flexibility, reliability and environmental impacts. The flexibility is associated with the scalability and the ability to utilize various energy conversion technologies and fuels. An improvement can be seen also in the reliability of energy supply because of the tendency to share the total load between more than one production units. This is related to their ability to operate in networks and utilize local resources too. In addition, they are environmental-friendly because of the absence of large power plants and transmission lines.

On the other side, the drawbacks of distributed energy generation are mainly associated with the fact that they are fragmented: there are problems to be solved linked to the questions of responsibility, the compatibility of single units and also the lack of common standards and laws.

Figure 3.1 shows an example of distributed energy system with centralized production units, transmission grids and local energy producers and consumers.

Table 3.1 summarizes benefits and drawbacks of a distributed generation system.

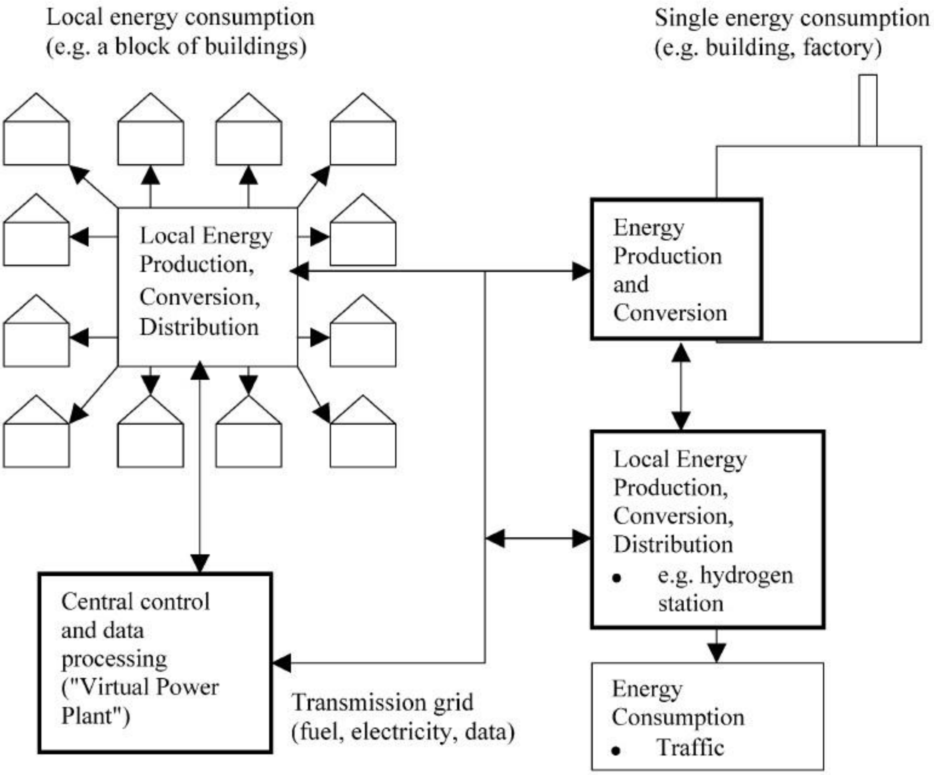
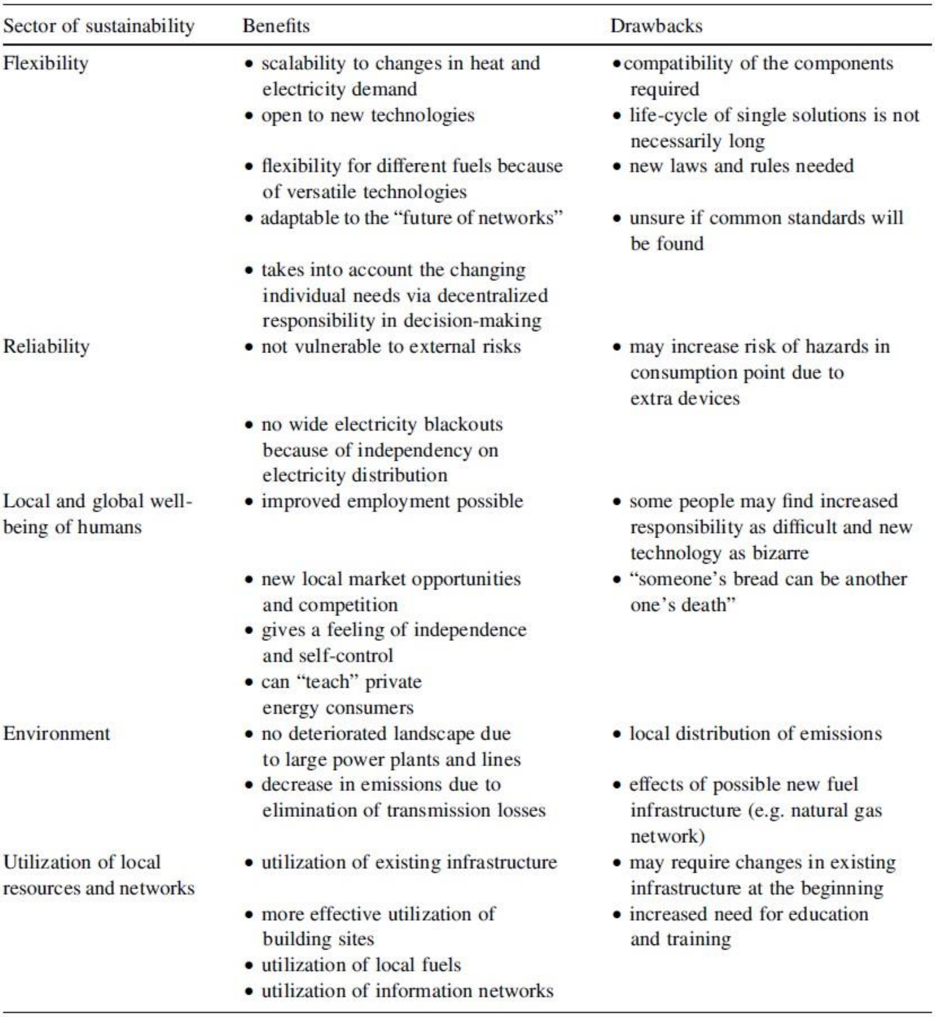


Figure 3.1 - An example of distributed energy system [66]



Sector of sustainability	Benefits	Drawbacks
Flexibility	• scalability to changes in heat and electricity demand	• compatibility of the components required
	• open to new technologies	• life-cycle of single solutions is not necessarily long
	• flexibility for different fuels because of versatile technologies	• new laws and rules needed
	• adaptable to the "future of networks"	• unsure if common standards will be found
	• takes into account the changing individual needs via decentralized responsibility in decision-making	
Reliability	• not vulnerable to external risks	• may increase risk of hazards in consumption point due to extra devices
	• no wide electricity blackouts because of independency on electricity distribution	
Local and global well-being of humans	• improved employment possible	• some people may find increased responsibility as difficult and new technology as bizarre
	• new local market opportunities and competition	• "someone's bread can be another one's death"
	• gives a feeling of independence and self-control	
	• can "teach" private energy consumers	
Environment	• no deteriorated landscape due to large power plants and lines	• local distribution of emissions
	• decrease in emissions due to elimination of transmission losses	• effects of possible new fuel infrastructure (e.g. natural gas network)
Utilization of local resources and networks	• utilization of existing infrastructure	• may require changes in existing infrastructure at the beginning
	• more effective utilization of building sites	• increased need for education and training
	• utilization of local fuels	
	• utilization of information networks	

Table 3.1 - Pons and cons of a distributed energy system [66]

4

MILP model of the industrial energy supply system

This chapter presents in detail the optimization model of the energy supply system under analysis. The optimization model helps the designers to determine the best configuration and operation of an energy system developed to supply electricity and heat to nine factories that belong to the Ponte Rosso Industrial Area of San Vito al Tagliamento (Italy). The energy demands of the users can be satisfied by centralized or decentralized CHP units and conventional boilers, and by ST modules and PV collectors. All the factories are connected together through a DHN and they can purchase electricity from the national grid as well as sell it. The algorithm used to solve the system optimization is based on a MILP model and the objective function to be minimized represents the total annual cost for purchasing, operating and maintaining the system. Due to the interactions between the various components, it is not possible to optimize the single units separately. The solution has therefore to be obtained by the simultaneous optimization of the whole energy supply system.

The complete MILP model of the industrial energy supply system developed in the thesis can be found in Appendix A.

4.1 Definition of the problem

The first phase when developing an optimal energy system is to define the problem that has to be solved. This step requires collecting as much information as possible about the specific problem: users' information, technical information of components, market information. The second phase is defining an optimization model which properly describes the system from a technical, economic and environmental point of view. At this point, the designer can perform the optimization, which ends with the identification of a final solution that responds to the needs of the research.

The model and the optimization procedure proposed in the following sections are rather general and can be adapted to different real problems, changing only the input data that characterize the specific case studies under investigation.

4.1.1 Users' information

All the users' information that characterize the optimization problem need to be gathered and organised. Those information can be grouped in three categories:

- Geographic location. It is important to evaluate the production of ST and PV collectors. Some useful information are: solar radiation, temperature, latitude, longitude, azimuth, natural obstacles, ground reflection etc. It is also necessary to calculate the distances between various users and to define the possible paths of the DHN.
- Humidity and temperature. Somehow related to the previous set of information, these data are required if the efficiencies of the components of the superstructure are affected by temperature and humidity.
- Energy demands. Electricity and heating demands represent the energy requirement of the users and are considered constant in each time interval of one hour. Hourly demand data are needed in order to accurately analyse and optimize the energy system. The best case is when the energy demands of the users are obtained directly through energy audits. However, sometimes demand data are available only on a monthly basis. In this case, demand energy trends can be estimated knowing the specific use, activity or process performed in the building during the day.

Due to the variability of the energy demands, hourly based optimization is recommended to accurately analyse and simulate the energy supply system. On the other hand, working with a lot of data requires very high or unfeasible computational time expenses. To overcome this problem, the most common practice is to reduce the number of hours used in the optimization procedure, considering only a set of representative days. Mitchell et al. [67], Domínguez-Muñoz et al. [68] and Ortiga et al. [69] presented procedures to reduce a full year of demand data to a few representative days that adequately preserve significant characteristics, such as peak demands, load annual load versus time curves etc. In order to reduce the variables number and the model complexity, the whole year is therefore represented by twelve typical weeks (1 week per month), each composed of seven days of 24 hours, for a total of 2016 time intervals. This kind of discretization allows keeping a realistic picture of the actual annual behaviour of the whole system.

4.1.2 Technical information

Technical information refer to all the components which may potentially be included in the final optimal energy system. The set of information required are:

- Relation between fuel and product. It can be represented by a single number (if it does not depend on the component load, e.g. constant efficiency), or can be represented by a characteristic curve. This relation could also depend on the ambient temperature and humidity.
- Relation between product and sub-products. As the previous relation, it can be represented by a single number or by a curve and it describes the relations between the main product of a system and its sub-products, which normally are products of second relevance. For example, for a CHP machine the main product is the electricity while the heat energy is considered as a sub-product.
- Maintenance costs. They can be either fixed (e.g. cost for annual maintenance of the component) or variable, when depend on the output produced.
- Technical limits. Load limits account the possibility of the components to operate at full or partial load, while size limits bound the size of the installed equipment.
- Technical constraints. They represent as all the technical constraints of the components that need to be considered when the model is defined. Examples are the heat losses of the HS and the DHN.
- Investment cost. The investment cost of a component depends on the size of the machine itself. If its size is pre-determined then the investment cost is a fixed single number. Otherwise, if the component has a variable size the investment cost depends on its size.
- Life span. It represents the technical life of a component. After that period the component is expected to be substituted by a new one, because of its obsolescence. The most of the time in fact the equipment is still able to perform its work after the life span, but with a considerable lower efficiency.

4.1.3 Boundary information

All the information not covered in the two previous categories are considered boundary information of the energy system:

- Market energy prices. These are the costs of the electricity (bought and sold) and of the different fuels used to power the machines.
- Incentives. They can be either fixed or depending on the output produced. Fixed incentives are generally recognized in the form of non-refundable subsidies and represent a capital cost reduction on the purchased of the appliance. Other incentives can instead be related to the quantity of products (e.g. energy produced with PV panels) or to the amount of fuels (e.g. fuel used to power cogenerators) and affect the operating annual cost.
- GHG emissions. They include the emissions related to the electricity purchased from the grid (through the electricity greenhouse emission coefficient that depends on the national electricity system) and the CO_2 emissions produced with the combustion of fossil fuels (that depend on the type and origin of each fuel).
- Interest rate. The interest rate is made of two factors: one is related to the current cost of money and the other represents the investment risk. In this thesis the interest rate is equal to 7%.
- Weight of representative hours. The weight depends on the strategy adopted to determine the representative hours. The whole year is represented by 2016 time intervals and the actual year is supposed to be made of 12 identical months of 28 days (i.e. each month made of 4 weeks). Therefore, under these assumptions, each hour of the model represents 4 real hours.

4.2 Definition of the MILP model

Once the problem is settled with all the necessary information, the designer of the energy supply system can move to the definition of the optimization model that represents the system itself. The mathematical problem of optimizing the design and operation of an energy system has to be generally considered as a variational calculus problem because several decision variables describing the components of the system are time dependent. However, a realistic description of the system can be represented by a MILP formulation, properly discretizing all dynamic variables in quasi-stationary variables and approximating all non-linear relations in a set of linear functions ([70] [71] [72] [73]).

4.2.1 System superstructure

The first step to the definition of an optimization model is to define a superstructure: a representation of the system that encompass every single machine and component which can appear in the final optimal configuration.

The superstructure of the energy supply system of case study under investigation is represented in Figure 4.1. The supply system has to provide the heating and electric energy needed by a set of industrial users. The superstructure can be seen as made of two parts: the one related to a generic user (i.e. *Site k* in the figure) and the one associated to the central production unit, at the right side of the figure. The green and red lines represent the physical distributions of the electric and heating energy respectively, while the orange arrows represent the fuel inputs. The electricity can be produced by CHP units, both centralized and decentralized (placed in the users' side), and by a central solar PV field or it can be purchased from the external grid. The surplus electricity can also be sold to the national grid. The required heating energy can be produced by CHP units, again centralized and decentralized, by conventional boilers, both centralized and decentralized (placed in the users' side), and by a central ST field. The surplus heating energy can also be stored in a HS and used when necessary. Looking at the superstructure, a general user may include only a cogenerator and a boiler (BOI), while in the central unit a cogenerator, a boiler, the HS, the ST modules and the PV panels may be installed. The users are connected together and to the central unit through a DHN of predefined layout and design. As the DHN connects all the factories together, the available heating energy can be consumed, exchanged between the users or sent to the HS. The electricity produced in the central unit by the internal combustion engine (ICE) can only be sold to the national electric grid, while the PV energy generated can be either sold or send to the users. This last assumption about the PV system is a model simplification because an internal electric network is actually not expected. Therefore the central PV field can be practically seen as a set of various smaller PV modules installed in each user side.

The superstructure of the energy model is specifically created by the designer of the case study under analysis, but it can be easily modified eliminating or adding other components. Also the number of users is not defined a priori by the superstructure as the proposed methodology is modular and can be applied to various contexts or sectors. However, the maximum number of users that can be included in the optimization is limited by the computational effort required to the calculator, which is quadratic whit the overall number of decision variables.

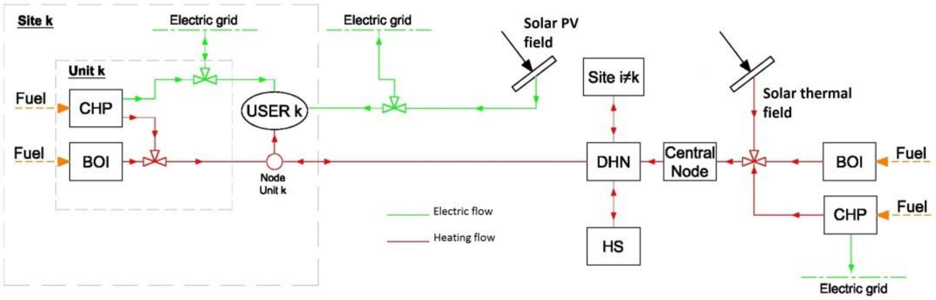


Figure 4.1 - Superstructure of the energy supply system

4.2.2 Decision variables

The decision variables of the optimization model can be grouped in two main categories:

- Binary variables: represent the existence/absence of each component and the operation status (on/off) of each component in each time interval. Other additional binary variables do not represent any physical quantity, but are added to linearize some relations.
- Continuous variables: represent the equipment's size, all the energy flows and the components' load in each time interval, and the energy stored in the HS.

In the following equations the decision variables are written whit bold characters, while the other remaining terms are data or values obtained as results of calculations. The index *h* represents the time interval and *u* the user.

4.2.3 Model constraints

The constraints specify the behaviour of the energy system. Equality constraints describe the performance characteristics of the equipment, which are the links between input (fuel), product (electricity) and sub-product (heat). Other important equality constraints are the energy balances that, for each node of the superstructure and for each time interval, regulate the direction of the energy flows. Inequality components' constraints define load and size limits of the components. Other inequality constraints represent operation restrictions and feasibility conditions. Moreover, a set of inequality constraints are added in order to guarantee a correct electricity and heat transfer between users, DHN and electric grid. In the following pages the constraints of the model are presented, grouped in four categories: components, DHN, HS and energy balances. The DHN and the HS are components too, but, due to their particular characteristics, they are presented separately from the rest of the system's components.

Components

The components' constraints relate the output to the input and introduce size and load limits. All the components of the superstructure have variable sizes and only one machine can be installed in each production unit.

Equation 4.1 and 4.2 describe the size limits of the users' CHP systems. Equation 4.3 and 4.4 specify the operating and existence conditions of the same cogenerators. The central unit ICE is represented by the same equations just adding the acronym *cu* (i.e. central unit) to the variables' names.

$$\boldsymbol{S\_cog}(u) \geq 0 \tag{4.1}$$

$$\boldsymbol{S\_cog}(u) \leq S\_cog\_max(u) \cdot \boldsymbol{ex\_cog}(u) \tag{4.2}$$

$$\boldsymbol{op\_cog}(h,u) \leq \boldsymbol{ex\_cog}(u) \tag{4.3}$$

$$\boldsymbol{ex\_cog}(u) \leq \boldsymbol{S\_cog}(u) \tag{4.4}$$

Equations 4.5 and 4.6 calculate the heat produced and the fuel consumed by the users' cogenerators from of the electric output. The equations represent the characteristic curves of the ICEs and the coefficients *h* and *f* are obtained through the linear regression of the performance data of the motors. The same equations are valid for the central unit cogenerator as before.

$$\boldsymbol{H\_cog}(h,u) = h_1 \cdot \boldsymbol{E\_cog}(h,u) + h_2 \cdot \boldsymbol{op\_cog}(h,u) \tag{4.5}$$

$$\boldsymbol{F\_cog}(h,u) = f_1 \cdot \boldsymbol{E\_cog}(h,u) + f_2 \cdot \boldsymbol{op\_cog}(h,u) \tag{4.6}$$

Equations 4.7 and 4.8 calculate the electric energy output of the users' ICEs.

$$\boldsymbol{E\_cog}(h,u) \geq out\_cog\_lim \cdot \boldsymbol{S\_cog}(u) \cdot \boldsymbol{op\_cog}(h,u) \tag{4.7}$$

$$\boldsymbol{E\_cog}(h,u) \leq \boldsymbol{S\_cog}(u) \cdot \boldsymbol{op\_cog}(h,u) \tag{4.8}$$

The equations entail the multiplication of two variables (one continuous and one binary), thus introducing a nonlinearity problem. The two nonlinear equations need therefore to be linearized as the algorithm is mixed integer linear. A standard linearization technique is used in the model [74] and is described in the following lines.

$P = x \cdot y \quad \forall \quad x_{min} \leq x \leq x_{max} \quad and \quad y \in \{0,1\}$ is linearized as:

$x - x_{max} \cdot (1 - y) \leq p \leq x - x_{min} \cdot (1 - y) \quad and \quad x_{min} \cdot y \leq y \leq x_{max} \cdot y$

According to the proposed linearization method, Equations 4.7 and 4.8 become:

$$\boldsymbol{E\_cog}(h,u) \geq 0 \tag{4.9}$$

$$\boldsymbol{E\_cog}(h,u) \geq out\_cog\_lim \cdot (\boldsymbol{S\_cog}(u) - (S\_cog\_max(u) \cdot (1 - \boldsymbol{op\_cog}(h,u)))) \tag{4.10}$$

$$\boldsymbol{E\_cog}(h,u) \leq \boldsymbol{S\_cog}(u) \tag{4.11}$$

$$\boldsymbol{E\_cog}(h,u) \leq S\_cog\_max(u) \cdot \boldsymbol{op\_cog}(h,u) \tag{4.12}$$

Again, the same set of equations is representative also for ICE installed in the central production unit.

Size limits, operating and existence conditions of boilers are represented in the model with the same equations used for the CHP machines. The only difference is the working characteristic of the boilers which is not a performance curve anymore, but heat produced and fuel consumption are simply related by the thermal efficiency of the BOI (η), as shown in equation 4.13.

$$\boldsymbol{F\_boi}(h,u) = \boldsymbol{H\_boi}(h,u) / \eta\_boi \tag{4.13}$$

The same equation is valid for the BOI of the central unit, identified by the addition of the acronym *cu*.

The ST and PV fields are modelled considering that their output energy is proportional to the size, in m^2, of the respective solar collectors. The hourly solar radiation is obtained by energy audits and the unitary outputs of the solar panels are calculated separately, according to the technical characteristic of the modules. The upper limit surface of the two solar fields ($20000 m^2$) is a boundary constraint that depends on the land available to install the collectors.

$$\boldsymbol{S\_pv} \geq 0 \tag{4.14}$$

$$\boldsymbol{S\_pv} \leq 20000 \tag{4.15}$$

$$\boldsymbol{E\_pv}(h) = \boldsymbol{S\_pv} \cdot pv(h) \tag{4.16}$$

$$\boldsymbol{H\_st} \geq 0 \tag{4.17}$$

$$\boldsymbol{S\_st} \leq 20000 \tag{4.18}$$

$$\boldsymbol{H\_st}(h) = \boldsymbol{S\_st} \cdot st(h) \tag{4.19}$$

District heating network

The DHN is a very important component in a centralized or distributed energy system because in such kinds of configurations it is likely that some users only rely on the heat supplied by external sources ([75] [76] [77] [78]). Moreover, the presence of the DHN heavily affects the whole operation of the system, as it connects all the utilities together. This is in fact one of the main reasons because the design and operation of the energy system have to be optimized simultaneously.

In the model, the DHN is seen as a transfer medium of heating energy from the production units to users. The layout of the network and the size of the pipelines are predefined and available from another research work conducted in the same industrial area [79]. The heat losses of the DHN are proportional to the amount of heat transferred by a fixed loss coefficient. According to a previous work of the author [80], the thermal inertia of the network is not included in the model, as it implies negligible effects on the optimal structure of the system.

The constraints of the DHN are thus reduced to an inequality equation that limits the flow rate in the pipes, according to their size, and a binary existence equation, whose value is pre-set by the designer according to the case study configuration.

$$\boldsymbol{ex\_net} = 1 \tag{4.20}$$

$$\boldsymbol{H\_net} \leq 12000 \tag{4.21}$$

The heating energy flowing in the network in the time interval h is calculated with equation 4.22 and is the sum of the heat coming from the central unit, from the HS, from the ST field and from the users.

$$\begin{aligned} &\boldsymbol{H\_net}(h) = \\ &\qquad \boldsymbol{H\_cog\_cu}(h) + \boldsymbol{H\_boi\_cu} + \boldsymbol{H\_st}(h) + \Sigma_u(\boldsymbol{H\_out}(h,u)) + \boldsymbol{H\_out\_sto}(h) \end{aligned} \tag{4.22}$$

Equation 4.23 describes the energy balance of the DHN: in each time interval h the input heating energy (***H_net***) is equal to the output one minus the heat losses. The energy leaving the network may be sent to the users or to the HS. The network heat loss coefficient (*k_net*) is 0.01 (i.e. 1% of the input energy to the DHN).

$$\boldsymbol{H\_net}(h) = (1 + k\_net) \cdot (\Sigma_u(\boldsymbol{H\_in}(h,u)) + \boldsymbol{H\_in\_sto}(h)) \tag{4.23}$$

Heat storage

Heat energy storages comprise several technologies which allow storing thermal energy for a later use. They can be employed either to decouple electric and heating demands or to balance the intermittent production of thermal energy, typical of solar energy systems. Therefore, they can be usefully coupled both with a CHP production unit and with a solar thermal system ([81] [82]).

HS in a CHP system is a very important measure applicable in large-scale DHN systems to enhance flexibility. In a system with CHP production units, there is one general problem that makes the use of thermal storage interesting: the fact that heat and power production are connected to each other, while the demand for these vectors are independent, meaning that the production has to follow one of the demands. Fluctuating heat load and electricity price at different time periods of the day have significant impacts on the operation of a cogenerator. 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 [83]. When the electricity price is high and the momentarily heat demand is low, the storage can be charged with excess heat from the CHP unit and this heat can be used later on. During summer time (in the north hemisphere), two conditions can appear simultaneously: very low heat demand and high electricity price. In this situation, it may be worth to generate electricity through CHP plants and dump the useless heat generated. With a seasonal HS it would be possible to run the CHP module and store the heat for a later use instead of dumping it. Moreover the electricity can generate revenues. Again, during summer time, for instance, the heat demand can be so low that the CHP plant must be shut down. In such circumstance, a 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: Using a HS, power generation can be increased and the use of fossil fuels reduced [84].

If renewable energy sources are considered, solar energy is an important alternative that will more likely be utilized in the future, and the HS 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 (in the north hemisphere). Small HS operates over short periods and can cover periods of inadequate sunshine, while large HS operates over long period and can partially cover the lower winter solar thermal production [85]. Many large scale solar district heating systems have been built in central and northern Europe [86]. They consist of large collector fields integrated into a DHN for supplying heat to residential and industrial areas. The sizes of those plants allow lower specific investment costs compared to small applications. When the system is coupled with seasonal heat storage it is possible to reach solar fraction of approximately 50% [87]. In a central SDH system the solar thermal field feeds in at the central node of the district heating network. The collector field is typically ground mounted in close connection to the heating plant, as well as the large long term storage. The most common collector types, utilized in SDH applications, are evacuated tubular collectors and flat plate collectors without vacuum. Concentrating collectors (e.g. parabolic trough, Fresnel, etc.) may also be used, but, since a large part of the annual irradiation is diffuse and these types do not utilize the diffuse part, they are not suitable for the application [88].

There are mainly four kinds of technologies employed worldwide as HS system. The decision to use a certain type of storage mainly relays on its heat capacity and on the geological condition of the site [89]:

- Tank HS. Water tanks can be either artificial constructs made of steel and concrete or geological cavities. Heat is transported to and from the tank by a flow of water going in and out of the tank, or by a fluid circulating in a heat exchanger inserted in the tank.
- Aquifer HS. 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 HS. Similar to tank HS, it 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 HS. It is a technology for storing thermal energy in underground geological formations. Hot or cold water is circulated in pipes set into boreholes.

In the optimization algorithm the HS is modelled accepting the approximation of the perfect stratification of the medium (water) inside the storage. This approximation corresponds to suppose that if the storage is not completely empty the residual energy is stored at the same temperature required by the DHN. The energy stored in the HS (H_{HS}) can be evaluated through the following relation, where ρ and c_p are respectively the density and the specific heat of water:

$$H_{HS} = V_{HS} \cdot \rho \cdot c_p \cdot \Delta t$$

The temperature difference (Δt) between inlet and outlet temperature is considered constant. Therefore, the energy stored in the HS is proportional to the volume of the medium inside the storage (V_{HS}).

The HS is a particular component because it operates continuously, meaning that its status at the generic hour *h* depends on what happened at the previous hour *h-1*. Thus, the energy balance of the HS considers that the energy stored in the time interval *h* is equal to the energy stored in the time interval *h-1* plus the input energy and minus the output energy and the thermal losses, all occurred in the time interval *h-1*. The thermal loss coefficient of the HS (*k_sto*) is a fixed percentage of the hourly heat stored.

$$\boldsymbol{H\_sto}(h) = \boldsymbol{H\_sto}(h-1) + \boldsymbol{H\_in\_sto}(h-1) - \boldsymbol{H\_out\_sto}(h-1) - k\_sto \cdot \boldsymbol{H\_sto}(h-1) \tag{4.24}$$

Other constraints have to be added in the model in order to limit the amount of heat stored, according to the size of HS, and in order to limit the energy exchanged with the DHN.

$$\boldsymbol{S\_sto} \geq 0 \tag{4.25}$$

$$\boldsymbol{H\_sto}(h) \leq \boldsymbol{S\_sto} \tag{4.26}$$

$$\boldsymbol{H\_out\_sto}(h) \leq \boldsymbol{H\_sto}(h) \tag{4.27}$$

$$\boldsymbol{H\_in\_sto}(h) \leq \boldsymbol{H\_net}(h) \tag{4.28}$$

Additional constraints are necessary to regulate the heat exchanged between the HS and the DHN. In particular, they are introduced to avoid that in the same time interval *h* the HS both receives and supplies heat from/to the DHN.

Energy balances

Energy balances are very important equality constraints and represent the heating and electric behaviour of the system. For each time interval and for each node, they ensure that the input energy is equal to the output one.

Equation 4.29 represents the thermal balance of the central unit. The total heat produced by the central unit and sent to the DHN is the sum of three elements: the cogenerated heat, the heat from the BOI and the heat from the ST field.

$$H\_out\_cu(h) = \boldsymbol{H\_cog\_cu}(h) + \boldsymbol{H\_boi\_cu} + \boldsymbol{H\_st}(h) \tag{4.29}$$

Equation 4.30 and 4.31 represent the electric balances of the central unit. All the cogenerated electricity is sold to the electric grid, while the photovoltaic electricity from the PV field can be either self-consumed by the users or sold to the national grid.

$$\boldsymbol{E\_cog\_cu}(h) = \boldsymbol{E\_sel\_cu}(h) \tag{4.30}$$

$$\boldsymbol{E\_pv}(h) = \boldsymbol{E\_sel\_pv}(h) + \Sigma_u(\boldsymbol{E\_pv\_u}(h,u)) \tag{4.31}$$

Equation 4.32 represents the thermal balance of the users. The sum of the cogenerated heat, the heat from the BOI and the heat from the DHN equalize the sum of the heating demand, the heat sent to the DHN and the dissipated heat. Certain dissipation is necessary to make the model feasible.

$$\boldsymbol{H\_cog}(h,u) + \boldsymbol{H\_boi}(h,u) + \boldsymbol{H\_in}(h,u) = H\_dem(h,u) + \boldsymbol{H\_out}(h,u) + \boldsymbol{H\_dis}(h,u) \tag{4.32}$$

Equation 4.33 represents the electric balance of the users. The cogenerated electricity plus the electricity from the PV field and the purchased electricity equalize the sum of the electric demand and the sold electricity.

$$\boldsymbol{E\_cog}(h,u) + \boldsymbol{E\_pv\_u}(h,u) + \boldsymbol{E\_buy}(h,u) = E\_dem(h,u) + \boldsymbol{E\_sel}(h,u) \tag{4.33}$$

Additional relations are added to the model in order to regulate the heat exchanged between users and DHN and the electricity flows. Specifically:

- a user cannot sell and purchase electricity in the same time interval;
- a user cannot purchase electricity and receive PV energy in the same time interval;
- a user cannot sell more electricity than the amount he produces;
- a user cannot receive and release heat from/to the DHN in the same time interval;
- a user cannot send more heating energy to the DHN than the amount he produces.

4.2.4 Objective function

The aim of the model is to minimize the total annual cost for owning, operating and maintaining the whole energy supply system. The objective function is:

$$minimize\ c\_tot = c\_inv + c\_ope + c\_man - SP \tag{4.34}$$

The annual investment cost is the sum of the purchasing cost of cogenerators, boilers, district heating network, solar thermal collectors, photovoltaic modules and heat storage, all multiplied by the respective amortization cost factor *f*. The amortization cost factor depends on the interest rate of capital *i* and on the life span *n* of each component.

$$\begin{aligned}
c\_inv = (cf\_cog \cdot (&\boldsymbol{ex\_cog\_cu} + \Sigma_u(\boldsymbol{ex\_cog}(u))) + \\
&cv\_cog \cdot (\boldsymbol{S\_cog\_cu} + \Sigma_u(\boldsymbol{S\_cog}(u)))) \cdot f\_cog + \\
&(cf\_boi \cdot (\boldsymbol{ex\_boi\_cu} + \Sigma_u(\boldsymbol{ex\_boi}(u))) + \\
&cv\_boi \cdot (\boldsymbol{S\_boi\_cu} + \Sigma_u(\boldsymbol{S\_boi}(u)))) \cdot f\_boi + \\
&c\_net \cdot \boldsymbol{ex\_net} \cdot f\_net + \\
&c\_sto \cdot \boldsymbol{S\_sto} \cdot f\_sto + \\
&c\_st \cdot \boldsymbol{S\_st} \cdot f\_st + \\
&c\_pv \cdot \boldsymbol{S\_pv} \cdot f\_pv
\end{aligned} \tag{4.35}$$

$$f = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{4.36}$$

The annual operating cost is the sum of the expenses for fuel and electricity minus the revenue from the sale of electricity.

$$c\_ope = p\_gas\_cog \cdot E\_cog\_tot + p\_gas\_boi \cdot H\_boi\_tot + p\_buy \cdot E\_buy\_tot - p\_sel \cdot E\_sel\_tot \quad (4.37)$$

The maintenance cost of the equipment is proportional to the amount of energy produced (heat or electricity) by the machines.

$$c\_man = m\_cog \cdot E\_cog\_tot + m\_boi \cdot H\_boi\_tot \quad (4.38)$$

SP is the support policy of the incentivized cases, that is the price for the society to achieve a certain benefit. It is obtained multiplying the value of the incentive *I* by the amount of resource saved or produced (e.g. the rate of pollutant emissions saved or the quantity of energy produced from renewable technologies).

An important economic parameter used to assess the profitability of an investment is the payback period (*PB*), which is calculated compared with the conventional reference energy supply system.

4.3 Future perspectives

There are some interesting perspectives which might be considered in the next future to extend and continue the research work developed in the thesis.

A possible integration concerns the evaluation of the cooling consumption of the energy users and therefore the analysis of specific equipment dedicated to meet the cooling demand, such as compression chillers, heat pumps and absorption refrigerators. In particular the absorption technology is promising when included in an integrated energy system because it gives the possibility to utilise the waste heat form production processes to power the absorption machine. The expected effect is a higher exploitation of the input source and thus a save of primary energy and a reduction of operating costs and pollutant emissions.

Another addition to the energy supply system might be the introduction of the biomass as energy source. Although the problem requires an accurate analysis, using the biomass as input fuel of a combined heat and power unit is expected to present two important advantages: a relatively lower fuel cost compared to natural gas and a very low environmental impact. While the environmental benefit is undoubtedly evident, being the biomass a renewable energy source, the economic aspect of the problem needs to be properly evaluated: a significant portion of the supply cost of the biomass is in fact represented by logistic cost (harvest, transport, treatment etc.) as the production one is almost negligible. The optimization of the biomass supply chain highly depends on the characteristic of the territory (i.e. the availability of the biomass) and it has to be performed before the optimization of the energy system.

One last suggestion to continue the research work of the thesis is to extend the optimization to a supervision level, developing a system control strategy. The purpose is to define an integrated management system which allows the controller to obtain the optimal operation of all the components of the energy system considering their dynamic behaviour.

5

Case study

The chapter presents all the information about the case study object of the investigation. The information include: users' location, factories' energy demands, technical data of all machines and components of the superstructure, market energy prices and economic support schemes.

5.1 Users' location and energy demands

The study considers nine factories of the Ponte Rosso Industrial Area located in San Vito al Tagliamento - Italy (latitude 45°56.42', longitude 12°52.20'). The region presents the typical climate of a continental European country with an average yearly solar radiation of about 1200kWh/m^2 [90].

The nine users belong to different economic sectors: plastic, food, furniture, engineering and tertiary. Their electric and heating demands are evaluated by means of energy audits presented in another research work [79]. The model simulation is approximated considering one typical week of seven days (of 24 hours) per month, for a total of 2016 representative hours. Supposing that a year is made of twelve months of four weeks each (i.e. 28 days per month), every single hour of the model represents four real hours.

Figure 5.1 shows a plan view of the whole industrial area. The blue line represents the layout of the main district heating network, which supply heating energy to the users. The locations of the nine factories are marked by red spots, while the yellow area indicates the space available for positioning the central unit, the solar fields and the heat storage.

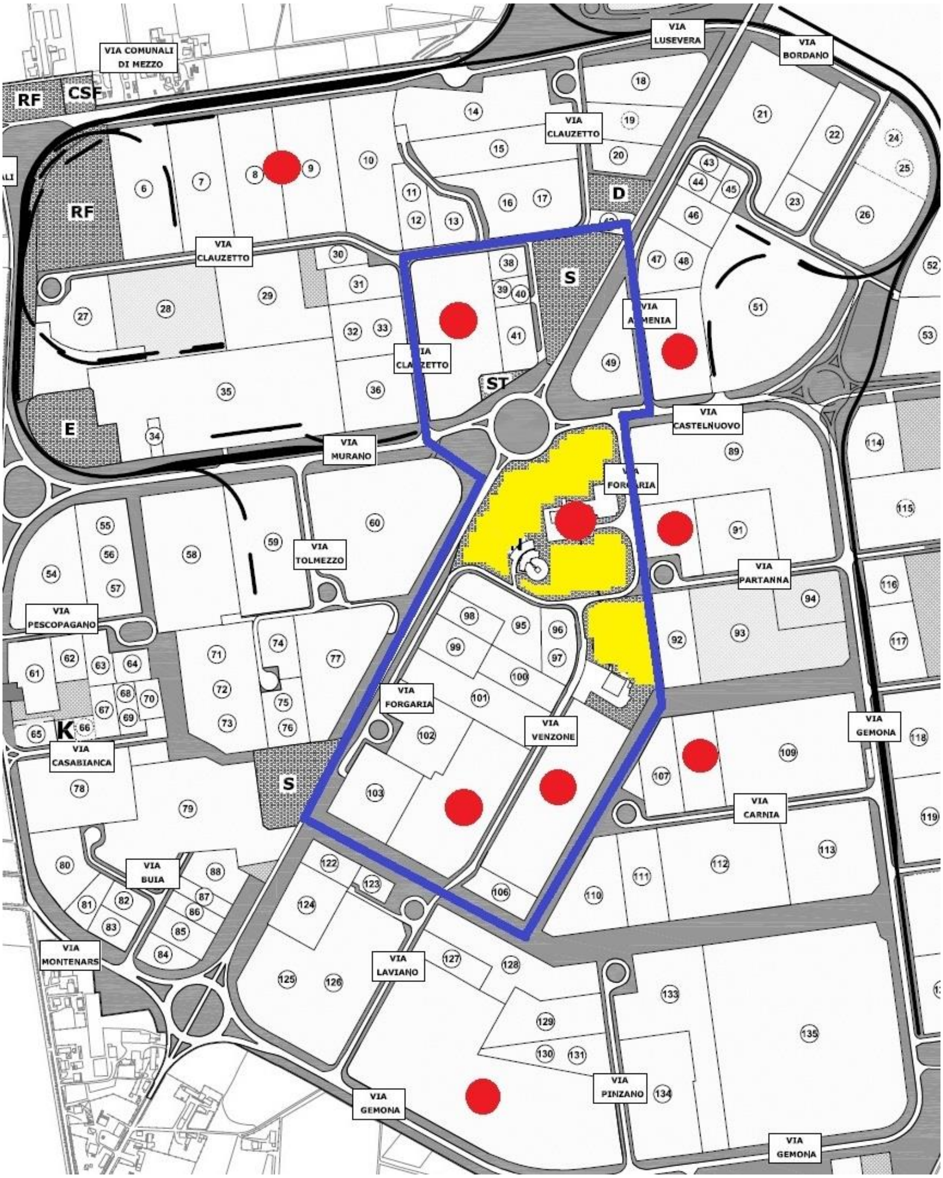


Figure 5.1 - Plan view of the industrial area

Despite the heterogeneity of the goods produced, the energy consumptions of the factories show quite regular trends along the year. Figure 5.2 shows the annual aggregated electric and heating load versus time curves of the nine users. Electric load (light green continuous line) is higher than zero all year round. This is because a certain amount of electricity is always required, even when factories are closed. Heating load (dark red dotted line) is higher than zero for about 7000 hours, higher than 2 MW for almost 6000 hours and higher than 4 MW for almost 3000 hours. The load versus time curves of the single factory are used to determine the size limits of the cogenerators installed in each production unit.

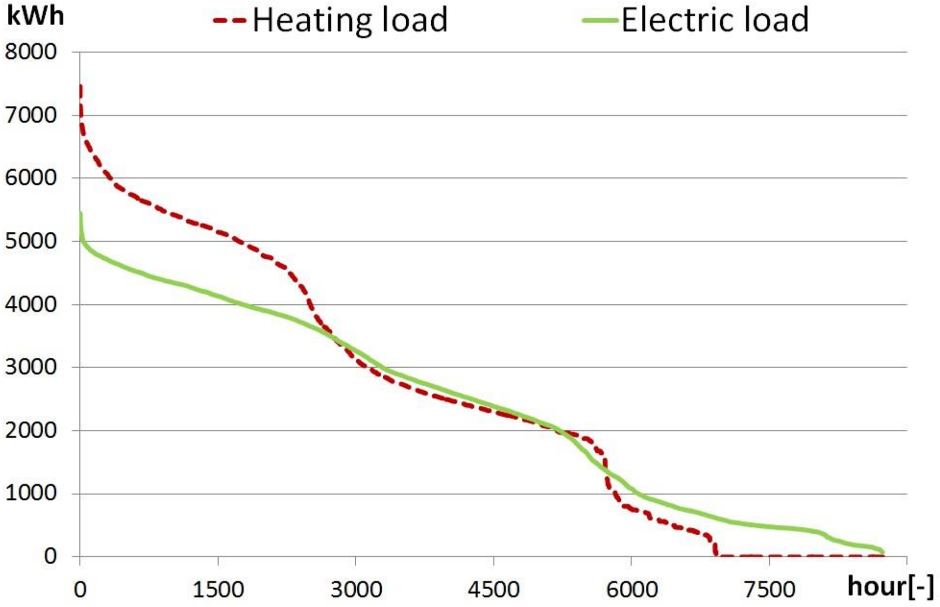


Figure 5.2 - Aggregated load versus time curves

Figure 5.3 shows the aggregated electric demand of the nine users in a typical winter (light blue continuous line) and summer (dark red dotted line) week. The profile is quite predictable: peaks during intensive working hours, low consumption during nights and very low demand in the weekend when the most of the factories are closed. The two trends are very similar; the difference is a higher consumption in summer because of the electricity required to power the air conditioning systems of the factories.

Figure 5.4 shows the aggregated heating demand of the nine users in a typical winter (light blue continuous line) and summer (dark red dotted line) week. It can be seen that heating load is slightly higher during coldest months, when space heating is operating. The Saturday's heat consumption is very small, while on Sunday neither process heat nor space heating is required.

Figure 5.3 and Figure 5.4 show that the energy demands of the users are just slightly affected by seasonal factors. That is because what characterize the electric and heating consumptions of the factories are clearly their daily activities.

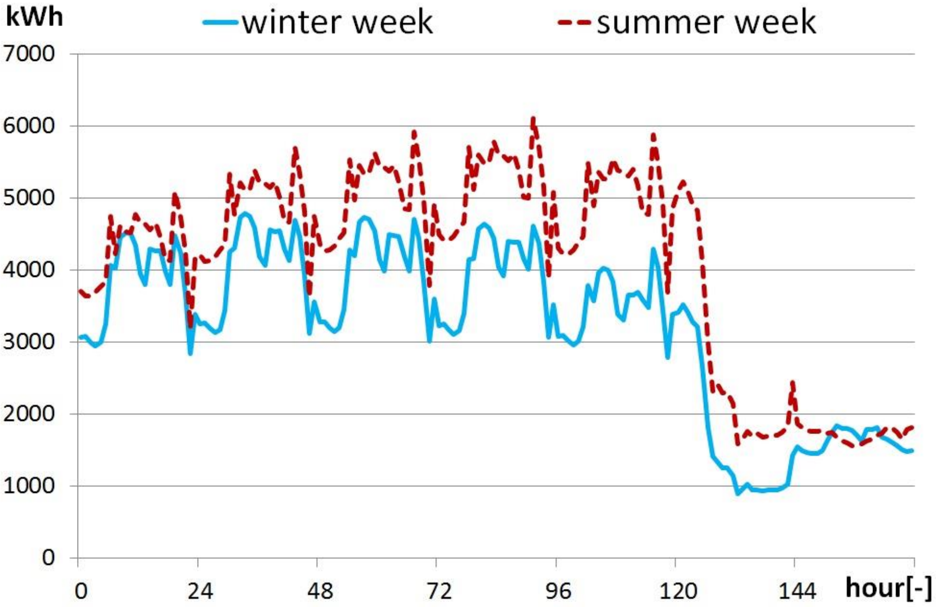


Figure 5.3 - Aggregated electric weekly demand

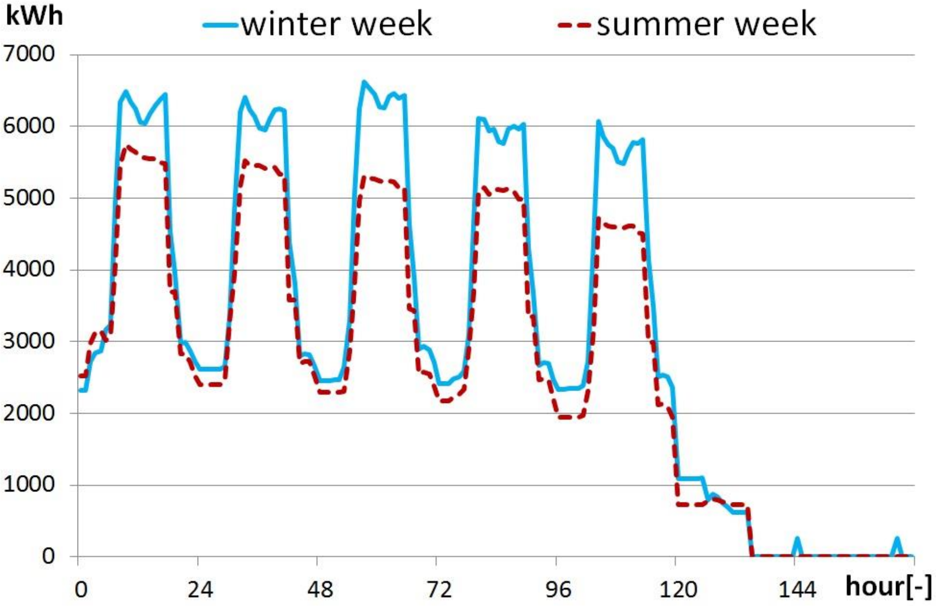


Figure 5.4 - Aggregated heating weekly demand

Table 5.1 shows the peak power consumption and the yearly energy demand of each user, for both electric and heating loads. Total peak power is the actual maximum hourly energy demand of the all users and it is lower than the sum of the single users' peaks because they do not appear simultaneously.

	ELECTRIC		HEATING	
	Peak power [kW]	Year demand [MWh]	Peak power [kW]	Year demand [MWh]
User 1	501	1169	561	434
User 2	951	1718	0	0
User 3	825	1553	891	950
User 4	754	1582	996	1650
User 5	799	2936	749	864
User 6	14	57	189	120
User 7	706	2631	1556	3667
User 8	987	3679	3720	13438
User 9	1313	4892	92	62
TOTAL	5239	20217	7083	21185

Table 5.1 - Users' energy demands

5.2 Superstructure's components data

The technical characteristics and the prices of the equipment included in the superstructure are presented in this section. All the components are commercially available and their technical data and prices are obtained from different sources: data sheets from machines' producers, literature and market surveys.

5.2.1 Combined heat and power units

The prime movers of the CHP modules are Caterpillar internal combustion engines powered by natural gas. The main parameters of the engines are taken from machines' data sheets [91] and are reported in Table 5.2. Their nominal sizes vary in the range 370kW-3.5MW, while the upper and lower size limits of each CHP unit of the MILP model depend on the users' demands and are listed in Table 5.3. The linear regression of electric output and thermal output data gives the coefficients *h1* and *h2*, while the linear regression of electric output and energy input (i.e. fuel) data gives the coefficients *f1* and *f2* used in the optimization model. Figure 5.5 shows the two characteristic curves of the ICEs and their linearization. The thermal energy is recovered at a temperature of 99°C through a heat exchanger from exhaust gases and engine cooling circuit. As the ICEs are variable size components, their investment cost is calculated by a linear relation made of a fixed cost part and a variable cost part that depends on the size of the selected machine. The values of these two parameters are taken from [92] and are reported in Table 5.4, together with the partial load limit of the cogenerators (*out_cog_lim*) and the maintenance cost, which is proportional to the amount of electricity produced.

CATERPILLAR MODEL	ENERGY INPUT [kW]	ELECTRIC OUTPUT [kW]	ELECTRIC EFFICIENCY [%]	THERMAL OUTPUT [kW]	THERMAL EFFICIENCY [%]
G3412	1052	370	0.352	493	0.469
G3508	1442	480	0.333	667	0.463
G3512	2115	770	0.364	932	0.441
G3516	2665	975	0.366	1229	0.461
G3156B	3056	1165	0.381	1428	0.467
G3520B	3886	1460	0.376	1731	0.445
G3516C	4057	1585	0.391	1804	0.445
G3520C	5019	2000	0.398	2134	0.425
G3612TA	6341	2584	0.408	2604	0.411
G3616TA	8400	3446	0.410	3436	0.409

Table 5.2 - Internal combustion engines' data [91]

	LOWER SIZE LIMIT [kW]	UPPER SIZE LIMIT [kW]
S_cog_cu	95	7335
S_cog_1	80	501
S_cog_2	45	951
S_cog_3	30	825
S_cog_4	30	788
S_cog_5	30	799
S_cog_6	0	0
S_cog_7	30	1229
S_cog_8	30	2933
S_cog_9	30	1313

Table 5.3 - Cogenerators' size limits

Partial load limit	40%
Fixed cost [€]	130000
Variable cost [€/kWh]	730
Maintenance cost [€/kWh]	0.017

Table 5.4 - Cogenerators' data

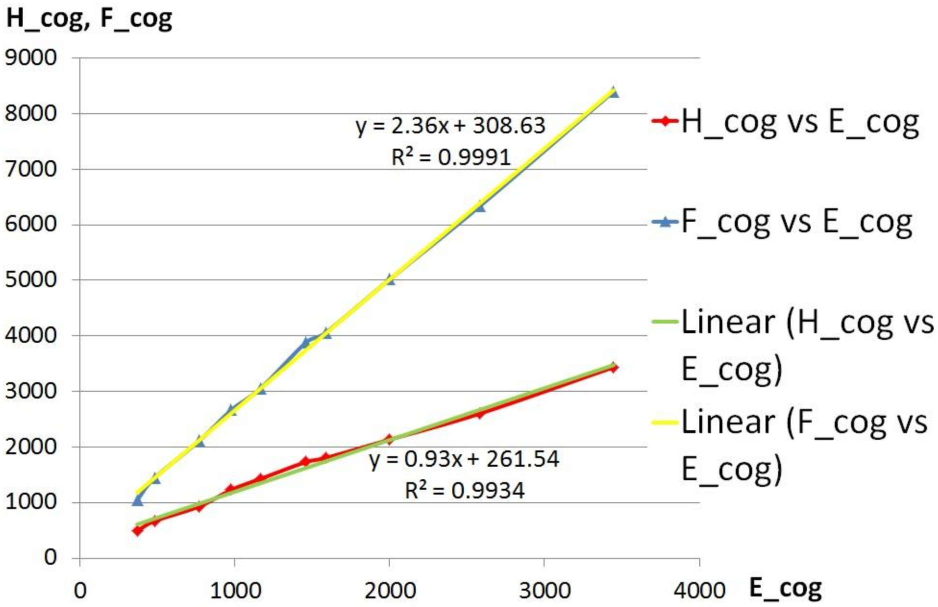


Figure 5.5 - Characteristic curves of the ICEs

5.2.2 Boilers

Boilers' operation depends only on their energy efficiency (*η_boi*) which is equal to 90%. The upper and lower size limits of each BOI of the model depend on the users' demands and are listed in Table 5.5.

	LOWER SIZE LIMIT [kW]	UPPER SIZE LIMIT [kW]
S_boi_cu	349	7083
S_ boi _1	61	561
S_ boi _2	0	0
S_ boi _3	63	891
S_ boi _4	23	996
S_ boi _5	21	749
S_ boi _6	18	189
S_ boi _7	834	1556
S_ boi _8	386	3720
S_ boi _9	16	92

Table 5.5 - Boilers' size limits

The maximum size of the central unit BOI is not the sum of the single boilers' maximum sizes, but is lower because not all the heating demand peaks occur simultaneously. As cogenerators, boilers are variable size machines too, whose sizes are chosen by the optimizer procedure. Therefore their investment cost is obtained through a fixed cost part and a variable cost part multiplied by the size of the boiler. Fixed cost, variable cost and maintenance cost (which is proportional to the heat produced) are taken from [92] and reported in Table 5.6 together with partial load limit.

Partial load limit	20%
Fixed cost [€]	6300
Variable cost [€/kWh]	18
Maintenance cost [€/kWh]	0.001

Table 5.6 - Boilers' data

5.2.3 Solar collectors

The ST and PV fields are modelled considering that their output energy is proportional to the size, in m^2, of the respective solar collectors. The hourly solar radiation is obtained by energy audits and the unitary outputs of the solar panels are calculated separately [93], according to technical characteristic of the modules and environmental parameters. The solar modules are south oriented and 38° tilted. This angle allows obtaining the maximum energy production distributed along the whole year. Other important parameters are: azimuth -2°, ground reflection coefficient 0.22 and absence of natural obstacles. Table 5.5 reports energy efficiencies, average annual productions and prices of the ST and PV modules. Flat plate collectors [94] and mono-crystalline silicone panels [95] are used in the application. Figure 5.5 and Figure 5.6 represent respectively the solar thermal production in a typical winter (light blue continuous line) and summer (dark red dotted line) day and the monthly solar thermal production of a $1m^2$ ST collector. Figure 5.7 and Figure 5.8 represent respectively the solar photovoltaic production in a typical winter (light blue continuous line) and summer (dark red dotted line) day and the monthly solar photovoltaic production of a $1m^2$ PV collector.

	ST COLLECTOR	PV COLLECTOR
Efficiency [%]	42	16
Annual production [kWh/m^2]	1315	286
Price [€/m^2]	250	350

Table 5.7 - Solar collectors' data

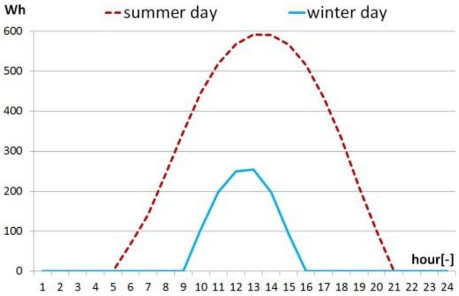


Figure 5.6 - Daily production of a 1m^2 ST panel

Figure 5.7 - Monthly production of a 1m^2 ST panel

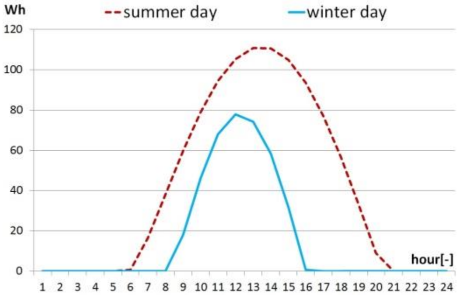


Figure 5.8 - Daily production of a 1m^2 PV panel

Figure 5.9 - Monthly production of a 1m^2 PV panel

5.2.4 District heating network

The design (layout and size) of the DHN is predefined and available from [79].The main pipeline of the DHN is 3 km long (Figure 5.1) and the diameter is 300mm. The hot water is delivered to the users at a temperature of 90°C and it returns back to the network at 70°C. With a nominal water flow velocity of 2m/s, the maximum transferable power is therefore almost 12000kW. The secondary network branches that feed the factories are not shown in the plan view of the industrial area, but they count for around one more kilometre of pipes and their diameters vary from 50 to 200mm. The cost of the DHN is fixed and equals to three million euro. The heat loss (*k_net*) is 1% of the water flow entering the network.

5.2.5 Heat storage

The heat loss is the most important parameter that describes a heat storage. It depends mostly on the type of the HS and consequently on the insulation factor. The hourly heat loss used in the optimization model (*k_sto*) is 0.2% of the energy stored in the previous time interval and corresponds to a dissipation coefficient of 1.6KJ/h·m^2·K [96]. 0.2% is the fixed rate heat loss that best approximates the real HS dissipation trend in the working temperature interval 70÷90°C. The unitary cost of the HS depends on its kind and size and can vary between 120 and 180€/m^3 [83]. An intermediate cost of 160€/m^3 is assumed.

5.3 Additional data

This section reports other data, mainly economic ones, which are not presented in the previous paragraphs, but that are required to complete the scenario of the case study.

5.3.1 Economic data

The interest rate *i* used in the application is 7% and it is the sum of a real economic interest rate of 5% and a risk rate of 2%. The life span of the components is reported in Table 5.8 and together with the interest rate is used to calculate the amortization cost factor *f* of each component.

ICE	BOI	ST COLLECTOR	PV COLLECTOR	DHN	HS
15	15	15	15	40	40

Table 5.8 - Components' life span [year]

Table 5.9 reposts the energy vector prices used in the optimization model and referred to the current Italian market.

Purchased electricity	0.12
Sold electricity	0.085
Cogenerator natural gas	0.045
Boiler natural gas	0.056

Table 5.9 - Energy prices [€/kWh]

5.3.2 Environmental data

Table 5.10 reports the values of CO_2 emissions (i.e. carbon intensity) related to the combustion of 1kWh of natural gas [97] and to the production of 1kWh of electricity [98]. The coefficients are referred to the average global chemical composition of natural gas and to the global electricity generation.

Natural gas carbon intensity	0.201
Electricity carbon intensity	0.496

Table 5.10 - Carbon intensity factors [$kgCO_2$/kWh]

5.3.4 Support policies

Economic support policies are widely adopted worldwide to stimulate the development of renewable energy technologies and to contribute to increase the heat and electric production efficiency of the energy conversion systems. These support schemes can be broadly classified as quota and price mechanisms. Quotas set a certain level of renewable production and let the market discover the price. Price mechanisms guarantee a certain level of support to renewable producers and allow this price to determine the level of development [99].

In the dissertation three different kinds of incentives are introduced. The objective is to evaluate the effect of these support policies on the optimal configuration of the energy supply system and to compare the achieved energy and cost savings by the implementation of each incentive with economic cost for society. The support schemes are:

- Feed in Premium for photovoltaic production. It provides an incentive (premium) of 0.133€ for each kWh of PV energy generated, no matter the final use [100]. The electricity produced by the PV modules may be either self-consumed or sold to the grid at market price.
- Tradable certificates (White Papers or Titles). The purpose is to stimulate energy producers to reduce their CO_2 emissions using renewable energy sources and non-conventional technologies. An incentive of 113.7€ is recognised for each tonne of oil equivalent (TOE) saved as result of cogeneration, ST and PV productions.
- Natural gas de-taxation for cogeneration use. A de-taxation on the natural gas price is applied if a cogeneration system respects the restrictions presented below. If the conditions are satisfied, the price of natural gas for CHP applications is reduced by 25%.

Cogeneration systems operate in Italy with natural gas de-taxation if comply with the two following conditions [101]:

- the Primary Energy Saving (PES) is greater than 0 for systems < 1MW or greater than 0.1 for system ≥ 1MW;
- the Thermal Limit (TL) is greater than 30%.

The parameter PES expresses the actual saving of primary energy compared with to the conventional production of heat and electricity, while the TL assures that the system operates in cogeneration mode and not only for the production of electricity.

Equation 5.1 is used to calculate the PES index for an internal combustion engine. η_{el_ref} and η_{th_ref} are the reference electric and thermal efficiencies and depend on the size of the cogeneration system.

$$PES = 1 - \frac{F\_cog}{\frac{E\_cog}{\eta el\_ref} + \frac{H\_cog}{\eta th\_ref}} > 0 \tag{5.1}$$

Equation 5.2 is used to determine the TL index.

$$TL = \frac{H_{cog}}{E_{cog} + H_{cog}} > 30\% \tag{5.2}$$

As the CHP units operation of the optimized model respects the two above conditions, the natural gas price used in the application is discounted by 25%.

6

Optimizations' results

The chapter describes the results of the optimization of the case study presented in chapter 5, using the MILP model introduced in chapter 4. The aim of the optimization is to determine the best configuration of an industrial supply energy system together with its optimal operational strategy.

The optimization procedure reduces the superstructure to the optimal energy system, considering the energy demands of nine factories located in the Ponte Rosso Industrial Area of San Vito al Tagliamento (Italy). The objective function minimizes the total annual cost for owing, operating and maintaining the whole supply system. Also the annual CO_2 emissions are evaluated considering the importance relates to their social impact.

The superstructure proposed in chapter 4 embeds all possible components which can be adopted in the optimal solution. However, additional constraints are added to reduce the complete superstructure by limiting the existence of some components, according to the specifications of the case study (e.g. no boiler in unit 2 and no cogenerator in unit 6). The model is optimized to obtain the best configuration and operation in the following cases, which are all presented in this chapter:

- Conventional system (CS).
- Decentralized system (DS).
- Distributed system with district heating network (DDHNS).
- Distributed solar district heating system (DSDHS).
- DSDHS with Feed in Premium (FiP) incentive.

- DSDHS with White Papers (WP) incentive.

At each step one or more components are added to the initial CS system till the DSDHS, which includes all the superstructure equipment. In this way it is possible to assess the influence of the different components and machines to the optimal design and operation of the system and how the different configurations contribute to achieve the minimization of the objective function. The model is also optimized introducing two real support schemes; the purpose is to compare the energy and cost savings achieved by implementing these incentives with the economic cost for society.

The MILP model is implemented in the Xpress Optimization Suite. Xpress is commercial software, produced by FICO, for solving large optimization problems by means of the application of integrated algorithms. The mathematical model is implemented through Mosel, a modelling and programming language that allows users formulating problems, using algorithm techniques to solve them and analysing the solutions.

The complete results of the optimized DSDHS with White Papers incentive can be found in Appendix B.

6.1 Model application

The mathematical model presented in chapter 4 is implemented through the Mosel language in the Xpress Optimization Suite. The users' data are 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. Those data are then elaborated to obtain the information required by the designer.

The optimization toolbox uses Simplex and Newton-Barrier (interior point) algorithms, together with Branch-and-Bound, Heuristic and cut generation techniques. The Simplex method can be used only if all variables are continuous. In the developed MILP model a lot of variables are not continuous (binary and discrete), thus the Simplex technique cannot be applied directly, but only after a relaxation procedure that removes one by one all the discrete constraints. The optimal solution of the relaxed problem is therefore considered the best achievable solution, because, with the introduction of a discrete constraint, the objective function is worsen or at least remains 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 way, but only in negative direction.

The Branch and Bound method starts with the optimization of the relaxed MILP problem, fixing step by step one discrete decision variable at a time. Therefore, 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 corresponds to the objective function of the real problem.

The percentage difference between the objective function of the relaxed problem and the one of the current problem is called gap. Figure 6.1 reports a graph that shows the trends of the gap, of the relaxed solution and of the current solution taken during a general optimization of the model.

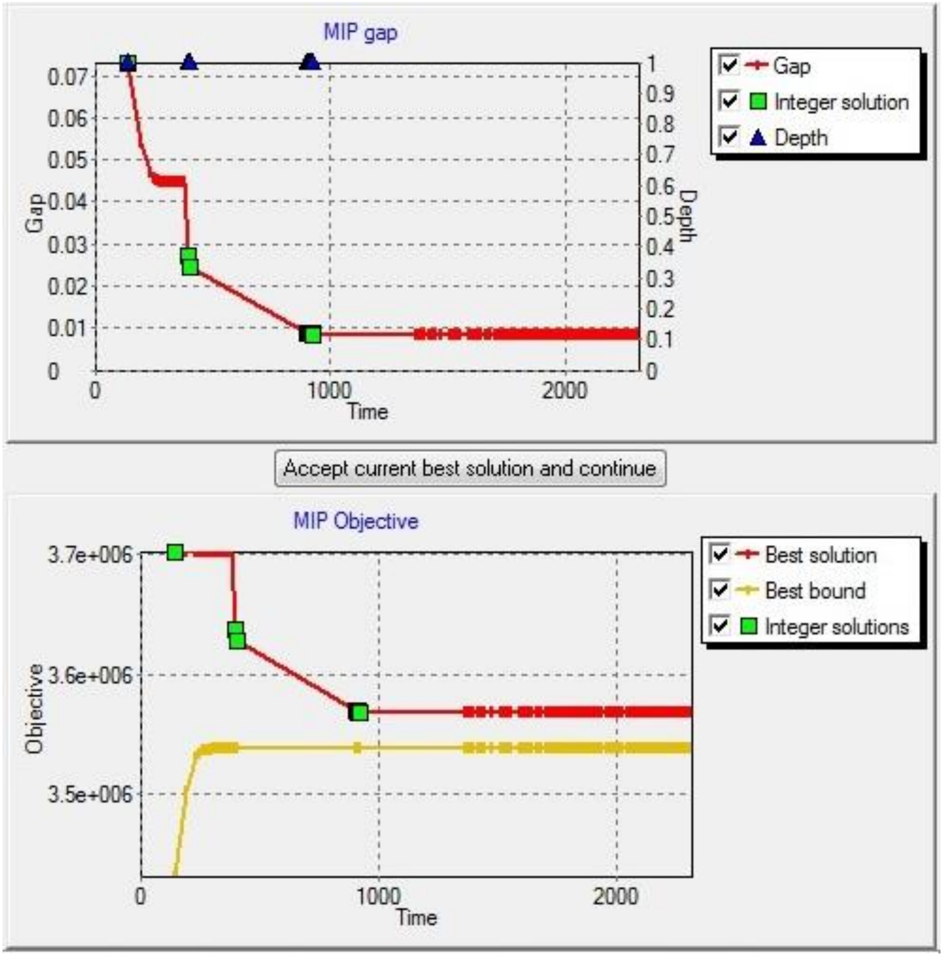


Figure 6.1 - Best solution, best bound and gap trends

The identification of the absolute objective function (gap = 0%) requires to examine all nodes of the Branch and Bound tree and, if the number of discrete variables is high, a very long optimization time is required. If the absolute objective function is not a priority and a near optimal solution is acceptable, the optimization can be stopped when a determined gap is reached. The optimization problem of the investigated case study can be considered a very large problem as it counts 358892 decision variables and 506427 constraints. As the determination of the absolute optimal solution would require too much time, the optimization procedure is automatically stopped when a 0.1% gap is reached.

The optimizations are performed with a desktop computer equipped with an Intel CoreTM i7CPU 920@2.67GHz processor and a 6GB RAM. The optimization of the overall problem, accepting a 0.1% optimality gap, lasts around six hours.

6.2 Conventional system

The conventional system is the reference case where each user is equipped with a boiler to satisfy its heating demand and all the required electricity is bought from the external grid. No other component is included in the superstructure apart the boilers (Figure 6.2).

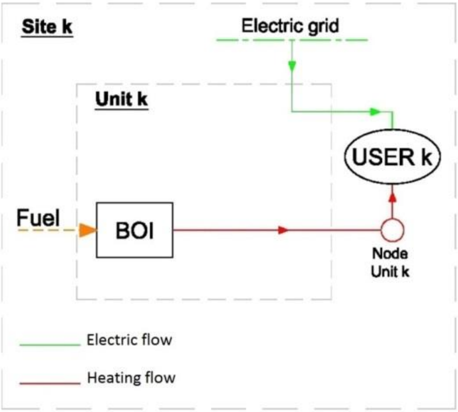


Figure 6.2 - Superstructure of the conventional system

The economic and environmental results of the CS configuration are used as reference values for the comparative analysis with the other optimized cases.

Table 6.1 reports the optimal configuration obtained for the CS. As expected, in each factory a boiler of the maximum allowed size (corresponding to the maximum heating demand of the each user) is installed.

	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOILER size [kW]	561	-	891	996	749	189	1556	3720	92

Table 6.1 - Optimal configuration of the CS

Table 6.2 reports the economic and environmental results of the optimization of the conventional system. The total annual cost is 3810k€ per year and it is almost all composed by the operating cost for fuel and electricity that together accounts for

98.8%, while the investment cost on boilers and the maintenance cost represent only both the 0.6%. The total CO_2 emissions of the CS are 14836Ton per year.

Electricity cost [k€/y]	2426
Fuel cost [k€/y]	1340
Operating cost [k€/y]	3766
Maintenance cost [k€/y]	22
Annual investment [k€/y]	23
Total investment [k€]	208
Total annual cost [k€/y]	3810
TOE [Ton/y]	5838
CO_2 emissions [Ton/y]	14836

Table 6.2 - Economic and environmental results of the CS

Table 6.3 reports the energy balances of the optimized CS. Each factory purchases the exact quantity of needed electricity from the external electric grid and receives the required heating energy from the boiler installed in its own production unit. A certain amount of heat is dissipated because of the partial load limit of the boilers that prevents to match exactly the users' demands.

Electric demand [MWh]	20217
Electricity purchased [MWh]	20217
Heating demand [MWh]	21185
Heat from boilers [MWh]	21528
Heat dissipated [MWh]	343

Table 6.3 - Energy balances of the CS

6.3 Decentralized system

Decentralized energy generation means that single buildings can be completely self-supporting in terms of electricity and heat energy [66]. The decentralized system analysed in the case study respects the definition above limited to the supply of heating energy because for the electrical part it is connected to the national grid, thus it can also receive electricity from the external.

The DS differs from the CS for the possibility to install the CHP modules in the production units and a solar photovoltaic field (Figure 6.3). As presented below, the optimization procedure does not select the PV collectors; the only new component is hence the CHP unit. Therefore, as cogenerators are the only addition to the superstructure, the DS gives the possibility to evaluate the economic and environmental results related to the introduction of the CHP technology.

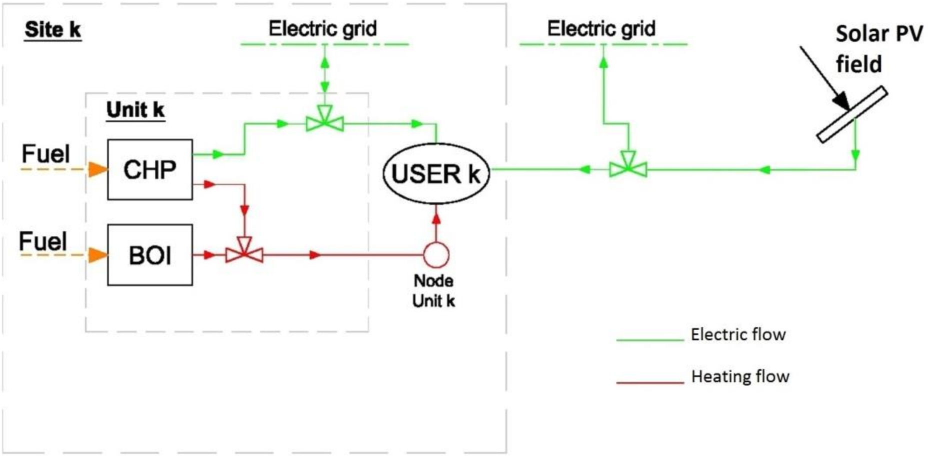


Figure 6.3 - Superstructure of the decentralized system

Table 6.4 reports the optimal configuration obtained for the decentralized system: three ICEs and eight boilers are installed. The PV panels are not included in the optimized structure, meaning that, with the reference prices and without incentives, the photovoltaic system is not profitable.

	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOILER size [kW]	561	-	891	212	749	189	834	1641	92
ICE size [kW]	0	0	0	538	0	-	550	1955	0

Table 6.4 - Optimal configuration of the DS

Moving to the economic and environmental aspects, it is immediately clear that the installation of three ICEs must produces some benefits, otherwise they would not have been chosen by the optimizer. CHP technology is cost-effective compared to the conventional solution: the objective function (total annual cost) decreases by around 220k€/y, corresponding to 5.8%. Also the total CO_2 emissions are reduced by 2753Ton/y, the 18.6%. The good performances are the consequence of the operations of the CHP units: even if total fuel cost increases by 549k€/y (+29.1%), electricity cost decreases by 641k€/y (-26.4%) and sold electricity generates an income of 574k€/y, producing a final operating cost reduction of 665k€/y (-17.7%). The investment cost on equipment is higher compared to the CS (+2315k€), but the payback period is almost 5 years, which is not too much time. Table 6.5 reports the economic and environmental results obtained from the optimization of the DS.

Electricity cost [k€/y]	1785
Electricity income [k€/y]	574
BOI fuel cost [k€/y]	437
ICE fuel cost [k€/y]	1451
Operating cost [k€/y]	3100
Maintenance cost [k€/y]	213
Annual investment [k€/y]	277
Total investment [k€]	2523
Total annual cost [k€/y]	3590
Cost reduction versus CS [%]	5.8
Payback period versus CS [y]	4.9
TOE [Ton/y]	4965
CO_2 emissions [Ton/y]	12083
CO_2 reduction versus CS [%]	18.6

Table 6.5 - Economic and environmental results of the DS

Table 6.6 shows the energy balances of the DS optimization. The influence of the ICEs is evident: 26.4% of electricity demand and 68.0% of heating demand (including heat losses) are covered by the CHP units. Besides that, 6750MWh of cogenerated electricity are sold to the external grid generating profit. Heating energy from boilers decreases by 14497MWh (-63.7%) compared to the CS.

Electric demand [MWh]	20217
Electricity from ICE [MWh]	12089
Self-consumed [MWh]	5339
Electricity purchased [MWh]	14878
Electricity sold [MWh]	6750
Heating demand [MWh]	21185
Heat from BOI [MWh]	7031
Heat from ICE [MWh]	14392
Heat dissipated [MWh]	238

Table 6.6 - Energy balances of the DS

6.4 Distributed system with district heating network

The distributed system (DDHNS) differs from the previous decentralized system for the introduction of the district heating network to the superstructure (Figure 6.4). The inclusion of the DHN entails consequently the presence of the central unit, where a boiler and a cogenerator may be installed. As explained in the previous chapters, the design (layout, size and cost) of the DHN is predefined, so, if it is included in the superstructure (as in the case of the DDHNS), its fixed cost is automatically added to the investment cost of the system.

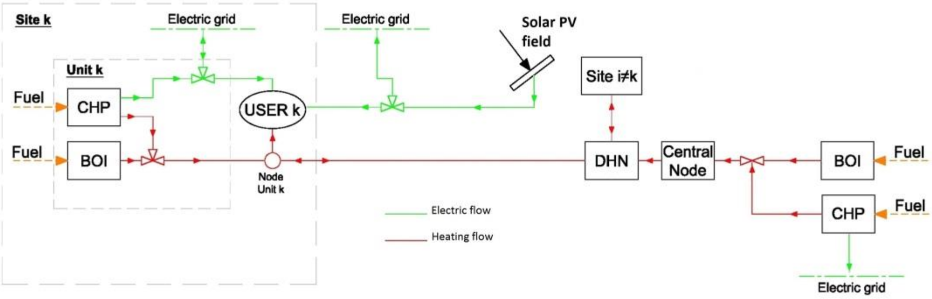


Figure 6.4 - Superstructure of the DDHNS

Table 6.7 reports the optimal configuration obtained for the DDHNS. Besides the DHN, whose presence is set by the designer, six ICEs and two BOIs are installed. Neither cogenerator nor boiler is installed in the central unit and the PV panels are still not included in the optimized structure.

	Central Unit	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOI size [kW]	0	562	-	0	0	0	0	1526	0	0
ICE size [kW]	0	0	0	478	457	532	-	516	746	981

Table 6.7 - Optimal configuration of the DDHNS

Looking at the economic and environmental results (Table 6.8), the total cost of the DDHNS is just slightly lower (-38k€/y) than the one of the decentralized system. The installation of six cogenerators and the DHN produces an increase in total investment cost of 4015k€ (+61.4%) that requires 7.5 years to be recovered, but it also produces positive effects on the CO_2 emissions, which decrease by 4.4% compared to the DS. The optimization shows that, even with small economic benefits, the presence of the DHN leads to reduce the total cost of the system: the optimizer is in fact able to rearrange the configuration of the DDHNS (doubling the number of CHP units and reducing the number of boilers from eight to two) to obtain a slightly lower objective function and important pollutant emissions savings.

Table 6.9 shows the energy balances of the optimized DDHNS. The increase in total installed cogeneration power compared to the DS produces, as expected, a substantial rise of cogenerated electricity (+16.8%) and heat (+28.4%). 66.5% of electricity demand and 94.9% of heating demand (including heat losses) are supplied by the CHP units. A very high quota (92.5%) of the electricity produced by the ICEs is self-consumed. The increase of cogenerated and self-consumed electricity together with a big decrease of sold electricity (-83.9%) is the reason of the important reduction in purchased electricity (-54.5%).

Electricity cost [k€/y]	812
Electricity income [k€/y]	92
BOI fuel cost [k€/y]	77
ICE fuel cost [k€/y]	1893
Operating cost [k€/y]	2690
Maintenance cost [k€/y]	248
Annual investment [k€/y]	614
Total investment [k€]	6538
Total annual cost [k€/y]	3552
Cost reduction versus CS [%]	6.8
Payback period versus CS [y]	7.5
TOE [Ton/y]	4799
CO_2 emissions [Ton/y]	11550
CO_2 reduction versus CS [%]	22.1

Table 6.8 - Economic and environmental results of the DDHNS

Electric demand [MWh]	20217
Electricity from ICE [MWh]	14533
Self-consumed [MWh]	13447
Electricity purchased [MWh]	6770
Electricity sold [MWh]	1086
Heating demand [MWh]	21185
Heat from BOI [MWh]	1238
Heat from ICE [MWh]	20095
Heat dissipated by users [MWh]	42
Heat dissipated by DHN [MWh]	106

Table 6.9 - Energy balances of the DDHNS

6.5 Distributed solar district heating system

The distributed solar district heating system includes, before the optimization, all the components of the superstructure (Figure 6.5). It differs from the previous DDHNS system for the introduction of the solar district heating system that embeds a solar thermal field and a heat storage. The heat produced by the ST collectors is sent directly to the DHN and then it can go either to the factories or to the HS if it is not immediately needed. As the SDH system is the only addition to the superstructure compared to the previous case, the DSDHS gives the possibility to evaluate the economic and environmental results related to the introduction of the solar technology.

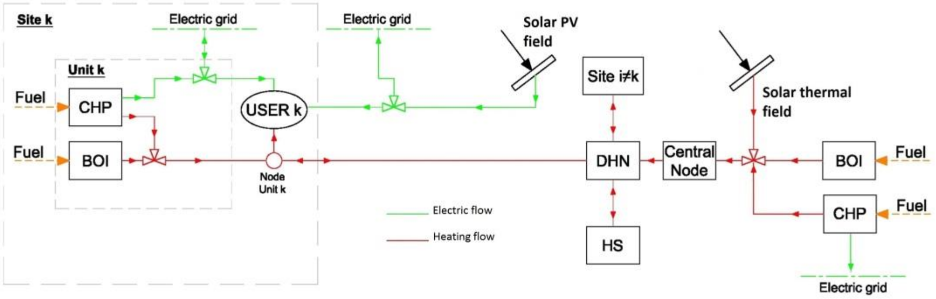


Figure 6.5 - Superstructure of the DSDHS

Table 6.10 reports the optimal configuration obtained for the DSDHS: one boiler, two ICEs, a ST field of 10299m^2 and a HS of 3541m^3 are installed. Even before looking at the economic results, it is already evident that the SDH system is cost-effective, otherwise it would not have been selected by the optimizer. Neither cogenerator nor boiler is present in the central unit: the self-consumption of the electricity generated by the ICEs is advantageous and the local production of heat (decentralization) is more favourable than installing a big size centralized machine and distributing the heat through the DHN. The PV panels are still not included in the optimized structure: with the reference prices and without incentives, the photovoltaic system is not profitable.

	Central Unit	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOI size [kW]	0	0	-	0	0	0	0	0	920	0
ICE size [kW]	0	0	0	0	0	0	-	0	672	923
ST field size [m^2]	10299	-	-	-	-	-	-	-	-	-
HS size [m^3]	3541	-	-	-	-	-	-	-	-	-

Table 6.10 - Optimal configuration of the DSDHS

The dimension of the optimal heat storage and the geological condition of the site suggest that tank HS is the most appropriate solution for the case study. A tank HS has the advantages of presenting high heat capacity and flexible installation conditions. Figure 6.6 shows the behaviour of the HS in a typical week along with the total factories' heat consumption. Due to the characteristics of the HS, in particular its size and dissipation coefficient, and due to the trend of the heating users' demand, the HS presents weekly charging/discharging cycles. It can be appreciated from the figure that during the weekend, when heating demand is low, the heat produced by the ST modules fills the HS, while during working days the HS gradually releases its hot water to supply the factories. The daily pick of heat stored corresponds to lunch time (12pm-1:30pm), when some factories are not operating and the ST production is maximum. The season of the year does not influence the HS behaviour.

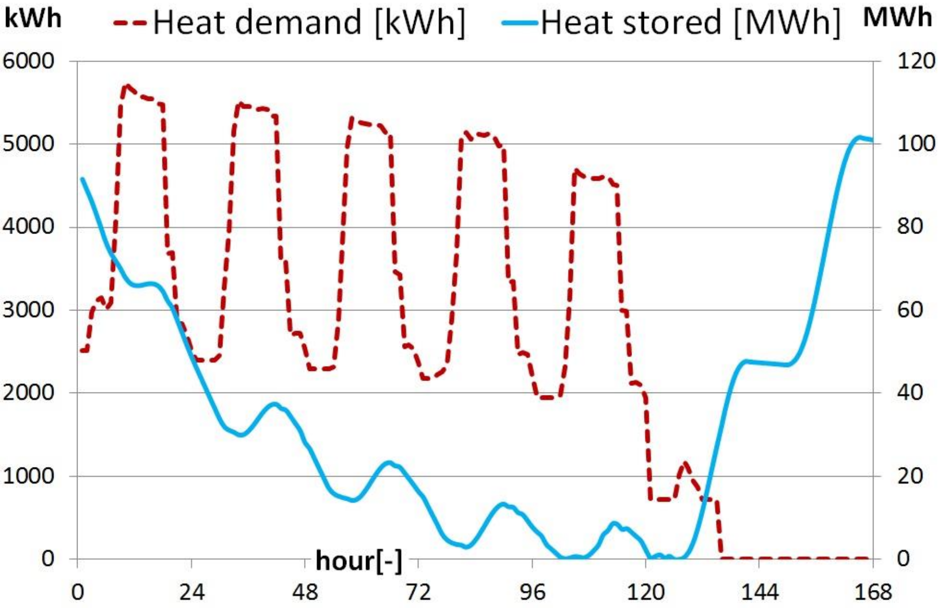


Figure 6.6 - Heat storage behaviour

Table 6.11 lists the economic and environmental results obtained from the optimization of the DSDHS. It is immediately clear that the SDH system produces important benefits on the total cost and CO_2 emissions of the supply system:

- the operating cost and the objective function are the lowest of the non-incentivized cases as they decrease respectively by 1258k€/y (-66.6%) and by 468k€/y (-12.3%) compared to CS;
- the CO_2 savings are the highest of the non-incentivized cases as the pollutant emissions decrease by 4308Ton/y (-29.0%) compared to CS.

On the other hand, in order to obtain these benefits, considerable investments are required (709k€/y) for the installation of solar technologies (ST collectors and HS), DHN and CHP units. Nevertheless, the payback period is 6.4 years, which is not too much time considering that the life span of ICE, BOI and ST collectors is 15 years and the life span of DHN and HS is 40 years.

Table 6.12 reports the energy balances of the optimized DSDHS. The majority of the electric demand (68.3%) is covered by purchased electricity, while ICEs produce 36.2% of the required electricity. The installation of the ST collectors produces a significant effect: 63.9% of the heating demand (including heat losses) is covered by heat energy coming from the ST modules.

Electricity cost [k€/y]	1657
Electricity income [k€/y]	78
BOI fuel cost [k€/y]	21
ICE fuel cost [k€/y]	909
Operating cost [k€/y]	2508
Maintenance cost [k€/y]	125
Annual investment [k€/y]	709
Total investment [k€]	7588
Total annual cost [k€/y]	3342
Cost reduction versus CS [%]	12.3
Payback period versus CS [y]	6.4
TOE [Ton/y]	4179
CO_2 emissions [Ton/y]	10528
CO_2 reduction versus CS [%]	29.0

Table 6.11 - Economic and environmental results of the DSDHS

Electric demand [MWh]	20217
Electricity from ICE [MWh]	7325
Self-consumed [MWh]	6412
Electricity purchased [MWh]	13805
Electricity sold [MWh]	913
Heating demand [MWh]	21185
Heat from BOI [MWh]	335
Heat from ICE [MWh]	9272
Heat from ST field [MWh]	13545
Heat from DHN to users [MWh]	17515
Heat from users to DHN [MWh]	5938
Heat from DHN to HS [MWh]	7134
Heat from HS to DHN [MWh]	5413
Heat dissipated by users [MWh]	0
Heat dissipated by DHN [MWh]	246
Heat dissipated by HS [MWh]	1722

Table 6.12 - Energy balances of the DSDHS

Figure 6.7 shows the electric balance of the optimized DSDHS.

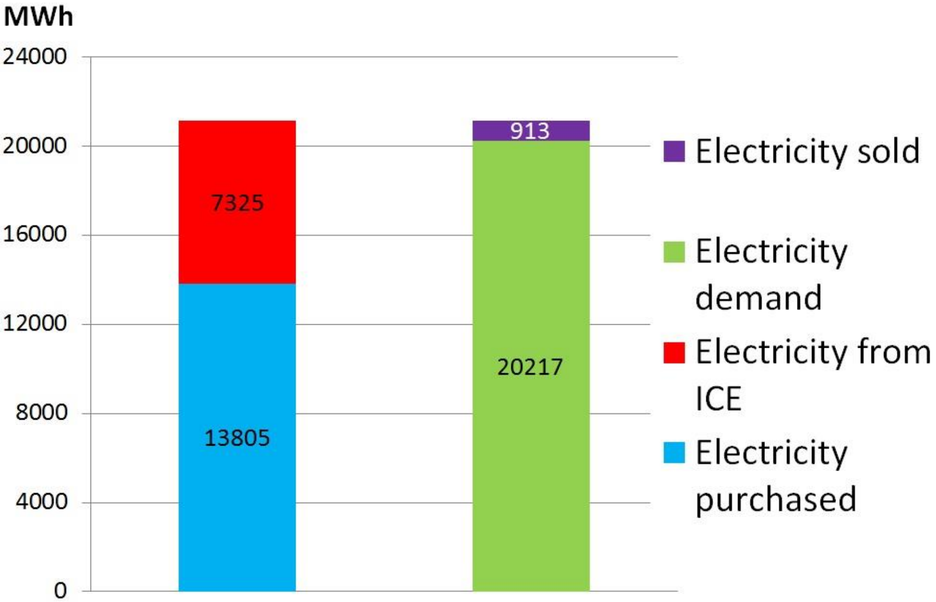


Figure 6.7 - Electric balance of the DSDHS

Figure 6.8 shows the heating balance of the optimized system.

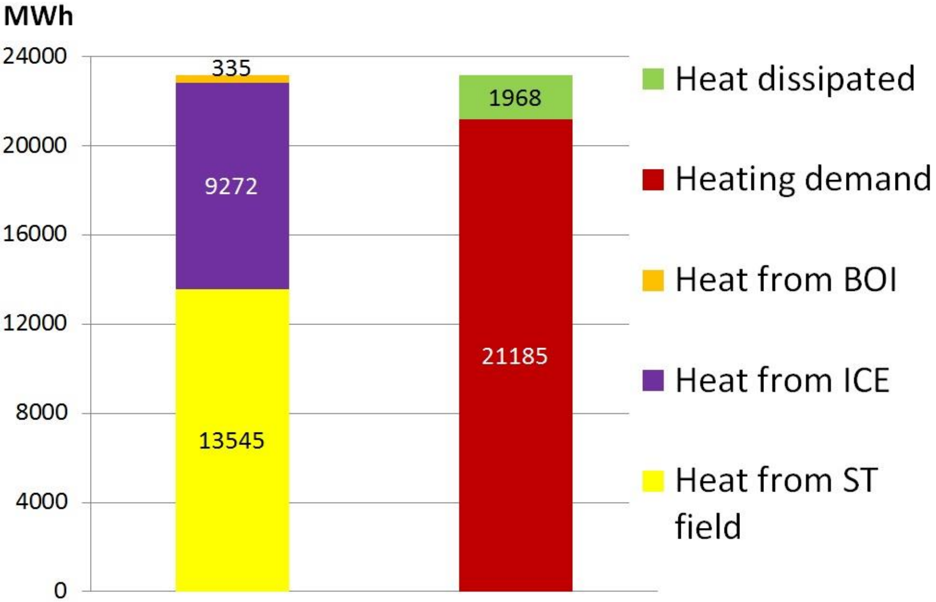


Figure 6.8 - Heating balance of the DSDHS

6.6 DSDHS with Feed in Premium incentive

The Feed in Premium for photovoltaic production is an incentive that recognises to the producer 0.133€ for each kWh of PV energy generated, no matter the final use.

The optimal structure of the system (Table 6.13) remains the same as the one of the DSDHS except for the addition of a PV field of 20000m^2, i.e. the maximum allowed size. The algorithm operates a trade-off between the price of purchased electricity and the cost of electricity produced by PV collectors. Until the price of purchased electricity is lower than the cost of the PV energy, the PV modules are not profitable. When this threshold is reached, PV production becomes cost-effective and the optimize model selects the surface of panels to install. The incentive introduced with the Feed in Premium scheme manages to reach this equilibrium point.

Incentivizing the PV production with the Feed in Premium scheme a minimum total annual cost of 2710k€/y (-18.9% compared to DSDHS) and a minimum CO_2 emissions rate of 7629Ton/y (-26.9% compared to DSDHS) are achieved. The highest total investment cost of the analysed cases (14707k€) requires 5.6 years to be recovered (i.e. the second best performance after the DS), possibly an acceptable period for investors. However, the support policy (price for the government to support the scheme) is 791k€/y, meaning a cost of 107€ per Ton of CO_2 saved, which may be too high for the correspondent social benefit obtainable. Table 6.14 lists the economic and environmental results of the optimization.

	Central Unit	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOI size [kW]	0	0	-	0	0	0	0	0	945	0
ICE size [kW]	0	0	0	0	0	0	-	0	647	877
PV field size [m^2]	20000	-	-	-	-	-	-	-	-	-
ST field size [m^2]	10835	-	-	-	-	-	-	-	-	-
HS size [m^3]	3763	-	-	-	-	-	-	-	-	-

Table 6.13 - Optimal configuration of the DSDHS with FiP incentive

Table 6.15 reports the energy balances of the optimized system. Despite the installation of 20000m^2 of PV collectors, 48.5% of the electric demand is covered by purchased electricity. The remaining amount is supplied by ICEs and PV field, which provide respectively 29.4% and 22.1% of the required electricity. A big quantity of the heating demand (67.3% including heat losses) is covered by heat energy coming from the ST modules. 88.5% of the electricity from the ICEs and 78.0% of the electricity from the PV field are self-consumed.

Electricity cost [k€/y]	1176
Electricity income [k€/y]	173
BOI fuel cost [k€/y]	22
ICE fuel cost [k€/y]	842
Operating cost [k€/y]	1867
Maintenance cost [k€/y]	115
Annual investment [k€/y]	1489
Total investment [k€]	14707
Support policy [k€/y]	761
Total annual cost [k€/y]	2710
Cost reduction versus DSDHS [%]	18.9
Cost reduction versus CS [%]	28.9
Payback period versus CS [y]	5.6
TOE [Ton/y]	3095
CO_2 emissions [Ton/y]	7692
CO_2 reduction versus DSDHS [%]	26.9
CO_2 reduction versus CS [%]	48.2
CO_2 saved cost [€/Ton]	107

Table 6.14 - Results of the DSDHS with FiP incentive

Electric demand [MWh]	20217
Electricity from ICE [MWh]	6725
Self-consumed [MWh]	5949
Electricity from PV field [MWh]	5724
Self-consumed [MWh]	4464
Electricity purchased [MWh]	9804
Electricity sold [MWh]	2036
Heating demand [MWh]	21185
Heat from BOI [MWh]	350
Heat from ICE [MWh]	8661
Heat from ST field [MWh]	14250
Heat from DHN to users [MWh]	17646
Heat from users to DHN [MWh]	5472
Heat from DHN to HS [MWh]	7422
Heat from HS to DHN [MWh]	5596
Heat dissipated by users [MWh]	0
Heat dissipated by DHN [MWh]	251
Heat dissipated by HS [MWh]	1825

Table 6.15 - Energy balances of the DSDHS with FiP incentive

6.6.1 Sensitivity analysis of DSDHS with FiP incentive

A sensitivity analysis of the DSDHS with Feed in Premium scheme is performed varying the amount of the incentive. The purpose is to investigate how the variation of the incentive affects the energy supply system and the society in terms of pollutant emissions and economic investment.

Figure 6.9 shows the amount of saved CO_2 (blue columns) and the CO_2 saved cost (yellow diamonds) decreasing the FiP incentive from -90% to -50%. The variation is consistent with the recent trend of the support schemes on PV production. It can be seen that reducing the value of the incentive by 70% allows the system to obtain the same CO_2 emissions saving compared to the DSDHS (-2847Ton or -27.0%) at a much lower cost for the society (80€/Ton). An incentive of 0.04€ per kWh of PV energy generated is in fact sufficient to install 20000m^2 of PV panels. Raising the incentive over this value does not produce further environmental benefits, but only the increase of support policy and CO_2 saved cost. Comparing the results to the CS, the CO_2 emissions are reduced by 7155Ton (-48.2%) and the CO_2 saved cost is 32€/Ton.

The economic and environmental results of the optimized system with the Feed in Premium incentive reduced by 70% are reported in Table 6.16. As the configuration of the energy system remains the same of the DSDHS with FiP incentive, the majority of the parameters do not vary. The only important change is the reduction of the support policy (from 761 to 228k€), which produces an increase of total annual cost (from 2710 to 3243k€) and payback period (from 5.6 to 7.1 years) and a decrease of CO_2 saved cost (from 107 to 32€/Ton).

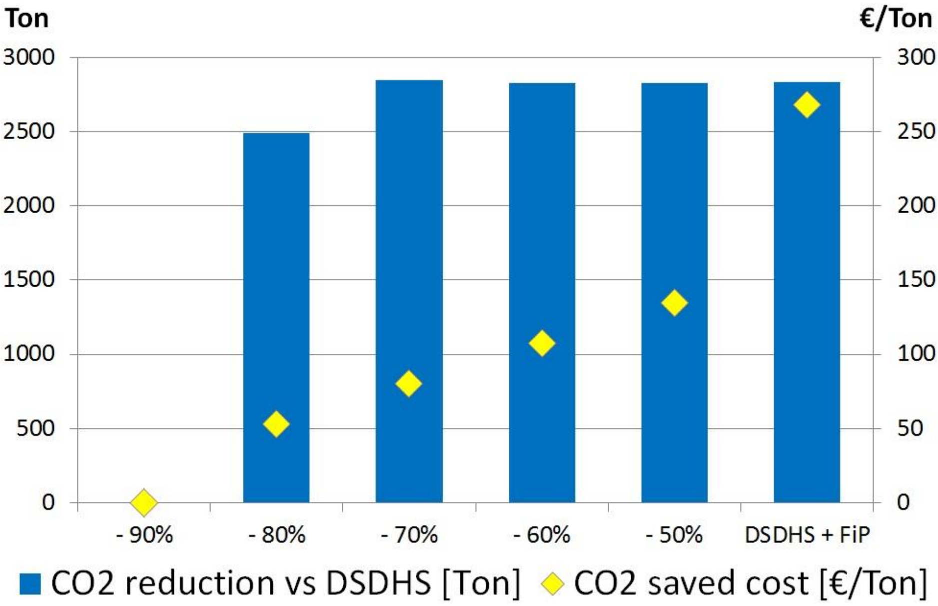


Figure 6.9 - Sensitivity analysis of DSDHS with FiP incentive

Electricity cost [k€/y]	1174
Electricity income [k€/y]	174
BOI fuel cost [k€/y]	20
ICE fuel cost [k€/y]	844
Operating cost [k€/y]	1864
Maintenance cost [k€/y]	115
Annual investment [k€/y]	1492
Total investment [k€]	14733
Support policy [k€/y]	228
Total annual cost [k€/y]	3243
Cost reduction versus DSDHS [%]	3.0
Cost reduction versus CS [%]	14.9
Payback period versus CS [y]	7.1
TOE [Ton/y]	3091
CO_2 emissions [Ton/y]	7681
CO_2 reduction versus DSDHS [%]	27.0
CO_2 reduction versus CS [%]	48.2
CO_2 saved cost [€/Ton]	32

Table 6.16 - Results of the DSDHS with FiP incentive - 70%

6.7 DSDHS with White Papers incentive

The White Papers support scheme recognises to the energy producer an incentive of 113.7€ for each Ton of oil equivalent saved as result of cogeneration, ST and PV productions.

Incentivizing the reduction of fossil fuel consumption, the configuration of the optimized system (Table 6.17) does not differ much compared to the DSDHS, but various interesting improvements are obtained. In particular, the optimizer fosters the installation of renewable energy technologies rather than fossil fuel equipment:

- for the first time no boilers are installed;
- the total installed ICEs size presents a little decrease (-3.0%) compared to the one of the DSDHS;
- for the first time 8436m^2 of PV modules are installed even without a direct incentive for the PV production;
- ST collectors' surface presents a size increasing of 2318m^2 (+18.4%) compared to the one of the DSDHS;
- HS tank presents a size increasing of 993m^3 (+22.0%) compared to the one of the DSDHS.

	Central Unit	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9
BOI size [kW]	0	0	-	0	0	0	0	0	0	0
ICE size [kW]	0	0	0	0	0	0	-	0	650	898
PV field size [m^2]	8436	-	-	-	-	-	-	-	-	-
ST field size [m^2]	12617	-	-	-	-	-	-	-	-	-
HS size [m^3]	4507	-	-	-	-	-	-	-	-	-

Table 6.17 - Optimal configuration of the DSDHS with WP incentive

Table 6.18 lists the economic and environmental results obtained from the optimization of the supply system. The White Papers scheme allows reducing the total annual cost by 205k€/y (-6.1%) and the total annual CO_2 emissions by 1373Ton/y compared with the DSDHS. The total investment cost (11218k€) is recovered in 6.3 years, a little bit less time than the payback period of the DSDHS (6.4 years). The support policy (price for the government to support the scheme) is 253k€/y, meaning a cost of 45€ per Ton of CO_2 saved, which is 58.0% lower than the CO_2 saved cost of the Feed in Premium incentive, therefore a much favourable rate for the social benefit obtainable.

Electricity cost [k€/y]	1583
Electricity income [k€/y]	83
BOI fuel cost [k€/y]	0
ICE fuel cost [k€/y]	693
Operating cost [k€/y]	2193
Maintenance cost [k€/y]	95
Annual investment [k€/y]	1102
Total investment [k€]	11218
Support policy [k€/y]	253
Total annual cost [k€/y]	3137
Cost reduction versus DSDHS [%]	6.1
Cost reduction versus CS [%]	17.7
Payback period versus CS [y]	6.3
TOE [Ton/y]	3609
CO_2 emissions [Ton/y]	9155
CO_2 reduction versus DSDHS [%]	13.0
CO_2 reduction versus CS [%]	38.3
CO_2 saved cost [€/Ton]	45

Table 6.18 - Results of the DSDHS with WP incentive

Table 6.19 reports the energy balances of the optimized system. 65.3% of the electric demand is covered by purchased electricity. The remaining amount is supplied by ICEs and PV field, which provide respectively 24.0% and 10.8% of the required electricity. The biggest quota of the heating demand (78.3% including heat losses) is covered by heat energy coming from the ST modules; the rest is provided by the two ICEs. 86.7% of the electricity from the ICEs and 90.2% of the electricity from the PV field are self-consumed.

Electric demand [MWh]	20217
Electricity from ICE [MWh]	5585
Self-consumed [MWh]	4843
Electricity from PV field [MWh]	2414
Self-consumed [MWh]	2178
Electricity purchased [MWh]	13196
Electricity sold [MWh]	978
Heating demand [MWh]	21185
Heat from BOI [MWh]	0
Heat from ICE [MWh]	7074
Heat from ST field [MWh]	16594
Heat from DHN to users [MWh]	18782
Heat from users to DHN [MWh]	4670
Heat from DHN to HS [MWh]	8739
Heat from HS to DHN [MWh]	6532
Heat dissipated by users [MWh]	1
Heat dissipated by DHN [MWh]	275
Heat dissipated by HS [MWh]	2207

Table 6.19 - Energy balances of the DSDHS with WP incentive

The complete results of the optimized DSDHS with White Papers incentive can be found in Appendix B. The results show in detail the electric and thermal energy flows of each single user.

Figure 6.10 shows the electric balance of the optimized system.

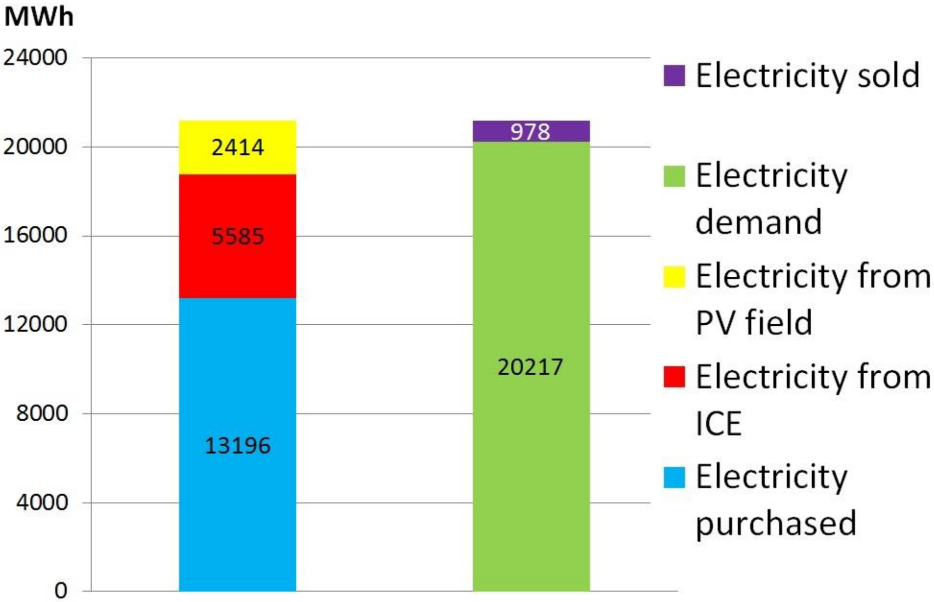


Figure 6.10 - Electric balance of the DSDHS with WP incentive

Figure 6.11 shows the heating balance of the optimized system.

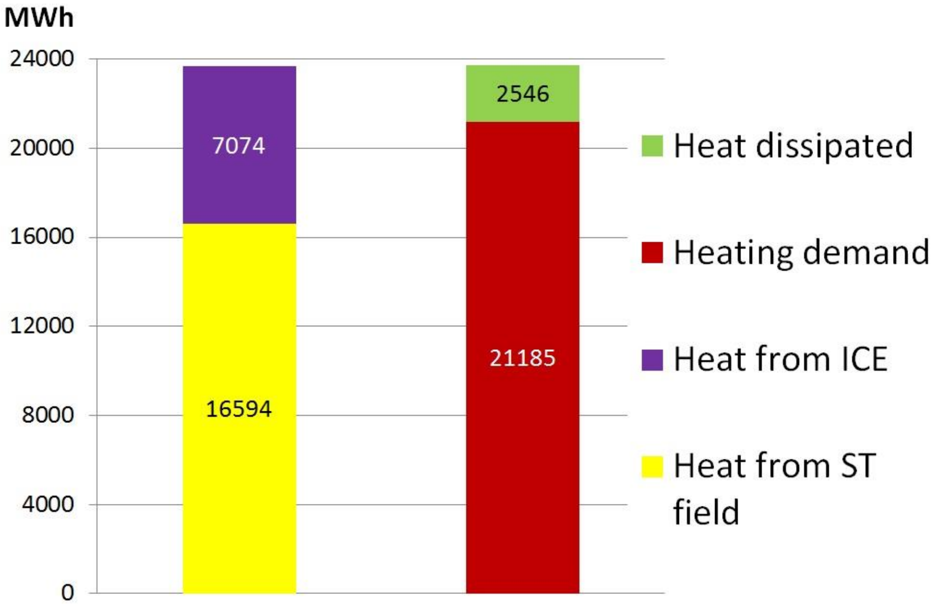


Figure 6.11 - Heating balance of the DSDHS with WP incentive

6.7.1 Sensitivity analysis of DSDHS with WP incentive

A sensitivity analysis of the DSDHS with White Papers scheme is performed varying the amount of the incentive. The purpose is to investigate how the variation of the incentive affects the energy supply system and the society in terms of pollutant emissions and economic investment.

Figure 6.12 shows the amount of saved CO_2 (blue columns) and the CO_2 saved cost (yellow diamonds) raising the WP incentive from 10% to 50%. It can be seen that increasing the value of the incentive by 30% allows the system to obtain the maximum CO_2 emissions saving compared to the DSDHS (-3021Ton or -28.7%) at a minimum cost for the society (140€/Ton). Comparing the results to the reference case CS, the CO_2 emissions are reduced by 7329Ton (-49.4%) and the CO_2 saved cost is 58€/Ton. The reason of these good performances is that, increasing the WP incentive by 30%, 20000m^2 of solar photovoltaic panels are installed (+58%). Raising the amount of the incentive over this quota does not produce further environmental benefits, but only the increase of support policy and CO_2 saved cost. On the other hand, lower values of the incentive do not allow the system to install the maximum available area of PV modules and thus to obtain the minimum CO_2 emissions.

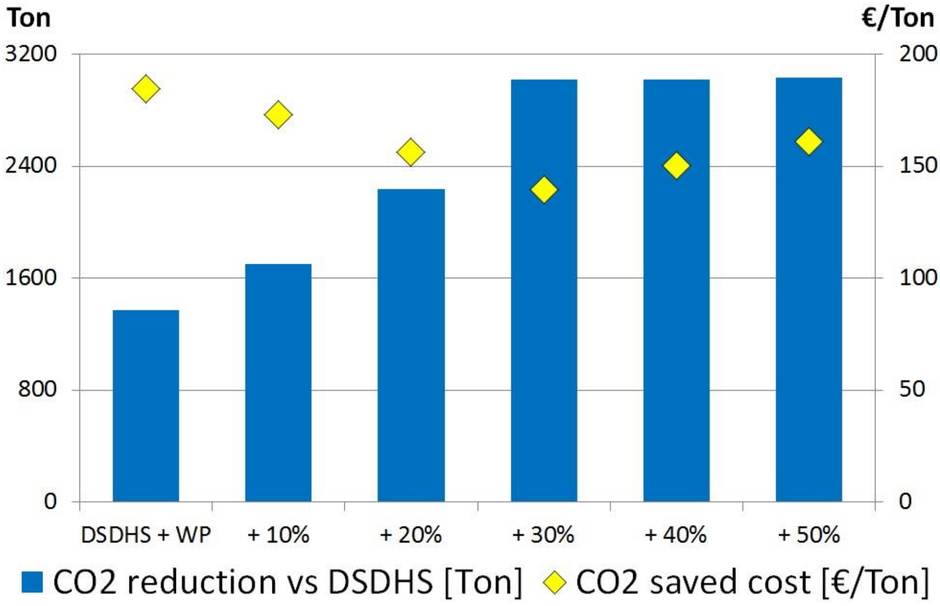


Figure 6.12 - Sensitivity analysis of DSDHS with WP incentive

The economic and environmental results of the optimized system with the White Papers incentive increased by 30% are reported in Table 6.20. The configuration of the energy system remains the same of the DSDHS with WP incentive apart for the addition of 11564m^2 of PV collectors. The bigger PV area entails important CO_2

emissions saving (-18% or -1648Ton) but also higher investment cost (from 11218 to 15337k€). The other important change is the increase of the support policy (from 253 to 422k€), which produces a decrease of total annual cost (from 3137 to 3054k€) and a raise of CO_2 saved cost (from 45 to 58€/Ton). The increased investment cost is only partially compensated for the higher support policy and the payback period rises from 6.3 to 6.6 years.

Electricity cost [k€/y]	1301
Electricity income [k€/y]	161
BOI fuel cost [k€/y]	0
ICE fuel cost [k€/y]	687
Operating cost [k€/y]	1827
Maintenance cost [k€/y]	94
Annual investment [k€/y]	1554
Total investment [k€]	15337
Support policy [k€/y]	422
Total annual cost [k€/y]	3054
Cost reduction versus DSDHS [%]	8.6
Cost reduction versus CS [%]	19.8
Payback period versus CS [y]	6.6
TOE [Ton/y]	2986
CO_2 emissions [Ton/y]	7507
CO_2 reduction versus DSDHS [%]	28.7
CO_2 reduction versus CS [%]	49.4
CO_2 saved cost [€/Ton]	58

Table 6.20 - Results of the DSDHS with WP incentive + 30%

6.8 Results' summary

Table 6.21 summarizes the main results of the optimized cases.

	CS	DS	DDHNS	DSDHS	FiP	FiP - 70%	WP	WP + 30%
BOI size [kW]	8754	5169	2088	920	945	925	0	0
ICE size [kW]	-	3043	3710	1595	1524	1559	1548	1643
PV field size [m^2]	-	0	0	0	20000	20000	8436	20000
ST field size [m^2]	-	-	-	10299	10835	10838	12617	12624
HS size [m^3]	-	-	-	3541	3763	3764	4507	4510
	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]
Electric demand	20217							
Electricity from ICE	-	12089	14533	7325	6725	6751	5585	5545
Electricity from PV field	-	0	0	0	5724	5724	2414	5724
Electricity purchased	20217	14878	6770	13805	9804	9784	13196	10844
Electricity sold	-	6750	1086	913	2036	2042	978	1896
Heating demand	21185							
Heat from BOI	21528	7031	1238	335	350	322	0	0
Heat from ICE	-	14392	20095	9272	8661	8668	7074	7003
Heat from ST field	-	-	-	13545	14250	14254	16594	16603
Heat dissipated	343	238	148	1968	2076	2060	2483	2422
Operating cost [k€/y]	3766	3100	2690	2508	1867	1864	2193	1827
Maintenance cost [k€/y]	22	213	248	125	115	115	95	94
Annual investment [k€/y]	23	277	614	709	1489	1492	1102	1554
Total investment [k€]	208	2523	6538	7588	14707	14733	11218	15337
Support policy [k€/y]	-	-	-	-	761	228	253	422
Total annual cost [k€/y]	3810	3590	3552	3342	2710	3243	3137	3054
Cost reduction vs. CS [%]	-	5.8	6.8	12.3	28.9	14.9	17.7	19.8
Payback period vs. CS [y]	-	4.9	7.5	6.4	5.6	7.1	6.3	6.6
CO_2 emissions [Ton/y]	14836	12083	11550	10528	7692	7681	9155	7507
CO_2 reduction vs. CS [%]	-	18.6	22.1	29.0	48.2	48.2	38.3	49.4
CO_2 saved cost [€/Ton]	-	-	-	-	107	32	45	58

Table 6.21 - Summary of the optimizations' results

Figure 6.13 shows the total annual cost reduction of the optimized cases compared to the conventional system.

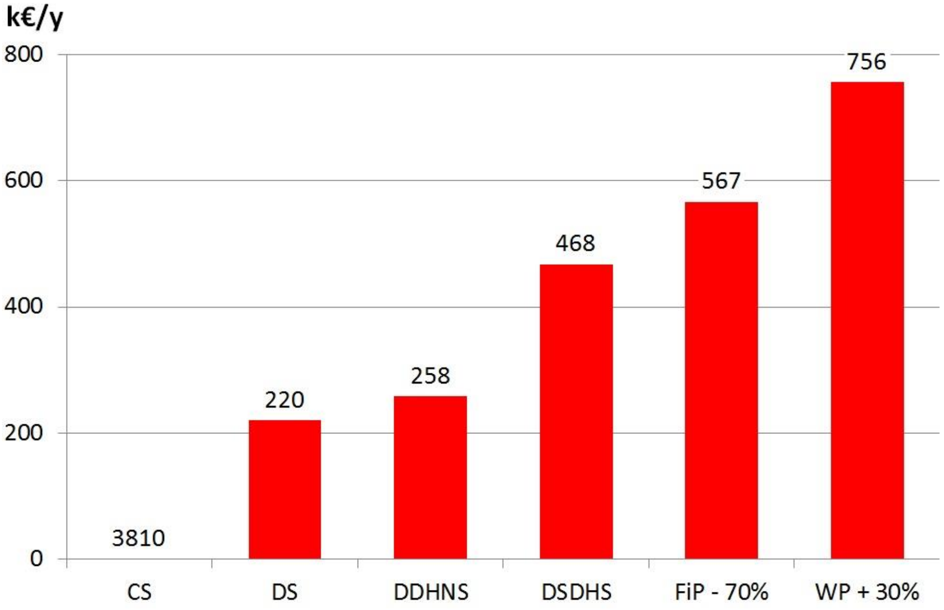


Figure 6.13 - Total annual cost reduction compared to the CS

Figure 6.14 shows the annual CO_2 emissions reduction of the optimized cases compared to the conventional system.

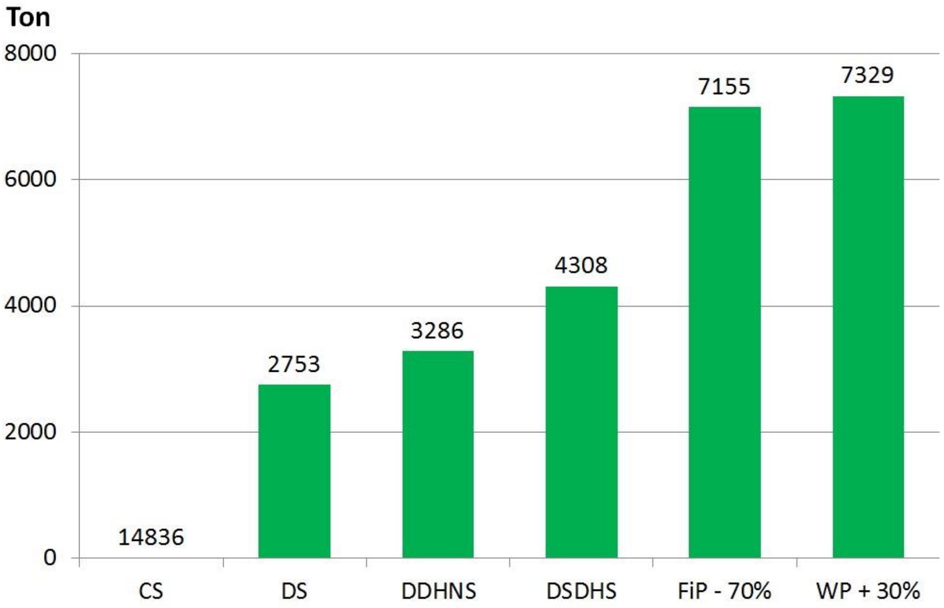


Figure 6.14 - Annual CO_2 emissions reduction compared to the CS

Conclusions

The thesis investigates the optimization of the energy supply to industrial sites. The evaluation is performed with reference to a real case study, made of nine factories belonging to the Ponte Rosso Industrial Area of San Vito al Tagliamento (Italy). The objective of the research, according to industrial stakeholders, is the minimization of the total annual cost for owning, operating and maintaining the energy system.

The energy generation system analysed is represented through a mixed integer linear programming model, specifically developed to determine the best synthesis, design and operation of the whole structure.

Although the minimum cost is the objective of the research, environmental issues, like pollutant emissions and availability of energy resources, need to be considered too. In fact, the industrial sector currently accounts for more than one third of the global energy consumptions and the quota is assumed to increase in the next future. However, the reduction of CO_2 emissions is an achievable target, but it requires the development of a wide range of energy efficiency measures and low-carbon technologies. Therefore, various low impact alternatives and renewable energies technologies are included in the problem and their benefits are evaluated: distributed generation, combine heat and power units, photovoltaic modules and solar district heating system (including district heating network, heat storage and solar thermal collectors).

The optimization model is designed to supply electricity and heat to the nine factories of the industrial area starting from a general superstructure: a representation of the system that encompass every single machine and component which can appear in the final optimal configuration. The electricity can be produced by cogeneration modules, centralized (placed in a central production unit) and decentralized (placed in the users' side), and by a central solar photovoltaic field, or it can be purchased from the external grid. The required heating energy can be produced by internal combustion engines and conventional boilers, both centralized and decentralized, and by a central solar thermal field. The surplus heat energy can also be stored in a heat storage and used when necessary because all the factories are connected together and to the central unit through a district heating network of predefined layout and design. Thus, each user can be thermally autonomous, satisfying its needs by a dedicated production unit, it can be completely dependent, receiving all the required heat from the district heating network, or it can implement both solutions.

The presence of the district heating network, connecting users and central units together, forces to optimize the design and operation of the energy supply system simultaneously as they are heavily interdependent. This characteristic makes the developed model a novelty because researches normally focus only on a specific target (e.g. operation or synthesis optimization) instead of optimizing the whole problem at the same time. On the other hand, the main limit of the proposed model is its computational complexity, which increases with the number of decision variables and constraints. A solution implemented in the thesis to limit the complexity of the problem is reducing the standard year to a set of representative days that allows keeping a realistic picture of the actual annual behaviour of the system. The whole year is hence represented by twelve typical weeks (one week per month), each composed of seven days of 24 hours, for a total of 2016 time intervals.

The model is optimized considering different cases: from a traditional supply structure to a complete system that includes various non-conventional equipment and renewable energy technologies, adding one or more components at each step. This procedure makes possible to evaluate the influence of the components and machines to the optimal design and operation of the system, and to assess how the different configurations contribute to achieve the minimization of the objective function and the reduction of pollutant emissions. The model is also optimized introducing two real support schemes; the purpose is to compare the energy and cost savings achieved by implementing these incentives with the economic cost for society.

The optimization of the decentralized system (DS) demonstrates the profitability of the combined heat and power production compared to the separate production of heat and electricity, typical of a conventional system (CS). The obtained benefits are clear: the total annual cost decreases by 220k€/y (-6%) and also the total CO_2 emissions are reduced by 2800Ton/y (-19%).

When the district heating network is included in the superstructure of the system (DDHNS), the optimization shows a rearrangement of the configuration and operation of the system to face the increased investment cost due to the addition of the network. The number of internal combustion engines is doubled (from three to six) and the number of boilers is reduced by three fourths (from eight to two) compared to the decentralized system. These changes allow producing a slightly lower total annual cost (-1%) and better environmental performances (-4%) compared with the DS. Nevertheless, the increased investment cost (6500k€) requires 7.5 years to be recovered, making the solution not really profitable.

The distributed solar district heating system (DSDHS) includes, before the optimization, all the components of the superstructure and differs from the previous DDHNS for the introduction of a solar thermal field and a heat storage, which are both selected by the optimization procedure. Neither cogenerator nor boiler is present in the central unit: the self-consumption of the electricity generated by the ICEs is advantageous (88% of the electricity produced is self-consumed) and the local production of heat (decentralization) is more favourable than installing a big size centralized machine and distributing the heat through the DHN. The photovoltaic panels are not included in the optimized structure: with the reference prices and without incentives, the PV system is not cost-effective. The installation of 10300m^2 of ST collectors and of a HS of 3500m^3 produce the best performances on both the total cost and the total CO_2 emissions of the system (excluding the incentivized cases) making the solution profitable: 3300k€/y and 10500Ton/y corresponding to -12% and -29% respectively, compared to the conventional case. On the other hand, in order to obtain these benefits, considerable investments are required (710k€/y). However, the payback period is 6.4 years, which is not too much time considering that the life span of the components vary between 15 and 40 years.

Incentivizing the photovoltaic production (Feed in Premium support scheme) the optimal structure of the system remains the same of the DSDHS, except for the addition of a PV field of 20000m^2, i.e. the maximum allowed size. A minimum total annual cost of 2700k€/y (-29%) and a minimum CO_2 emissions rate of 7600Ton/y (-48%) are achieved. The highest total investment cost of the analysed cases (14700k€) requires 5.6 years to be recovered, possibly an acceptable period for investors. However, the support policy (price for the government to support the scheme) is 790k€/y, meaning a cost of 107€ per Ton of CO_2 saved, which may be too high for the correspondent social benefit obtainable.

The sensitivity analysis of the DSDHS with Feed in Premium scheme suggests that reducing the amount of the incentive by 70% allows the energy system to obtain the same CO_2 emissions saving (-7200Ton) at a minimum cost for the society (32€/Ton). However, the reduction of the support policy produces a lower economic benefit for the energy supply system (the total annual cost decreases by 15% compared to the CS) and an increase of the payback period (7.1 years).

The purpose of the White Papers support scheme is to stimulate the energy producers to reduce their CO_2 emissions using renewable energy sources and non-conventional technologies: an incentive is recognised for each tonne of oil equivalent saved as result of cogeneration, ST and PV productions. The optimization fosters the installation of renewable energy technologies rather than fossil fuel equipment: no boilers are selected; the total cogeneration power decreases by 3.0% compared to the DSDHS; 8500m^2 of photovoltaic modules are installed even without a direct incentive for the PV production; solar thermal collectors' surface rises by 2300m^2 (+18%) compared with the DSDHS; heat storage size increases by 1000m^3 (+22%) versus the DSDHS. The White Papers scheme allows obtaining a total annual cost of 3100k€/y and total annual CO_2 emissions of 9200Ton/y, -18% and - 38% respectively, compared to the conventional supply. The total investment cost (11200k€) is recovered in 6.3 years, a little bit less time than the payback period of the DSDHS. The support policy is 250k€/y, meaning a cost of 45€ per Ton of CO_2 saved, which is 58% lower than the CO_2 saved cost of the Feed in Premium incentive, therefore a much favourable rate for the social benefit obtainable. Besides the environmental advantages, if the investors accept a payback period of 6.3 years, the configuration is definitely profitable.

The dimension of heat storage in the optimal configurations (varying between 3500 and 4500m^3) and the geological condition of the industrial site suggest that tank HS is the most appropriate solution for the application. Due to the characteristics of the HS (size and dissipation coefficient in particular) and due to the trend of the heating users' demand, the HS presents weekly charging/discharging cycles. During the weekend, when heating demand is low, the heat produced by the ST modules fills the HS, while during working days the HS gradually releases its hot water to supply the factories.

The sensitivity analysis of the DSDHS with White Papers scheme shows that increasing the amount of the incentive by 30% allows the energy system to produce the minimum CO_2 emissions of all the cases (7500Ton) at an acceptable higher cost for the society (58€/Ton). The increased support policy (420k€) entails to reduce the total annual cost and the CO_2 emissions of the industrial energy supply system by 20% and 49% respectively, compared to the conventional system. Nevertheless, the installation of 20000m^2 of solar photovoltaic panels determines the highest investment cost of all the analysed cases (15300k€) and a payback period of 6.6 years.

The elaborated optimization model is aimed to be a reliable and flexible tool that can be applied, with appropriate adjustments, to other real case studies. The obtained results are supposed to be used by energy suppliers and end-users in order to assist making economic and managerial decisions and to help implementing proper operation control strategies, based on objective criteria instead on personal experience, in a complex environment.

There are some interesting perspectives which might be considered in the next future to extend and continue the research work developed in the thesis.

A possible integration concerns the evaluation of the cooling consumption of the energy users and therefore the analysis of specific equipment dedicated to meet the cooling demand, such as compression chillers, heat pumps and absorption refrigerators. In particular the absorption technology is promising when included in an integrated energy system because it gives the possibility to utilise the waste heat form production processes to power the absorption machine. The expected effect is a higher exploitation of the input source and thus a save of primary energy and a reduction of operating costs and pollutant emissions.

Another addition to the energy supply system might be the introduction of the biomass as energy source. Although the problem requires an accurate analysis, using the biomass as input fuel of a combined heat and power unit is expected to present two important advantages: a relatively lower fuel cost compared to natural gas and a very low environmental impact. While the environmental benefit is undoubtedly evident, being the biomass a renewable energy source, the economic aspect of the problem needs to be properly evaluated: a significant portion of the supply cost of the biomass is in fact represented by logistic cost (harvest, transport, treatment etc.) as the production one is almost negligible.

One last suggestion to continue the research work of the thesis is to extend the optimization to a supervision level, developing a system control strategy. The purpose is to define an integrated management system which allows the controller to accurately operate all the components of the energy system and therefore to obtain the optimal identified results.

A

Optimization model

```
model "Ph.D. thesis model"

uses "mmxprs"

parameters

!limite funzionamento inferiore cogeneratori
out_cog_lim=0.4

!caldaie
eta_cal=0.9             !efficienza caldaie
out_cal_lim=0.2         !limite funzionamento inferiore caldaie

!accumulo
perd_sto=0.002          !percentuale oraria di perdita accumulo

!rete
perd_ret=0.01           !percentuale di perdita rete

!costi energetici
c_comp=0.12             ![€/kWh]
```

```
c_vend=0.085            ![€/kWh]
c_gas_cal=0.056         ![€/kWh]
c_gas_cog=0.045         ![€/kWh]

!incentivi
i=113.7                 !certificato bianco per combustibile risparmiato [€/TEP]

!rendimento medio parco termoelettrico nazionale
eta=0.44

!dati ambientali
![t/kWh] (1TEP = 5347.6kWh) tonnellate equivalenti di petrolio per la produzione di
un kWh di energia elettrica
tep_el=0.000187
![t/kWh] (1TEP = 11630kWh) tonnellate equivalenti di petrolio consumate nella
combustione di un kWh di gas naturale
tep_term=0.000086
![t/kWh] tonnellate di CO2 emessa per la produzione di un kWh di energia elettrica
CO2_el=0.000496
![t/kWh] tonnellate di CO2 emessa dalla combustione di un kWh di gas naturale
CO2_term=0.000201

!costi componenti
cf_cog=130000           !costo fisso cogeneratori (MCI) [€]
cv_cog=730              !costo variabile cogeneratori (MCI) [€/kW]
cf_cal=6300             !costo fisso caldaie [€]
cv_cal=18               !costo variabile caldaie [€/kW]
c_ret=3000000           !costo rete [€]
c_pan_st=250            !costo pannelli solari termici [€/m2]
c_pan_fv=350            !costo pannelli fotovoltaici [€/m2]
c_sto=1.72              !costo serbatoio [€/kWh] = 160 [€/m3]

!costi di manutenzione
m_cog=0.017
m_cal=0.001

!anni di ammortamento
!n_cog=15
!n_cal=15
!n_sto=40
!n_ret=40
!n_pan=15
!i=0.07                 !interesse
f_cog=0.109794625
f_cal=0.109794625
```

```
f_sto=0.075009139
f_ret=0.075009139
f_pan=0.109794625

!limiti taglia massima macchine unità centrale
s_cog_cu_max=7335       !limiti taglia cogeneratore centralizzato [kW]
s_cal_cu_max=7083       !limiti taglia caldaia centralizzata [kW]

end-parameters

declarations

!indici
hour=1..2016            !indice ore
user=1..9               !indice utenze

!variabili decisionali
!esistenza rete
ex_ret:           mpvar
!esistenza cogeneratore centralizzato
ex_cog_cu:        mpvar
!esistenza caldaia centralizzata
ex_cal_cu:        mpvar
!esistenza cogeneratori unità
ex_cog:           array(user) of mpvar
!esistenza caldaie unità
ex_cal:           array(user) of mpvar
!taglia cogeneratore centralizzato [kW]
s_cog_cu:         mpvar
!taglia caldaia centralizzata [kW]
s_cal_cu:         mpvar
!taglia cogeneratori unità [kW]
s_cog:            array(user) of mpvar
!taglia caldaie unità [kW]
s_cal:            array(user) of mpvar
!taglia serbatoio [kWh]
s_sto:            mpvar
!dimensione campo solare termico [m2]
cam_st:           mpvar
!dimensione campo fotovoltaico [m2]
cam_fv:           mpvar
!funzionamento cogeneratore centralizzato
op_cog_cu:        array(hour) of mpvar
!funzionamento caldaia centralizzata
op_cal_cu:        array(hour) of mpvar
```

```
!funzionamento cogeneratori unità
op_cog:         array(hour,user) of mpvar
!funzionamento caldaie unità
op_cal:         array(hour,user) of mpvar
!energia elettrica prodotta
E_cog_cu:       array(hour) of mpvar
cogeneratore centralizzato [kWh]
!energia termica prodotta cogeneratore centralizzato [kWh]
Q_cog_cu:       array(hour) of mpvar
!combustibile consumato cogeneratore centralizzato [kWh]
F_cog_cu:       array(hour) of mpvar
!energia termica prodotta caldaia centralizzata [kWh]
Q_cal_cu:       array(hour) of mpvar
!combustibile consumato caldaia centralizzata [kWh]
F_cal_cu:       array(hour) of mpvar
!energia termica prodotta cogeneratori unità [kWh]
Q_cog:          array(hour,user) of mpvar
!combustibile consumato cogeneratori unità [kWh]
F_cog:          array(hour,user) of mpvar
!energia termica prodotta caldaie unità [kWh]
Q_cal:          array(hour,user) of mpvar
!combustibile consumato caldaie unità [kWh]
F_cal:          array(hour,user) of mpvar
!energia elettrica venduta dall'unità centrale [kWh]
E_cu_vend:      array(hour) of mpvar
!energia elettrica ceduta dal campo fotovoltaico alle utenze [kWh]
E_fv_ut:        array(hour,user) of mpvar
!energia fotovoltaica venduta [kWh]
E_fv_vend:      array(hour) of mpvar
!energia elettrica acquistata dalle utenze [kWh]
E_comp:         array(hour,user) of mpvar
!energia elettrica venduta dalle utenze [kWh]
E_vend:         array(hour,user) of mpvar
!flusso termico dalla rete alle utenze [kWh]
Q_in:           array(hour,user) of mpvar
!flusso termico dalle utenze alla rete [kWh]
Q_out:          array(hour,user) of mpvar
!flusso termico dalla rete all'accumulo [kWh]
Q_in_sto:       array(hour) of mpvar
!flusso termico dall'accumulo alla rete [kWh]
Q_out_sto:      array(hour) of mpvar
!energia termica prodotta dal campo solare termico [kWh]
Q_st:           array(hour) of mpvar
!energia termica accumulata nel serbatoio [kWh]
Q_sto:          array(hour) of mpvar
```

```
!energia termica nella rete [kWh]
Q_ret:           array(hour) of mpvar
!energia termica dissipata dalle utenze [kWh]
Q_dis:           array(hour,user) of mpvar
!variabili binarie ausiliarie
delta_E_comp:    array(hour,user) of mpvar
delta_E_vend:    array(hour,user) of mpvar
delta_E_fv_ut:   array(hour,user) of mpvar
delta_Q_in:      array(hour,user) of mpvar
delta_Q_out:     array(hour,user) of mpvar
delta_Q_in_sto:         array(hour) of mpvar
delta_Q_out_sto:        array(hour) of mpvar

!parametri
!coefficienti relativi al calore prodotto dai cogeneratori delle utenze
q:               array(1..2) of real
!coefficienti relativi al combustibile consumato dai cogeneratori delle utenze
f:               array(1..2) of real
!limiti taglia cogeneratori unità [kW]
s_cog_max:       array(user) of real
!limiti taglia caldaie unità [kW]
s_cal_max:       array(user) of real
!richieste elettriche utenze [kWh]
E_dem:           array(hour,user) of real
!richieste termiche utenze [kWh]
Q_dem:           array(hour,user) of real
!produzione unitaria da solare termico [kWh/m2]
st:              array(hour) of real
!produzione unitaria da solare fotovoltaico [kWh/m2]
fv:              array(hour) of real

end-declarations

!Stop when the current integer solution is within 0.1% of optimal
setparam("XPRS_MIPRELSTOP", 0.001)

q::[0.93,261.54]
f::[2.36,308.63]
s_cog_max::[501, 951, 825, 788, 799, 0, 1229, 2933, 1313]
s_cal_max::[561, 0, 891, 996, 749, 189, 1556, 3720, 92]

initializations from "E_dem_2016.dat"
E_dem
end-initializations
```

```
initializations from "Q_dem_2016.dat"
Q_dem
end-initializations

initializations from "st_2016.dat"
st
end-initializations

initializations from "fv_2016.dat"
fv
end-initializations

!definizione variabili binarie e intere
ex_ret is_binary
ex_cog_cu is_binary
ex_cal_cu is_binary
forall (u in user) ex_cog(u) is_binary
forall (u in user) ex_cal(u) is_binary
forall (h in hour) op_cog_cu(h) is_binary
forall (h in hour) op_cal_cu(h) is_binary
forall (h in hour, u in user) op_cog(h,u) is_binary
forall (h in hour, u in user) op_cal(h,u) is_binary
forall (h in hour, u in user) delta_E_comp(h,u) is_binary
forall (h in hour, u in user) delta_E_vend(h,u) is_binary
forall (h in hour, u in user) delta_E_fv_ut(h,u) is_binary
forall (h in hour, u in user) delta_Q_in(h,u) is_binary
forall (h in hour, u in user) delta_Q_out(h,u) is_binary
forall (h in hour) delta_Q_in_sto(h) is_binary
forall (h in hour) delta_Q_out_sto(h) is_binary
s_cog_cu is_semint 95
s_cal_cu is_semint 349
s_cog(1) is_semint 80
s_cog(2) is_semint 45
s_cog(3) is_semint 30
s_cog(4) is_semint 30
s_cog(5) is_semint 30
s_cog(7) is_semint 30
s_cog(8) is_semint 30
s_cog(9) is_semint 30
s_cal(1) is_semint 61
s_cal(3) is_semint 63
s_cal(4) is_semint 23
s_cal(5) is_semint 21
s_cal(6) is_semint 18
s_cal(7) is_semint 834
```

```
s_cal(8) is_semint 386
s_cal(9) is_semint 16
cam_st is_integer
cam_fv is_integer
s_sto is_integer

!cogeneratore centralizzato
!vincoli di taglia
s_cog_cu>=0
s_cog_cu<=s_cog_cu_max*ex_cog_cu
forall(h in hour) do
!vincoli di funzionamento
op_cog_cu(h)<=ex_cog_cu
ex_cog_cu<=s_cog_cu
!energia elettrica cogenerata
!E_cog_cu(h) >= out_cog_lim * s_cog_cu * op_cog_cu(h)
!E_cog_cu(h) <= s_cog_cu * op_cog_cu(h)
E_cog_cu(h)>=out_cog_lim*(s_cog_cu-(s_cog_cu_max*(1-op_cog_cu(h))))
E_cog_cu(h)<=s_cog_cu
E_cog_cu(h)>=0
E_cog_cu(h)<=s_cog_cu_max*op_cog_cu(h)
!carico termico in funzione del carico elettrico
Q_cog_cu(h)=q(1)*E_cog_cu(h)+q(2)*op_cog_cu(h)
!combustibile consumato in funzione del carico elettrico
F_cog_cu(h)=f(1)*E_cog_cu(h)+f(2)*op_cog_cu(h)
end-do

!cogeneratori utenze
!nessuna cogeneratore nell'utenza 6
ex_cog(6)=0
!vincoli di taglia
forall(u in user) do
s_cog(u)>=0
s_cog(u)<=s_cog_max(u)*ex_cog(u)
end-do
forall(h in hour,u in user) do
!vincoli di funzionamento
op_cog(h,u)<=ex_cog(u)
ex_cog(u)<=s_cog(u)
!energia elettrica cogenerata
!E_cog(h,u) >= out_cog_lim * s_cog(u) * op_cog(h,u)
!E_cog(h,u) <= s_cog(u) * op_cog(h,u)
E_cog(h,u)>=out_cog_lim*(s_cog(u)-(s_cog_max(u)*(1-op_cog(h,u))))
E_cog(h,u)<=s_cog(u)
E_cog(h,u)>=0
```

```
E_cog(h,u)<=s_cog_max(u)*op_cog(h,u)
!carico termico in funzione del carico elettrico
Q_cog(h,u)=q(1)*E_cog(h,u)+q(2)*op_cog(h,u)
!combustibile consumato in funzione del carico elettrico
F_cog(h,u)=f(1)*E_cog(h,u)+f(2)*op_cog(h,u)
end-do

!caldaia centralizzata
!vincoli di taglia
s_cal_cu>=0
s_cal_cu<=s_cal_cu_max*ex_cal_cu
forall(h in hour) do
!vincoli di funzionamento
op_cal_cu(h)<=ex_cal_cu
ex_cal_cu<=s_cal_cu
!energia termica prodotta
!Q_cal_cu(h) >= out_cal_lim * s_cal_cu * op_cal_cu(h)
!Q_cal_cu(h) <= s_cal_cu * op_cal_cu(h)
Q_cal_cu(h)>=out_cal_lim*(s_cal_cu-(s_cal_cu_max*(1-op_cal_cu(h))))
Q_cal_cu(h)<=s_cal_cu
Q_cal_cu(h)>=0
Q_cal_cu(h)<=s_cal_cu_max*op_cal_cu(h)
!combustibile consumato
F_cal_cu(h)=Q_cal_cu(h)/eta_cal
end-do

!caldaie utenze
!nessuna caldaia nell'utenza 2
ex_cal(2)=0
!vincoli di taglia
forall(u in user) do
s_cal(u)>=0
s_cal(u)<=s_cal_max(u)*ex_cal(u)
end-do
forall(h in hour,u in user) do
!vincoli di funzionamento
op_cal(h,u)<=ex_cal(u)
ex_cal(u)<=s_cal(u)
!energia termica prodotta
!Q_cal(h,u) >= out_cal_lim * s_cal(u) * op_cal(h,u)
!Q_cal(h,u) <= s_cal(u) * op_cal(h,u)
Q_cal(h,u)>=out_cal_lim*(s_cal(u)-(s_cal_max(u)*(1-op_cal(h,u))))
Q_cal(h,u)<=s_cal(u)
Q_cal(h,u)>=0
Q_cal(h,u)<=s_cal_max(u)*op_cal(h,u)
```

```
!combustibile consumato
F_cal(h,u)=Q_cal(h,u)/eta_cal
end-do

!campo solare termico
!limite massimo produzione
Q_st_max:=20000*0.679167044
!vincolo esistenza campo solare termico
cam_st>=0
cam_st<=20000
!energia termica prodotta dal campo solare termico
forall(h in hour) do
Q_st(h)=cam_st*st(h)
Q_in(h,2)=0
end-do

!campo solare fotovoltaico
!limite massimo produzione
E_fv_max:=20000*0.138878966
!vincolo esistenza campo solare fotovoltaico
cam_fv>=0
cam_fv<=20000
!energia elettrica prodotta dal campo solare fotovoltaico
forall(h in hour) do
E_fv(h):=cam_fv*fv(h)
end-do

!rete di teleriscaldamento
!la rete esiste
ex_ret=1
!energia termica oraria nella rete
forall(h in hour) do
Q_ret(h)=Q_out_cu(h)+sum(u in user)(Q_out(h,u))+Q_out_sto(h)
!limite dettato dal dimensionamento della rete (D=300mm, v=2m/sec)
Q_ret(h)<=11838
end-do
!bilancio termico della rete
forall(h in hour) do
Q_out_cu(h)+sum(u in user)(Q_out(h,u))+Q_out_sto(h)=
=(1+perd_ret)*(sum(u in user)(Q_in(h,u))+Q_in_sto(h))
end-do

!accumulo termico
!vincoli accumulo termico
forall(h in hour) do
```

```
Q_out_sto(h)<=Q_sto(h)
Q_in_sto(h)<=Q_ret(h)
end-do
!bilancio accumulo termico
forall(h in hour|h>1) do
Q_sto(h)=Q_sto(h-1)+Q_in_sto(h-1)-Q_out_sto(h-1)-perd_sto*Q_sto(h-1)
end-do
forall(h in hour|h=1) do
Q_sto(1)=Q_sto(2016)+Q_in_sto(2016)-Q_out_sto(2016)-perd_sto*Q_sto(2016)
end-do
!vincolo esistenza accumulo
s_sto>=0
!vincolo taglia accumulo
forall(h in hour) do
Q_sto(h)<=s_sto
end-do

!bilancio termico unità centrale
forall(h in hour) do
!calore totale prodotto dall'unità centrale
Q_out_cu(h):=Q_cog_cu(h)+Q_cal_cu(h)+Q_st(h)
end-do

!bilancio elettrico unità centrale
forall(h in hour) do
E_cog_cu(h)=E_cu_vend(h)!+sum(u in user)(E_cu_ut(h,u))
E_fv(h)=E_fv_vend(h)+sum(u in user)(E_fv_ut(h,u))
end-do

!bilancio termico utenze
forall(h in hour,u in user) do
Q_cog(h,u)+Q_cal(h,u)+Q_in(h,u)=Q_dem(h,u)+Q_out(h,u)+Q_dis(h,u)
end-do

!bilancio elettrico utenze
forall(h in hour, u in user) do
E_cog(h,u)+E_fv_ut(h,u)+E_comp(h,u)=E_dem(h,u)+E_vend(h,u)
end-do

!calcolo quantità energetiche unità centrale
E_cog_cu_t:=sum(h in hour)(4*E_cog_cu(h))
Q_cog_cu_t:=sum(h in hour)(4*Q_cog_cu(h))
F_cog_cu_t:=sum(h in hour)(4*F_cog_cu(h))
Q_cal_cu_t:=sum(h in hour)(4*Q_cal_cu(h))
F_cal_cu_t:=sum(h in hour)(4*F_cal_cu(h))
```

```
E_fv_t:=sum(h in hour)(4*E_fv(h))
E_cu_vend_t:=sum(h in hour)(4*E_cu_vend(h))
E_fv_vend_t:=sum(h in hour)(4*E_fv_vend(h))
E_vend_t:=E_cu_vend_t+E_fv_vend_t
E_fv_ut_t:=E_fv_t-E_fv_vend_t
Q_st_t:=sum(h in hour)(4*Q_st(h))
Q_in_sto_t:=sum(h in hour)(4*Q_in_sto(h))
Q_out_sto_t:=sum(h in hour)(4*Q_out_sto(h))

!calcolo dei costi della centrale
cost_gas_cog_cu:=c_gas_cog*F_cog_cu_t
cost_gas_cal_cu:=c_gas_cal*F_cal_cu_t
ric_vend_t:=c_vend*E_vend_t
cost_man_cu:=m_cog*E_cog_cu_t+m_cal*Q_cal_cu_t
cost_inv_cu:=(cf_cog_cu*ex_cog_cu+cv_cog_cu*s_cog_cu)*f_cog+
+(cf_cal*ex_cal_cu+cv_cal*s_cal_cu)*f_cal

!calcolo quantità energetiche delle utenze
forall(u in user) do
E_cog_u(u):=sum(h in hour)(4*E_cog(h,u))
F_cog_u(u):=sum(h in hour)(4*F_cog(h,u))
Q_cog_u(u):=sum(h in hour)(4*Q_cog(h,u))
Q_cal_u(u):=sum(h in hour)(4*Q_cal(h,u))
Q_u_t(u):=Q_cog_u(u)+Q_cal_u(u)
F_cal_u(u):=sum(h in hour)(4*F_cal(h,u))
Q_dis_u(u):=sum(h in hour)(4*Q_dis(h,u))
E_dem_u(u):=sum(h in hour)(4*E_dem(h,u))
Q_dem_u(u):=sum(h in hour)(4*Q_dem(h,u))
E_comp_u(u):=sum(h in hour)(4*E_comp(h,u))
E_vend_u(u):=sum(h in hour)(4*E_vend(h,u))
E_fv_ut_u(u):=sum(h in hour)(4*E_fv_ut(h,u))
E_auto_u(u):=E_cog_u(u)-E_vend_u(u)
Q_in_u(u):=sum(h in hour)(4*Q_in(h,u))
Q_out_u(u):=sum(h in hour)(4*Q_out(h,u))
end-do

!calcolo dei costi in ogni utenza
forall(u in user) do
cost_gas_cog_u(u):=c_gas_cog*F_cog_u(u)
cost_gas_cal_u(u):=c_gas_cal*F_cal_u(u)
cost_comp_u(u):=c_comp*E_comp_u(u)
ric_vend_u(u):=c_vend*E_vend_u(u)
man_u(u):=m_cog*E_cog_u(u)+m_cal*Q_cal_u(u)
cost_inv_u(u):=(cf_cog*ex_cog(u)+cv_cog*s_cog(u))*f_cog+
+(cf_cal*ex_cal(u)+cv_cal*s_cal(u))*f_cal
```

```
cost_u(u):=cost_gas_cog_u(u)+cost_gas_cal_u(u)+
+cost_comp_u(u)-ric_vend_u(u)+man_u(u)+cost_inv_u(u)
end-do

!condizioni sull'energia elettrica acquistata e venduta dagli utenti
forall(h in hour, u in user) do
E_vend(h,u)>=0
E_vend(h,u)<=E_cog(h,u)
E_vend(h,u)<=s_cog_max(u)*delta_E_vend(h,u)
E_comp(h,u)>=0
E_comp(h,u)<=E_dem(h,u)*delta_E_comp(h,u)
delta_E_vend(h,u)+delta_E_comp(h,u)<=1
E_fv_ut(h,u)>=0
E_fv_ut(h,u)<=E_fv_max*delta_E_fv_ut(h,u)
delta_E_vend(h,u)+delta_E_fv_ut(h,u)<=1
end-do

!condizione per la quale un utente non può vendere più energia elettrica di quella che
produce
forall(h in hour, u in user) do
E_vend(h,u)<=E_cog(h,u)
end-do

!condizione per la quale l'energia termica immessa in rete dall'utente dev'essere
minore di quella prodotta
forall(h in hour, u in user) do
Q_out(h,u)<=Q_cog(h,u)+Q_cal(h,u)
end-do

!condizioni sull'energia termica scambiata tra gli utenti
forall(h in hour, u in user) do
Q_in(h,u)>=0
Q_in(h,u)<=Q_dem(h,u)*delta_Q_in(h,u)
Q_out(h,u)>=0
Q_out(h,u)<=(s_cog_max(u)+s_cal_max(u))*delta_Q_out(h,u)
delta_Q_in(h,u)+delta_Q_out(h,u)<=1
end-do

!condizioni sull'energia termica scambiata tra l'accumulo e la rete
forall(h in hour) do
Q_in_sto(h)>=0
Q_in_sto(h)<=(s_cal_cu_max+Q_st_max)*delta_Q_in_sto(h)
Q_out_sto(h)>=0
Q_out_sto(h)<=(s_cal_cu_max+Q_st_max)*delta_Q_out_sto(h)
delta_Q_in_sto(h)+delta_Q_out_sto(h)<=1
```

```
end-do

!calcolo quantità energetiche totali annue
E_cog_ut_t:=sum(u in user)(E_cog_u(u))
E_cog_tot:=E_cog_cu_t+E_cog_ut_t
Q_cog_ut_t:=sum(u in user)(Q_cog_u(u))
Q_cog_tot:=Q_cog_cu_t+Q_cog_ut_t
F_cog_tot:=F_cog_cu_t+sum(u in user)(F_cog_u(u))
Q_cal_ut_t:=sum(u in user)(Q_cal_u(u))
Q_cal_tot:=Q_cal_cu_t+Q_cal_ut_t
F_cal_tot:=F_cal_cu_t+sum(u in user)(F_cal_u(u))
F_tot:=F_cog_tot+F_cal_tot
E_vend_ut_t:=sum(u in user)(E_vend_u(u))
E_vend_tot:=E_vend_t+E_vend_ut_t
E_comp_tot:=sum(u in user)(E_comp_u(u))
E_auto_tot:=sum(u in user)(E_auto_u(u))
Q_dis_tot:=sum(u in user)(Q_dis_u(u))
Q_dis_sto_tot:=perd_sto*sum(h in hour)(4*Q_sto(h))
Q_in_u_tot:=sum(u in user)(Q_in_u(u))
Q_out_u_tot:=sum(u in user)(Q_out_u(u))
Q_dis_ret_tot:=perd_ret*(Q_in_u_tot+Q_in_sto_t)
E_dem_tot:=sum(u in user)(E_dem_u(u))
Q_dem_tot:=sum(u in user)(Q_dem_u(u))

!calcolo TEP e CO2
TEP:=(F_tot*tep_term)+(E_comp_tot-E_vend_tot)*tep_el
CO2:=(getsol(F_tot)*CO2_term)+(getsol(E_comp_tot)*CO2_el)-
(getsol(E_vend_tot)*CO2_el)

!calcolo benefici ambientali
CO2_saved_vs_CS:=14836-CO2
Energy_Saving_vs_CS:=69867770-F_tot-(E_comp_tot-E_vend_tot)/eta

!taglia accumulo
s_sto_m3:=getsol(s_sto)/93

!potenza picco solare fotovoltaico
P_fv:=0.1356*getsol(cam_fv)

!verifica bilanci energetici
bilancio_elettrico_utenze:=E_cog_ut_t+E_fv_ut_t+E_comp_tot-E_dem_tot-
E_vend_ut_t
bilancio_termico_utenze:=Q_cog_ut_t+Q_cal_ut_t+Q_in_u_tot-Q_dem_tot-
Q_out_u_tot-Q_dis_tot
bilancio_termico_accumulo:=Q_in_sto_t-Q_out_sto_t-Q_dis_sto_tot
```

```
bilancio_termico_rete:=sum(h in hour)(4*Q_out_cu(h))+Q_out_u_tot+Q_out_sto_t-
Q_in_u_tot-Q_in_sto_t-Q_dis_ret_tot
bilancio_termico_centrale:=sum(h in hour)(4*Q_out_cu(h))-Q_cog_cu_t-Q_cal_cu_t-
Q_st_t

!costi di operazione
!cost_gas_cog:=sum(h in hour)(cost_gas_cog_h(h))
cost_gas_cog:=c_gas_cog*F_cog_tot
!cost_gas_cal:=sum(h in hour)(cost_gas_cal_h(h))
cost_gas_cal:=c_gas_cal*F_cal_tot
!cost_comp:=sum(h in hour)(cost_comp_h(h))
cost_comp:=c_comp*E_comp_tot
!ric_vend:=sum(h in hour)(ric_vend_h(h))
ric_vend:=c_vend*E_vend_tot

!costo componenti
C_rete:=c_ret*f_ret*getsol(ex_ret)
C_st:=c_pan_st*getsol(cam_st)*f_pan
C_fv:=c_pan_fv*getsol(cam_fv)*f_pan
C_sto:=c_sto*getsol(s_sto)*f_sto
C_cog_cu:=cf_cog_cu*getsol(ex_cog_cu)+cv_cog_cu*getsol(s_cog_cu)
C_cal_cu:=cf_cal*getsol(ex_cal_cu)+cv_cal*getsol(s_cal_cu)
C_cog:=cf_cog*getsol(ex_cog(u))+cv_cog*getsol(s_cog(u))
C_cal:=cf_cal*getsol(ex_cal(u))+cv_cal*getsol(s_cal(u))

!costi di manutenzione
cost_man:=m_cog*E_cog_tot+m_cal*Q_cal_tot

!investimento annuo
cost_inv:=(cf_cog*(ex_cog_cu+sum(u in user)(ex_cog(u)))+
+cv_cog*(s_cog_cu+sum(u in user)(s_cog(u))))*f_cog+
+(cf_cal*(ex_cal_cu+sum(u in user)(ex_cal(u)))+
+cv_cal*(s_cal_cu+sum(u in user)(s_cal(u))))*f_cal+c_ret*f_ret*ex_ret+
+c_sto*s_sto*f_sto+c_pan_st*cam_st*f_pan+c_pan_fv*cam_fv*f_pan

!investimento totale
cost_inv_tot:=cf_cog_cu*ex_cog_cu+cv_cog_cu*s_cog_cu+
+cf_cog*sum(u in user)(ex_cog(u))+cv_cog*sum(u in user)(s_cog(u))+
+cf_cal*(ex_cal_cu+sum(u in user)(ex_cal(u)))+
+cv_cal*(s_cal_cu+sum(u in user)(s_cal(u)))+c_ret*ex_ret+c_sto*s_sto+
+c_pan_st*cam_st+c_pan_fv*cam_fv

!costo operativo annuo
cost_ope:=cost_gas_cog+cost_gas_cal+cost_comp-ric_vend
```

```
!support policy
Support_Policy:=i*(5838-TEP)
!costo incentivo per la società
CO2_saved_cost_vs_CS:=Support_Policy/CO2_saved_vs_CS
Energy_Saving_cost_vs_CS:=getsol(Support_Policy)/((getsol(Energy_Saving_vs_CS))/1
000)

!payback period
PB:= (cost_inv_tot-207972)/(3787091-(cost_ope+cost_man-Support_Policy))

!costo totale annuo
cost_tot:=cost_inv+cost_ope+cost_man-Support_Policy

setparam("XPRS_verbose",true)
minimize(cost_tot)

fopen("results_White Papers.txt",F_OUTPUT)
writeln
writeln(">>>>>>>>>>>Costi sistema<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<")
writeln
writeln("Costo gas cogeneratori [€]:
                  ",strfmt(getsol(cost_gas_cog),10,0))
writeln("Costo gas caldaie [€]:
                  ",strfmt(getsol(cost_gas_cal),10,0))
writeln("Costo energia elettrica acquistata [€]:
                  ",strfmt(getsol(cost_comp),10,0))
writeln("Ricavo energia elettrica venduta [€]:
                  ",strfmt(getsol(ric_vend),10,0))
writeln("Costi di manutenzione [€]:
                  ",strfmt(getsol(cost_man),10,0))
writeln("Investimento annuo [€]:
                  ",strfmt(getsol(cost_inv),10,0))
writeln("Investimento totale [€]:
                  ",strfmt(getsol(cost_inv_tot),10,0))
writeln("Costo operativo [€]:
                  ",strfmt(getsol(cost_ope),10,0))
writeln("Paybak period [€]:
                  ",strfmt(getsol(PB),10,0))
writeln("Support Policy [€]:
                  ",strfmt(getsol(Support_Policy),10,0))
writeln("Costo annuo [€]:
                  ",strfmt(getobjval,10,0))
writeln
writeln(">>>>>>>>>>>Quantità energetiche sistema<<<<<<<<<<<<<<<<<<<<<<<<<<")
```

```
writeln
writeln("Energia elettrica richiesta [kWh]:
                    ",strfmt(getsol(E_dem_tot),10,0))
writeln("Calore richiesto [kWh]:
                    ",strfmt(getsol(Q_dem_tot),10,0))
writeln("Energia elettrica cogenerata [kWh]:
                    ",strfmt(getsol(E_cog_tot),10,0))
writeln("Energia elettrica cogenerata utenze [kWh]:
                    ",strfmt(getsol(E_cog_ut_t),10,0))
writeln("Calore prodotto cogeneratori [kWh]:
                    ",strfmt(getsol(Q_cog_tot),10,0))
writeln("Calore prodotto cogeneratori utenze [kWh]:
                    ",strfmt(getsol(Q_cog_ut_t),10,0))
writeln("Calore prodotto caldaie [kWh]:
                    ",strfmt(getsol(Q_cal_tot),10,0))
writeln("Calore prodotto solare termico [kWh]:
                    ",strfmt(getsol(Q_st_t),10,0))
writeln("Gas cogeneratori [kWh]:
                    ",strfmt(getsol(F_cog_tot),10,0))
writeln("Gas caldaie [kWh]:
                    ",strfmt(getsol(F_cal_tot),10,0))
writeln("Energia elettrica acquistata [kWh]:
                    ",strfmt(getsol(E_comp_tot),10,0))
writeln("Energia elettrica autoconsumata [kWh]:
                    ",strfmt(getsol(E_auto_tot),10,0))
writeln("Energia elettrica venduta totale [kWh]:
                    ",strfmt(getsol(E_vend_tot),10,0))
writeln("Energia elettrica venduta utenze [kWh]:
                    ",strfmt(getsol(E_vend_ut_t),10,0))
writeln("Energia elettrica da solare fotovoltaico [kWh]:
                    ",strfmt(getsol(E_fv_t),10,0))
writeln("Energia fotovoltaica autoconsumata [kWh]:
                    ",strfmt(getsol(E_fv_ut_t),10,0))
writeln("Energia elettrica fotovoltaica venduta [kWh]:
                    ",strfmt(getsol(E_fv_vend_t),10,0))
writeln("Calore dissipato utenti [kWh]:
                    ",strfmt(getsol(Q_dis_tot),10,0))
writeln("Calore dissipato rete [kWh]:
                    ",strfmt(getsol(Q_dis_ret_tot),10,0))
writeln("Calore dissipato accumulo termico [kWh]:
                    ",strfmt(getsol(Q_dis_sto_tot),10,0))
writeln("Flusso termico dalla rete alle utenze [kWh]:
                    ",strfmt(getsol(Q_in_u_tot),10,0))
writeln("Flusso termico dalle utenze alla rete [kWh]:
                    ",strfmt(getsol(Q_out_u_tot),10,0))
```

```
writeln("Flusso termico dalla rete al serbatorio [kWh]:
                ",strfmt(getsol(Q_in_sto_t),10,0))
writeln("Flusso termico dal serbatoio alla rete [kWh]:
                ",strfmt(getsol(Q_out_sto_t),10,0))
writeln("Tonnellate Equivalenti Petrolio (TEP) [ton]:
                ",strfmt(getsol(TEP),10,0))
writeln("Tonnellate di CO2 emesse [ton]:
                ",strfmt(CO2,10,0))
writeln("CO2 Saved_vs_CS [ton]:
                ",strfmt(getsol(CO2_saved_vs_CS),10,0))
writeln("CO2 Saved Cost_vs_CS [€/ton]:
                ",strfmt(getsol(CO2_saved_cost_vs_CS),10,0))
writeln("Energy Saving_vs_CS [kWh]:
                ",strfmt(getsol(Energy_Saving_vs_CS),10,0))
writeln("Energy Saving Cost_vs_CS [€/MWh]:
                ",strfmt(getsol(Energy_Saving_cost_vs_TC),10,0))
writeln("Verifica bilancio elettrico utenze:
                ",strfmt(getsol(bilancio_elettrico_utenze),10,0))
writeln("Verifica bilancio termico utenze:
                ",strfmt(getsol(bilancio_termico_utenze),10,0))
writeln
writeln(">>>>>>>>>>>Struttura e costi centrale<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<")
writeln
writeln("Investimento annuo rete [€]:
                ",strfmt(C_rete,10,0))
writeln("Area campo solare termico [m2]:
                ",strfmt(getsol(cam_st),10,0))
writeln("Investimento annuo campo solare termico [€]:
                ",strfmt(C_st,10,0))
writeln("Area campo solare fotovoltaico [m2]:
                ",strfmt(getsol(cam_fv),10,0))
writeln("Potenza di picco solare fotovoltaico [kW]:
                ",strfmt(getsol(P_fv),10,0))
writeln("Investimento annuo campo solare fotovoltaico [€]:
                ",strfmt(C_fv,10,0))
writeln("Taglia accumulo termico [m3]:
                ",strfmt(s_sto_m3,10,0))
writeln("Investimento annuo accumulo termico [€]:
                ",strfmt(C_sto,10,0))
writeln("Taglia cogeneratore [kW]:
                ",strfmt(getsol(s_cog_cu),10,0))
writeln("Costo cogeneratore [€]:
                ",strfmt(C_cog_cu,10,0))
writeln("Taglia caldaia [kW]:
                ",strfmt(getsol(s_cal_cu),10,0))
```

```
writeln("Costo caldaia [€]:
                    ",strfmt(C_cal_cu,10,0))
writeln("Costo gas cogeneratore [€]:
                    ",strfmt(getsol(cost_gas_cog_cu),10,0))
writeln("Costo gas caldaia [€]:
                    ",strfmt(getsol(cost_gas_cal_cu),10,0))
writeln("Ricavo energia elettrica venduta [€]:
                    ",strfmt(getsol(ric_vend_t),10,0))
writeln("Costi di manutenzione [€]:
                    ",strfmt(getsol(cost_man_cu),10,0))
writeln("Investimento annuo macchine [€]:
                    ",strfmt(getsol(cost_inv_cu),10,0))
writeln
forall(u in user) do
writeln(">>>>>>>>>>>Struttura e costi utente ",u," <<<<<<<<<<<<<<<<<<<<<<<<<<<")
writeln
writeln("Taglia cogeneratore [kW]:
                    ",strfmt(getsol(s_cog(u)),10,0))
writeln("Costo cogeneratore [€]:
                    ",strfmt(C_cog,10,0))
writeln("Taglia caldaia [kW]:
                    ",strfmt(getsol(s_cal(u)),10,0))
writeln("Costo caldaia [€]:
                    ",strfmt(C_cal,10,0))
writeln
writeln("Costo gas cogeneratore [€]:
                    ",strfmt(getsol(cost_gas_cog_u(u)),10,0))
writeln("Costo gas caldaia [€]:
                    ",strfmt(getsol(cost_gas_cal_u(u)),10,0))
writeln("Costo energia elettrica acquistata [€]:
                    ",strfmt(getsol(cost_comp_u(u)),10,0))
writeln("Ricavo energia elettrica venduta [€]:
                    ",strfmt(getsol(ric_vend_u(u)),10,0))
writeln("Costi di manutenzione [€]:
                    ",strfmt(getsol(man_u(u)),10,0))
writeln("Investimento annuo [€]:
                    ",strfmt(getsol(cost_inv_u(u)),10,0))
writeln("Costo totale annuo [€]:
                    ",strfmt(getsol(cost_u(u)),10,0))
writeln
end-do
writeln(">>>>>>>>>>>Quantità energetiche annue centrale<<<<<<<<<<<<<<<<<<<<")
writeln
writeln("Energia elettrica cogenerata [kWh]:
                    ",strfmt(getsol(E_cog_cu_t),10,0))
```

```
writeln("Energia elettrica cogenerata venduta [kWh]:
                    ",strfmt(getsol(E_cu_vend_t),10,0))
writeln("Energia elettrica venduta totale [kWh]:
                    ",strfmt(getsol(E_vend_t),10,0))
writeln("Calore prodotto cogeneratore [kWh]:
                    ",strfmt(getsol(Q_cog_cu_t),10,0))
writeln("Calore prodotto caldaia [kWh]:
                    ",strfmt(getsol(Q_cal_cu_t),10,0))
writeln("Gas cogeneratore [kWh]:
                    ",strfmt(getsol(F_cog_cu_t),10,0))
writeln("Gas caldaia [kWh]:
                    ",strfmt(getsol(F_cal_cu_t),10,0))
writeln("Verifica bilancio accumulo termico:
                    ",strfmt(getsol(bilancio_termico_accumulo),10,0))
writeln("Verifica bilancio termico rete:
                    ",strfmt(getsol(bilancio_termico_rete),10,0))
writeln("Verifica bilancio termico centrale:
                    ",strfmt(getsol(bilancio_termico_centrale),10,0))
writeln
forall(u in user) do
writeln(">>>>>>>>>>>Quantità energetiche utente ",u,"<<<<<<<<<<<<<<<<<<<<<<<")
writeln
writeln("Energia elettrica prodotta cogeneratore [kWh]:
                    ",strfmt(getsol(E_cog_u(u)),10,0))
writeln("Energia elettrica acquistata [kWh]:
                    ",strfmt(getsol(E_comp_u(u)),10,0))
writeln("Energia elettrica ricevuta dal campo fotovoltaico [kWh]:
                    ",strfmt(getsol(E_fv_ut_u(u)),10,0))
writeln("Energia elettrica autoconsumata [kWh]:
                    ",strfmt(getsol(E_auto_u(u)),10,0))
writeln("Energia elettrica richiesta [kWh]:
                    ",strfmt(getsol(E_dem_u(u)),10,0))
writeln("Energia elettrica venduta [kWh]:
                    ",strfmt(getsol(E_vend_u(u)),10,0))
writeln("Calore prodotto cogeneratore [kWh]:
                    ",strfmt(getsol(Q_cog_u(u)),10,0))
writeln("Calore prodotto caldaia [kWh]:
                    ",strfmt(getsol(Q_cal_u(u)),10,0))
writeln("Calore richiesto [kWh]:
                    ",strfmt(getsol(Q_dem_u(u)),10,0))
writeln("Calore dissipato [kWh]:
                    ",strfmt(getsol(Q_dis_u(u)),10,0))
writeln("Flusso termico dalla rete all'utente [kWh]:
                    ",strfmt(getsol(Q_in_u(u)),10,0))
writeln("Flusso termico dall'utente alla rete [kWh]:
```

```
               ",strfmt(getsol(Q_out_u(u)),10,0))
writeln("Gas cogeneratore [kWh]:
               ",strfmt(getsol(F_cog_u(u)),10,0))
writeln("Gas caldaia [kWh]:
               ",strfmt(getsol(F_cal_u(u)),10,0))
writeln
end-do
writeln
writeln(">>>>>>>>>>>>Comportamento rete<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<")
forall(h in hour) do
writeln(strfmt(getsol(Q_ret(h)),10,0))
end-do
writeln
writeln(">>>>>>>>>>>>Comportamento accumulo<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<")
forall(h in hour) do
writeln(strfmt(getsol(Q_sto(h)),10,0))
end-do
writeln
writeln(">>>>>>>>>>>>Calore prodotto campo solare termico<<<<<<<<<<<<<<<<<<<<<")
forall(h in hour) do
writeln(strfmt(getsol(Q_st(h)),10,0))
end-do
writeln

fclose(F_OUTPUT)

end-model
```

B

Optimization results

```
>>>>>>>>>>>Costi sistema<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Costo gas cogeneratori [€]:                          692990
Costo gas caldaie [€]:                               0
Costo energia elettrica acquistata [€]:              1583493
Ricavo energia elettrica venduta [€]:                83166
Costi di manutenzione [€]:                           94950
Investimento annuo [€]:                              1102218
Investimento totale [€]:                             11217764
Costo operativo [€]:                                 2193317
Support Policy [€]:                                  253435
Costo annuo [€]:                                     3137050

>>>>>>>>>>>Quantità energetiche sistema<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica richiesta [kWh]:                   20216976
Calore richiesto [kWh]:                              21184664
Energia elettrica cogenerata [kWh]:                  5585312
Energia elettrica cogenerata utenze [kWh]:           5585312
Calore prodotto cogeneratori [kWh]:                  7074290
```

```
Calore prodotto cogeneratori utenze [kWh]:          7074290
Calore prodotto caldaie [kWh]:                      0
Calore prodotto solare termico [kWh]:               16593826
Gas cogeneratori [kWh]:                             15399769
Gas caldaie [kWh]:                                  0
Energia elettrica acquistata [kWh]:                 13195779
Energia elettrica autoconsumata [kWh]:              4843379
Energia elettrica venduta totale [kWh]:             978429
Energia elettrica venduta utenze [kWh]:             741933
Energia elettrica da solare fotovoltaico [kWh]:     2414314
Energia fotovoltaica autoconsumata [kWh]:           2177818
Energia elettrica fotovoltaica venduta [kWh]:       236496
Calore dissipato utenti [kWh]:                      997
Calore dissipato rete [kWh]:                        275204
Calore dissipato accumulo termico [kWh]:            2207251
Flusso termico dalla rete alle utenze [kWh]:        18781503
Flusso termico dalle utenze alla rete [kWh]:        4670132
Flusso termico dalla rete al serbatorio [kWh]:      8738944
Flusso termico dal serbatoio alla rete [kWh]:       6531693
Tonnellate Equivalenti Petrolio (TEP) [ton]:        3609
Tonnellate di CO2 emesse [ton]:                     9155
CO2 Saved_vs_TC [ton]:                              5681
CO2 Saved Cost_vs_TC [€/ton]:                       45
Energy Saving_vs_TC [kWh]:                          26701297
Energy Saving Cost_vs_TC [€/MWh]:                   9
Verifica bilancio elettrico utenze:                 0
Verifica bilancio termico utenze:                   0

>>>>>>>>>>>Struttura e costi centrale<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Investimento annuo rete [€]:                        225027
Area campo solare termico [m2]:                     12617
Investimento annuo campo solare termico [€]:        346320
Area campo solare fotovoltaico [m2]:                8436
Potenza di picco solare fotovoltaico [kW]:          1144
Investimento annuo campo solare fotovoltaico [€]:   324180
Taglia accumulo termico [m3]:                       4507
Investimento annuo accumulo termico [€]:            54072
Taglia cogeneratore [kW]:                           0
Costo cogeneratore [€]:                             0
Taglia caldaia [kW]:                                0
Costo caldaia [€]:                                  0
Costo gas cogeneratore [€]:                         0
Costo gas caldaia [€]:                              0
Ricavo energia elettrica venduta [€]:               20102
```

```
Costi di manutenzione [€]:                        0
Investimento annuo macchine [€]:                  0

>>>>>>>>>>>Struttura e costi utente 1 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                         0
Costo cogeneratore [€]:                           0
Taglia caldaia [kW]:                              0
Costo caldaia [€]:                                0

Costo gas cogeneratore [€]:                       0
Costo gas caldaia [€]:                            0
Costo energia elettrica acquistata [€]:           115323
Ricavo energia elettrica venduta [€]:             0
Costi di manutenzione [€]:                        0
Investimento annuo [€]:                           0
Costo totale annuo [€]:                           115323

>>>>>>>>>>>Struttura e costi utente 2 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                         0
Costo cogeneratore [€]:                           0
Taglia caldaia [kW]:                              0
Costo caldaia [€]:                                0

Costo gas cogeneratore [€]:                       0
Costo gas caldaia [€]:                            0
Costo energia elettrica acquistata [€]:           180523
Ricavo energia elettrica venduta [€]:             0
Costi di manutenzione [€]:                        0
Investimento annuo [€]:                           0
Costo totale annuo [€]:                           180523

>>>>>>>>>>>Struttura e costi utente 3 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                         0
Costo cogeneratore [€]:                           0
Taglia caldaia [kW]:                              0
Costo caldaia [€]:                                0

Costo gas cogeneratore [€]:                       0
Costo gas caldaia [€]:                            0
Costo energia elettrica acquistata [€]:           145238
Ricavo energia elettrica venduta [€]:             0
Costi di manutenzione [€]:                        0
```

```
Investimento annuo [€]:                     0
Costo totale annuo [€]:                     145238

>>>>>>>>>>>Struttura e costi utente 4 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                   0
Costo cogeneratore [€]:                     0
Taglia caldaia [kW]:                        0
Costo caldaia [€]:                          0

Costo gas cogeneratore [€]:                 0
Costo gas caldaia [€]:                      0
Costo energia elettrica acquistata [€]:     158705
Ricavo energia elettrica venduta [€]:       0
Costi di manutenzione [€]:                  0
Investimento annuo [€]:                     0
Costo totale annuo [€]:                     158705

>>>>>>>>>>>Struttura e costi utente 5 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                   0
Costo cogeneratore [€]:                     0
Taglia caldaia [kW]:                        0
Costo caldaia [€]:                          0

Costo gas cogeneratore [€]:                 0
Costo gas caldaia [€]:                      0
Costo energia elettrica acquistata [€]:     303766
Ricavo energia elettrica venduta [€]:       0
Costi di manutenzione [€]:                  0
Investimento annuo [€]:                     0
Costo totale annuo [€]:                     303766

>>>>>>>>>>>Struttura e costi utente 6 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                   0
Costo cogeneratore [€]:                     0
Taglia caldaia [kW]:                        0
Costo caldaia [€]:                          0

Costo gas cogeneratore [€]:                 0
Costo gas caldaia [€]:                      0
Costo energia elettrica acquistata [€]:     5612
Ricavo energia elettrica venduta [€]:       0
Costi di manutenzione [€]:                  0
```

```
Investimento annuo [€]:                         0
Costo totale annuo [€]:                         5612

>>>>>>>>>>>Struttura e costi utente 7 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                       0
Costo cogeneratore [€]:                         0
Taglia caldaia [kW]:                            0
Costo caldaia [€]:                              0

Costo gas cogeneratore [€]:                     0
Costo gas caldaia [€]:                          0
Costo energia elettrica acquistata [€]:         283155
Ricavo energia elettrica venduta [€]:           0
Costi di manutenzione [€]:                      0
Investimento annuo [€]:                         0
Costo totale annuo [€]:                         283155

>>>>>>>>>>>Struttura e costi utente 8 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                       650
Costo cogeneratore [€]:                         604500
Taglia caldaia [kW]:                            0
Costo caldaia [€]:                              0

Costo gas cogeneratore [€]:                     253414
Costo gas caldaia [€]:                          0
Costo energia elettrica acquistata [€]:         208899
Ricavo energia elettrica venduta [€]:           24550
Costi di manutenzione [€]:                      33709
Investimento annuo [€]:                         66371
Costo totale annuo [€]:                         537843

>>>>>>>>>>>Struttura e costi utente 9 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Taglia cogeneratore [kW]:                       898
Costo cogeneratore [€]:                         785540
Taglia caldaia [kW]:                            0
Costo caldaia [€]:                              0

Costo gas cogeneratore [€]:                     439576
Costo gas caldaia [€]:                          0
Costo energia elettrica acquistata [€]:         182271
Ricavo energia elettrica venduta [€]:           38514
Costi di manutenzione [€]:                      61241
```

```
Investimento annuo [€]:                                  86248
Costo totale annuo [€]:                                  730822

>>>>>>>>>>>>Quantità energetiche annue centrale<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica cogenerata [kWh]:                      0
Energia elettrica cogenerata venduta [kWh]:              0
Energia elettrica venduta totale [kWh]:                  236496
Calore prodotto cogeneratore [kWh]:                      0
Calore prodotto caldaia [kWh]:                           0
Gas cogeneratore [kWh]:                                  0
Gas caldaia [kWh]:                                       0
Verifica bilancio accumulo termico:                      0
Verifica bilancio termico rete:                          0
Verifica bilancio termico centrale:                      0

>>>>>>>>>>>>Quantità energetiche utente 1<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           0
Energia elettrica acquistata [kWh]:                      961026
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 208194
Energia elettrica autoconsumata [kWh]:                   0
Energia elettrica richiesta [kWh]:                       1169220
Energia elettrica venduta [kWh]:                         0
Calore prodotto cogeneratore [kWh]:                      0
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  434108
Calore dissipato [kWh]:                                  0
Flusso termico dalla rete all'utente [kWh]:              434108
Flusso termico dall'utente alla rete [kWh]:              0
Gas cogeneratore [kWh]:                                  0
Gas caldaia [kWh]:                                       0

>>>>>>>>>>>>Quantità energetiche utente 2<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           0
Energia elettrica acquistata [kWh]:                      1504362
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 213266
Energia elettrica autoconsumata [kWh]:                   0
Energia elettrica richiesta [kWh]:                       1717628
Energia elettrica venduta [kWh]:                         0
Calore prodotto cogeneratore [kWh]:                      0
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  0
Calore dissipato [kWh]:                                  0
```

```
Flusso termico dalla rete all'utente [kWh]:              0
Flusso termico dall'utente alla rete [kWh]:              0
Gas cogeneratore [kWh]:                                  0
Gas caldaia [kWh]:                                       0

>>>>>>>>>>>Quantità energetiche utente 3<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           0
Energia elettrica acquistata [kWh]:                      1210317
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 342947
Energia elettrica autoconsumata [kWh]:                   0
Energia elettrica richiesta [kWh]:                       1553264
Energia elettrica venduta [kWh]:                         0
Calore prodotto cogeneratore [kWh]:                      0
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  950488
Calore dissipato [kWh]:                                  0
Flusso termico dalla rete all'utente [kWh]:              950488
Flusso termico dall'utente alla rete [kWh]:              0
Gas cogeneratore [kWh]:                                  0
Gas caldaia [kWh]:                                       0

>>>>>>>>>>>Quantità energetiche utente 4<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           0
Energia elettrica acquistata [kWh]:                      1322539
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 259953
Energia elettrica autoconsumata [kWh]:                   0
Energia elettrica richiesta [kWh]:                       1582492
Energia elettrica venduta [kWh]:                         0
Calore prodotto cogeneratore [kWh]:                      0
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  1649664
Calore dissipato [kWh]:                                  0
Flusso termico dalla rete all'utente [kWh]:              1649664
Flusso termico dall'utente alla rete [kWh]:              0
Gas cogeneratore [kWh]:                                  0
Gas caldaia [kWh]:                                       0

>>>>>>>>>>>Quantità energetiche utente 5<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           0
Energia elettrica acquistata [kWh]:                      2531384
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 404508
Energia elettrica autoconsumata [kWh]:                   0
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Energia elettrica richiesta [kWh]:                        2935892
Energia elettrica venduta [kWh]:                          0
Calore prodotto cogeneratore [kWh]:                       0
Calore prodotto caldaia [kWh]:                            0
Calore richiesto [kWh]:                                   863592
Calore dissipato [kWh]:                                   0
Flusso termico dalla rete all'utente [kWh]:               863592
Flusso termico dall'utente alla rete [kWh]:               0
Gas cogeneratore [kWh]:                                   0
Gas caldaia [kWh]:                                        0

>>>>>>>>>>>Quantità energetiche utente 6<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:            0
Energia elettrica acquistata [kWh]:                       46770
Energia elettrica ricevuta dal campo fotovoltaico [kWh]:  10518
Energia elettrica autoconsumata [kWh]:                    0
Energia elettrica richiesta [kWh]:                        57288
Energia elettrica venduta [kWh]:                          0
Calore prodotto cogeneratore [kWh]:                       0
Calore prodotto caldaia [kWh]:                            0
Calore richiesto [kWh]:                                   120296
Calore dissipato [kWh]:                                   0
Flusso termico dalla rete all'utente [kWh]:               120296
Flusso termico dall'utente alla rete [kWh]:               0
Gas cogeneratore [kWh]:                                   0
Gas caldaia [kWh]:                                        0

>>>>>>>>>>>Quantità energetiche utente 7<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:            0
Energia elettrica acquistata [kWh]:                       2359627
Energia elettrica ricevuta dal campo fotovoltaico [kWh]:  271341
Energia elettrica autoconsumata [kWh]:                    0
Energia elettrica richiesta [kWh]:                        2630968
Energia elettrica venduta [kWh]:                          0
Calore prodotto cogeneratore [kWh]:                       0
Calore prodotto caldaia [kWh]:                            0
Calore richiesto [kWh]:                                   3666720
Calore dissipato [kWh]:                                   0
Flusso termico dalla rete all'utente [kWh]:               3666720
Flusso termico dall'utente alla rete [kWh]:               0
Gas cogeneratore [kWh]:                                   0
Gas caldaia [kWh]:                                        0
```

```
>>>>>>>>>>>Quantità energetiche utente 8<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           1982884
Energia elettrica acquistata [kWh]:                      1740827
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 243773
Energia elettrica autoconsumata [kWh]:                   1694060
Energia elettrica richiesta [kWh]:                       3678660
Energia elettrica venduta [kWh]:                         288824
Calore prodotto cogeneratore [kWh]:                      2650671
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  13437884
Calore dissipato [kWh]:                                  997
Flusso termico dalla rete all'utente [kWh]:              11094903
Flusso termico dall'utente alla rete [kWh]:              306694
Gas cogeneratore [kWh]:                                  5631421
Gas caldaia [kWh]:                                       0

>>>>>>>>>>>Quantità energetiche utente 9<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Energia elettrica prodotta cogeneratore [kWh]:           3602428
Energia elettrica acquistata [kWh]:                      1518927
Energia elettrica ricevuta dal campo fotovoltaico [kWh]: 223318
Energia elettrica autoconsumata [kWh]:                   3149319
Energia elettrica richiesta [kWh]:                       4891564
Energia elettrica venduta [kWh]:                         453109
Calore prodotto cogeneratore [kWh]:                      4423618
Calore prodotto caldaia [kWh]:                           0
Calore richiesto [kWh]:                                  61912
Calore dissipato [kWh]:                                  0
Flusso termico dalla rete all'utente [kWh]:              1732
Flusso termico dall'utente alla rete [kWh]:              4363438
Gas cogeneratore [kWh]:                                  9768348
Gas caldaia [kWh]:                                       0
```

C

List of publications

Journal publications

M Casisi, A De Nardi, P Pinamonti and M Reini. Effect of different economic support policies on the optimal synthesis and operation of a distributed energy supply system with renewable energy sources for an industrial area. *Energy Conversion and Management*, 95:131-139, 2015.

D Buoro, M Casisi, A De Nardi, P Pinamonti and M Reini. Multicriteria optimization of a distributed energy supply system for an industrial area. *Energy*, 58:128-137, 2013.

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C Covassin, A De Nardi and M Reini. Examples of energy integration opportunities in an industrial area. In: Production engineering and management for furniture industry, M Nicolich and A Riegel. *Edizioni Goliardiche*, 2011.

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